ON-ORBIT SERVICEABILITY OF SPACE SYSTEM ARCHITECTURES

by

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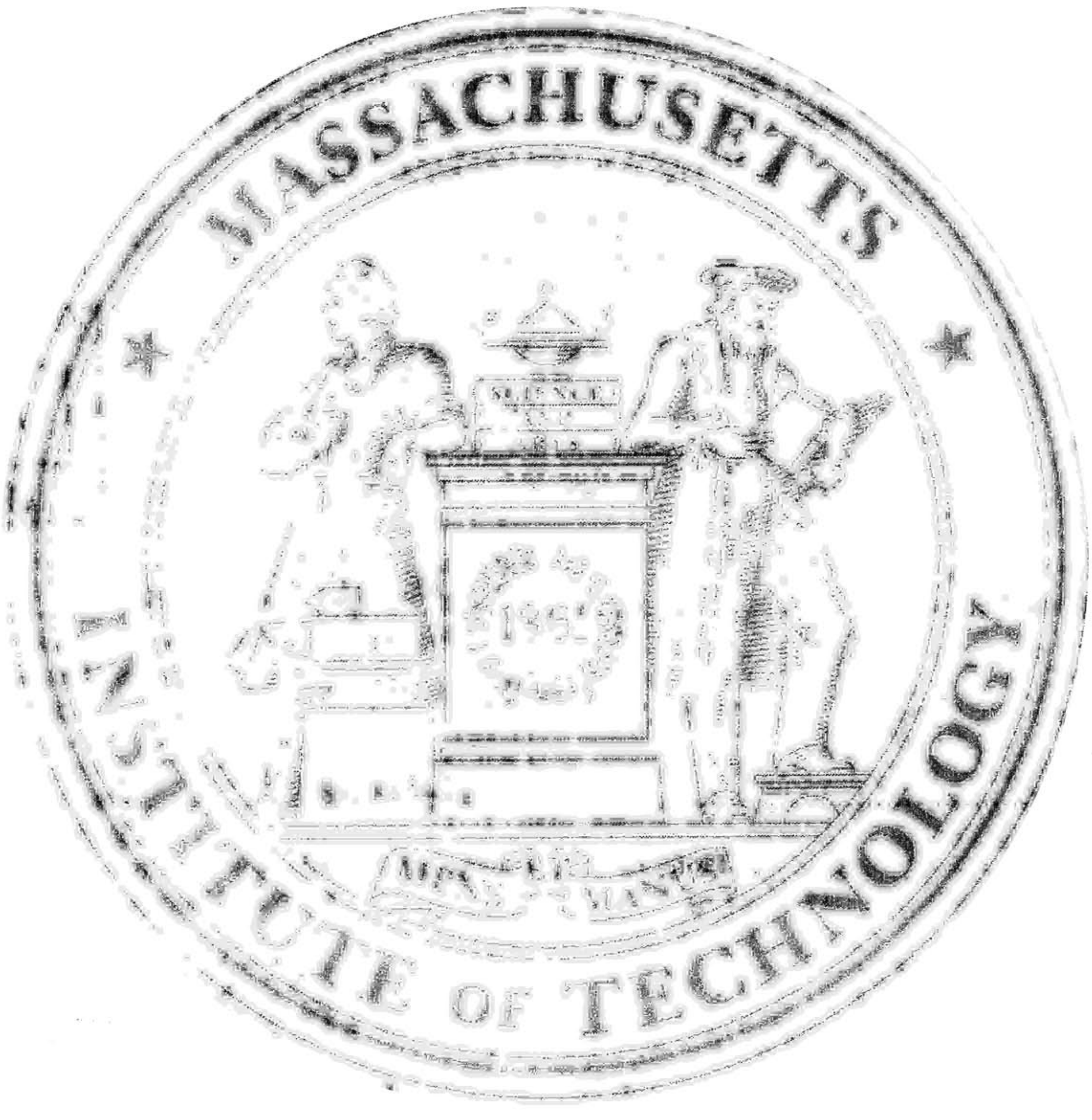
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Abstract

On-orbit servicing is the process of improving a space-based capability through a combination of in-orbit activities which may include inspection; rendezvous and docking; and value-added modifications to a satellite's position, orientation, and operational status. As a means to extend the useful life or operational flexibility of spacecraft, on-orbit servicing constitutes one pathway to a responsive space enterprise. Following launch, traditional satellite operations are tightly constrained by an inability to access the orbiting vehicle. With the exception of software upgrades from ground controllers, operators are wedded to supporting payload technologies that become rapidly obsolete and to bus structures that deform during the stress of launch and degrade in the harsh environment of space. On-orbit servicing offers satellite operators an option for maintaining or improving space-based capabilities without launching a new spacecraft.

Numerous studies have been performed on on-orbit servicing, particularly regarding the architecture of the servicing provider. Several customer valuation case studies have also been performed to identify the economic case (or lack thereof) for different categories of servicing missions. Little work, however, has been done to analyze the tradespace of potential on-orbit servicing customers—a global analysis of operational satellites currently orbiting the Earth. The goal of this research is to develop and test a methodology to assess the physical amenability of satellites currently in operation to on-orbit servicing. As defined here, physical amenability of a target satellite, or "serviceability," refers to the relative complexity required of a teleoperated or autonomously controlled robotic vehicle to accomplish on-orbit servicing.

A three-step process is followed to perform serviceability assessments. First, a taxonomy of space systems is constructed to add structure to the problem and to identify satellite attributes that drive servicing mission complexity. Second, a methodology is proposed to assess serviceability across the four servicing activities of rendezvous, acquire, access, and service. This includes development of an agent-based model based on orbital transfers as well as a generalized framework in which serviceability is decomposed into four elements: (1) knowledge, (2) scale, (3) precision, and (4) timing. Third, the value of architecture frameworks and systems engineering modeling languages for conducting serviceability assessments is explored through the development of a discrete event simulation of the Hubble Space Telescope. The thesis concludes with prescriptive technical considerations for designing serviceable satellites and a discussion of the political, legal, and financial challenges facing servicing providers.

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To God for the opportunity, my family for the confidence, and Dr. Wheelon for the inspiration.

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Acronyms

ACS	attitude control system
AEHF	Advanced Extremely High Frequency
AERCam	Autonomous Extravehicular Robotic Camera
AFRL	Air Force Research Lab
ASTRO	Autonomous Space Transfer and Robotic Orbiter
BOL	beginning-of-life
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CIMOSA	Computer Integrated Manufacturing Open Systems Architecture
CMG	control-moment gyro
CONUS	continental United States
COUPOS	Committee on Peaceful Uses of Outer Space (UN)
DARPA	Defense Advanced Research Projects Agency
DARS	DoD Architecture Repository System
DART	Demonstration of Autonomous Rendezvous Technology
DMSP	Defense Meteorological Satellite Program
DoDAF	Department of Defense Architecture Framework
DSP	Defense Support Program
EEFBD	Enhanced Functional Flow Block Diagram
EELV	Evolved Expendable Launch Vehicle
ESD	Engineering Systems Division
EOL	end-of-life
ESA	European Space Agency
ETS	Engineering Test Satellite
EVA	extravehicular activity
FALCON	Force Application and Launch from CONUS
FEAF	Federal Enterprise Architecture Framework
FOV	field of view
FY	fiscal year
GEO	geosynchronous Earth orbit
GPS	Global Positioning System
GSO	geostationary Earth orbit
GSV	Geosynchronous Servicing Vehicle
HEO	high Earth orbit
IAF	Integrated Architecture Framework
ISO RM-ODP	International Standards Organization Reference Model for Open Distributed Processing
ISS	International Space Station
ITAR	International Traffic in Arms Regulations
LEO	low Earth orbit
MATE	Multi-Attribute Tradespace Exploration
MEO	medium Earth orbit
Mini AERCAM	Miniature Autonomous Extravehicular Robotic Camera
MIT	Massachusetts Institute of Technology
MMU	Manned Maneuvering Unit

MoDAF	Ministry of Defence Architecture Framework
MUOS	Mobile User Objective System
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NATO	North American Treaty Organization
NDT	non-destructive testing
NPOESS	National Polar Operational Environmental Satellite System
NRC	National Research Council
NRL	Naval Research Laboratory
NSTC	National Science and Technology Council
OE	Orbital Express
OMV	Orbital Maneuvering Vehicle
OOS	on-orbit servicing
ORU	orbital replacement unit
OTV	Orbital Transfer Vehicle
P3I	Preplanned Product Improvement
PDD	Presidential Decision Directive
POES	Polar Operational Environmental Satellite
PPP	public-private partnership
RASCAL	Responsive Access Small Cargo Affordable Launch
RMS	Remote Manipulator System
ROV	remotely operated vehicle
SBIRS High	Space-Based Infrared System High
SDI	SpaceData International
SLES	Spacecraft Life Extension System
STOCC	Space Telescope Operations Control Center
STScI	Space Telescope Science Institute
STS	Space Transportation System
SUMO	Spacecraft for the Universal Modification of Orbits
TDRSS	Tracking Data Relay Satellite System
TOGAF	The Open Group Architecture Framework
TRL	technology readiness level
UCS	Union of Concerned Scientists
USAF	United States Air Force
USML	United States Munitions List
WFPC	Wide Field Planetary Camera
WGS	Wideband Gapfiller Satellites
ZCS	Zero Closing Speed

1 Introduction

Since the dawn of the space age with the launch of the Soviet Union's Sputnik satellite on October 4, 1957, the human footprint in space has grown from fleeting missions by two superpowers into a global enterprise. Early space system development was driven primarily by the Cold War-era objectives of the United States and Soviet Union: delivery vehicles for nuclear war (ballistic missiles), target detection (strategic reconnaissance), and international prestige (space race). Nearly a half-century separated from those formative years, a global space industry has emerged in which approximately 800 active satellites are operated by 38 countries (Union of Concerned Scientists, 2005). Applications today include communications, navigation, environmental monitoring, remote-sensing, and scientific research. Satellites have become indispensable tools for maintaining international security, enabling global communications, and providing early warning of natural disasters.

Produced by the "flagship" aerospace industry, the goal of space systems has traditionally been high technical performance. This legacy—embodied by the Apollo program—was ill-equipped to respond to global economic competition which has commoditized many of the services offered by the space industry.

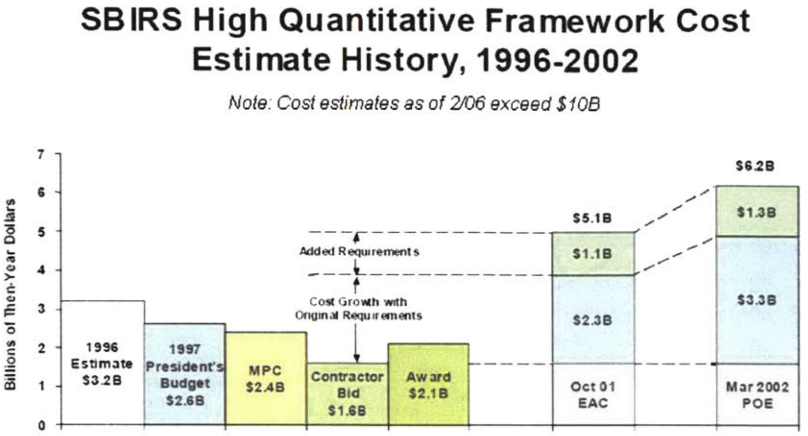
> As in so many industries, infrastructure, institutions, and even mindsets have become misaligned with the environment and are now "monuments" blocking forward progress. Attempts to address these barriers through downsizing, outsourcing, mergers, acquisitions, and regulatory reform all fail to engage the root cause of the challenge. What's needed is a fundamentally different orientation to creating value for the many stakeholders in this industry, other sectors, and society at large—over the lifecycle of a wide range of aerospace systems (Murman *et al.*, 2002).

Additional features of the space industry, including low-volume production and highly complex products, further challenge efforts to implement efficient business processes. Perhaps the greatest barriers to a space industry better aligned to delivering stakeholder value are the significant sources of market instability. The past decade has been characterized by changing tactical and strategic threats, funding instability, transient acquisition practices, and a collapse in the projected demand for satellite communications due to an extraordinary installation of fiber optics cables and proliferation of cell phone service during the late 1990's.

The current paradigm for designing, acquiring, and operating space systems is underperforming within this highly uncertain environment. Traditional "divide and conquer" systems engineering processes are not well-suited to the conceptual design of system-of-systems into which satellites are increasingly integrated. Space system acquisitions are often characterized by tremendous cost overruns and schedule slips. In particular, acquisition of government space systems in the U.S. is in turmoil (Table 1.1) as reduced government oversight in the 1990's resulted in high-risk, underfunded programs (Caceres, 2006). Flaws exist across civil, military, and intelligence acquisition efforts as evident in the National Polar Operational Environmental Satellite System (NPOESS), Space-Based Infrared System High (SBIRS High - Figure 1.1), and Future Imagery Architecture (Defense Science Board, 2003). Finally, satellite operations are tightly constrained by the physical inability to access systems following launch. The cumulative weight of these problems and limitations is significant for the U.S. given that most government mission areas in space (including early warning, weather, communications, navigation) are currently in transition (Defense Science Board, 2003).

Table 1.1 Troubled Government Space System Acquisitions

	Original Projection	Best Estimate (as of January 2006)
AEHF Name: Advanced Extremely High Frequency Satellites Contractor: Lockheed Martin Description: constellation of secure, survivable, and jam-resistant GEO communications satellites; follow-on to Air Force's MILSTAR	Attributes: five satellites, including one ground spare Cost: $2.5 billion Schedule: first launch by 2004	Attributes: three satellites Cost: $5.3 billion, expected to reach $6 billion Schedule: first launch no earlier than 2008
GPS III Name: Global Positioning System Contractor: TBD Description: fifth-generation series of replenishment satellites with higher power levels, increased anti-jamming capabilities, a more precise civil signal, and additional military signals	Attributes: initial procurement plans called for a block upgrade of 51 satellites Cost: not reported Schedule: first launch by 2009	Attributes: 24-36 satellites Cost: $2.5-5 billion Schedule: first launch by 2012; a launch as late as 2015 has been proposed by the Air Force because of a SBIRS-High funding crunch
MUOS Name: Mobile User Objective System Contractor: Lockheed Martin Description: constellation of narrowband mobile communications satellites; follow-on to Navy's UHF Follow-On satellite system	Attributes: ten satellites Cost: $6 billion Schedule: first launch by 2007 with a full operational capability by 2010	Attributes: six satellites Cost: expected to grow with increased development time Schedule: first launch by 2013 with a full operational capability by 2020
NPOESS Name: National Polar Orbiting Operational Environmental Satellite System Contractor: Northrop Grumman Description: Air Force-NOAA collaboration to develop joint meteorological satellites, follow-on to DMSP and POES	Attributes: six satellite constellation and a technology demonstration satellite Cost: $6.9 billion Schedule: first launch by 2008	Attributes: restructuring; may eliminate instruments and technology demonstration Cost: $8.1-9.1 billion Schedule: first launch around 2012
SBIRS High Name: Space-Based Infrared System High Contractor: Lockheed Martin Description: GEO component of a two-tiered ballistic missile early warning satellite system, DSP follow-on	Attributes: five satellites Cost: $3.9 billion Schedule: first launch by 2002	Attributes: five satellites Cost: $10-12 billion Schedule: first launch by 2007
WGS Name: Wideband Gapfiller Satellites Contractor: Boeing Description: high-capacity communication satellites to augment Air Force and Navy systems	Attributes: five satellites Cost: $1.5 billion Schedule: first two launches in 2004	Attributes: five satellites Cost: $2 billion Schedule: first two launches in 2006



Source: BAH Study Space Systems Development Growth Analysis Report

- MPC: Most Probable Cost
- EAC: Estimate at Completion
- POE: Program Office Estimate

Figure 1.1 Cost overruns of Space-Based Infrared System High (Defense Science Board, 2003)

The Space Systems, Policy, and Architecture Research Group was formed at MIT to tackle these issues with interdisciplinary research that touches upon space systems architecture and design, systems engineering, and economics. In particular, a theory of flexibility is being applied to space system design to provide a better understanding of cost, schedule, and performance risk. The general goal of this research is to address the problems and limitations associated with traditional design, acquisition, and operation of space systems by proposing and demonstrating the value of a more flexible approach.

1.1 Background

This section begins by highlighting the importance of front-end conceptual design and back-end maintenance for complex systems and identifies limitations in traditional spacecraft design and operation. Next, on-orbit servicing (OOS) is presented as a paradigm shift that addresses many of these limitations. This section concludes by decomposing OOS mission areas and mapping OOS applications to physical forms of servicing.

1.1.1 Complex Systems Problems

Empirical data indicates a relationship between product quality metrics and systems engineering effort. Figure 1.1 displays the results of an internal study by NASA which compared program cost overruns with the percentage of the budget dedicated to preliminary design and requirements definition. The impact of "upfront" systems engineering was tremendous. Although the majority of costs are committed during these early phases, it was found that most programs allocated less than 10% and went over budget by more than 40%. Furthermore, no NASA program in the study that invested less than 5% in preliminary design and requirements definition overran by less than 80% (Gruhl, 1992). In exploring the value of systems engineering, Honour (2004) synthesized the results of six studies, including the NASA study, and found that an optimum systems engineering effort will typically be 15-20% of total development cost.

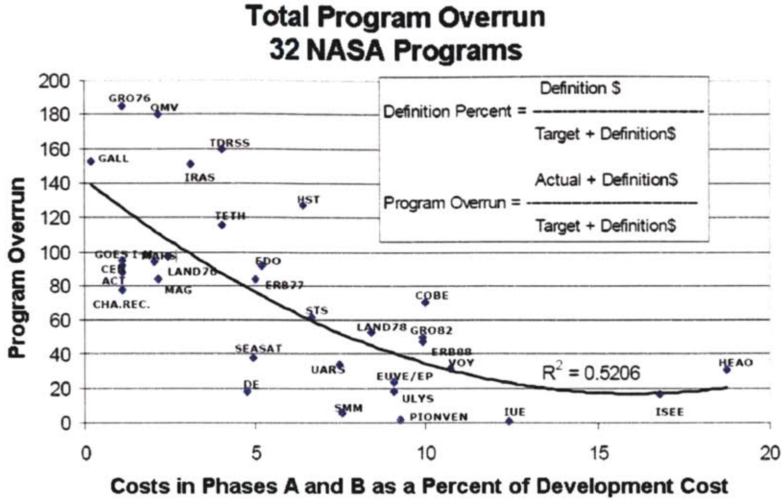


Figure 1.2 Importance of 'Upfront' Systems Engineering (Gruhl, 1992)

Just as the ease of change in early system design leads to fluid requirements and system uncertainty in early lifecycle phases, component wear-out and degradation during operations leads to high-variability in the distribution of system states towards end-of-life (EOL). Figure 1.3 notionally depicts the uncertainty in the state of complex systems that are hard to access as a function of lifecycle phase.[1] For systems which are deployed in harsh environments or for extremely long operational lives (*e.g.*, satellites, nuclear weapons), this problem is further exacerbated.

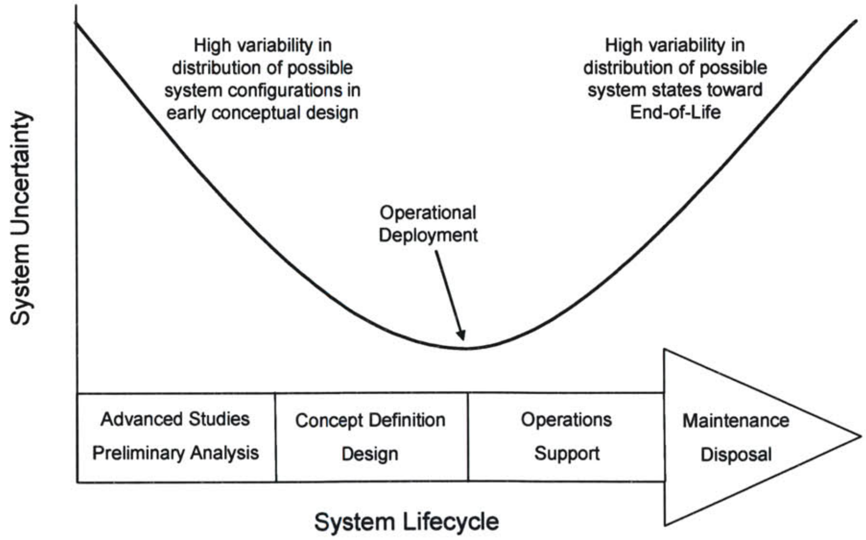


Figure 1.3 Lifecycle Uncertainty for Inaccessible Systems

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[1] A surge in system uncertainty might also occur at beginning-of-life if the system is one of the first units produced or if operational deployment is risky (*e.g.*, spacecraft).

1.1.2 Limitations of Traditional Spacecraft Design

Consider a national transportation system in which cars and trucks are unique. Forget about automobiles with standard mechanical designs and exchangeable parts. Drivers have their own custom vehicle built with unique tires, steering wheels, and other parts. Cars and trucks are designed to last for a decade without any maintenance or refueling. Rather than visiting repair shops when something breaks, cars carry their customized parts in a large trunk. This trunk would contain spare batteries, extra steering wheels, and a complete set of new tires. Of course, without access to service stations, cars would need to carry fuel as well. This would be accomplished by every vehicle towing its own oil tank. When the car runs dry, its owner pushes it off the road. To take its place, an entirely new custom-made vehicle is purchased by the driver. This would be a poor way to build a transportation system (Hastings *et al.*, 2001). Made-from-scratch vehicles are extremely expensive. Hauling a lifetime of fuel and spare parts is inefficient. Dumping vehicles because the fuel tank is empty is a waste. Yet this transportation scenario is representative of how most space systems are designed and how virtually all are operated.[2]

Following launch, traditional satellite operations are tightly constrained by an inability to access the orbiting vehicle. With the exception of software upgrades from ground controllers, operators are wedded to supporting payload technologies that become rapidly obsolete, and to bus structures that deform during the stress of launch and degrade in the harsh environment of space. The inaccessibility of satellites following launch makes them vulnerable to failures before reaching EOL. Historical analysis indicates that the combination of the 9% failure rate of satellites during their operational lives with the 4-5% failure rate of launch vehicles will cause approximately one out of seven satellites to fail before EOL (Sullivan, 2001). This is particularly unfortunate given that a typical geosynchronous Earth orbit (GEO) satellite costs around $125 million for the satellite and launch (Pratt *et al.*, 2003).

The critical mission areas fulfilled by government space programs and the drive for investor return in the commercial space industry combined with the high cost of space systems has led to an extremely risk-averse industry. Long (2005) notes that this environment has driven satellite designers toward three common elements of design: redundancy, proven technology, and long operational lives.

- **Redundancy** – Space systems incorporate massive redundancy to mitigate the risk of component failure. Components may fail due to design flaws, emergent interaction effects with other spacecraft systems, exposure to the harsh environment of space, or other random events. Incorporating redundancy leads to very complex systems, increasing spacecraft mass and cost. The value of redundant systems is only delivered in the event of component failure.

- **Proven technology** – Designers are pressured to incorporated legacy hardware on space systems. Technology readiness level (TRL) is metric developed by NASA to label

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[2] While the GEO communications industry has converged to some extent on a small number of standard buses as a result of orbit geometries and payloads that are similar across most missions, satellites certainly lack the repair and refuel architecture of the automobile industry.

technological maturity. Classified on a scale of one through nine, most designs incorporate a TRL of at least eight to insure "flight qualified" hardware. While use of proven technology mitigates mission risks, it also limits potential satellite performance and industry innovation.

- **Long operational lifetimes** – Given that break-even points of modern GEO communications satellites do not occur until around the 6th operational year and that communications satellites are commonly referred to as 'cash cows' in later years of operation (due to low recurring costs), satellites typically are designed for long lives. The high costs associated with increasingly complex payloads and improvements in supporting bus subsystems (*e.g.,* ion propulsion) has lead to increases in satellite design lifetimes (Figure 1.4).

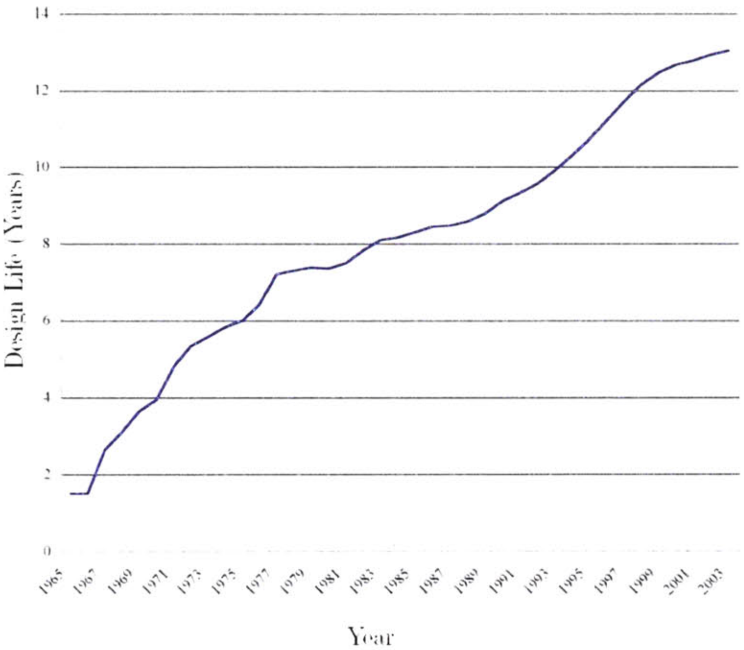

Figure 1.4 Average Design Life of Active GEO Satellites (Sullivan, 2005)

One downside of long design lifetimes is the inability to update space-based capabilities with modern avionics in a timely manner during an era dictated by "Moore's Law" (*i.e.,* the doubling of processing speed of new computer chips every 18-24 months). This slowdown of the space industry's "clockspeed" also limits the agility of satellite operators in capturing emergent terrestrial markets.

1.1.3 What is On-Orbit Servicing?

On-orbit servicing is the process of improving a space-based capability through a combination of in-orbit activities which may include inspection; rendezvous and docking; and value-added modifications to a satellite's position, orientation, and operational status. OOS activities include remote-sensing, orbital modification, satellite rescue, refueling, upgrading, assembly, and repair operations. Five high-level functions of OOS are defined here: (1) inspect, (2) relocate, (3) restore, (4) augment, and (5) assemble.[3] These functions are not mutually exclusive. For example, inspection may be required to support the docking activity of relocation missions.

1) **Inspect** – Observation of a space object from an attached position or a remote surveillance vehicle provides space situational awareness and may be a necessary precursor for other OOS activities. This includes proximity operations to assess a space object's physical state (*i.e.*, position, orientation, and operational status). In the case of a satellite, inspection may include characterization of the spacecraft payload and assessment of the bus exterior for damage. For example, on the Space Shuttle's return to flight mission (STS-114), Discovery's robotic arm incorporated an Orbiter Boom Sensor System with a camera and laser to inspect for tile damage on Shuttle's protective skin (Heiney, 2005).

2) **Relocate** – Modification of the orbit of a space object may be desired to support constellation reconfiguration, tactical maneuvering, boosting of GEO satellites to higher orbits for EOL retirement, controlled reentry of low Earth orbit (LEO) spacecraft, debris cleanup, and rescuing satellites that became stranded from a maneuver or launch vehicle failure. A rescue capability could have saved $1.2 billion of taxpayer dollars in April 1999 when the Milstar 3 satellite failed to reach its operational slot in GEO due to an upper stage failure. Although stranded in a useless orbit without enough fuel to do orbit-raising on its own, two years could have elapsed before the spacecraft would have sufficiently degraded to rule out a rescue mission (McVey, 2004).

3) **Restore** – Returning a satellite to a previous state (or intended state) enables a wide range of capabilities. Restoration activities include refueling for lifetime extension and maneuverable spacecraft, docking and providing stationkeeping to extend mission life, fixing or replacing faulty hardware, and deploying appendages which fail to reach operational orientations at beginning-of-life (BOL). In October 1984, the crew of Challenger on STS-41G demonstrated the feasibility of on-orbit refueling by transferring 60 kg of hydrazine to a typical satellite. A three-hour extravehicular activity (EVA) consisting of two astronauts was used to complete the operation (NASA, 1984).

4) **Augment** – Increasing the capability of a satellite consists of replacing or adding hardware which improves spacecraft performance. The Hubble Space Telescope's modular design has allowed NASA to equip it with state-of-the-art instruments every few years. Joppin (2004) developed a utility metric for Hubble instrumentation called "discovery efficiency" which is defined as the product of the field of view and the throughput of the instrument. Applying this metric, it was found that the third-generation Wide Field Planetary Camera (WFPC) envisioned for the fourth servicing mission has a discovery efficiency 180 times greater than the first-generation WFPC.

5) **Assemble** – Mating modules to construct space systems enables the construction of large space platforms which could not be transported by existing launch vehicles. For

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[3] The uplink of software updates does constitute improving a space-based capability but is excluded from this definition of *in-orbit* servicing activities. This function is considered outside the scope of this thesis.

example, the International Space Station (ISS), which is still being built, has a mass of nearly 200,000 kg while Space Shuttle and planned heavy-lift variants of the Evolved Expendable Launch Vehicle (EELV) program cap out at approximately 25,000 kg of payload to LEO (Isakowitz, *et al.*, 2004).

A variety of physical architectures have been proposed and developed to provide on-orbit servicing capabilities. In general, four broad categories of servicing forms exist: (1) proximity inspector, (2) space tug, (3) pre-planned servicer, and (4) all-purpose servicer. A comprehensive analysis of past, present, and future servicing provider architectures is included in Chapter 2.

1) **Proximity inspector** – A proximity inspector is a free-floating vehicle or attached surveillance instrument which characterizes a space object without physical contact. For example, NASA Johnson Space Center is currently developing a free-floating nanosatellite for external inspection and remote viewing of human space flight activities called the Miniature Autonomous Extravehicular Robotic Camera (Mini AERCam) (Fredrickson *et al.*, 2002).

2) **Space tug** – A space tug is a vehicle designed to rendezvous and dock with a space object; make an assessment of its current position, orientation, and operational status; and then either stabilize the object in its current orbit or move the object to a new location with subsequent release. Space tug missions include applications of the relocation servicing activity: stationkeeping maneuvers to maintain the orbit of target satellites and reposition spacecraft, including the rescue of satellites launched into incorrect orbits, the retirement of satellites into 'graveyard' orbits, and on-demand maneuvers to meet changing mission requirements. Orbital Recovery Corporation is currently developing an "orbital tugboat" called the Spacecraft Life Extension System (SLES) to supply propulsion, navigation, and guidance to target satellites in their orbital slots for 10+ years (Wingo, 2004).

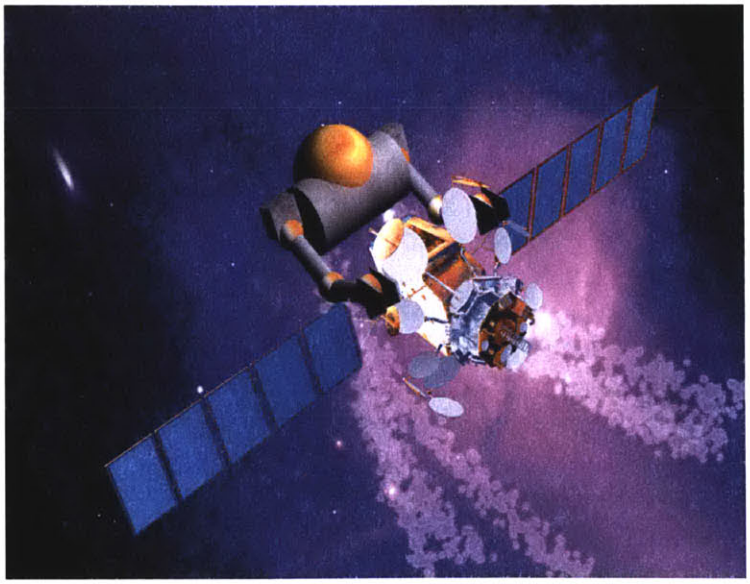

Figure 1.5 Artistic representation of a space tug

3) **Pre-planned servicer** – A pre-planned servicer is a vehicle that is able to improve the state of target satellites that have been designed for servicing. Pre-planned servicers incorporate most of the functionality of space tugs (with arbitrary docking capability being a key exception) in a vehicle that is also capable of fluid transfer and change-out of spacecraft components termed orbital replacement units (ORU). The Defense Advanced Research Projects Agency (DARPA) is currently developing an autonomous servicing system known as Orbital Express (OE) for target satellites with standardized interfaces (Potter, 2003).

4) **All-purpose servicer** – An all-purpose servicer is a vehicle that is able to improve the state of target satellites, regardless of whether that target satellite has been designed for servicing. All-purpose servicers incorporate the functionality of space tugs and pre-planned servicers in a vehicle that also is able to repair faulty spacecraft components and conduct assembly operations.

1.1.4 Why Service Satellites?

The only existing operational satellites that are serviced are the Hubble Space Telescope and the ISS. These space systems are maintained by humans in expensive servicing operations carried out by the Space Shuttle and Russian spacecraft. In the case of Hubble, the initial $1 billion cost of deploying the Orbiting Observatory has been exceeded by four servicing missions estimated to cost $500 million apiece (Hastings *et al.*, 2001). Given these costs, the human servicing model is clearly not applicable to the majority of commercial space systems. On-orbit servicing will not occur if the perceived costs outweigh the perceived benefits. However, developments in autonomous and teleoperated vehicle technology as well as the potential for sharing the cost of an on-orbit servicing infrastructure across multiple target satellites enable a business case to be made for robotic servicing in certain markets.

Servicing provides options for space missions traditionally constrained by inaccessible satellites, mitigates vulnerabilities to monolithic spacecraft, and generally enables a more robust space enterprise. Benefits of servicing can be divided into five broad categories: reduce risk of mission failure, reduce mission cost, increase mission performance, improve mission flexibility, and enable new missions.

- **Reduce risk of mission failure** – A space-based servicing infrastructure reduces the risk of satellite failure across the entire lifecycle. The failure of Milstar 3's upper stage would not have compromised its mission had a space tug been available for a rescue mission. Faulty spacecraft systems discovered at BOL can be fixed (*e.g.*, science-critical aberrations in Hubble's optical assembly were fixed in the first servicing mission). Servicing vehicles may be employed to mitigate the risk posed by orbital debris through cleanup operations.[4] Brown (2004) has also explored the possibility of replacing the

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[4] Using ground-based optical and radar telescopes, U.S. Space Command tracks more than 9,000 space objects with major axes in excess of ten centimeters. An additional 100,000 objects ranging from one to ten centimeters is estimated to be in Earth orbit. Debris consists primarily of dead satellites, spent upper stages, separation devices, bolts, and paint chips. It is estimated that the debris population continues to grow by more than 175 metric tons per year (Futron Corporation, 2002).

paradigm of launching monolithic systems on a single heavy lift vehicle (single-point failures) with the launch of redundant spacecraft components separately on small launch vehicles followed by on-orbit assembly.

Table 1.2 Recent Satellite Failures

Russian Telecom Satellite Fails After Sudden Impact
Space Daily
30 March 2006

The Russian Satellite Communications Company's Express AM11 telecommunications satellite suffered a sudden failure on Wednesday. "At present, providing services via the Express-AM11 satellite is impossible," the company said in a statement.

Telemetry showed the failure, which occurred at 6:55 a.m. Moscow Time, was caused by "a sudden external impact on the spacecraft," RSCC said in a statement. The cause most probably was space garbage of unknown origin. The result was instantaneous depressurization of the satellite's thermal control system fluid circuit, followed by "a sudden outburst of the heat-carrying agent."

The spacecraft subsequently lost its geostationary orientation and proper rotation. Although ground engineers were able to maintain marginal control, RSCC said the AM11 "started approaching the crucial values that can result in the total loss of the satellite."

Along with the effective loss of the satellite, the company said the presence of space garbage most likely also renders its orbital slot unusable. Therefore engineers have engaged "organizational and technical measures aimed at removing the Express-AM11 from 96.5 East into space disposal orbit."

RSCC has downloaded the satellite's backup capacities on the east orbital arc and as a result all Russian commercial TV and radio broadcasting has been restored. In addition, engineers have transferred all official communications channels to the Express-A2 (103 East), Express-AM2 (80 East) and Express-AM3 (140 East) satellites.

Sky TV Knocked Off Air as Satellite Goes 'Missing'
The National Business Review
31 March 2006

Sky Television's [NZSX:SKT] satellite may be missing without hope of recovery. Subscribers around the country lost their signals Thursday evening from about 7pm in an outage that was initially described as being due to weather conditions. That automated announcement included an invitation to click through and check the satellite feed strength -- but that screen revealed there was no feed at all.

Inundated with telephone calls, the operator eventually put up a new front page on its website advising that the problem was based in an outage on Sky's Singtel-owned Optus B1 satellite. That web page said Sky Sport 1 was free-to-air on UHF for fans trying to tune into the Live Cricket Awards, but gave no indication of when the problem might be resolved.

According to Newswire, the outage affected all customers in both New Zealand and Australia. Sky TV has about 550,000 subscribers in New Zealand alone. Newswire reported that the outage followed a routine repositioning maneuver and that the company expected to resume normal operations within hours. In a later report, it quoted a Sky spokesman* who said the satellite was communicating but out of position and that Optus was undertaking a "re-pointing" maneuver.

But unconfirmed reports received by *The National Business Review* suggest that the satellite has gone 'missing' entirely and communications with it may not be recovered at all. Those reports did not specify the nature of the problem or whether it was limited to loss of telemetry.

Two replacement satellites are in construction but are not likely to be launched for months. The Optus B1 satellite is about 14 years old and, according to industry sources, has been in urgent need of a replacement for almost a year after losing its primary satellite control processor.

- **Reduce mission cost** – Given the Hubble and Shuttle experience, on-orbit servicing is typically associated with higher mission costs. The servicing provider requires an additional fee and the target satellite may pay a mass penalty for incorporating a modular bus structure with docking and refueling ports.[5] However, servicing does offer several pathways to reduced mission cost. First, operators may choose to incorporate less redundancy into spacecraft. Second, operators may choose to design satellites for a shorter life, reducing upfront costs while delaying the decision either to allocate funds for servicing or to abandon at a later date. Third, the high-value components of a satellite (*i.e.* payload, bus structure) might be separated from low-value components (*i.e.*, propellant) during the launch phase. Traditional, expensive launch vehicles might be used for high-level components while emerging, low-cost launch vehicles (*e.g.*, DARPA's RASCAL, DARPA/USAF's Falcon) are used to launch propellant to servicers that refuel the satellite at BOL.

- **Increase mission performance** – Servicing activities may improve spacecraft performance in terms of mission life and payload utility. Servicing tasks may be performed to extend spacecraft life (*e.g.*, refuel, dock and provide stationkeeping, repair faulty components.). More notably, servicing may be employed to increase the payload capabilities. Operators may choose to upgrade to maximize revenue generation, science returns, and/or to prevent technological obsolescence, particularly in the later years of a satellite's operation.

- **Improve mission flexibility** – An on-orbit servicing infrastructure also offers satellite operators an option to modify space system requirements following launch. New payloads may be incorporated for new missions. Emergent terrestrial markets might be captured more efficiently, and spiral deployment of fleets of satellites might be enabled with the benefits of constellation reconfiguration. Relocating satellites with space tugs might be particularly valuable in the development of a wartime surge capability over theaters of operation.

- **Enable new missions** – Perhaps the strongest case for emerging technologies (*e.g.*, robotic on-orbit servicing) can be made when identifying capabilities of such technology that cannot be offered by existing systems. The refueling servicing activity enables new missions in the areas of tactical maneuvering for unpredictable orbits and extremely low altitude, high-drag orbits for Earth observation satellites. While low altitude orbits are important for imaging satellites, they would be particularly valuable for space-based synthetic aperture radar systems in which the power of the radar signal decreases as the inverse of the altitude to the fourth power (Roberts, 2003).

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[5] Target satellite mass penalties for docking and refueling interfaces are relatively low. The redundant docking mechanism and refueling mechanism associated with DARPA's Orbital Express program have masses of 32 kg and 50 kg, respectively (McVey, 2002). GEO communications spacecraft currently weigh upwards of 6000 kg (Pratt *et al.*, 2003).

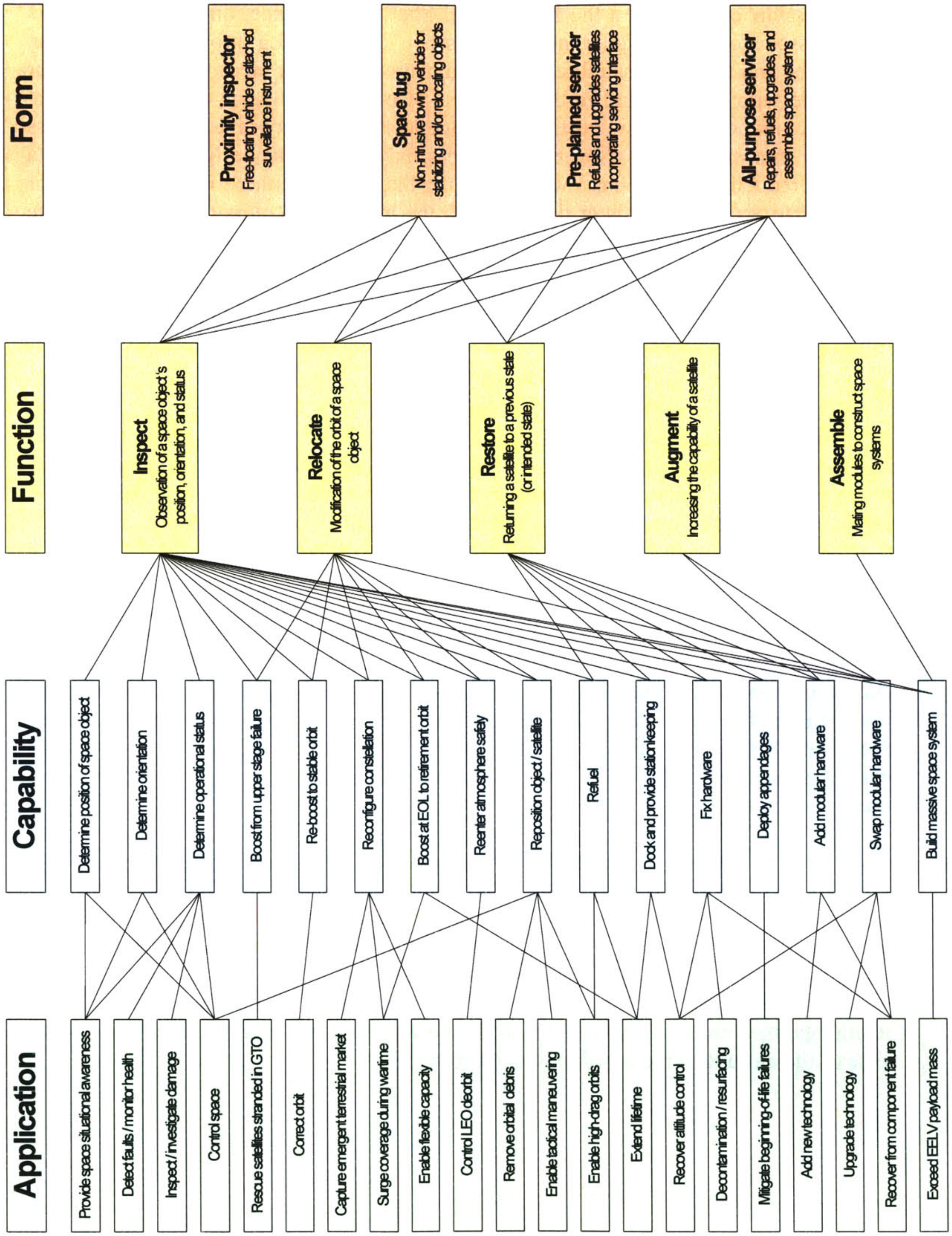

Figure 1.6 Decomposition of On-Orbit Servicing Mission Areas

1.2 Problem Statement

Numerous studies have been completed on OOS. While most studies have converged on point designs for the servicing provider architecture, a few have dealt with servicing customer valuation, estimating the price the market might bear for various forms of servicing (see Section 2.4). The work that does exist on customer satellite architecture (*i.e.*, serviceable satellites) focuses on implementing design changes in future satellites (*e.g.*, Orbital Express). Little work, however, has been done on assessing the amenability of satellites already in orbit to OOS (see Section 2.5). The central aim of this research is to fill this void by surveying the serviceability of space system architectures currently in Earth orbit.[6]

If a decision on whether to service a satellite is to be made, evaluating the perceived value received by the customer needs to be combined with an analysis of the system to be serviced. This requires an understanding of the amenability of different orbits to OOS as well as the degree of complexity associated with servicing various satellite bus designs. Serviceability assessments also require simulations of satellite behavior and operation. An implicit assumption in the research questions outlined below is that static models are not sufficient for deriving meaningful results for the question of serviceability. Given the evolution of satellite health (*e.g.*, failing gyroscopes) and servicer availability (*e.g.*, limited ΔV budget) over time, the question of serviceability is inherently a dynamic one necessitating executable models.

Before multi-purpose servicing vehicles are stationed on-orbit, a host of issues need to be resolved in the areas of national policy, export control, and international law to inform concepts of operation and potential financing arrangements. However, little previous work exists on OOS that couples qualitative analysis in the political, legal, and financial domains with quantitative analysis in the technical domain. As such, an opportunity exists to contribute to provider architecture research by treating OOS as an "engineering system," a technologically-enabled system characterized by non-trivial feedback from a heterogeneous set of stakeholders.

1.2.1 Research Questions

1) In what areas might original contributions be made to the study of OOS?
    a. What is the state of on-orbit servicing?
    b. What OOS programs have been executed and what programs have been proposed?
    c. What are the findings of key OOS studies?

2) How might a taxonomy of space systems for serviceability be constructed?
    a. What activities comprise a servicing mission?
    b. What are the attributes for categorizing the active population of Earth orbiting satellites?
    c. Which satellite attributes drive serviceability assessments?

3) What is the amenability of existing satellites to OOS?

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[6] In this thesis, serviceability is defined as the cooperativeness of a technical system to *in-situ*, value-added modifications.

    a. Given deployment of a limited OOS capability, in what orbits would a servicing capability most likely be available?
    b. How might relative serviceability assessments be made across various satellite bus designs?

4) How can architecture frameworks inform dynamic serviceability assessments?
    a. What forms of architecture description exist to expand the scope of OOS understanding to both the physical and functional domains?
    b. Can static representations of space systems in the Department of Defense Architecture Framework be extended to incorporate time as a dimension in serviceability assessments?

5) What are the "architectural principles" for developing serviceable spacecraft?
    a. What are the technical challenges facing servicing providers?
    b. What are prescriptive technical considerations for enabling serviceability?

6) What are the non-technical challenges facing OOS implementation?
    a. What are the political issues and legal constraints for OOS?
    b. What economic themes characterize OOS? What financial models make sense for servicing providers?

1.2.2 Potential Contributions

The goal of this research is to improve the state of knowledge regarding on-orbit servicing and the practice of systems engineering as it relates to system architecture and design. Potential contributions include a comprehensive survey of past, present, and future OOS studies and programs; a structured framework for classifying space systems; a generalized process for assessing system serviceability; a framework for the ordering of space systems according to on-orbit serviceability; prescriptive technical considerations for designing serviceable spacecraft; and strategies for overcoming hurdles to OOS implementation.

1.3 Methodology

Figure 1.7 depicts the general research methodology and potential contributions of this thesis. Inputs to each step are listed on the left. Although each step roughly maps to a chapter, this figure is best interpreted as the general process that was followed to conduct the research. In some cases, steps span multiple chapters (*e.g.*, theoretical development of serviceability framework includes the decomposition of servicing activities in Chapter Two, lessons learned from servicing offshore oil platforms in Chapter Three, and application of architecture frameworks in Chapter Six).

First, an extensive literature review of existing OOS programs and studies is conducted to assess the state of on-orbit servicing. Emphasis is placed on servicing programs that have actually flown or for which hardware has been developed. **Second**, structure is added to the problem of conducting serviceability assessments through the development of a taxonomy of servicing activities and space systems (with a focus on satellite attributes that might inform later serviceability assessments). **Third**, a general theory of serviceability is developed. This step begins with extracting lessons learned from servicing offshore oil platforms. Satellite databases provide a context for understanding what information is widely available for developing an "actionable" serviceability framework. **Fourth**, the serviceability framework is implemented in two models. One model analyzes serviceability as a function of orbital location and is applied to the GEO satellites. The other model analyzes serviceability as a function of all four servicing activities and is applied to the Hubble space telescope. **Fifth**, lessons learned from the previous four steps are synthesized to derive architectural characteristics of "serviceable" spacecraft. **Sixth**, structured interviews and further qualitative and quantitative analyses were performed to examine the political, legal, operational, and financial challenges facing implementation of an OOS infrastructure.

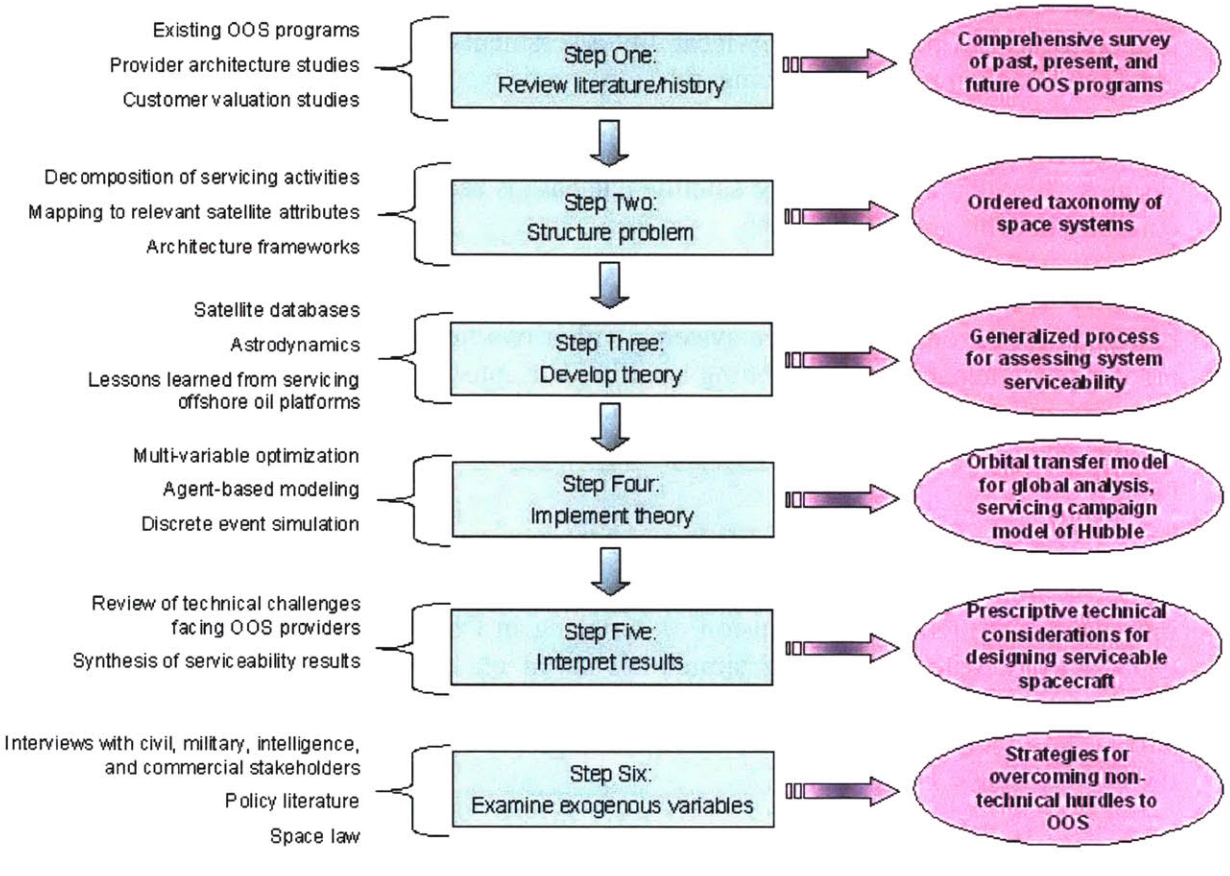


Figure 1.7 Research Methodology and Contributions

1.4 Thesis Outline

The thesis is composed of nine chapters. Each of the next six chapters seeks to answer one of the six research questions asked in Section 1.2.1. Having introduced the general issue of OOS in Chapter 1, Chapter 2 explores existing OOS literature and focuses the thesis on areas rich for further inquiry. Chapter 3 adds structure to the largely technical analysis performed in Chapters 4 and 5 regarding the serviceability of potential target satellites for OOS across both static and dynamic contexts. Chapter 6 synthesizes the technical results with prescriptive statements for the design of future serviceable spacecraft. Chapter 7 broadens the discussion to include the servicing provider with a GEO space tug serving as an illustration of the larger political, legal, and financial issues facing OOS implementation. Chapter 8 discusses the implications of the thesis, how it relates to ongoing research at MIT, and discusses potential extensions of the work. Finally, Chapter 9 offers general conclusions regarding the state of OOS.

- **Chapter 2, On-Orbit Servicing Overview**, surveys historical milestones, current programs, ongoing technology development efforts, and contemporary studies on OOS. Key findings include a summary of on-going programs and research opportunities to contribute to existing work.

- **Chapter 3, Development of an Ordered Taxonomy for Space Systems**, adds structure to the problem of performing serviceability assessments. Initially, four unique activities are found to compose a servicing mission: rendezvous, acquire, access, and service. Next, universal satellite attributes such as mission area, attitude control system, and payload configuration are enumerated as means to standardize the description of space systems. Finally, an open-source satellite database is used to survey operational satellites currently in orbit around the Earth.

- **Chapter 4, Methodology to Assess Amenability of Satellites to On-Orbit Servicing**, builds on the taxonomy of space systems with a two-tiered approach: (1) assessment of rendezvous amenability by inputting satellite data into an agent model based on orbital transfers and (2) development of a framework for comparing the relative amenability of various satellite bus designs to the full set of OOS activities including acquire, access, and service.

- **Chapter 5, Development of a Dynamic Servicing Architecture Model**, explores the value of architecture frameworks for conducting serviceability assessments. Having investigated the temporal dimension of servicing in Chapter 4 for only the rendezvous OOS activity with a servicing simulation based on orbital transfers, this simulation incorporates all four OOS activities—rendezvous, acquire, access, and service—in a single executable model. In particular, a multi-year servicing campaign is modeled for the Hubble Space Telescope.

- **Chapter 6, Architecting for Satellite Servicing: Prescriptive Technical Considerations**, synthesizes the lessons learned from Space Shuttle servicing missions, previous studies, and Chapters 2 through 5 to determine how the design of future satellites may be affected by an OOS requirement.

- **Chapter 7, On-Orbit Servicing Implementation**, addresses OOS issues located at the interface of technology and policy. In particular, the chapter surveys political, legal, and financial challenges facing OOS and proposes implementation strategies for the realization of a satellite servicing infrastructure.

- **Chapter 8, Discussion**, discusses the applicability and implications of the thesis, surveys related ongoing research at MIT, and proposes extensions for future work.

- **Chapter 9, Conclusions**, discusses the performance of the thesis across the objectives identified in the introduction and draws general conclusions regarding the future of OOS.

2 On-Orbit Servicing Overview

This chapter surveys historical milestones, current programs, ongoing technology development efforts, and contemporary studies on on-orbit servicing. Approximately 200 journal articles, conference papers, and technical and media reports were reviewed for a comprehensive OOS literature review (see References). Although numerous servicing provider architectures have been proposed, the focus here is on servicing programs and missions that have actually flown or for which hardware has been developed. The following questions are addressed in this chapter:

- In what areas might original contributions be made to the study of OOS?
    - What is the state of on-orbit servicing?
    - What OOS programs have been executed and what programs have been proposed?
    - What are the findings of key OOS studies?

2.1 *Historical Milestones*

The ability to service satellites has evolved from a series of growing on-orbit capabilities over nearly five decades of human experience in space. The legacy of attempts to service spacecraft in the early U.S. and Soviet manned space programs (*e.g.,* Skylab and Salyut space stations) to recent tests of autonomous servicing technology (*e.g.,* Japanese ETS-VII, Air Force XSS-10) provides a foundation for understanding future OOS capabilities. Figure 2.1 depicts a timeline of historical milestones in the evolution of OOS technology.

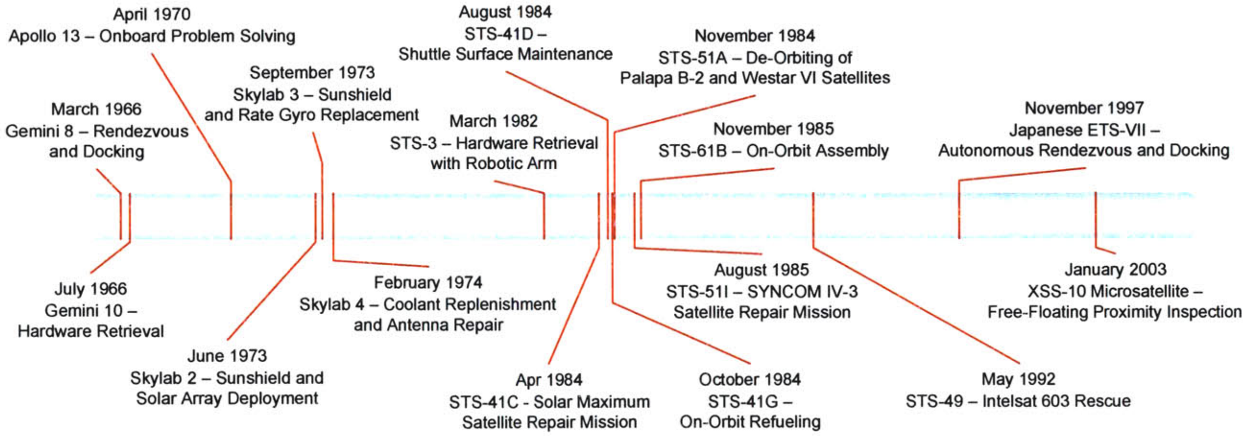


Figure 2.1 Timeline of Historical Milestones

2.1.1 Project Gemini

The follow-on to Project Mercury, Project Gemini was the second U.S. human spaceflight program. Gemini missions were designed to test advanced space travel techniques for Project Apollo. Key advances in the Gemini spacecraft from Mercury included a modular architecture, an orbital modification capability, and an onboard computer (Hacker and Grimwood, 1977). Satellite servicing capabilities demonstrated include the first American EVA (Gemini 4), the feasibility of on-orbit rendezvous (Gemini 6/7), rendezvous and docking with a target vehicle (Gemini 8), hardware retrieval (Gemini 10), and long-duration EVAs (Gemini 12) (NASA Office of Space Flight, 1988). Gemini 8 and Gemini 10 were deemed most relevant to the development of fundamental servicing capabilities (*e.g.,* accomplished specific OOS activities as opposed to

EVA demonstrations which are only applicable to an inhabited servicing architecture). Therefore Gemini 8 and Gemini 10 are highlighted in this section.

2.1.1.1 Gemini 8 – Rendezvous and Docking (1966)

Gemini 8 was the first mission ever to accomplish one of the most fundamental activities of OOS: rendezvous and docking. With a series of burns, Neil Armstrong maneuvered the Gemini capsule into the orbital plane of the Agena target vehicle which was designed to test in-orbit rendezvous and docking. Radar picked up the Agena at approximately 300 km. Inside 50 km, Armstrong and David Scott inspected Agena for damage and then, upon finding none, initiated an automated docking procedure with a velocity of 8 centimeters per second (Hacker and Grimwood, 1977).

2.1.1.2 Gemini 10 – Hardware Retrieval (1966)

Gemini 10 demonstrated the ability to retrieve hardware from the exterior of a spacecraft. On the second of two EVAs, Michael Collins retrieved a micrometeorite collector attached to the Agena target vehicle from Gemini 8. Collins used a gas gun to maneuver between the undocked Gemini capsule and Agena target vehicle. He remained connected to Gemini throughout the EVA through a 15 m umbilical cord (Hacker and Grimwood, 1977).

2.1.2 Project Apollo

Satellite servicing capabilities continued to evolve through the demonstration of live television broadcast (an essential element for future telerobotic servicing) on Apollo 7. Apollo 13 is especially important for understanding the value of servicing for extensive onboard problem solving, mission modification, and resource management (NASA Office of Space Flight, 1988).

2.1.2.1 Apollo 13 – Onboard Problem Solving (1970)

Apollo 13 was aborted after 56 hours of flight due to a loss of service module cryogenic oxygen and consequent loss of capability to generate electrical power in the command module. The astronauts onboard responded by powering down the command module and configuring the lunar module to supply the necessary power and consumables for the trip back to Earth (Apollo 13 Review Board, 1970).

2.1.3 Skylab Space Station

America's first space station, Skylab, sustained severe damage during launch when the meteoroid shield accidentally deployed and subsequently tore off due to atmospheric drag. One of Skylab's main solar panels was also torn off and another solar panel failed to deploy because debris from the meteoroid shield pinned it to the side of the station. This accident precipitated the need for various unplanned repair activities by future crews. The problematic experience with Skylab had one positive consequence: proof that major elements of satellite servicing were technically feasible (NASA Office of Space Flight, 1988).

2.1.3.1 Skylab 2 – Sunshield and Solar Array Deployment (1973)

The launch damage sustained by Skylab was first dealt with on Skylab 2 with astronaut EVAs. First, a makeshift replacement sunshield was installed to deal with high temperatures inside the space station. Initial attempts failed to deploy the jammed solar panel. Two weeks into the 27 day mission, Pete Conrad and Joseph Kerwin were able to deploy the pinned solar panel after a struggle (Belew, 1977).

2.1.3.2 Skylab 3 – Sunshield and Rate Gyro Replacement (1973)

Skylab 3 extended the crew's stay on the space station from one month to two months to study human physiological adaptation to space. Repairs continued from the unmanned launch failure on Skylab 1. During the first EVA, a twin-pole sunshade was installed to supplement the makeshift replacement. The crew also replaced Skylab's rate gyros (Belew, 1977).

2.1.3.3 Skylab 4 – Coolant Replenishment and Antenna Repair (1974)

Skylab 4, the last of the three manned Skylab missions, included the first demonstration of fluid replenishment (laboratory coolant). The mission lasted almost three months and set a record of seven hours for a single EVA which involved replacing film in the solar observatory and repair of an external antenna (Belew, 1977).

2.1.4 Salyut Space Stations

The Soviet Salyut program included seven space station launches between 1971 and 1982. It consisted of many firsts for human spaceflight, including the first space station ever orbited (Bluth and Helppie, 1986). The Salyut program provided the technological basis for the Mir space station.

2.1.4.1 Soviet Salyut 6 – Replenishment with Uninhabited Vehicle (1977)

Salyut 6 constituted the second generation of Salyut stations with a docking port for an uninhabited Progress cargo ship for refueling the station. Progress would dock automatically before being opened and unlocked by cosmonauts on Salyut (Bluth and Helppie, 1986).

2.1.5 Space Shuttle Program

At the outset, the Space Shuttle program promised to be an integral part of an on-orbit servicing infrastructure given its unique remote manipulation capabilities, flexibility, and planned frequency of flights (NASA Office of Space Flight, 1988). The Space Shuttle program's official name is Space Transportation System (STS) as it was originally designed to lower the cost of placing mass in space through a reusable design. During the 1980's, several satellites were serviced with successful results. Although Shuttle was designed to retrieve satellites in-orbit and return them to the Earth, this capability has not been used often. The Space Shuttle program failed to deliver on its promises of lowering the cost of space access given its final design that was only partially reusable, a flight frequency that was an order of magnitude below original estimates, and a safety record plagued by the Challenger and Columbia accidents.

Section 2.1.5 surveys the history of the Space Shuttle's OOS accomplishments including the Solar Maximum satellite repair on STS-41C, the de-orbiting of the Palapa B-2 and Westar VI satellites on STS-51A, the SYNCOM IV-3 satellite repair on STS-51I, and the rescue of Intelsat 603 on STS-49.

2.1.5.1 STS-3 – Hardware Retrieval with Robotic Arm (1982)

OOS capabilities were flight-qualified early in Shuttle's test flights. On STS-3, the capability of the Remote Manipulator System (RMS) was demonstrated for the first time when a sampling device was lifted into space for measurements. The RMS then swung the device back into its mount in the Shuttle cargo bay (NASA Office of Space Flight, 1988).

2.1.5.2 STS-41C – Solar Maximum Satellite Repair Mission (1984)

NASA conducted its first formal servicing and repair of a satellite on STS-41C (Figure 2.2). The target satellite, Solar Maximum, had a failed attitude control module. Docking with Solar Max proved difficult as attempts to manually attach with the Manned Maneuvering Unit (MMU) failed. According to former Astronaut Jeffrey Hoffman, the crew of STS-41C encountered difficulties due to the placement of thermal insulation on the exterior of Solar Max that was not captured in design documents. Eventually, the RMS succeeded in grasping the satellite and moving it into Shuttle's cargo bay. Inside the bay, astronauts replaced the attitude control module and performed minor repairs on the science instruments (NASA Office of Space Flight, 1988). The operational life of Solar Max was successfully extended, enabling it to continue its long-term study of solar activity.

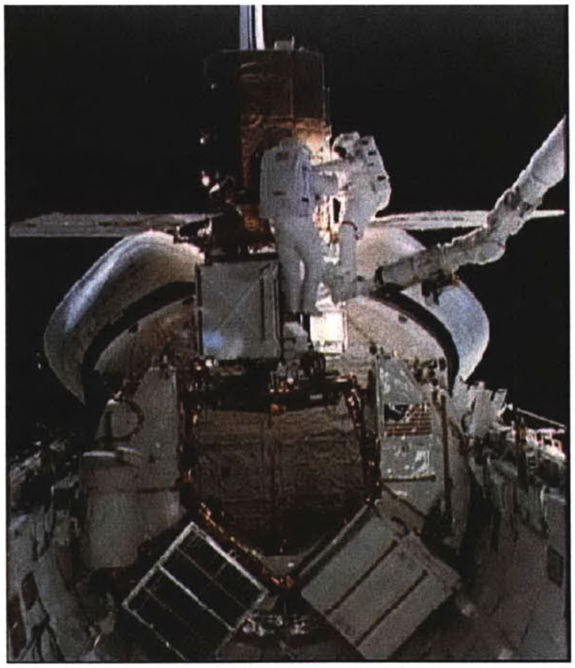


Figure 2.2 Solar Maximum Satellite Repair Mission (Photo Credit: NASA)

2.1.5.3 STS-41D – Shuttle Surface Maintenance (1984)

The next Shuttle flight successfully completed maintenance on the exterior of a spacecraft when the RMS removed a waste-water icicle from Discovery's exterior surface (NASA Office of Space Flight, 1988).

2.1.5.4 STS-41G – On-Orbit Refueling (1984)

The STS-41G mission demonstrated the feasibility of on-orbit refueling system for satellites. An EVA was conducted to attach a hose from a supply of hydrazine to a typical satellite valve in the payload hardware. Six fluid transfers were conducted with no reported anomalies, transferring 130 pounds of hydrazine (NASA, 1984).

2.1.5.5 STS-51A – De-Orbiting of Palapa B-2 and Westar VI Satellites (1984)

Shuttle mission STS-51A was the first to retrieve satellites from orbit and return them to the Earth. After deploying two communications satellites, the crew went about capturing two satellites that had been deployed by Shuttle earlier in the year on STS-41B. Borth Palapa B-2 and Westar VI had been placed in improper orbits due to failures in their kick motors. STS-51A was successful in demonstrating NASA's ability to recover LEO spacecraft (NASA Office of Space Flight, 1988).

2.1.5.6 STS-51I – SYNCOM IV-3 Satellite Repair Mission (1985)

Mission STS-51I included two EVAs to repair the SYNCOM IV-4 satellite which was unsuccessfully deployed on STS-51D (Lethbridge, 1998).

2.1.5.7 STS-61B – On-Orbit Assembly (1985)

The ability of Shuttle to support space station assembly operations was demonstrated on STS-61B. Two sample truss structures for the International Space Station (ISS) were repeatedly erected, manipulated, and disassembled to gather data on assembly time. Simulated utility lines and repair operations were also performed (NASA Office of Space Flight, 1988).

2.1.5.8 STS-49 – Intelsat 603 Rescue (1992)

STS-49 demonstrated the ability to rescue satellites stranded in useless orbits (Figure 2.3). In 1992, Space Shuttle Endeavor captured Intelsat 603, a GEO communications satellite, which had been in an unusable orbit (200 mile perigee) since its launch aboard a Titan in 1990. (Ground controllers used much of the satellite's limited supply of propellant to maintain this low orbit while the rescue mission was planned.) Initial captured attempts failed as Astronaut Pierre Thuot, maneuvering on the RMS, was unable to attach the grapple arm. Among the problems encountered were poor visibility on the Earth's dark side, insufficient positioning of the end of the RMS, and an unexpected susceptibility of the satellite to wobbling. The following day, five more attempts failed as well due to a faulty capture bar. Eventually, a plan was devised where three astronauts would grab and stabilize the satellite for attachment to Endeavor's RMS for transfer to the cargo bay. The three-astronaut EVA succeeded in manually capturing the satellite. As a result, Intelsat 603 was fitted with a new apogee kick motor and successfully transferred to GEO (NASA, 1992).

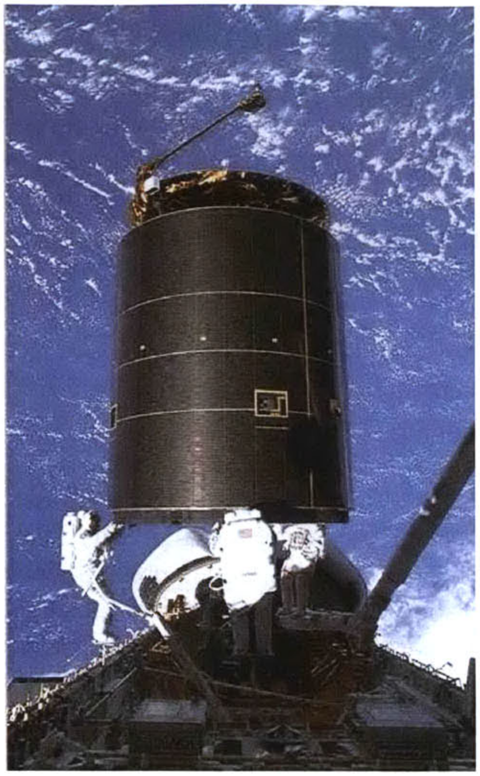


Figure 2.3 Intelsat 603 Rescue (Photo Credit: NASA)

2.1.6 Recent Demonstrations

The technology for using robotic vehicles for on-orbit servicing of satellites is in development with key stakeholders, including the U.S., Canadian, German, Japanese governments as well as commercial enterprises. In order to assess operational feasibility, several areas need to be investigated. For satellite servicing, these technologies include autonomy, rendezvous and docking, ORU exchange, and fluid transfer. Autonomous robotic operations are possible in space due to the well-structured environment (minimum clutter), potential for a well understood servicer and target satellite, and potential for a limited set of decision points if the target satellite incorporates a modular architecture and standardized interfaces (Cuplin and Chun, 2000).

2.1.6.1 Japanese ETS-VII – Autonomous Rendezvous and Docking (1997)

The Engineering Test Satellite (ETS) VII mission of Japan's National Space Development Agency (NASDA) consisted of a variety of on-orbit, robotic tasks. Equipped with a 2 meter long, six-degree-of-freedom manipulator arm, ETS-VII successfully demonstrated teleoperation from the ground with a large time delay, ORU exchange, space structure deployment, dynamic coordination control between a manipulator and a target satellite, and autonomous capture and berthing of a target satellite (Yoshida, 2003). It is important to note that the target satellite launched on the ETS-VII was designed for autonomous rendezvous and docking with a built-in interface.

2.1.6.2 XSS-10 Microsatellite – Free-Floating Proximity Inspection (2003)

Launched as a secondary payload aboard a Delta II, AFRL's 31 kg microsatellite performed a 24-hour mission to demonstrate autonomous operations. In particular, the XSS-10 navigated around its Delta II second stage, taking photographs at preplanned positions and relaying them to Earth in real time (Davis, 2003). The mission was a milestone in the development of responsive space systems for enhancing space situational awareness—a critical element of any on-orbit servicing infrastructure.

2.2 Current Programs

Over the last decade, the only space systems benefiting from on-orbit servicing were the Hubble Space Telescope (Space Shuttle) and International Space Station (primarily Space Shuttle, Soyuz, and Progress). With the high-cost associated with these human servicing architectures (even Progress requires human interaction for unloading operations), on-orbit servicing was not economically viable for the vast majority of spacecraft. The emergence of robotic servicing architectures may change this. The autonomous ConeXpress Spacecraft Life Extension System (SLES), a space tug intended for communications satellites, is scheduled for on-orbit testing in 2007 with initial operational missions in 2009 (Orbital Recovery Corporation, 2005).

2.2.1 Hubble Space Telescope

The Hubble Space Telescope was the first uninhabited space system designed for on-orbit servicing (Welch and Brown, 1987). On-orbit servicing is not only possible on Hubble; it is an integral part of its operation. Scheduled servicing missions have occurred approximately every three years to upgrade Hubble's scientific payload and replenish supporting subsystems. To date, four servicing missions have occurred (SM-1, SM-2, SM-3A, SM-3B). A fifth servicing mission is currently on hold pending Shuttle's return to flight following the Columbia tragedy. The servicing model of Hubble represents a paradigm from earlier spacecraft in which servicing was undertaken only to deal with unexpected failures (*e.g.*, Skylab sun shield).

The Hubble Space Telescope is a joint venture of NASA and the European Space Agency. Launched into low Earth orbit in April 1990 by the Space Shuttle Discovery on STS-31, Hubble's location above the Earth's atmosphere enables high resolution imaging of astronomical objects. Its main scientific objectives are to determine the constitution, physical characteristics, and dynamics of celestial bodies; the nature of processes which occur in the extreme physical conditions existing in and between astronomical objects; the history and evolution of the universe; and whether the laws of nature are universal in the space-time continuum. Hubble features a 2.4 meter primary mirror, is comprised on more than 400,000 parts, and contains 26,000 miles of electrical wiring. The orbiting observatory weighs 11,110 kg and has dimensions of 13.3 meters in length and 4.3 meters in diameter (Baker, 2005). The Hubble Space Telescope program includes the orbiting observatory, the Space Telescope Science Institute, and the Space Telescope Operations Control Center. The system is supported by the Space Shuttle, the Tracking and Data Relay Satellite System, and the NASA Communications Network (Clubb and Ingels, 1987).

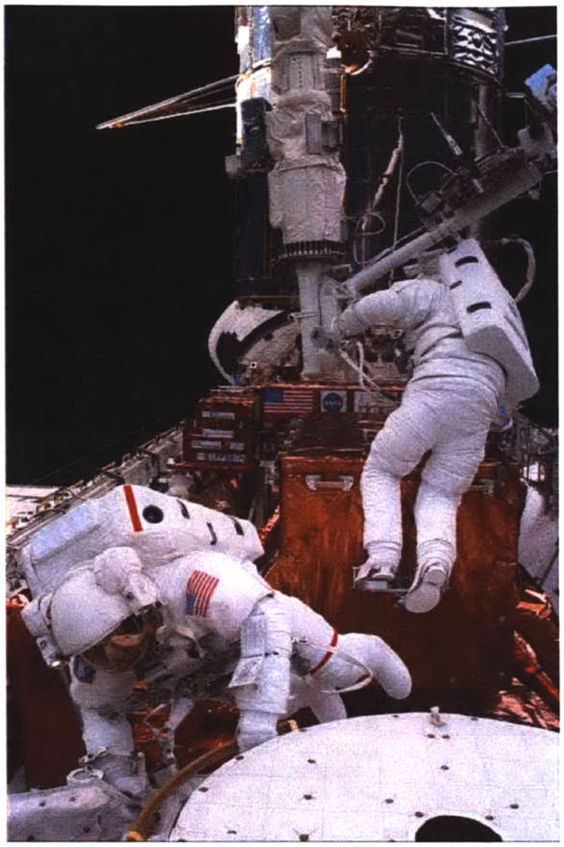
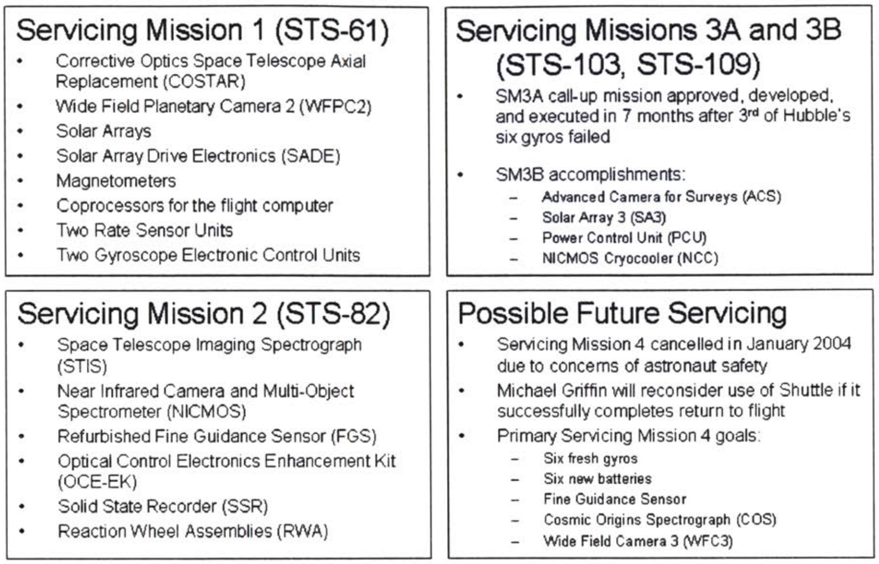


Figure 2.4 Second Hubble Servicing on STS-82 (Photo Credit: NASA)

The 15-year design lifetime of Hubble was without precedent and would require the replacement of failed components. An initial maintenance concept of returning the orbiting observatory to the ground for maintenance every five years (via Shuttle) augmented by some on-orbit servicing was abandoned following cost studies which indicated a doubling in program lifecycle cost due to the ground infrastructure required to support such operations. With the selection of an on-orbit servicing architecture, Hubble designers increased the number of ORU types from 8 to a total of 29 (Welch and Brown, 1987). This modular architecture has allowed Hubble to exceed its 15-year design lifetime. The Compton Gamma Ray Observatory, the second of NASA's "Great Observatories," did not incorporate a serviceable architecture and was de-orbited during its 10th year of operation after one of its gyroscopes failed.

In addition to enabling a 15-year design lifetime, a modular architecture allows Hubble to be equipped with a state-of-the art set of science instruments every time it is serviced. The latest servicing mission occurred in March 2002 (SM-3B) and included the installation of a new camera for visible and ultraviolet light, repair of the cooling system for the infrared imager, and installation of new solar arrays that produce 30% more power (Nelson, 2002). Table 2.1 outlines the four servicing missions carried out by Space Shuttle and the proposed fifth servicing mission.

Table 2.1 Hubble Servicing History



Servicing Mission 1 (STS-61)

- Corrective Optics Space Telescope Axial Replacement (COSTAR)
- Wide Field Planetary Camera 2 (WFPC2)
- Solar Arrays
- Solar Array Drive Electronics (SADE)
- Magnetometers
- Coprocessors for the flight computer
- Two Rate Sensor Units
- Two Gyroscope Electronic Control Units

Servicing Missions 3A and 3B (STS-103, STS-109)

- SM3A call-up mission approved, developed, and executed in 7 months after 3rd of Hubble's six gyros failed
- SM3B accomplishments:
  - Advanced Camera for Surveys (ACS)
  - Solar Array 3 (SA3)
  - Power Control Unit (PCU)
  - NICMOS Cryocooler (NCC)

Servicing Mission 2 (STS-82)

- Space Telescope Imaging Spectrograph (STIS)
- Near Infrared Camera and Multi-Object Spectrometer (NICMOS)
- Refurbished Fine Guidance Sensor (FGS)
- Optical Control Electronics Enhancement Kit (OCE-EK)
- Solid State Recorder (SSR)
- Reaction Wheel Assemblies (RWA)

Possible Future Servicing

- Servicing Mission 4 cancelled in January 2004 due to concerns of astronaut safety
- Michael Griffin will reconsider use of Shuttle if it successfully completes return to flight
- Primary Servicing Mission 4 goals:
  - Six fresh gyros
  - Six new batteries
  - Fine Guidance Sensor
  - Cosmic Origins Spectrograph (COS)
  - Wide Field Camera 3 (WFC3)

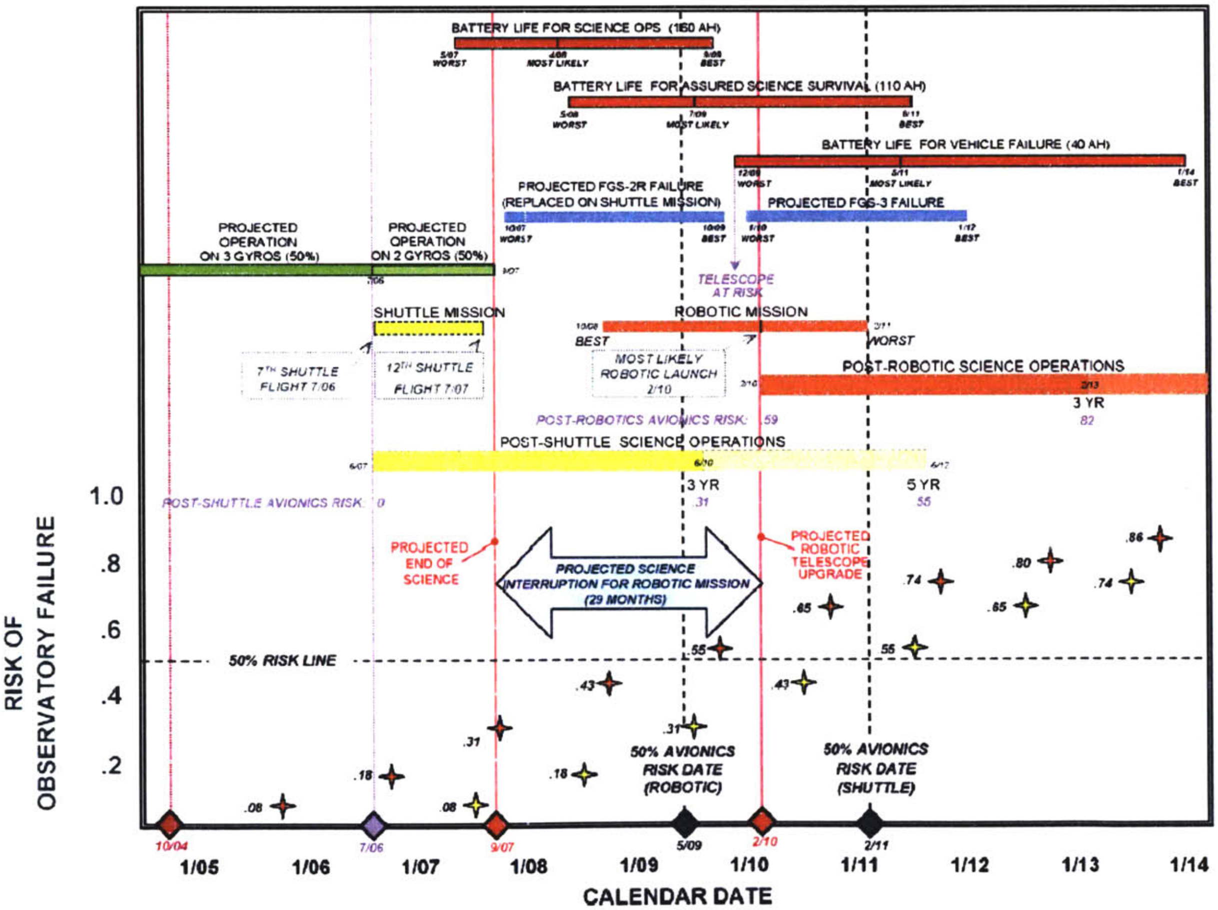


Figure 2.5 Hubble System Lifetime and Servicing Assessment (National Research Council, 2005)

Following the loss of Columbia in February 2003, NASA suspended all Space Shuttle flights. In January 2004, NASA announced that the fifth servicing mission to Hubble would not be pursued based upon risk to the crew. This cancellation led to strong objections in the scientific community and prompted NASA to explore the robotic servicing option. A National Research Council study, "Assessment of Options for Extending the Life of the Hubble Space Telescope," found that the chance of achieving three or more years of post-servicing science operations to be 70% for a Shuttle servicing mission and 20% for a robotic mission. The primary problem with the robotic servicing option for Hubble is the schedule risk. With subsystems critical to science operations expected to fail in 2007 (see Figure 2.5), the TRLs of the sensors, software and control algorithms, and machine vision required for robotic operations are inconsistent with the need to service Hubble as soon as possible.

2.2.2 International Space Station

The International Space Station, a joint venture of 14 nations that provides a sustained human presence in LEO, is the second space system currently serviced in space. Servicing is conducted primarily by the Space Shuttle, Soyuz, and Progress spacecraft (O'Keefe *et al.*, 1998). Construction activities are on-going albeit behind schedule due to the grounding of the Space Shuttle Fleet. Currently, the Japanese Aerospace Exploration Agency is developing an uninhabited spacecraft intended as a replacement for the Russian Progress vehicle. The European Space Agency is also developing a Progress replacement called the Automated Transfer Vehicle (ATV) for ISS cargo delivery, refueling, and orbit restoration. Potential on-orbit servicing missions being explored for ATV-derived vehicles include ferrying cargo between a future reusable launch vehicle and the ISS and servicing other spacecraft in LEO (Perroton and Busson, 1999).

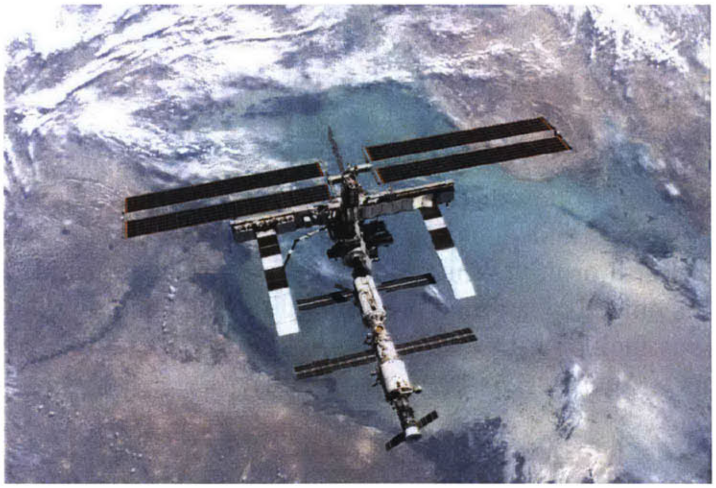


Figure 2.6 ISS Photo Taken by Discovery on STS-114 (Photo Credit: NASA)

2.2.3 ConeXpress Spacecraft Life Extension System

The ConeXpress SLES is a space tug designed to mate with existing communications spacecraft in GEO and provide stationkeeping as well as attitude control. SLES plans to utilize the apogee kick stage nozzle as the docking interface on target spacecraft and stationary plasma thrusters for propulsion. SLES will be light enough for launch as a secondary payload on EELVs or as the primary payload on emerging low-cost launch vehicles (Wingo, 2004). ConeXpress SLES is being developed by Orbital Recovery Corporation, a public-private partnership of the European Space Agency that includes Dutch Space, Kayser-Threde, the DLR German Space Agency, and Arianespace. In 2005, the company entered into a Memorandum of Agreement for a telecommunications satellite life extension mission. Approximately 130 operational communications satellites have been identified as candidates for SLES based upon the revenue-generating potential of the customer (Orbital Recovery Corporation, 2005). The SLES has been proposed for government space missions in LEO and discussions have been held with potential customers operating Boeing 702 spacecraft that are experiencing solar array degradation problems. Orbital Recovery Corporation plans to evolve the initial SLES "space tug" design into that of a "preplanned servicer" capable of component replacement (Wingo, 2004).

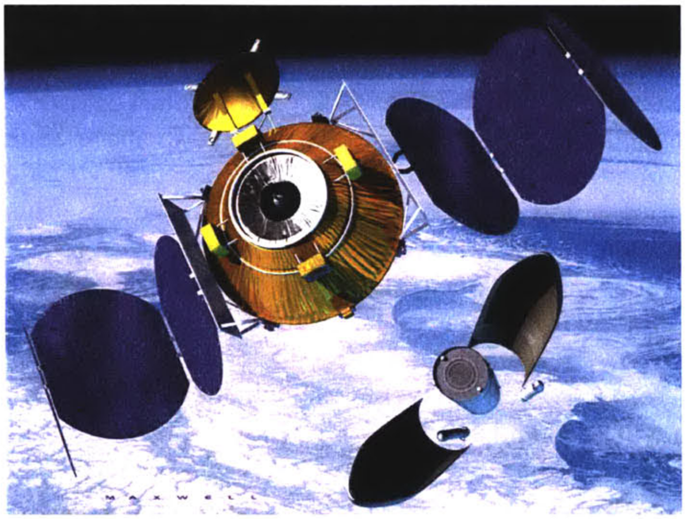


Figure 2.7 ConeXpress Spacecraft Life Extension System (Image Credit: Orbital Recovery Corporation)

2.3 U.S. Technology Demonstrations

The U.S. Space Transportation Policy directs a sustained research and development effort that includes "automated rendezvous and docking, and the ability to deploy, service, and retrieve payloads or spacecraft in Earth orbit" (White House Office of Science and Technology Policy, 2005). To accomplish this objective, a broad portfolio of OOS technology development is being conducted by organizations including the Air Force Research Laboratory (AFRL), the Defense Advanced Research Projects Agency (DARPA), and NASA.

2.3.1 AFRL – XSS-11 Microsatellite

Following the successful XSS-10, AFRL designed the advanced XSS-11, a three-axis stabilized microsatellite with a hydrazine-based propulsion system. One of the major challenges in designing spacecraft for proximity operations is the method by which relative position and velocity is determined as differential GPS, radar corridors, ground-tracking updates, and visual pattern recognition are not useful around space debris or damaged spacecraft. XSS-11 accomplishes relative navigation using a combination of a visible imager, star tracker, and active radar and laser imaging (Partch *et al.*, 2004). Launched in April 2005, XSS-11 has repeatedly conducted rendezvous maneuvers along "passively safe trajectories" with the Minotaur upper stage that placed it in orbit. Total cost of the XSS-11 was $82 million including launch, spacecraft, operations, and ground control hardware. Requirements for a XSS-12 mission are currently being defined (David, 2005). In conducting responsive space missions, the Air Force envisions a future capability of being able to deploy a low-cost satellite for proximity operations around a space object without months of planning, intersatellite communication, or a large mission operations center (Partch *et al.*, 2004).

2.3.2 DARPA – Orbital Express

Orbital Express (OE) is a DARPA technology development program designed to validate autonomous on-orbit refueling and reconfiguration of satellites. In the 2006, DARPA plans to launch a prototype servicing vehicle, Autonomous Space Transfer and Robotic Orbiter (ASTRO), to service a next-generation serviceable satellite (NEXTSat) (Potter, 2003). Within the OE context, a serviceable satellite is one that incorporates a non-proprietary docking interface, electrical coupler interfaces, modular storage bays for component swapping, and a fluid transfer system. As a pre-planned servicer, the two missions of OE are refueling and component change-out. From DARPA's perspective, "...refueling satellites will enable frequent maneuvers to improve coverage, change arrival times to counter denial and deception, and improve survivability, as well as extend satellite lifetime. Electronics upgrades on-orbit can provide performance improvements and dramatically reduce the time to deploy new technology" (Shoemaker and Wright, 2004). If future government and commercial satellite designs incorporate OE's docking interface, DARPA may facilitate the creation of an on-orbit servicing industry (Stamm and Motaghedi, 2004).

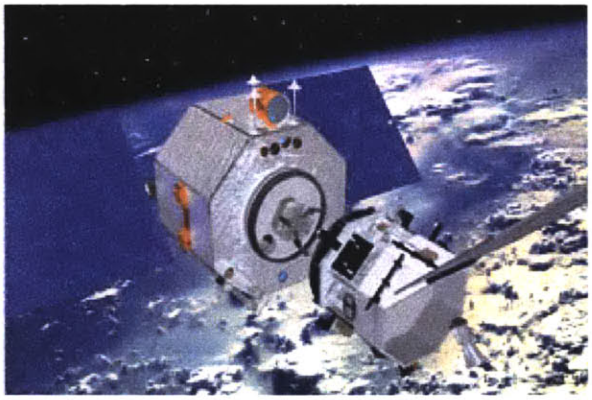


Figure 2.8 Orbital Express (Image Credit: DARPA)

2.3.3 DARPA – Spacecraft for the Universal Modification of Orbits

In contrast to its Orbital Express program which only may "add value" to target satellites designed for servicing, DARPA's Spacecraft for the Universal Modification of Orbits (SUMO) is intended to stabilize or relocate all satellites, including those already in orbit (Figure 2.9). As currently structured, SUMO is a risk reduction program being carried out by the Naval Research Laboratory (NRL) for advanced servicing technology. In particular, SUMO has demonstrated the integration of machine vision, robotics, mechanisms, and control algorithms for autonomous rendezvous and docking/grappling (Bosse *et al.*, 2004). Following a series of successful demonstrations at NRL in April 2005 which included six degree freedom motion control for both the servicer and target satellite, the Pentagon has included $12.6 million for SUMO in its FY06 budget request to begin work on a flight test (Iannotta, 2005).

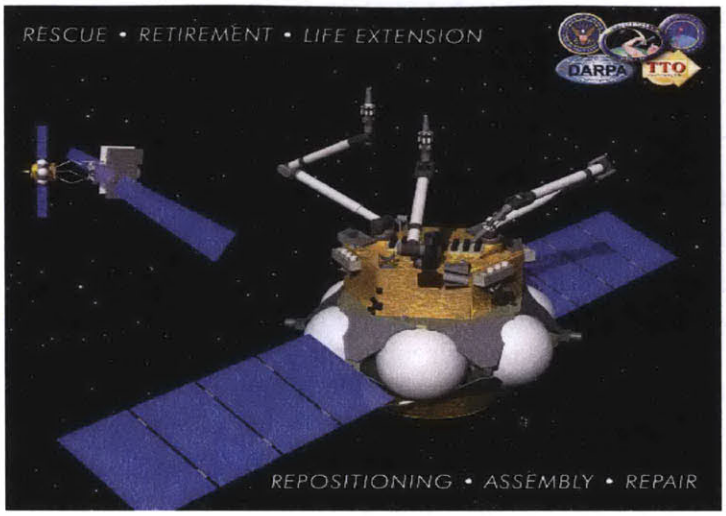


Figure 2.9 Spacecraft for the Universal Modification of Orbits (Image Credit: DARPA)

2.3.4 NASA – Autonomous Extravehicular Robotic Camera

NASA Johnson Space Center has designed, developed, and tested a Miniature Autonomous Extravehicular Robotic Camera (Mini AERCam). As an externally-based, free-flying, 5 kg spacecraft with a recharge capability, Mini AERCam is envisioned to operate from a larger spacecraft. At just 7.5 inches in diameter, potential applications include close-up inspection of external surfaces, routine autonomous scanning, anomaly detection and reporting, chemical leak detection, and thermal mapping (Fredrickson, 2002). The Mini AERCam is derived from the larger AERCam Sprint which was flight-tested on STS-87 (Figure 2.10).

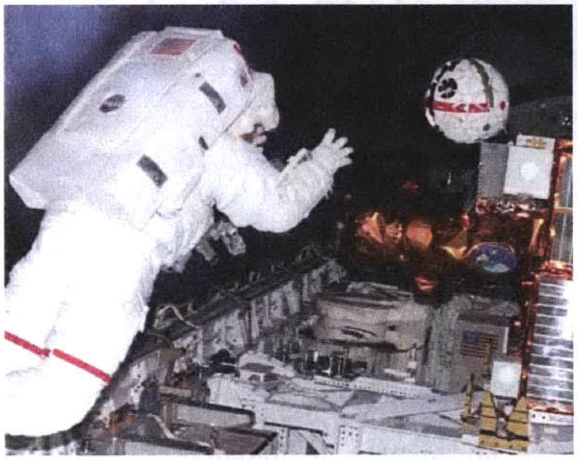


Figure 2.10 AERCam Sprint Retrieval on STS-87 (Photo Credit: NASA)

2.3.5 NASA – Demonstration of Autonomous Rendezvous Technology

In April 2005, NASA's Demonstration of Autonomous Rendezvous Technology (DART) failed to repeat the success of Japan's ETS-VII when the $110 million DART spacecraft bumped into its target satellite and also ran out of fuel faster than expected. DART was designed to approach within 5 meters of the target satellite and perform a series of maneuvers over the course of 24 hours. Instead, telemetry shows that the two spacecraft collided. Although no damage was detected to either DART or the target satellite, the mission was terminated early because of a shortage of onboard propellant due to excessive thrusting caused by noisy GPS inputs (Berger, 2005).

2.3.6 NASA – Robonaut

The Robonaut program is a collaboration between NASA and DARPA to demonstrate a teleoperated robotic system that can function as an astronaut on an EVA (Figure 2.11). Robonaut is controlled by a human operator and moves via the Shuttle/ISS robotic arms or a "space leg" adapter that allows it to plug into the ISS ports used by astronauts as foot restraints. The first Robonaut developed, Robonaut A, is a stationary test platform at Johnson Space Flight Center. Robonaut B is a smaller, portable version featuring wireless control. Future versions may be developed for flight testing, either aboard the Space Shuttle or ISS (Malik, 2004). The Robonaut program aims to leverage the lessons learned by previous servicing operations given that all past servicing activities involving operational spacecraft and physical contact have been conducted by humans.

Figure 2.11 Robonaut (Photo Credit: NASA)

2.3.7 University of Maryland – Ranger Telerobotic Shuttle Experiment

The Ranger Telerobotic Shuttle Experiment was designed to test dexterous robotics for EVA operations. It was developed by the University of Maryland's Space System Laboratory where a neutrally buoyant environment is available for integrated testing of humans and robots working together in a simulated space environment (Akin *et al.*, 2001). Ranger was intended for a Shuttle test flight in 2004 until the Columbia accident brought about programmatic cutbacks. In analyzing the EVA operations during the first Hubble servicing mission, the developers of Ranger at the University of Maryland estimate that a single robotic assistant would have increased productivity by 60% and that up to 80% of the EVA tasks could have been reassigned to a robot with Ranger capabilities (Akin *et al.*, 2003).

2.4 Contemporary Studies

A variety of studies have addressed various aspects of OOS. The majority of these studies have been conducted by industry and constitute point designs of servicing provider architectures. Some work has also been done on evaluating the economics of OOS, including several graduate theses at the Massachusetts Institute of Technology (MIT).

2.4.1 Industry and Government Reports

Industry and government reports on how to service satellites date from the start of the commercial space industry (Kiersarksy, 1969). OOS studies grew during the 1970's and 1980's as the development of the Space Transportation System (Shuttle) progressed. Rather than providing a complete history of the numerous OOS studies conducted throughout the space age, this section documents the findings of key studies from the past two decades.

2.4.1.1 NASA Report to Congress on Satellite Servicing (1988)

According to Section 118 of the National Aeronautics and Space Administration Authorization Act of 1988, Congress stipulates that "...the capital investment in space satellites and vehicles should be enhanced and protected by establishing a system of servicing, rehabilitation, and repair capabilities in orbit (hereinafter referred to as 'satellite servicing')." Congress also requested a comprehensive study of OOS, including flight experience, the use of Shuttle and ISS to support OOS activities, potential customers, the impact of OOS on space insurance, and economic viability. NASA responded with a report documenting past experience with OOS as well as a vision of future Shuttle-based and ISS-based satellite servicing with the Orbital Maneuvering Vehicle (OMV) and Orbital Transfer Vehicle (OTV).[1]

NASA's report to Congress included many other interesting elements. In discussing design considerations for OOS, NASA noted that a Martin Marietta study estimated a 4% incremental cost increase for design of a serviceable spacecraft. Recurring costs were estimated to grow by 8% and mass penalties were expected to be in the range of 5-10%. Regarding the impact of OOS on insurance, a leading underwriter stated that it would look favorably on the ability to repair and retrieve satellites (*i.e.,* reduced premiums) but also that it cannot require satellite manufacturers to incorporate these features. Finally, in reference to pricing policies, NASA stated that the costs charged to date for satellite servicing (STS 51-A, STS 51-D, and STS 51-I) were only associated with mission planning, development of unique hardware and training, and retrieval operations. The report stated that these charges (all less than $10 million) occurred at a time when NASA was strongly interested in demonstrating its Shuttle-based servicing capabilities and that it was "NASA's intent, in accordance with the civil space policy, to seek full cost recovery for pricing of Shuttle servicing" (NASA Office of Space Flight, 1988).

2.4.1.2 Space Systems/Loral Economic Study (1990)

In 1990, NASA Marshall Space Flight Center funded Space Systems/Loral to estimate the cost of various servicing activities for an OOS provider (*e.g.*, NASA). Previous economic models had been created but all were in different formats and employed different assumptions. Using a stochastic space mission lifecycle cost model, economic data from 14 past studies was correlated to produce parametric curves showing the sensitivity of satellite cost, reliability, and servicer costs on the lifecycle cost of servicing future spacecraft. The study found an average of 19.6% in lifecycle cost savings when a servicing architecture was employed. The data also indicated

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[1] Neither the OMV nor the OTV were developed. The OMV was intended to be a free-flying OOS system deployed by Shuttle, extending the 28-57 degree inclination and 320 nautical mile altitude range of Shuttle by 7.5 degrees and 1400 miles. The OTV was intended as an advanced upper stage for Shuttle, carrying cargo, and perhaps humans, from to LEO to GEO (NASA Office of Space Flight, 1988).

that a servicing architecture based on a space station was not cost effective and that the high cost associated with Shuttle launch greatly reduces servicing benefits. Expendable vehicles were endorsed as the most cost effective servicing method in all cases except for polar orbiters in which case no cost-effective servicing method was found to exist if total payload replacement was a requirement (Space Systems/Loral, 1990).

2.4.1.3 NASA Advisory Council Report on Satellite Rescue and Repair (1992)

In 1992, the NASA Advisory Council released a report reviewing the policies, pricing, and implementation of Shuttle-based satellite repair and rescue missions. The study began with a survey of launch vehicle and spacecraft failures from 1970 to 1992, identifying a total of 42 failures. Of these 42 failures, 15 were identified as servicing opportunities for Shuttle rescue given orbital accessibility, damage that was not irreversible, and safety and economic considerations.[2] Noting that NASA's pricing has not recovered the full cost of satellite rescue missions, the NASA Advisory Council advocated charging U.S. government agencies the marginal cost for future rescue missions while charging commercial and international customers the marginal cost and a portion of the full cost as a negotiated portion of revenues. Among numerous conclusions and recommendations, the report found that the time required to prepare Shuttle for rescue missions has varied from approximately 4 months to 2.5 years and that NASA needed to develop a routine training program for astronauts in rendezvous techniques and RMS operations (NASA Advisory Council, 1992).

2.4.1.4 Space Assembly, Maintenance and Servicing Study (1993)

The Space Assembly, Maintenance and Servicing study (Waltz, 1993) defined where cost-effective OOS missions could be carried out to improve space system capabilities, flexibility, and affordability. Five orbital zones were identified as candidate servicing regimes and generic design reference missions were created for typical satellites in each zone. Servicing was found to be potentially cost effective when ORU cost is less than 50% of the satellite replacement cost and when servicing time intervals are shorter than 5 years.

2.4.1.5 Spacecraft Modular Architecture Design Study (1999)

The Spacecraft Modular Architecture Design study ((Reynerson, 1999) identified a cost-effective level of OOS for a classified constellation of LEO satellites and developed a conceptual design for a servicing vehicle. It was found that approximately one-third of all satellite components could be replaced and that this fraction could be easily increased with the adoption of a more modular bus and payload design. A detailed technical assessment of enabling OOS technologies was conducted including laser ranging, docking mechanisms, and autonomy. In the study, a serviceable spacecraft is defined as any spacecraft for which the benefits of OOS outweigh the associated cost.

The servicing architecture envisioned in the Spacecraft Modular Architecture Design study includes a Rendezvous/Docking Servicer which can repair two satellites. Each servicer has two payload modules for connection to a satellite's electrical power system, data buses, and

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[2] Five of the 15 candidate failed spacecraft were rescued by Shuttle (NASA Advisory Council, 1992).

propellant lines. Rather than requiring the servicer to conduct repair operations, the satellite simply turns off failed components and reroutes functionality to the replacement components which remain at the docking interface. This architecture was found to achieve a lifecycle cost savings of 10.3% to 38.2%, depending on the targeted life extension (2-6 years) and the number of servicers used (1 or 2).

Problems and issues associated with OOS are identified, including the possible inadequacy of available telemetry points to pinpoint the exact cause of on-orbit failures and the need precisely to align the reference coordinate system or allow for on-orbit calibration in the case of replacement of attitude determination and control components. Also discussed are operational downtime, the impact of varying radiative surfaces and heat sources on the thermal control system after servicing, and the need to design electrical power and attitude control systems with adequate margin for the extra load caused by the payload module.

2.4.1.6 Draper Modular Servicing Architecture (2000)

The Draper Modular Servicing Architecture study explored high-level OOS trades, analyzed enabling avionics architectures, and proposed a point design for a servicing provider vehicle. One of the more interesting elements of the study was a comparison of two module servicing arrangements: (1) remove and replace and (2) plug and stay. The plug and stay approach was found to be superior because it allows traditional satellite design and packaging to be maintained, allows new hardware to be brought on-line before turning off old hardware, does not require de-orbit of failed components, and is lower risk than the remove and replace strategy (Moynahan and Tuohy, 2000).

2.4.1.7 MIT Space Tug Architecture and Design Study (2002)

Work done at MIT in 2002 explored the architectural tradespace of space tugs and defined point designs for specific space tug applications. First, several orbital zones were surveyed for target satellites in GEO along with four LEO planes that were selected for further analysis. Next, a rapid system design methodology called Multi-Attribute Tradespace Exploration (MATE) with Concurrent Design (Ross, 2004) was used to identify "optimal" architectures for each orbital zone for further analysis. Architectures are defined with design parameters (*e.g.*, propellant type, parking location, level of autonomy, and hardware sophistication) and assessed with a utility metric composed of performance attributes (*i.e.*, timeliness, mating capability, and delta-v capability). A space tug employing electric propulsion was found to maximize utility for the GEO servicing missions while conventional bipropellant was adequate for the LEO missions (McManus and Schuman, 2003).

For the second phase of the MIT study, detailed space tug designs were developed based upon promising architectures (*i.e.* pareto-efficient regions of the cost-utility tradespace). Seven designs were built during integrated concurrent engineering sessions, including design of propulsion, power, attitude determination and control, thermal, and communications subsystems (Galabova *et al.*, 2003).

Figure 2.12 depicts the cost-utility tradespace of the architecture analysis and incorporates the SLES space tug being developed by ConeXpress (triangle labeled CX-OLEV). As can be observed in the lower right portion of the tradespace, the ConeXpress architecture lies near the pareto-efficient region identified previously by the MIT study. Table 2.2 compares the characteristics of GEO electric cruiser from the MIT space tug study and the ConeXpress system.

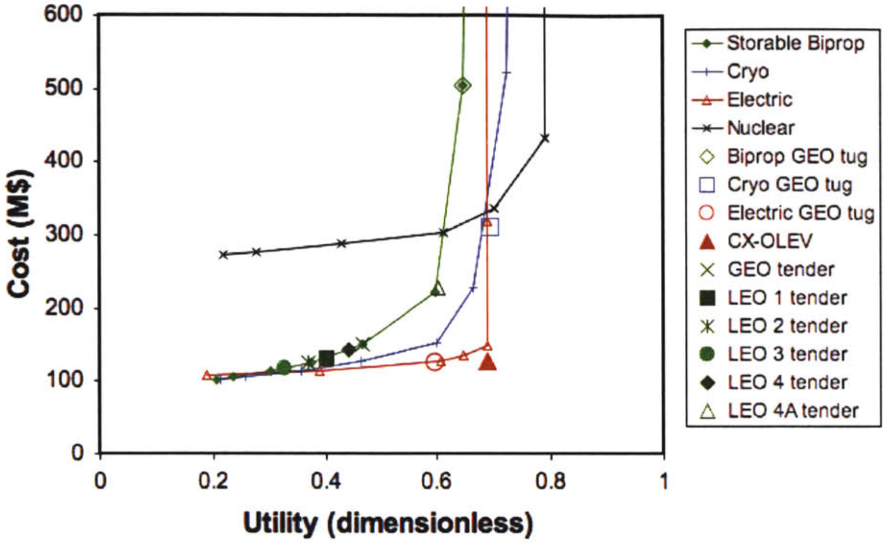

Figure 2.12 Tradespace of MIT Space Tug Study

Table 2.2 Comparison of Electric Cruiser in MIT Space Tug Study and ConeXpress SLES

	Electric Cruiser (2002 study)	CX-SLES (2009 launch)
Wet Mass kg	1405	1400
Dry Mass kg	805	670*
Propellant kg	600	730*
Equipment kg	300	213*
DV m/s	12000 – 16500***	15900**
Utility	0.69	0.69
Cost	148	130*

* back-calculated using space tug tradespace tool
** calculated based on stated 3 km/s capability attached to target, normalized to space tug ability to move in orbit
*** higher figure is using original 3000 sec thrusters, lower uses 2200 assumed by CX-OLEV

2.4.1.8 NRC Assessment of Hubble Servicing Options (2005)

In addition to finding that the chance of achieving three or more years of post-servicing Hubble science to be 70% for a Shuttle servicing mission and 20% for a robotic mission (due primarily to schedule risk—see Figure 2.5), the 2005 NRC report "Assessment of Options for Extending the Life of the Hubble Space Telescope" also identified mission risks associated with autonomous or teleoperated rendezvous and docking and robotic instrument replacement. The report noted that relative attitude control with safe pause points, vital for proximity operations, is only rated at a TRL of 3 and that the requisite autonomous grapple system for final capture is a capability that has never been accomplished in the history of the U.S. space program (Orbital Express to demonstrate in 2006).

Risky elements of robotic instrument change-out operations include the chance of encountering bent connector pins and losing free-floating parts during disassembly and assembly tasks. Loss of situational awareness is also a concern (*e.g.,* impact of sagging thermal insulation on machine vision). Also, astronauts on past servicing missions have encountered difficulty opening and closing bay doors which have become warped over time (National Research Council, 2005).

2.4.2 Customer Valuation Research

Most existing OOS studies, including many of those discussed in Section 2.4.1 (Industry and Government Reports), focus on the design of a servicing architecture for specific space missions. These studies estimate a servicing cost based upon historical data and assess the improvement in mission cost-effectiveness. While these point designs may provide some insights for particular OOS applications, this method cannot be used to yield general results. The servicing price assumed in these models is highly uncertain due to inadequate historical cost models and the fact that price is not necessarily equal to cost.

To understand the maximum price a customer is willing to pay, it is necessary to calculate the intrinsic value of servicing. Research at MIT and the University of Maryland has addressed this question by treating OOS as a real option for a space system. In the five recent student theses summarized here, satellite operators choose among several alternatives along a mission timeline to maximize future mission value. The combination of real options theory with decision tree analysis in the presence of uncertainty has proven effective in capturing the three main components of the value of servicing: cost, performance, and flexibility.

2.4.2.1 Lamassoure (2001)

In "A Framework to Account for Flexibility in Modeling the Value of On-Orbit Servicing for Space Systems," Lamassoure (2001) proposes a generalized real options approach for space systems. In particular, a decision tree analysis incorporating elements of real options theory is developed by allowing an infinite number of branches for an uncertain parameter (*e.g.*, market dynamics, military contingency location, random failures). It is assumed that this uncertainty parameter follows a Markov process (path independence) and that government satellite operators are risk-neutral (risk-free interest rate discounting) while commercial entities are risk-averse (requiring a risk premium).

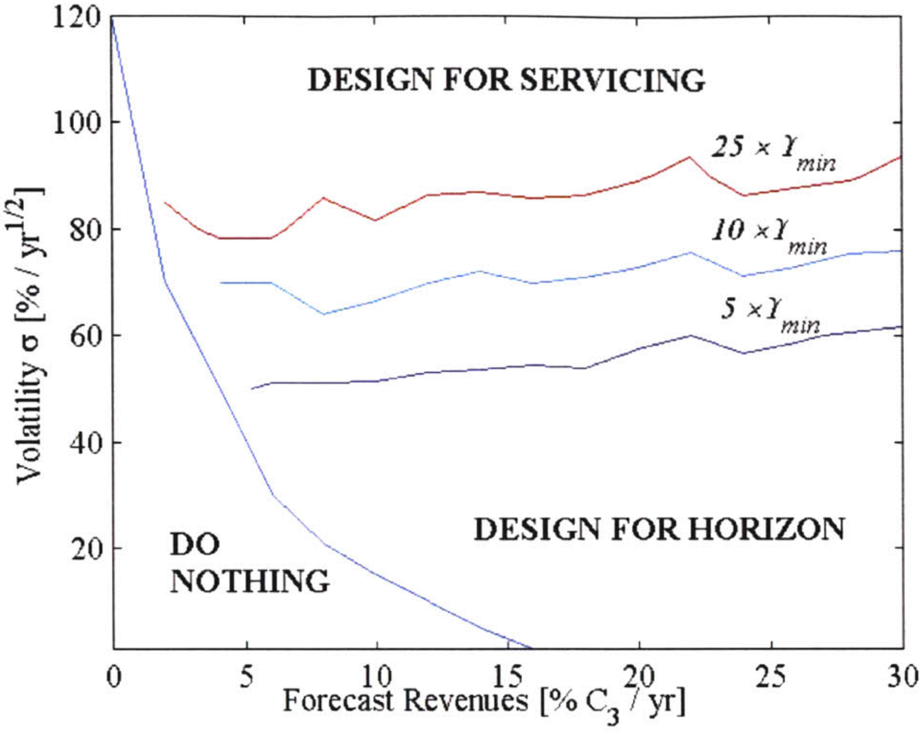

Figure 2.13 Decision Making Map as a Function of Servicing Price (Lamassoure, 2001)

After conducting a trade study of several servicing infrastructures and space missions using the traditional cost-effectiveness metric, Lamassoure calculates the value of servicing for commercial missions with uncertain revenues. Servicing is found to maximize value in highly-volatile markets (Figure 2.13), illustrated with Iridium and Globalstar case studies.

Following the commercial cases, maximizing military utility with maneuverable satellites via refueling is explored. The potential for reducing the number of satellites in a LEO radar constellation and the potential for improving capacity of a fleet of GEO communications satellites are both considered. Results indicate that while no value is derived from thinning a LEO radar constellation, the maneuverability concept is very promising for a fleet of GEO satellites.

2.4.2.2 Saleh (2002)

In "Weaving Time into System Architecture: New Perspectives on Flexibility, Spacecraft Design Lifetime, and On-Orbit Servicing," Saleh (2002) develops a comprehensive framework for evaluating the benefits of flexibility for system architecture. The latter part of the dissertation develops a customer-centric perspective on OOS (Figure 2.14) and proposes three main ideas: (1) estimating the value of servicing independent of its cost or specific implementation, (2) OOS as a real option offering future flexibility for space systems, and (3) benefits of OOS include cost savings as well as the ability to meet new mission requirements. A formal valuation process combining decision tree analysis and real options is also introduced whereby a customer may determine if the value generated by OOS exceeds the servicing cost.

Saleh's work showing how the value of OOS may be assessed independent of its cost was instrumental in enabling a series of customer valuation studies at MIT (Lamassoure, 2001; Joppin, 2004; Long, 2005). Furthermore, by explaining how OOS provides satellite operators with options to react to the resolution of uncertain parameters, Saleh added flexibility as a dimension to be added to OOS studies.

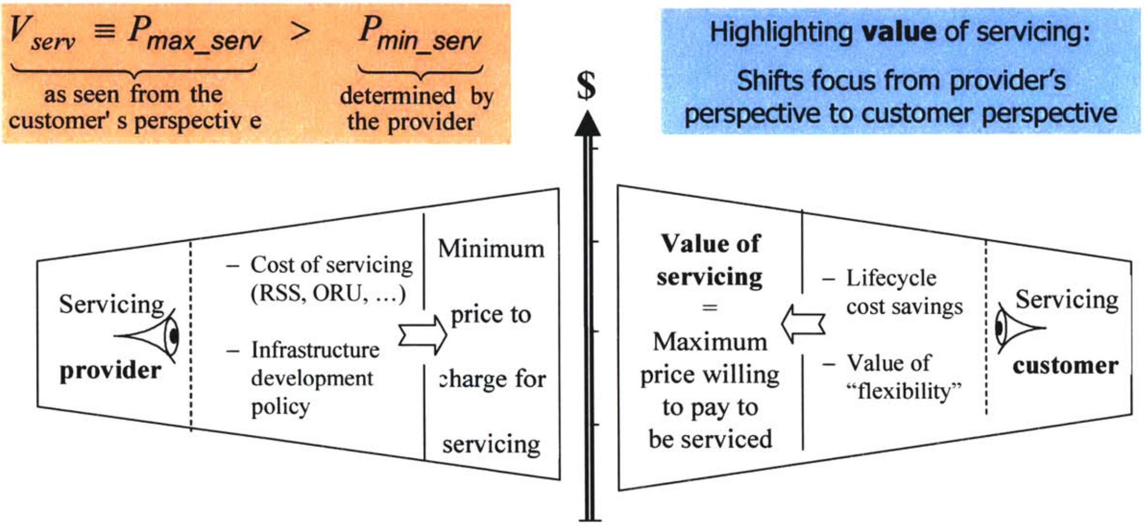

Figure 2.14 Customer-Centric Perspective on On-Orbit Servicing (Saleh, 2002)

2.4.2.3 Joppin (2004)

In "On-Orbit Servicing for Satellite Upgrades," Joppin (2004) applies the customer-centric OOS valuation methodology introduced by Lamassoure (2001) and Saleh (2002) in two case studies: (1) a power upgrade for a typical commercial GEO communications satellite facing uncertain demand and (2) upgrade of scientific instruments on the Hubble Space Telescope. Regarding the GEO commercial upgrade, OOS was not an attractive option given predictable power degradation and the ability to mitigate such phenomena with design modifications. OOS was found to be desirable for Hubble as its modular design maximized scientific returns over its long mission life.[3]

Joppin (2004) develops a model of Hubble to estimate the value of servicing for a scientific mission. In particular, a utility metric is developed to capture scientific return and the decision to upgrade or repair is made if the utility per cost metric exceeds a predefined threshold. Empirical data was used to estimate the probability of Hubble failures, instrument utility, and servicing costs. A Monte Carlo simulation models four sources of uncertainty: the appearance of a new instrument, the emergence of new satellite bus technology, spacecraft failure, and servicing failure. Figure 2.15 depicts one of the model results—the high sensitivity of Hubble lifetime utility improvements to servicing risk and cost assumptions.

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[3] The ability to service Hubble saved the actual Orbiting Observatory from significantly degraded scientific capacity when flaws in the primary mirror (discovered at BOL) were corrected on the first servicing mission (see Table 2.1).

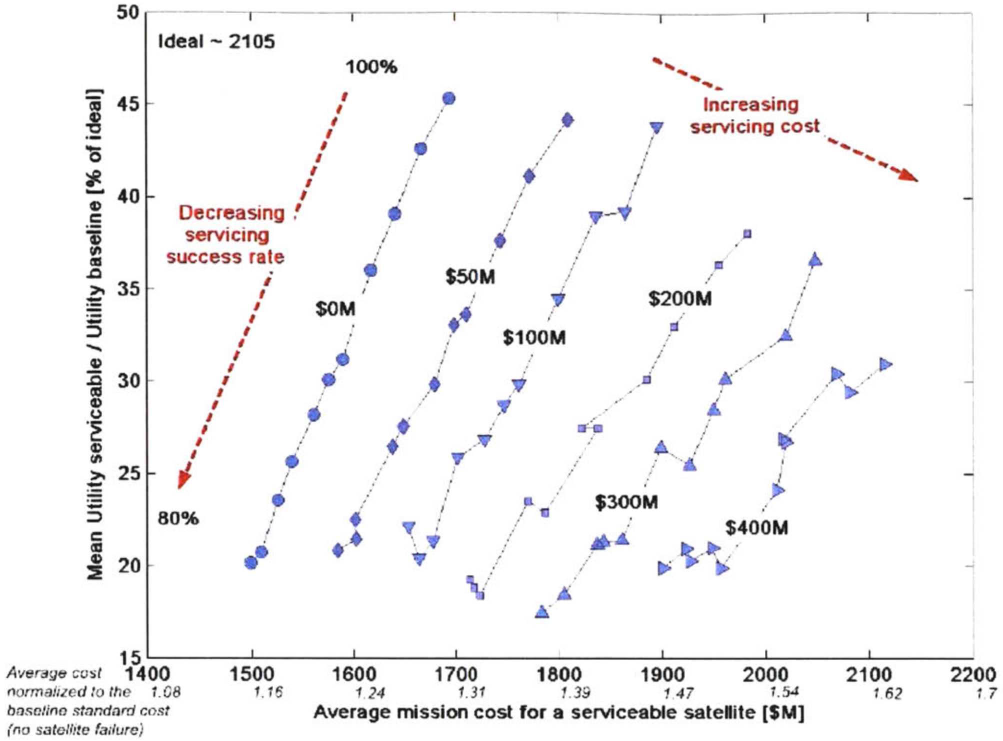

Figure 2.15 Evolution of Hubble Mission Utility and Cost Depending on OOS Assumptions (Joppin, 2004)

2.4.2.4 Sullivan (2005)

In "Technical and Economic Feasibility of Telerobotic On-Orbit Satellite Servicing," Sullivan (2005) develops a comprehensive database of satellite characteristics and on-orbit failures to estimate the size of various servicing markets. The database contains all civilian, military, commercial, and nongovernmental organization spacecraft launched from 1957 through 2000. For successfully launched satellites, it is found that more than 6% suffer from BOL failures—an opportune time for OOS given that satellites at BOL would provide the longest payback period. Sullivan's database includes satellite information, orbital elements, and failure information. Mechanism failures include problems with separation events (*e.g.,* failure to separate from upper stage) and solar array and antenna deployment. Component failures include degradation of transponders, control processors, and payload instrumentation. Other failures recorded are collisions with upper stages or launch vehicle fairings, software bugs, human error, and inadvertent consumable depletion. In order to tailor use of the database for market assessments of OOS, some spacecraft failures were omitted (*e.g.,* satellites that failed to achieve orbit, spacecraft beyond Earth orbit, classified spacecraft, amateur radio satellites).

Having developed a database of on-orbit failures, Sullivan analyzes the frequency and value of OOS opportunities. Table 2.3 displays the results from this analysis, including the breakeven servicing fee for a variety of OOS missions, the average number of annual opportunities, and the total annual value for each OOS market. The breakeven servicing fee is the maximum fee chargeable for the revenue of the serviced satellite to balance the servicing fee and possible negative outcomes. Sullivan employs decision trees and the expected value method to calculate the breakeven servicing fee. As such, results are dependent on the probabilities assigned to the chance nodes. The average number of annual opportunities comes from empirical data compiled in his on-orbit failures database. A key assumption in Sullivan's OOS market assessment is that satellite failure rates follow a "bathtub" curve whereby reliability is constant during the operational life of a satellite (with high failures during BOL "infant mortality" and EOL wear-out). Empirical data in his doctoral dissertation somewhat conforms to this assumed Poisson failure distribution.

For example, the expected value for "Relocation in GEO" (row in Table 2.3) was calculated as follows. Initially, the Satellite Encyclopedia and Jonathan's Space Report were consulted to identify an annual market of 13 maneuvers (averaging 36.2 degrees per maneuver) for GEO communications satellites. The rocket equation and orbital mechanics were then used to relate fuel mass expended and time out of service. Without conducting a sensitivity analysis on reaction time, it appears a fixed transfer time is assumed, costing approximately one month of transfer time and one month worth of stationkeeping propellant (translating to a total cost of $9.2 million). It is then assumed that, while a servicer could not make up for operational time lost during transfer, it could provide the fuel for the burn. As such, $4.6 million of value is assumed for each relocation mission.

Table 2.3 Expected Value of Various Servicing Markets (Sullivan, 2005)

Service	Break-Even Servicing Fee	Average Annual Opportunities	Annual Market Value
Refuel	$40M	20	$800M
Remove Inactive	$41.9M	10.5	$440M
ORU Replacement	$81M	4.4	$356M
General Repair	$81M	3.8	$308M
GEO Retirement	$10.9M	20	$218M
LEO To GEO Transfer	$131M	1	$131M
Relocation In GEO	$4.6M	13	$60M
Deployment Monitoring	$1.4M	20	$28M
Deployment Assistance	$84M	0.3	$25M
Health Monitoring	$0	200	$0
Total			$2.366M

In his doctoral dissertation, Sullivan also documents the past economic impact of satellite failures and uses his extensive database to inform a decision tree analysis incorporating operational uncertainties. The expected value market assessment is proposed as a tool for validating the financial viability of servicing architectures and then applied to a GEO EOL retirement mission. Lifetime extension (*e.g.,* relocation, retirement maneuvers, refueling) is identified as the leading OOS opportunity for commercial enterprise.

2.4.2.5 Long (2005)

In "Framework for Evaluating Customer Value and the Feasibility of Servicing Architectures for On-Orbit Satellite Servicing," Long (2005) calculates the customer's maximum servicing price and proposes a framework for identifying feasible OOS markets. Case studies include life extension for commercial GEO communications satellites and upgrades for commercial and government spacecraft. Figure 2.16 depicts a typical result of the analysis—the value of servicing options (*i.e.*, three-year life extensions) for the Intelsat 801 as a function of servicing price and time. To promote the adoption of OOS by the satellite industry, Long recommends that servicing providers focus on medium volatility markets as well as low-risk servicing missions and incorporate fast-evolving technologies that result in significant increases in satellite value.

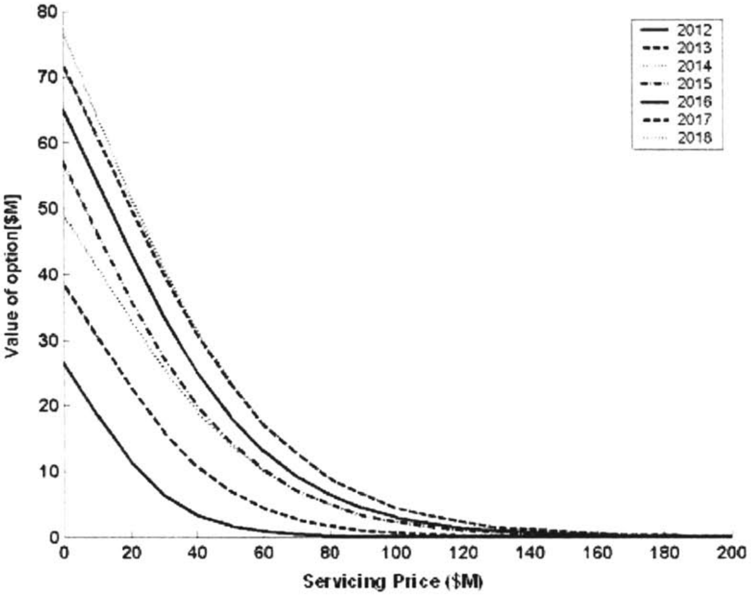

Figure 2.16 Value Provided for Intelsat 801 Through 3-Year Life Extensions (Long, 2005)

2.4.3 Provider Architecture Research

Graduate research at MIT and the Air Force Institute of Technology has addressed the servicing provider side of OOS. Leisman (1999) analyzed servicing architectures for the Global Positioning System (GPS) constellation, and McVey (2002) explored OOS applications of a low-cost launch vehicle being studied by Space Systems/Loral. Galabova (2004) proposed the application of families of space tugs to generic servicing missions in multiple orbital zones. McConnell (2005) investigated servicing architectures for a future constellation of space radar satellites.

2.4.3.1 Leisman (1999)

In "Design and Analysis of On-Orbit Servicing Architectures for the Global Positioning System Constellation," Leisman (1999) evaluates OOS architectures for decreasing the cycle time for incorporating new technologies into GPS. The thesis proposes a large design space consisting of all possible combinations of 8 different orbital architectures, 3 different ORU capacities, 3 types of robotic servicers, and 2 different GPS constellations. However, rather than analyzing the entire tradespace, only 30 alternatives are subjected to a cost-benefit analysis over a 15-year operational period. An arbitrary "value" metric is assumed. The possibility of servicing vehicle failure does not appear to be accounted for in the model. Predictably, robotic servicing is found to be more cost effective than replacing entire spacecraft for infusing current technology into the GPS constellation.

2.4.3.2 McVey (2002)

In "Valuation Techniques for Complex Space Systems: An Analysis of a Potential Satellite Servicing Market," McVey (2002) combines a real options valuation approach with several servicing provider architecture baseline missions to identify feasible OOS markets. A low-cost launch vehicle called Aquarius is used for fuel delivery across potential servicing missions (Table 2.4). Electric propulsion is discussed as a leading competitor to life extension servicing missions and two feasible OOS markets in GEO are identified: space tug for north-south stationkeeping and preplanned servicer for refueling.

Table 2.4 Provider Architecture Configurations (McVey, 2002)

Case	**Servicing Task**	**Initial Orbit**	**Propulsion**	**Configuration Approach**
Baseline	None	GTO‡	Standard Biprop	Current s/c design
AQR 1	Fuel 1-Time at Staging Orbit for OR§ and SK	Staging**	Standard Biprop (launched dry)	Reduced Launch Cost 1a: 2 s/c, 1 LV 1b: Cheaper LV
AQR 2	Tug for OR and NSSK	Staging	Biprop used only for EWSK and contingency	2a: Reduced Launch Cost 2b: Additional Transponders
AQR 3	Tug for NSSK	GEO	Biprop used only for EWSK and contingency	Additional Transponders
AQR 4	Refuel before each NSSK maneuver	GEO	Refuelable Biprop Tanks	Additional Transponders
AQR 5	"Optimal Just in Time" Refueling	GEO	Refuelable Biprop Tanks	Additional Transponders
AQR 6	Tug for OR	Staging	OR: Biprop SK: Electric Propulsion	6a: Reduced Launch Cost 6b: Additional Transponders
AQR 7	Tug for NSSK	Staging	Use Separable Biprop Apogee Stage for OR	Additional Transponders
AQR 8	Fuel 1-Time at Staging Orbit for OR	Staging	OR: Biprop SK: Electric Propulsion	Reduced Launch Cost or Additional Transponders

2.4.3.3 Galabova (2004)

In "Architecting a Family of Space Tugs based on Orbital Transfer Mission Scenarios," Galabova (2004) expanded upon the MIT Space Tug Architecture and Design Study (Section 2.4.1.7). For GEO retirement missions, a space tug in GEO parking orbit using storable bipropellant is found to be technically and economically feasible. For satellite rescue missions, a space tug launched on-demand and employing electric propulsion is found to be optimal.

2.4.3.4 McConnell (2005)

The AFIT Master's thesis by Captain McConnell entitled "An Approach for Optimizing the On-Orbit Servicing Architecture for a Given Client Satellite Constellation" investigated applications of a future Orbital Express servicing capability for a future constellation of space radar satellites. Developing a servicing model as a large combinatorial optimization problem, several provider architecture attributes are calculated including the optimal number and type of servicing vehicles and the most efficient routing to meet client satellite demand for two commodities within multiple time windows. The objective function seeks to minimize the total launch costs for servicing vehicles while finding the least expensive path through the constellation (in terms of ΔV). Rather than treating timing as a parameter, time windows for servicing events are assumed constraints in the model. McConnell found the use of one small servicing vehicle and one supply depot for each plane of three space radar satellites to be optimal. Furthermore, McConnell recommends launching the servicing vehicles dry to the depot spacecraft for refueling before visiting each of the space radar satellites in that plane.

2.4.4 Related Research

Related graduate research at MIT has explored issues relevant to OOS: modularity and evaluating flexibility in space systems.

2.4.4.1 Shah (2004)

In "Modularity as an Enabler for Evolutionary Acquisition," Shah (2004) explores the design features of modularity as well as the characteristics of evolutionary acquisition, a strategy for acquiring a minimum capability early and then enhancing that capability as risks are resolved. Modularity is a requisite for several servicing missions including upgrade and repair missions. Evolutionary acquisition provides a rationale for several missions enabled by OOS such as expanding satellite constellations through reconfiguration. The thesis concludes with a case study of Space-Based Radar and shows how a modular constellation architecture maximizes expected stakeholder value over the lifecycle of the system.

2.4.4.2 Nilchiani (2005)

In "Measuring the Value of Space Systems Flexibility: A Comprehensive Six-element Framework," Nilchiani (2005) identifies interfaces, time horizon, system properties, uncertainty, responsiveness, and accessibility as key attributes for understanding flexibility in space systems. Case studies include measuring the flexibility created by DARPA's Orbital Express program for sets of LEO and GEO client satellites.

Among Nilchiani's contributions in her doctoral dissertation is a framework to evaluate provider-side flexibility for an orbital transfer network. Three types of flexibilities are included in the framework: mix flexibility (the ability of an organization to produce different combinations of products economically and effectively), volume flexibility, and emergency service flexibility. Overall flexibility for an orbital transportation network such as an OOS provider is then defined as a combination of these three flexibilities. Figure 2.17 displays these flexibilities and shows how each relate to long-term, medium-term, and short-term time scales, respectively.

One key finding from Nilchiani's framework to evaluate provider-side flexibility is that smaller architectures with lower investment costs have the highest volume flexibilities, while larger architectures have higher emergency flexibility. Given that volume flexibilities may be more important to an OOS system for commercial clients, and that emergency flexibilities are more valuable to an OOS system for military applications, it is recommended that separate architectures be developed for each customer set.

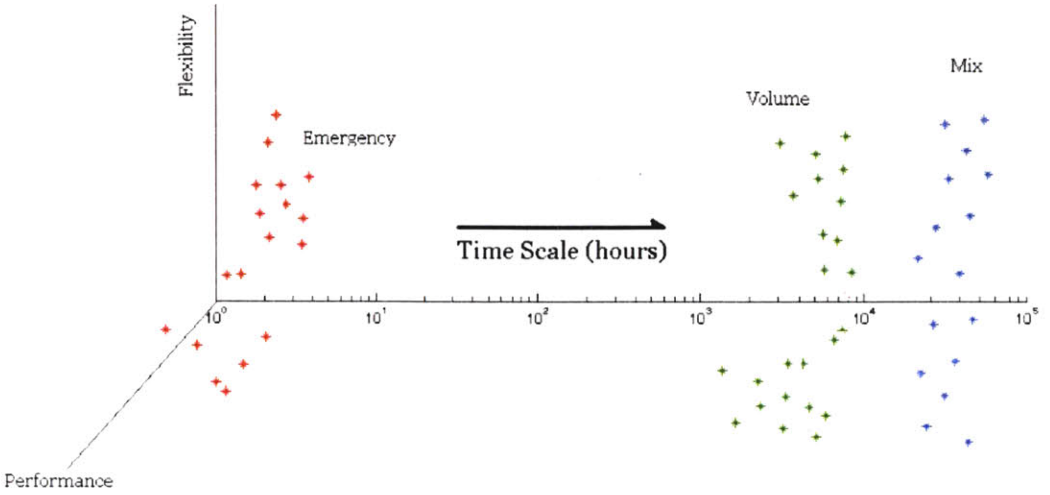

Figure 2.17 Service Flexibility Components and their Respective Time Scales (Nilchiani and Hastings, 2003)

2.5 Key Findings

Given the history of OOS, current programs and studies, conclusions may be drawn regarding its degree of success. Technically, OOS by human servicing architectures has been validated when target satellites are within range of Shuttle. However, the economic case for human servicing architectures is not strong. As originally envisioned, Shuttle would fly 60 times a year at a mission cost of less than $20 million (NASA Advisory Council, 1992). Shuttle hasn't come close to meeting this goal with estimates of marginal mission costs in excess of $55 million and total mission costs (including supporting ground infrastructure) of $1.3 billion (Pielke, 1993). Furthermore, *Challenger* stranded commercial programs based on Shuttle (Wheelon, 1988) and *Columbia* has grounded the fleet from operational use.

The short history of robotic servicing is promising. Beginning with the Japanese ETS-VII autonomous rendezvous and docking demonstration (Section 2.1.6.1), several robotic systems with minimal capabilities have been successfully flight-tested. The AFRL series of XSS microsatellites and NASA's AERCam have qualified free-floating proximity inspection capabilities. Military (*e.g.*, DARPA's SUMO and OE) and commercial (*e.g.*, ConeXpress's SLES) systems that offer expanded OOS capabilities are in development. Although technological successes for robotic OOS far outnumber failures (*e.g.*, NASA's DART), more on-orbit validation of critical technologies is needed before robotic servicing technology can be considered an operational capability. The commercial viability of robotic OOS is an open question as one of the most lucrative markets identified (*i.e.*, GEO lifetime extension) is poised to shrink due to the shift of GEO communications satellites to electric propulsion (Figure 2.18).

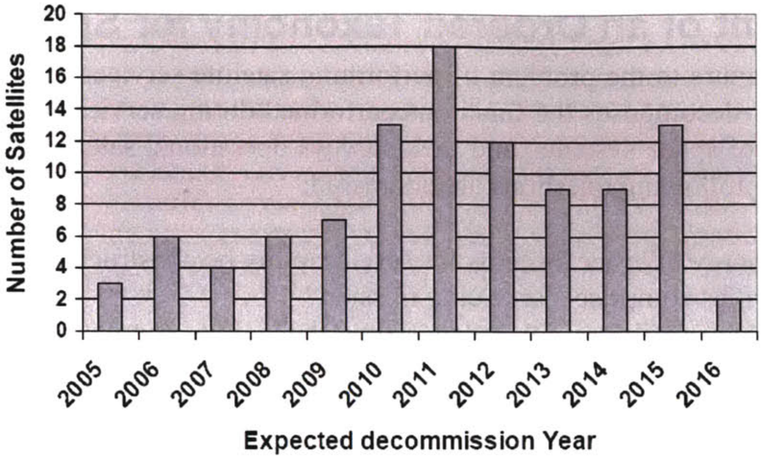

Figure 2.18 Number of Bipropellant Satellites Reaching End-of-Life (Long and Hastings, 2004)

In reviewing contemporary government, industry, and academic studies, it was found that much OOS work has been done on servicing provider architecture and some on customer valuation. However, little work was found on the satellite architecture of the customer. Furthermore, the work that does exist on serviceable spacecraft was found to focus on implementing design changes in future satellites. Although an understanding of the amenability of different orbits to OOS (Section 4.2), as well as the degree of complexity associated with servicing various satellite bus designs (Section 4.4), are necessary precursors to evaluating servicing missions, no studies were found that address these questions for existing satellites. The central goal of this thesis is to build on previous OOS studies by developing and implementing a framework to assess the serviceability of spacecraft currently in orbit around the Earth.

Opportunities also exist to contribute to the OOS literature in the technology and policy domain. Little work was found that deals with the political and financial challenges associated with OOS or the impact of export control and international law on servicing operations. As such, another goal of this thesis is to couple quantitative analysis with qualitative analysis as a means to address both the technical and non-technical challenges facing the implementation of robotic on-orbit servicing.

3 Development of an Ordered Taxonomy for Space Systems

This chapter adds structure to the problem of performing satellite serviceability assessments. In particular, this chapter decomposes the functions performed during servicing missions, develops an ordered taxonomy of space systems, and then surveys operational satellites currently in orbit around the Earth. The following questions are addressed:

- How might a taxonomy of space systems for serviceability be constructed?
    - What activities comprise a servicing mission?
    - What are the attributes for categorizing the active population of Earth orbiting satellites?
    - Which satellite attributes drive serviceability assessments?

3.1 Decomposition of Servicing Activities

This section decomposes the process of servicing into general activities and then maps these activities to on-orbit servicing missions. Four unique activities are found to compose a servicing mission: (1) rendezvous, (2) acquire, (3) access, and (4) service.

3.1.1 Rendezvous

Rendezvous is the movement of a servicing vehicle from a starting position to the vicinity of the servicing target. For OOS missions, rendezvous comprises two steps. First, the servicing vehicle moves from a starting position (*e.g.,* launch pad, parking orbit) to a position where relative navigation is possible with laser ranging, radar, and cameras (< 500 meters). The second step of rendezvous involves the positioning of the servicing vehicle for acquisition (< 3 meters).

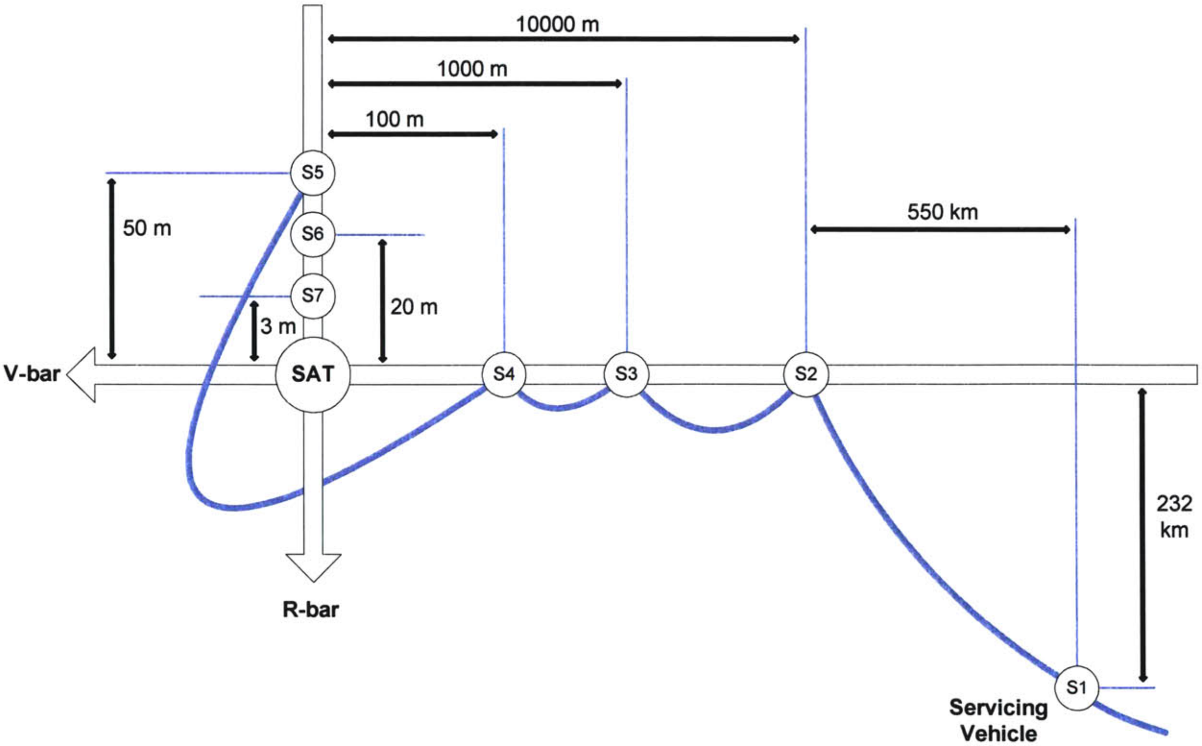

Figure 3.1 Rendezvous Phases – Geosynchronous Servicing Vehicle

Figure 3.1 illustrates the basic phases of rendezvous for a Geosynchronous Servicing Vehicle proposed by the European Space Agency (ESA) (Yasaka and Ashford, 1996). In the first phase (up to S1), the servicer is in a phasing orbit a couple hundred kilometers below the target satellite. Once within 10000 km, the servicer transitions to GEO and closes in on the target (S2 to S4). Next, the servicer flies around the target satellite for inspection (S4 to S5) before final approach (S5-S7).

3.1.2 Acquire

Acquire is a servicing activity involving the transfer of a servicing vehicle from the target vicinity to the holding of the target. In OOS, acquire is defined as the docking or mating of a servicing vehicle to the target satellite. Most proposed mating operations involve approaching the target satellite from behind, along the Earth direction. For spin-stabilized spacecraft, the servicing vehicle is "spun up" to synchronize with the target. A similar approach may work for mating with uncontrolled satellites as the main axis of inertia is typically perpendicular to the plane of the solar array (de Peuter, *et al.*, 1994).

3.1.3 Access

Access is a servicing activity involving the deployment of servicing tools from a stowed position to the area of interest on or within the target. For OOS, access consists of all the steps required to deploy the stowed tools, upgrades, and replacement parts of the servicing vehicle to the target satellite components that require servicing. With the servicing vehicle expected to mate with the back of the satellite and with most payload located on the front of the satellite (*e.g.*, antennae reflectors), the accessibility of the repair area for the servicing vehicle is a non-trivial element of serviceability.

3.1.4 Service

Service is a value-added servicing activity involving the operation of deployed servicer to improve the components of a system. For OOS, service may comprise a variety of activities including the repair, replacement, upgrade, addition, and/or removal of satellite components.

The undocking, separation, and escape of the servicing from the target spacecraft is the final step in an OOS mission. The functions during this phase are essentially the same as rendezvous, acquire, and access but performed in the opposite order. Although the separation and escape step will require significant mission planning, no new technology development is required (Wertz and Bell, 2003). As such, it is assumed that separation and escape will not be a driver for serviceability assessments, and this step is not assigned its own category in the set of unique servicing activities.

3.1.5 Mapping of Servicing Activities to OOS Functions

Table 3.1 relates the four servicing activities to the five high-level on-orbit servicing functions identified in Chapter 1. The rendezvous activity is part of all OOS functions, and the acquire activity is part of all functions except proximity inspection. Access and service are activities composing augmentation and assembly operations but not necessarily the restore function. Although the restore function might be manifested in a repair mission requiring the accessing and servicing of faulty components, restore might only constitute the recovery of attitude control via external grappling.

Table 3.1 Mapping Servicing Activities to OOS Functions

function / activity	inspect	relocate	restore	augment	assemble
rendezvous	X	X	X	X	X
acquire		X	X	X	X
access			?	X	X
service			?	X	X

3.2 *Towards a Taxonomy for Space System Serviceability*

The number of operational satellites in orbit around the Earth is approximately 800. This section proposes a classification system for space systems to add structure to the problem of conducting serviceability assessments. Five satellite attributes comprise this proposed framework: (1) mission area, (2) orbital elements, (3) attitude control system, (4) bus structure, and (5) payload configuration. Each attribute is judged to impact the degree of difficulty for conducting at least one of the servicing activities discussed in Section 3.1. The following discussion analyzes the attributes and introduces a combination of discrete and continuous categories for classifying space systems within each attribute.

3.2.1 Mission Area

Satellites perform a wide range of missions from weather monitoring to imaging distant stars. Satellite mission areas may be used to understand physical and temporal constraints on servicing operations. For example, Earth observation payloads will typically incorporate optics sensitive to thruster plume impingement from other spacecraft. An example in the temporal domain is the need to minimize satellite downtime given the criticality of availability for communication satellite operators (typically on the order of 99.95%). Table 3.2 defines four broad mission areas independent of the user community (*e.g.*, commercial, civil, military).

Table 3.2 Satellite Mission Areas

Astronomy	Observation of space objects and phenomena such as distant planets, galaxies, and radiation fields; includes miscellaneous civil space science and engineering missions
Communications	Telecommunications using radio at microwave frequencies
Earth Observation	Terrestrial observation for applications such as environmental monitoring, meteorology, map making, reconnaissance, and launch detection
Navigation	Radio time signal transmitters that enable mobile ground receivers to determine their exact location

3.2.2 Orbital Elements

Orbits may be completely characterized with five constants and one parameter that varies with time. The location of satellites in space is perhaps the most fundamental element of conducting serviceability assessments as all OOS activities require proximity operations and propulsion is a key driver in servicing vehicle design. Table 3.3 defines the Keplerian orbital elements.

Table 3.3 Classical Orbital Elements

Semimajor axis (*a*)	Orbit size: half of the long axis of the ellipse
Eccentricity (*e*)	Orbit shape: ratio of half the foci separation to the semimajor axis
Inclination (*i*)	Orbital plane's tilt: angle between the orbital plane and equatorial plane, measured counterclockwise at the ascending node
Right ascension of the ascending node (Ω)	Orbital plane's rotation about the Earth: angle from the vernal equinox to the ascending node (measured eastward)
Argument of perigee (*w*)	Orbit's orientation in the orbital plane: angle from the ascending node to perigee (measured in the direction of satellite motion)
True anomaly (*v*)	Satellite's location in its orbit: angle from perigee to the satellite's location (measured in the direction of satellite motion)

Figure 3.2 displays the classical orbital elements.

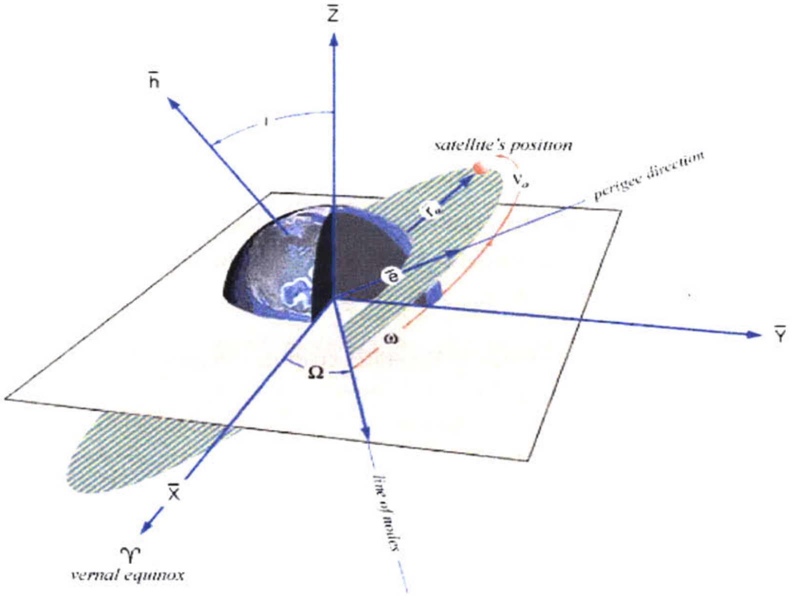

Figure 3.2 Orbital Elements (Credit: NASA)

Table 3.4 identifies various orbital zones, principally in terms of orbital altitude. Further refinement of orbital zones as a function of inclination will be required later as plane changes require large quantities of propellant.

Table 3.4 Orbital Zones

Low Earth Orbit	200 to 1200 km above the Earth's surface, includes sun-synchronous orbits in which the surface illumination angle is the same every time for any given point on the Earth's surface
Medium Earth Orbit	1200 to 35,286 km, *e.g.* GPS constellation of consists of 24 satellites in six orbital planes at 20,200 km
Subsynchronous	35,286 to 35,786 km, drift orbit for GEO in easterly direction
Geosynchronous Earth Orbit	35,786 km, includes most communications spacecraft in geostationary orbits with i=0
Supersynchronous	35,786 to 36,286 km, drift orbit for GEO in westerly direction
High Earth Orbit	Above 36,286 km, *e.g.*, satellites launched to detect nuclear explosions in space or to Lagrangian points
Highly Elliptic	An orbit with an eccentricity less than 1, includes Molniya orbits (i=64.4 degrees and e=.72 with a period of ~12 hours) that feature apogee dwell

3.2.3 Attitude Control System

The attitude control system (ACS) maintains the angular position and rotation of the satellite. Tightly coupled with other spacecraft subsystems such as propulsion and navigation, the ACS is comprised of sensors for monitoring external disturbance torques and actuators for controlling attitude. Sensor data from star trackers, sun sensors, magnetometers, Earth horizon indicators, and inertial gyroscopes are input to actuators which may include momentum/reaction wheels, control-moment gyros (CMG), electromagnets, and thrusters (Wertz and Larson, *et al.*, 1999). The current population of operational satellites employs numerous methods for attitude control. In general, however, control methods can be divided into three broad areas: passive control, spin control, and three-axis control. Tumbling satellites with failed ACS but otherwise healthy are potential targets for OOS (as is orbital debris removal). Table 3.5 describes the spectrum of potential target satellite attitude control facing servicing vehicles.

Table 3.5 Spectrum of Satellite Attitude Control

Tumbling	Uncontrolled angular position and rotation (analogous to orbital debris)
Gravity gradient control	Inertial properties keep satellite pointed towards Earth (*i.e.*, elongated object in a gravity field aligns its longitudinal axis through Earth's center)
Spin control	Passively resist disturbance torques about two axes by spinning about axis with largest moment of inertia, some satellites incorporate dual-spin stabilization
Three-axis stabilization	Most expensive and complex (and most common), employs thrusters or magnetic torquers as well as momentum wheels

Understanding and cooperating with the ACS of target satellites is critical for conducting satellite serviceability assessments. Assuming cooperative spacecraft, ACS sophistication is inversely proportional to the complexity required in the servicing vehicle docking system.

Understanding the ACS is also an important element in understanding the OOS value proposition for satellite operators. In some cases, a satellite's operational life may be limited by the ACS. Bearings on momentum wheels are subject to wear-out, sensors may fail, and supply of thruster propellant is a limiting factor in conventional propulsion systems. One OOS business in development is focused on the GEO lifetime extension market by taking over the ACS of target satellites with a space tug (see Section 2.2.3 - ConeXpress Spacecraft Life Extension System).

3.2.4 Bus Structure

The satellite bus structure is also important for serviceability assessments as it constrains servicing vehicle docking strategies and may impact other proximity operations. Unlike mission area and orbital element categories, a discrete framework for assessing the ease of docking with a particular bus structure is difficult to develop. Likert scales are one possible means by which it may be possible to characterize the ease of docking with common satellite bus structures. This type of analysis may be practical given the limited number of satellite bus structures currently in production.[1] Numerous attributes of satellite bus structures are relevant to serviceability assessments. Five are discussed in this section: (1) bus shape and size, (2) solar arrays, (3) antennae, (4), boom-mounted instruments and other appendages, and (5) launch vehicle mating interface.

3.2.4.1 Bus Shape and Size

Knowledge of satellite bus shape and size informs design of the servicing vehicle's capture system. With spacecraft launched in cylindrically symmetric containers, with the axis of symmetry parallel to the thrust axis, satellite buses are typically cylindrical in shape with diameters in the range of 1-5 meters. Booster diameters serve as an upper limit for satellite bus diameters.

3.2.4.2 Solar Arrays

Satellites typically have solar arrays either mounted on external panels or on the surface of the equipment compartment. If mounted on external panels, solar arrays are more vulnerable to sustaining damage during proximity operations; but more surface area may be available on the surface of the bus. Solar arrays attached to the bus surface may limit the ability of a servicing vehicle to safely grapple with a target satellite.

3.2.4.3 Antennae

As with solar arrays, the antenna configuration on a satellite may constrain OOS docking activities. Antenna aperture size (along with transmitter power) is critical in driving satellite mass. In general, high-gain antennae are utilized to support high data rates with low transmitter

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[1] In 2004, only 15 commercial satellites were launched worldwide. They were built by only five prime contractors (Boeing, EADS, Lockheed Martin, Prikladnoi Mekhaniki, and Space Systems/Loral) and were based on just five satellite bus families—BSS-601, Eurostar 3000, A2100, Express-M, and LS-1300 (Caceres, 2005).

power. Basic antenna types include the reflector, lens, and phased array whereby multiple beams may be formed simultaneously. The parabolic reflector is a common antenna type on communications satellites. For a peak gain of 19.1 dBi and an 18 degree beam at 400MHz, the aperture diameter of a parabolic reflector is 2.9 meters. Other reflector antenna types for satellite systems include the helix and horn (Wertz and Larson, *et al.*, 1999).

3.2.4.4 Boom-Mounted Instruments

Some spacecraft feature boom-mounted instruments which constitute additional appendages relevant to an OOS provider. Boom-mounted instruments are often unique to individual missions and may include sensors for detecting particle and radiation measurements.

3.2.4.5 Launch Vehicle Mating Interface

As the leading candidate location of capture for space tug providers, the launch vehicle mating interface of the satellite bus is a critical element for assessing serviceability. For example, the end effectors on the robotic arms of DARPA's proposed space tug (see SUMO, Section 2.3.3) are designed to fit inside the launch bolt holes of Boeing 702 satellites. SUMO's three-fingered end effectors grab the hole from the inside and apply 300 pounds per square inch of gripping force. Designers are also developing end effectors for launch vehicle adaptor rings on the Lockheed Martin A2100 (Iannotta, 2006). With the ability to exchange end effectors while in orbit and given the finite number of satellite bus designs, SUMO is positioned to offer tugging services to the vast majority of space systems.

3.2.5 Payload Configuration

Spacecraft configuration is driven by many factors including legacy bus designs, booster diameter, thermal constraints, radiation environment, and field-of-view requirements. Payloads configured with a modular architecture (*i.e.*, consisting of modules with tightly controlled interfaces) are more serviceable than otherwise similar satellites configured with highly integrated components. Modularity increases the range of "manageable" complexity by limiting the scope of interaction, allowing multiple components of a system to be worked on concurrently and accommodating uncertainty (Baldwin and Clarke, 2000).

Although motivated by the potential for improvements in manufacturing efficiency, industry efforts to develop modular spacecraft configurations may aid future OOS activities. Northrop Grumman, in association with AFRL's Materials and Manufacturing Directorate, is running the Flexible Space Vehicle Production Line Program (FSVPL) with stated goals of reducing cost by 50% and cycle time by 70%. While most spacecraft are custom-designed for a single purpose with a given payload (resulting in costly and time consuming integration and test activities due to unique structural, electrical, and thermal properties), the FSVPL has reduced costs through standardization. With common interfaces, modules developed for one spacecraft can be used in another (Shah, 2004).

As with various satellite bus structures, a framework for assessing the degree of modularity in a satellite's payload configuration is difficult to structure. Likert scales are a candidate method for characterizing the degree of modularity in common satellite payload configurations.

3.3 *Spacecraft Currently in Earth Orbit*

Approximately 800 functioning satellites are currently in orbit around the Earth.[2] As a means to rapidly survey the operational population of satellites for OOS targets, the Union of Concerned Scientists (UCS) Satellite Database was utilized. The database is derived from open-source information and is available in Excel as well as a tab-delimited text format (Union of Concerned Scientists, 2006). Updated quarterly, the database includes 21 fields of basic information on each active satellite. Technical information about each satellite, its orbit, as well as its user, owner, operator, and builder are included in the database (Table 3.6). While specifications are provided for launch mass, dry mass, power, and launch vehicle type, satellite volume is not made available. Launch vehicle fairing volume is readily available from other sources (Isakowitz and Hopkins, *et al.*, 2004) but may not represent satellite volume given the possibility of multiple satellites having been launched on a single vehicle. As a comprehensive and easily manipulated source of information on all active Earth satellites with orbit types, the UCS Database is well-suited as an input to a low-fidelity, astrodynamics-based model of satellite serviceability (see Section 4.2).

Table 3.6 UCS Satellite Database Fields

A: Name of Satellite, Alternate Names
B. Country of Operator/Owner
C: Operator/Owner
D: Users
E: Purpose
F: Type of Orbit
G: Perigee
H: Apogee
I: Inclination
J: Period
K: Satellite Launch Mass
L: Satellite Dry Mass
M: Power
N: Date of Launch
O: Expected Lifetime
P: Contractor
Q: Country of Contractor
R: Launch Site
S: Launch Vehicle
T: COSPAR Number
U: NORAD Number

3.3.1 General Distributions

Of the 773 satellites included in the UCS database, 534 are communications satellites (318 of which reside in GEO and 203 in LEO). Astronomy and earth observation spacecraft reside

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[2] Included in this thesis are all operational satellites launched through March 11, 2006—773 satellites. Classified U.S. Government launches were omitted from the UCS database.

primarily in LEO (with GEO early warning satellites being the primary exception for earth observation). Navigation satellites (*i.e.,* U.S. Navstar GPS and Russian Glonass) comprise the preponderance of MEO systems.

Table 3.7 General Distribution of Active Satellites

	LEO	MEO	GEO	Elliptical	Total
Astronomy	53	0	1	17	71
Communications	203	2	318	11	534
Earth Observation	87	0	23	2	112
Navigation	9	44	3	0	56

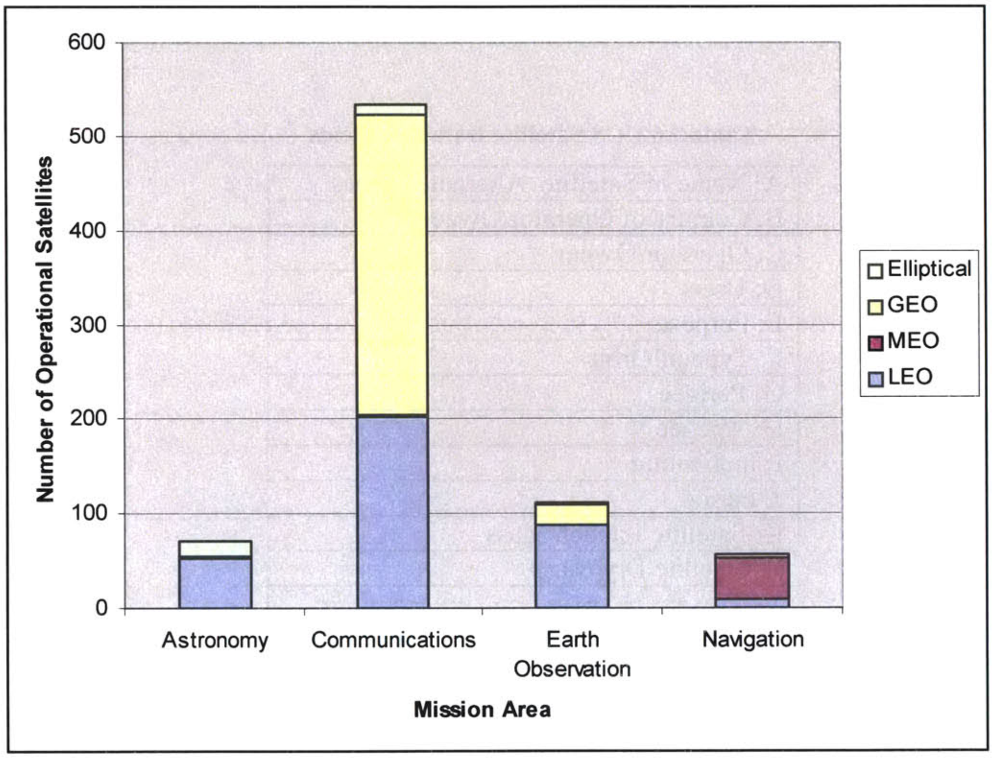

Figure 3.3 Distribution of Satellites by Mission Area

3.3.2 Satellite Locations

Other than navigation satellites in MEO, operational satellite orbits largely consists of LEO for mapping Earth resources, meteorology, and communications and GEO for communications spacecraft. In LEO, resolution and aperture requirements drive orbits to lower altitudes while coverage, lifetime, and survivability drive orbits to higher altitudes (Wertz and Larson, *et al.*, 1999). Of the 352 operational LEO satellites, one is in equatorial orbit, 141 are in intermediate orbits (with inclination between 20° and 85°), 86 are in polar orbits (with inclination between 85° and 95°), 122 are in sun-synchronous orbit (with inclination between 95° and 104°), and two are in retrograde orbits (with inclination between 104° and 180°). Figure 3.4 displays the distribution of satellites as a function of inclination and apogee altitude. Due to the concentration of satellites in GSO, it is not clear that over 90% of active satellites are present in LEO and GEO. Figure 3.5 alleviates this problem somewhat by zooming in on satellites near GEO altitude with inclinations less than 15°.

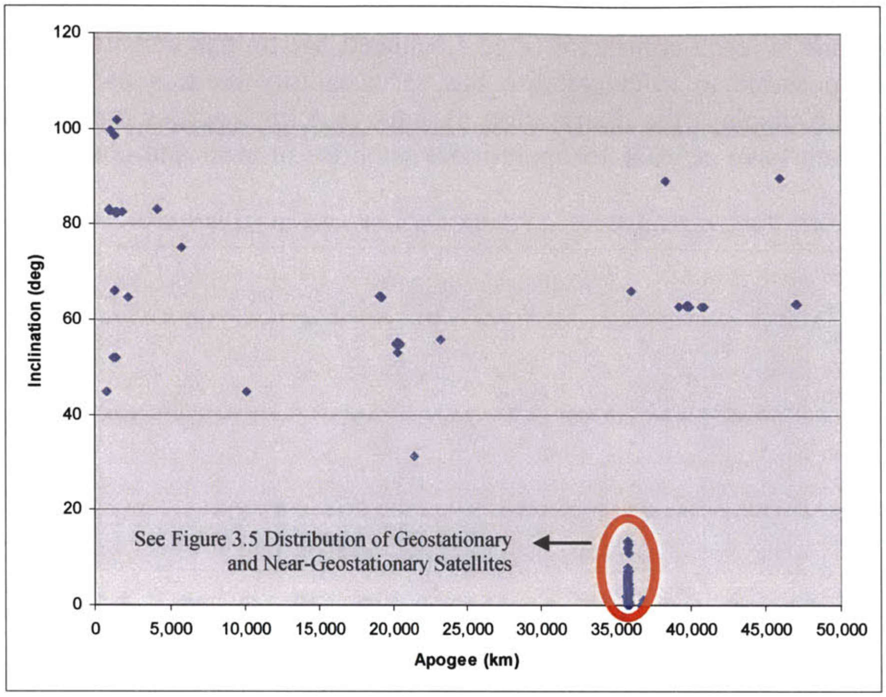

Figure 3.4 Satellite Locations

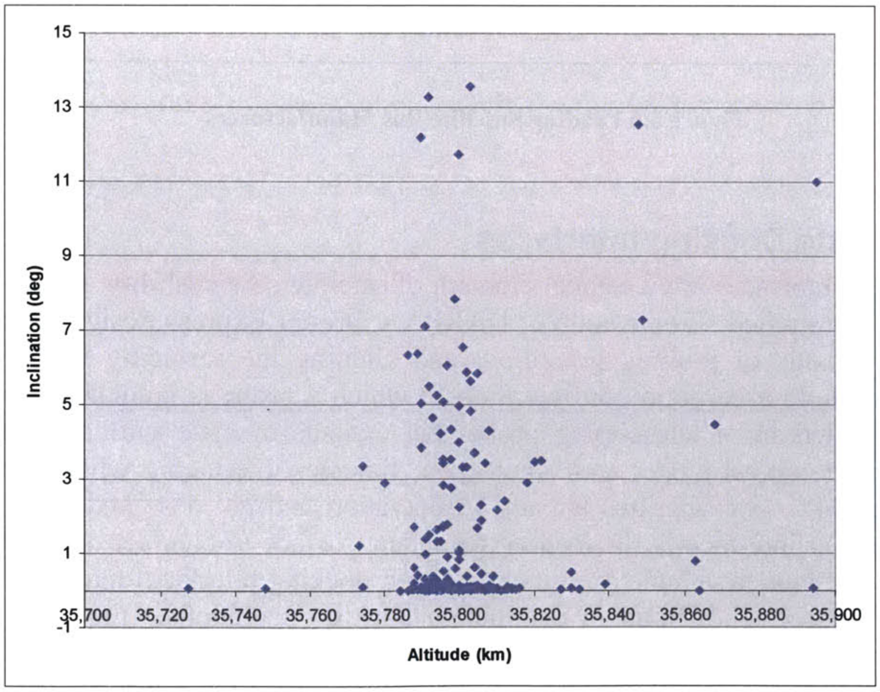

Figure 3.5 Distribution of Geostationary and Near-Geostationary Satellites

3.3.3 Bus Manufacturers

The attributes of satellite bus design relevant to conducting serviceability assessments are discussed in Section 3.2.4. While the UCS Satellite Database does not provide the bus type, it does provide the name of the contractor that built the satellite. Given the limited number of satellite bus types built by each contractor (*e.g.,* Lockheed Martin has converged on the A2100 design), it may be possible to infer satellite bus serviceability metrics as a function of the contractor. Figure 3.6 displays the distribution of active satellites across top contractors. The top 13 contractors each have at least 16 operational satellites in-orbit and constitute 75% of all active satellites.

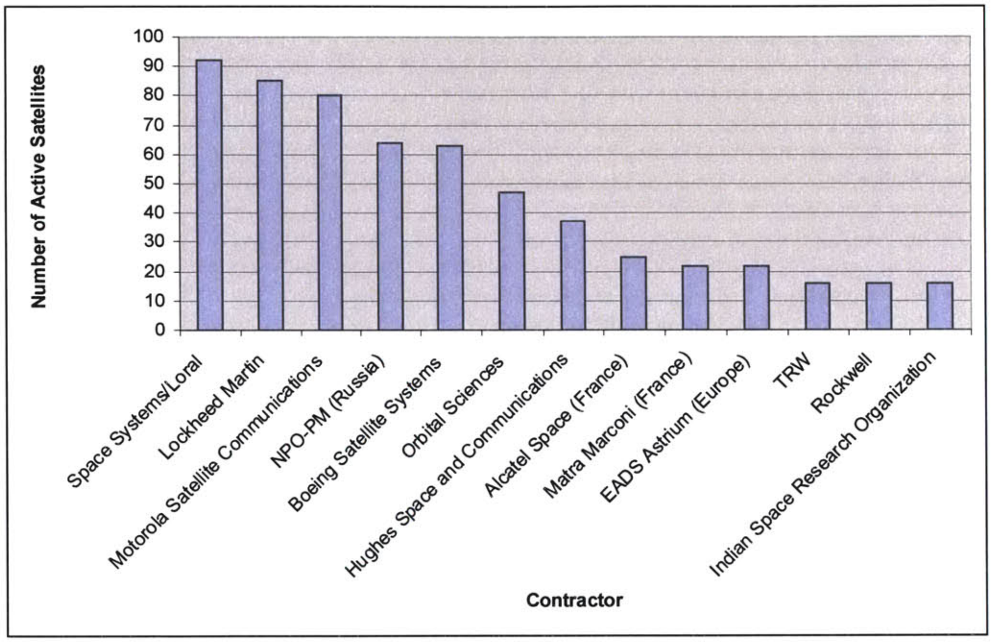

Figure 3.6 Leading Satellite Bus Manufacturers

3.3.4 Candidate Docking Interfaces

Given that docking interfaces are a critical element of satellite serviceability, numerous docking strategies have been studied. For example, DARPA's Orbital Express design team has traded many different methods of joining, grappling, and aligning the servicing vehicle and target satellite. These include a harpoon configuration in which a probe is launched onto the target, latched on, and reeled in; a telescoping probe that extends to mate with the target; impact docking with a large conical guide; and "claw-type" linkages interfacing with a trefoil (Stamm and Motaghedi, 2004). For satellites already in operation and not designed for servicing, the launch vehicle mating interface is the leading candidate surface to conduct docking operations. As such, the satellite launch vehicle (and its associated docking interface) may serve as a proxy for assessing the degree of difficult in conducting docking operations. Figure 3.7 shows the distribution of active satellites across launch vehicle providers. The top 10 launch vehicle families are responsible for transporting 84% of active satellites to their orbits.

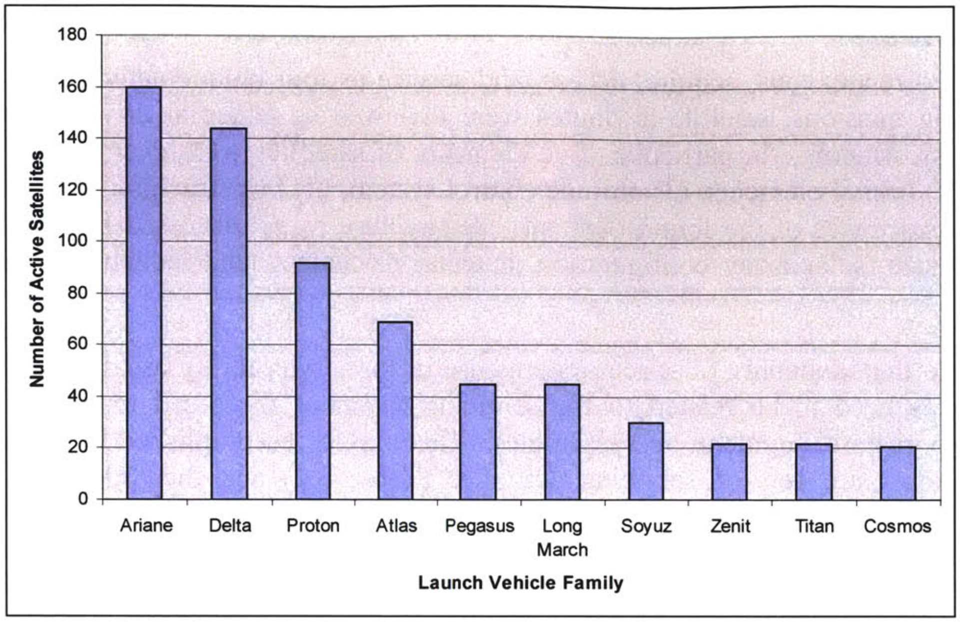

Figure 3.7 Leading Launch Providers

3.3.5 Expected Life

Empirical data suggests that satellite failures follow a bathtub distribution whereby failures are concentrated during initial check-out operations at BOL and around EOL due to expected degradation (Sullivan, 2005). Figure 3.8 shows the distribution of remaining life for satellites. As illustrated by the red bars, over 38% of active satellites have exceeded EOL projections.

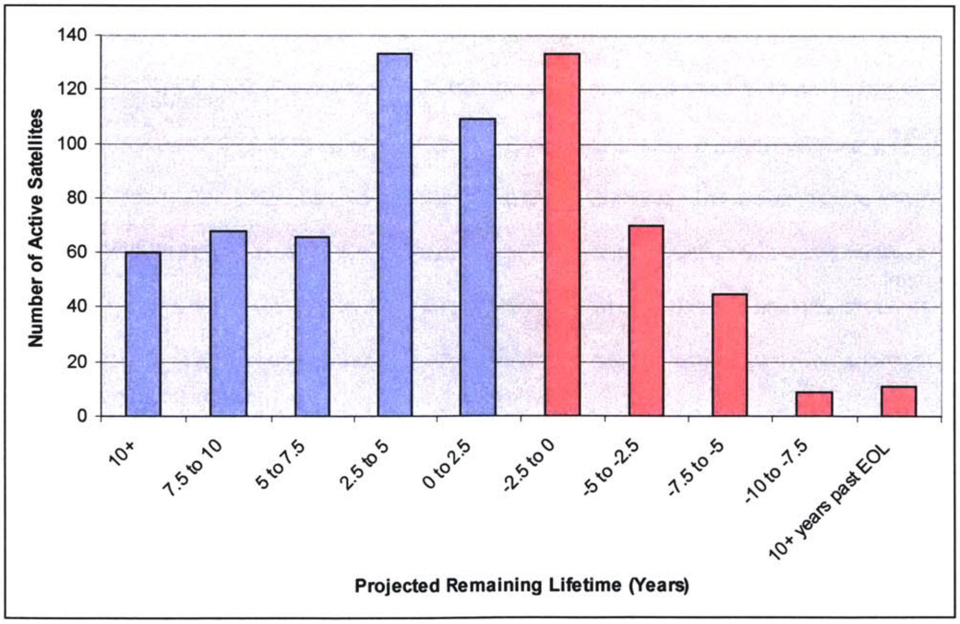

Figure 3.8 Distribution of Remaining Life for Active Satellites

3.4 Synthesis

Having identified rendezvous, acquire, access, and service as four unique activities comprising generic servicing missions, satellite attributes were reviewed as potential drivers for on-orbit serviceability assessments. In particular, five elements of satellites were deemed relevant: (1) mission area, (2) orbital elements, (3) attitude control system, (4) bus structure, and (5) payload configuration. Attributes of the fourth element, bus structure, were discussed further including bus shape and size, solar array configuration, antenna placement, and launch vehicle mating interface.

In order to make this taxonomy of space systems useful for serviceability assessments, the five satellite attributes need to be related to the servicing functions discussed in Chapter 1 (*i.e.*, inspect, relocate, restore, augment, and assemble). This may be accomplished by decomposing servicing functions into sets of servicing activities (Table 3.1) and then identifying which satellite attributes affect the degree of difficulty of each servicing activity (Figure 3.9). In this way, the attributes of a satellite may be related to the degree of difficulty of servicing missions.

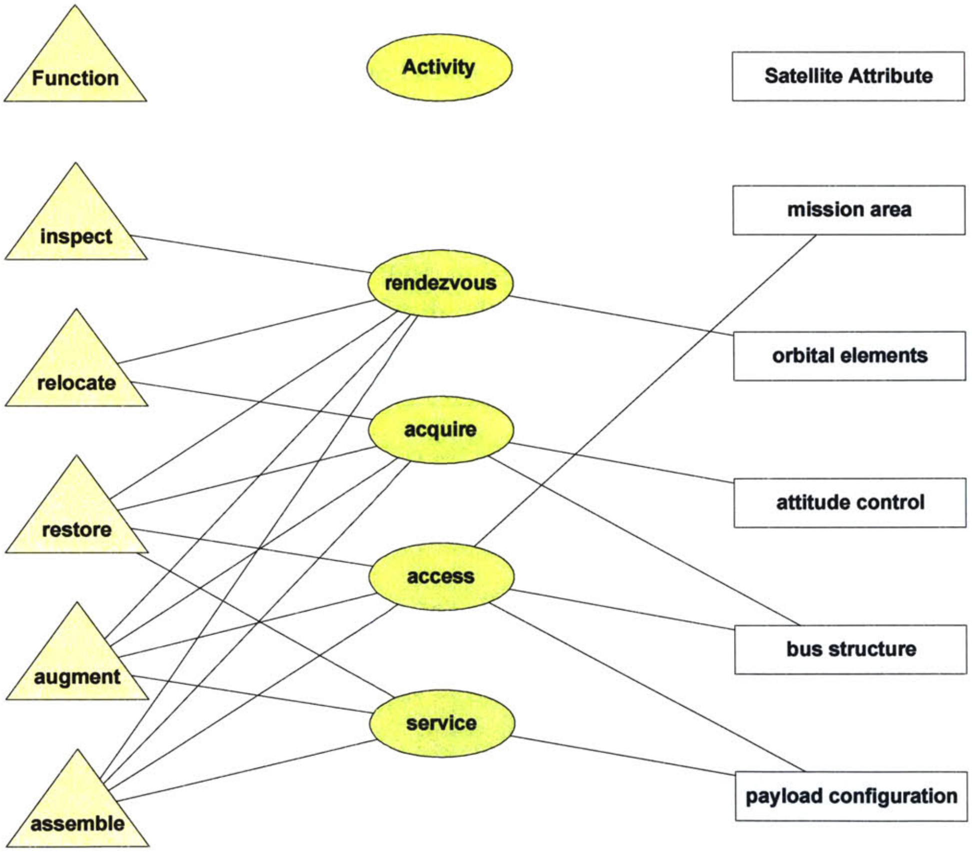

Figure 3.9 Tracing OOS Functions to Satellite Attributes

The availability of data for populating the taxonomy is critical for making serviceability assessments. However, global databases such as the one maintained by the Union of Concerned Scientists offer only general satellite information. While mission area and orbital elements data are available, detailed technical information on attitude control, bus structure, and payload configuration is not included. Fortunately, this information may be derived from an analysis at the spacecraft bus level given the limited number of satellite designs currently in production.

Looking ahead to a methodology for assessing satellite amenability to OOS, the availability of data informs the research approach: utilize the data contained in comprehensive satellite databases (*i.e.*, mission area, orbital elements) as much as possible and, then, gather information on satellite attitude control, bus structure, and payload configuration. Figure 3.9 shows the dependencies of each satellite attribute on assessing serviceability for the OOS activity. The mission area and orbital element attributes drive rendezvous and access activities. However, the degree of difficulty of the access activity is also a function of bus structure and payload configuration. Therefore, only the serviceability of the rendezvous activity can be assessed from the metrics contained in comprehensive satellite databases. Serviceability assessments of acquire, access, and service activities must be derived from other sources.

Chapter 4 builds on the taxonomy of space systems for serviceability with a two-tiered approach: (1) assessment of rendezvous amenability by inputting the UCS data into an agent model based on orbital transfers and (2) development of a framework for comparing the relative amenability of various satellite bus designs to the full set of OOS activities including acquire, access, and service.

4 Methodology to Assess Amenability of Satellites to On-Orbit Servicing

This chapter proposes and tests a methodology for performing satellite serviceability assessments across the four OOS activities discussed in Chapter 3. First, relative motion between satellites is reviewed and the amenability of satellites to orbital rendezvous is investigated. A servicing campaign simulation in GEO is employed to conduct serviceability assessments of the rendezvous activity. The simulation is based upon orbital transfers, and may be extended to other orbital zones to identify clusters of satellites warranting further investigation. Second, a framework is proposed for comparing the relative amenability of various satellite bus designs for all OOS activities including acquire, access, and service. The following questions are addressed in this chapter:

- What is the amenability of existing satellites to OOS?
    - Given deployment of a limited OOS capability, in what orbits would a servicing capability most likely be available?
    - How might relative serviceability assessments be made across various satellite bus designs?

4.1 Relative Motion between Satellites

In order to accomplish OOS, it is necessary to rendezvous a servicing vehicle with target satellites. To maneuver between orbits, a servicing vehicle's velocity vector is changed in magnitude and direction using a thruster. Since most propulsion systems operate for only a short period of time relative to the orbital period, maneuvers are treated as an impulsive change in velocity while the positions remain fixed. In general, the change in the servicing vehicle's velocity vector, ΔV, to maneuver to from one orbit to another is given by:

$$\Delta \mathrm{V} = V_{\mathrm{final}} - V_{initial} \tag{4-1}$$

Initial and final velocity vectors may be derived from the orbital elements. Depending on the starting location of a servicing vehicle and assuming circular orbits, total ΔV required to maneuver to a target satellite may consist of five maneuvers: (1) inclination changes, (2) changes in the right ascension of the ascending node, (3) coplanar orbit transfers, (4) phasing maneuvers, and (5) proximity operations for final rendezvous. The time required to accomplish each maneuver is also an important attribute of relative motion for a vehicle servicing multiple satellites with potentially limited availability.

4.1.1 Inclination Changes

Changing the inclination of a satellite's orbital plane requires changing the direction of the velocity vector. Inclination changes are very expensive in terms of ΔV and associated fuel consumption. For satellites in elliptical orbit, inclination changes are conducted at apogee when velocity is at its lowest to minimize required ΔV. In some cases, ΔV may be minimized by boosting a satellite into a higher orbit, conducting the inclination change at apogee, and then returning the satellite to its original orbit (Wertz and Larson *et al.*, 1999).

In the case of a simple inclination change for a circular orbit where final velocity (V_f) is equal to initial velocity (V_i) the velocity change reduces to

$$\Delta V_{inclination} = 2V_i \sin(\theta/2) \tag{4-2}$$

where θ is the angle change required (Wertz and Larson *et al.,* 1999).

Inclination changes are impulsive maneuvers that require no time themselves. However, there is a wait time associated with proper alignment which is discussed in Section 4.1.4, Phasing Maneuvers for Rendezvous.

4.1.2 Changes in the Right Ascension of the Ascending Node

For circular orbits, there are two points of intersection at which a burn can be applied to match up the line of nodes. Solving this problem requires determining the location of the common point for the burn, the angle (v) through which the orbit plane must rotate, and the required ΔV. Because both the initial and final orbits are circular, velocity is equal at all points and the problem of changing the ascending node reduces to solving the following two equations:

$$\cos(v) = \cos^2(i_{initial}) + \sin^2(i_{initial})\cos(\Delta\Omega) \tag{4-3}$$

$$\Delta V_{\Omega} = 2V_{initial}\sin(\frac{v}{2}) \tag{4-4}$$

As with inclination changes, changes in the right ascension of the ascending node are impulsive maneuvers that require no time themselves. There is a wait time associated with proper alignment (Section 4.1.4, Phasing Maneuvers for Rendezvous).

4.1.3 Coplanar Orbit Transfers

Unless the initial and final orbits intersect, in-plane maneuvering requires a transfer orbit. Hohmann transfers are maneuvers between circular orbits of different altitudes that minimize ΔV expenditures. The Hohmann transfer orbit consists of half of an elliptical orbit that is tangent to both the initial and final circular orbits. Because the Hohmann transfer orbit is tangential to both circular orbits, the velocity vectors are collinear at the intersection points. Two impulsive burns are required: one to initiate the transfer ellipse and one to apply a velocity change to match the velocity of the final orbit.

Total ΔV for the Hohmann transfer is the sum of the velocity changes at perigee (ΔV_A) and at apogee (ΔV_B) of the transfer ellipse (*i.e.*, differences in magnitudes of the velocities in each orbit). Differences in velocities are calculated from the orbital elements using the energy equation

$$\Delta V_{Hohmann} = \Delta V_A + \Delta V_B = \sqrt{\mu}\left[\left|\left(\frac{2}{r_A} - \frac{1}{a_{tx}}\right)^{\frac{1}{2}} - \left(\frac{1}{r_A}\right)^{\frac{1}{2}}\right| + \left|\left(\frac{2}{r_B} - \frac{1}{a_{tx}}\right)^{\frac{1}{2}} - \left(\frac{1}{r_B}\right)^{\frac{1}{2}}\right|\right] \tag{4-5}$$

where μ is the product of the universal constant of gravitation and the mass of the Earth, r_A is the altitude of the lower altitude circular orbit, r_B is the altitude of the higher altitude circular orbit, and a_{tx} is the semimajor axis of the transfer ellipse (which is the average of the radii of the initial and final orbits) (Wertz and Larson *et al.,* 1999).

The time required for a Hohmann transfer is equal to half the period of the transfer orbit. Minutes of transfer time may be computed from the energy equation in terms of r_A and r_B as follows:

$$T_{Hohmann} = \frac{P}{2} = \frac{(r_a + r_b)^{\frac{3}{2}}}{620703} \tag{4-6}$$

Transferring a satellite between orbits in less time than that required for a Hohmann transfer may be accomplished with a one-tangent burn (*e.g.,* ~3.5 hours rather than ~5.3 hours for LEO to GEO transfers). However, one-tangent burns require more fuel than Hohmann transfers (~3.9 km/s ΔV rather ~4.7 km/s ΔV for LEO to GEO transfers). For a one-tangent burn, the transfer orbit is tangential to the initial orbit and intersects the final orbit at an angle relative to the flight-path of the transfer. A third option for coplanar orbit transfers is the spiral transfer which uses a constant low-thrust burn.

When orbital transfer involves rendezvousing with another space object, precise timing of when to initiate the coplanar transfer is required. For example, the servicing vehicle may remain in its initial orbit until the relative motion between itself and the target satellite results in the desired geometry. This wait time in the initial orbit, T_{wait}, is calculated as a function of angular velocities

$$T_{wait} = \frac{(\phi_i - \phi_f + 2k_{target}\pi)}{(\omega_{servicer} - \omega_{target})} \tag{4-7}$$

where ϕ_i is the angular separation of the initial positions, ϕ_f is the angular separation required for rendezvous, k is the number of revolutions of the target satellite, $\omega_{servicer}$ is the angular velocity of the servicing vehicle, and ω_{target} is the angular velocity of the target satellite (Wertz and Larson *et al.,* 1999).

4.1.4 Phasing Maneuvers for Rendezvous

Phasing maneuvers may also be required within one orbital plane in the case of a servicing vehicle transferring between two satellites in the same circular orbit. Phasing maneuvers may be performed by lowering or raising the orbit and waiting for the difference in period to cancel the difference in phase. Two circular phasing scenarios exist: (1) target satellite leading the servicing vehicle and (2) servicing vehicle trailing the target satellite (Figure 4.1). The initial angular separation or phase angle (ϑ) is measured from the target satellite to the servicing vehicle (with the direction of the target satellite's motion defined as the positive direction). Because the two satellites are in the same orbit, $\omega_{servicer}$ is the same as ω_{target} which is given in Vallado and McClain (2001):

$$\omega_{target} = \sqrt{\frac{\mu}{a_{target}^3}} \tag{4-8}$$

For the case of circular rendezvous with the servicing vehicle trailing the target satellite, the target satellite may complete one revolution minus the initial separation (ϑ) in the time that the servicing vehicle revolves once in the phasing orbit. The formula for phase time is

$$T_{phase} = \frac{k_{target}(2\pi) + \vartheta}{\omega_{target}} \tag{4-9}$$

where multiple revolutions of the target satellite enumerate multiple solutions.

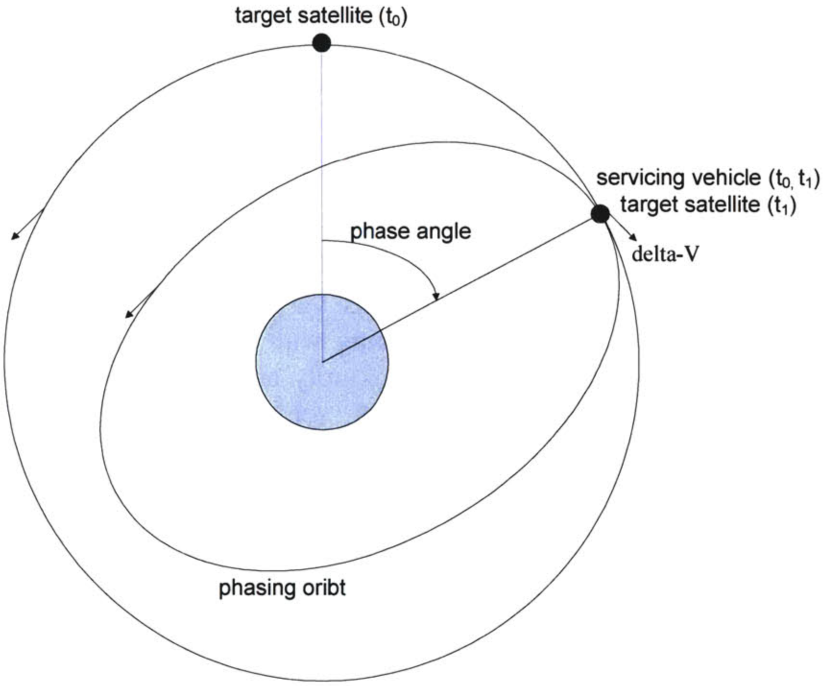

Figure 4.1 Circular Coplanar Rendezvous (Servicing Vehicle Trailing Target Satellite)

Given that these are only circular orbits with tangential burns, ΔV is simply the change in magnitudes of the different orbits. Total ΔV is twice the change in velocity of the initial burn because the servicing vehicle must reenter the original orbit. Therefore, total ΔV for phasing maneuvers is calculated as

$$\Delta V_{phase} = 2\left|v_{phase} - v_{servicer}\right| = 2\left|\sqrt{\frac{2\mu}{a_{target}} - \frac{\mu}{a_{phase}}} - \sqrt{\frac{\mu}{a_{target}}}\right| \tag{4-10}$$

where a_{target} is the semimajor axis of the target satellite's orbit. The semimajor axis of the phasing orbit, a_{phase} is calculated as

$$a_{phase} = \left(\mu \left(\frac{T_{phase}}{2\pi k_{servicer}} \right)^2 \right)^{1/3} \qquad \textbf{(4-11)}$$

where $k_{servicer}$ is the number of revolutions of the servicing vehicle (Vallado and McClain, 2001).

4.1.5 Proximity Operations

Relative motion for two close orbiting satellites is addressed by the Clohessy-Wiltshire or Hill's equations. The satellite coordinate system is used for relative motion whereby the system moves with the target satellite. Radial positions are parallel to the position vector (along the R axis), transverse displacements are along-track or normal to the position vector (along the S axis), and normal positions are normal to the orbital plane (W axis). Assuming circular motion and writing each vector component separately yields

$$\begin{aligned} \ddot{x} - 2\omega\dot{y} - 3\omega^2 x &= f_x \\ \ddot{y} + 2\omega\dot{x} &= f_y \\ \ddot{z} + w^2 z &= f_z \end{aligned} \qquad \textbf{(4-12)}$$

where x, y, and z represent the three components of the target satellite's relative range vector (Vallado and McClain, 2001). Proximity operations vary across the set of possible OOS activities. Whether OOS involves cooperative docking with a preplanned servicer or external grappling with a space tug, ΔV expenditures for proximity operations are difficult to predict *a priori* (*e.g.,* Intelsat 603 satellite rescue on STS-49, see Section 2.1.5.8). Maneuvers are composed of small velocity increments which are highly dependent upon control algorithms. As a first-order estimate, 50 m/s is assumed for ΔV for proximity operations, $\Delta V_{proximity}$ (Meissinger and Collins, 1999).

4.2 Agent Model of Satellite Servicing Based on Orbital Transfers

Having reviewed relative motion between satellites, the amenability of satellites to the rendezvous servicing activity is assessed through the development of an agent-based model of OOS. With the context of a multi-year servicing campaign in the GEO belt, the model consists of a series of phasing maneuvers between GEO parking slots. OOS is treated as a multi-variable optimization problem with the principal trade of minimizing both ΔV expenditures and transfer time. Assuming current launch vehicle, propulsion, and robotic technology for servicing vehicles, the focus in the model is on the serviceability of target satellites. Servicing vehicle operations are simulated over time, completing maneuvers as a function of path-dependent servicing operations. With servicing operations initiated by requests from target satellites that issue "tickets" in a binomial process, a Monte Carlo analysis is performed to derive general results. Primary outputs of the agent model are the cost of servicing (mean ΔV expenditure by servicing vehicle for satisfying tickets) and the performance of target satellites (availability for mission operations). Although the focus is on serviceability assessments of target satellites, the model is readily adapted to the design of concept-of-operations for servicing vehicles.

Upon explaining the scope of the model, the two agents (target satellites and servicing vehicles) are described with a discussion of potential states and the rules governing state transitions. Assumptions regarding servicing vehicle capabilities and initial conditions are also discussed before presenting results. Other parts of the thesis related to the agent model include Section 8.3.2, which suggests possible extensions for future work, and Appendix A that documents some of the underlying MATLAB code.

4.2.1 Scope

While Sections 4.3 and 4.4 discuss serviceability assessments at the satellite bus level (acquire, access, and service activities), this section is focused on the rendezvous servicing activity. As such, activities involving physical manipulation of target satellites are "black box" operations in the agent-model. Also, while the serviceability framework developed in Sections 4.3 and 4.4 applies to satellites in any orbit, Section 4.2 focuses on servicing multiple satellites at or near GEO. This initial focus on GEO is driven by the two main factors, the high propulsive cost of LEO plane changes using existing technology and the current concentration of high-value satellites in GEO. Differences in transmission delay times are factors as well.

For a typical satellite in LEO, a plane change of only three degrees requires on the order of 10% of the mass of the satellite. With cost of propellant approximately $10,000/kg, the lifecycle cost of a LEO servicing system would be high. Servicing operations in GEO require relatively small amounts of propulsive effort. Despite large physical distances separating GEO satellites, most satellites are in essentially the same orbit. Large servicing demands are possible with the concentration of high-value satellites. Furthermore, continuous visibility from a single ground station keeps the supporting infrastructure simple. This also leads to less transmission delay time. Although GEO is nearly 70 times farther from the ground than LEO, transmission delays are cut in half (assuming that continuous coverage in LEO is provided through GEO relays) (Yasaka and Ashford, 1996).

4.2.2 Agents, States, and Behaviors

The two agents in the OOS model, target satellites and servicing vehicles, each has a variety of potential states which are governed by underlying behavioral models.

4.2.2.1 Target Satellites

Target satellites may be in one of three states: full health with no need of servicing, full health with a request for scheduled servicing, and not operational with a request for urgent servicing. Requests are communicated to servicing vehicles through tickets by target satellites in need of attention. Table 4.1 illustrates the annual OOS market size in GEO. Based on empirical data compiled on satellite operations between 1957 and 2000 (Sullivan, 2005), five types of servicing missions are identified: refuel, ORU replacement, general repair, relocation in GEO, and deployment assistance. The probabilities in Table 4.1 inform the frequency of servicing ticket requests in the OOS model with tickets issued in a binomial (discrete Poisson) process. One hour is used as the time step in the model with annual servicing requests mapped to the hourly probability of an individual satellite requesting a given servicing mission. Over the course of a given ten year servicing campaign, 175 of the 335 GEO satellites modeled can be expected to generate at least one servicing request (on average).

If in need of servicing, two types of tickets may be issued by the target satellite: scheduled and urgent. Whether a ticket is scheduled or urgent is assumed to be a function of the predictability of the servicing operation (*i.e.*, unpredictable servicing missions cause urgent servicing tickets to be initiated).[1] Table 4.1 captures the assumed predictability of each OOS mission. With refueling needs readily projected and ORU replacement a preplanned activity, the first two OOS missions trigger normal servicing tickets. Repair and deployment assistance missions are assumed to be opportunistic servicing events that are not generally predictable. These trigger urgent servicing tickets. Relocation missions are assumed to be equally divided between predictable (*e.g.*, movement of commercial communications satellites to capture emergent terrestrial markets, retirement) and unpredictable (*e.g.*, surge communication need in war time, sudden loss of attitude control).

Table 4.1 Annual Number of GEO Servicing Opportunities

Service	Average Annual Opportunities	Average Annual Opportunities in GEO	Predictable?
Refuel	20.0	8.9	yes
ORU Replacement	4.4	2.0	yes
General Repair	3.8	1.7	no
Relocation in GEO	13.0	13.0	yes and no
Deployment Assistance	0.3	0.1	no

4.2.2.2 Servicing Vehicles

Servicing vehicles may be in one of four states: parked in GEO, in transit to a target satellite, servicing a target satellite, or out of fuel. When a ticket is issued, each servicing vehicle calculates the ΔV required to complete the mission ($\Delta V_{phase} + \Delta V_{proximity}$) and compares this value to its remaining propellant. Of the servicing vehicles possessing enough fuel, the servicing vehicle that will expend the least amount of ΔV is selected for the servicing mission. Having "grabbed" a ticket, the servicing vehicle transits to the target satellite with the circular coplanar phasing maneuvers discussed in Section 4.1.4.[2]

One of the parameters subjected to sensitivity analysis in the simulation is the transit time for the servicing vehicles to the target satellite. The key trade in the model is between transfer time and ΔV efficiency. Should a servicing provider expend extra fuel to transit more quickly (*i.e.*, reducing the number of phasing orbit revolutions) to a target satellite that has issued an urgent ticket? This issue is addressed by treating response time as a parameter and modeling two servicing architectures: (1) treating all servicing tickets as equals, using a constant number of phasing orbit revolutions and (2) distinguishing between servicing tickets by varying the number of phasing orbit revolutions as a function of ticket urgency. Incorporating Equation 4-8 and then Equation 4-9 into Equation 4-11 informs the selection of the number of phasing orbit revolutions.

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[1] In this discussion, a predictable mission does not imply that it is known years in advance. Rather, it implies that a servicing vehicle may respond in weeks rather than days without strongly affecting the value proposition to the target satellite.

[2] Shen and Tsiotras (2002) have studied the issue of optimal scheduling for servicing multiple satellites in a circular constellation. A similar minimum-ΔV two-impulse maneuver is used for each rendezvous. In contrast to the agent model of OOS, which is a dynamic simulation driven by probabilistic servicing requests, Shen and Tsiotras seek to find the best sequence with the minimum total ΔV to service all the satellites in the constellation (regardless of order).

$$a_{phase} = \left(\mu\left(\frac{T_{phase}}{2\pi k_{servicer}}\right)^2\right)^{1/3} = \left(\mu\left(\frac{k_{target}(2\pi)+\vartheta}{\omega_{target} * 2\pi k_{servicer}}\right)^2\right)^{1/3} = \left(\mu\left(\frac{k_{target}(2\pi)+\vartheta}{\sqrt{\frac{\mu}{a_{target}^3}} * 2\pi k_{servicer}}\right)^2\right)^{1/3} \qquad \textbf{(4-13)}$$

$$= a_{target}\left(\frac{k_{target}(2\pi)+\vartheta}{2\pi k_{servicer}}\right)^{2/3}$$

As observed in the simplification of Equation 4-13, given a common orbit and an initial phase angle, the only parameters to trade are the number of revolutions for the target satellite and for the servicing vehicle during phasing. Since ΔV is minimized the closer a_{phase} is to a_{target}, the quantity in parentheses in Equation 4-13 should be as close to one as possible. Given that the phasing angle varies between $-\pi$ and π, it follows that $k_{servicer}$ and k_{target} should be equal.

The next issue to resolve is to determine the appropriate number for $k_{servicer}$ and k_{target}. The greater their value, the smaller the ΔV expenditure will be. However, large numbers of phasing revolutions will take more time (Figure 4.2a). In general, this trade between speed and fuel efficiency should be settled by a competitive OOS market (*i.e.*, servicing urgency may drive OOS market segmentation). For the purposes of the agent model of OOS here, it is only necessary to select a baseline value. A heuristic investigation indicates that an optimal tradeoff between fuel expenditure and time of travel occurs at around $k_{servicer} = k_{servicer} = 5$ (Figure 4.2b). A formal investigation of this tradeoff is left to future work.

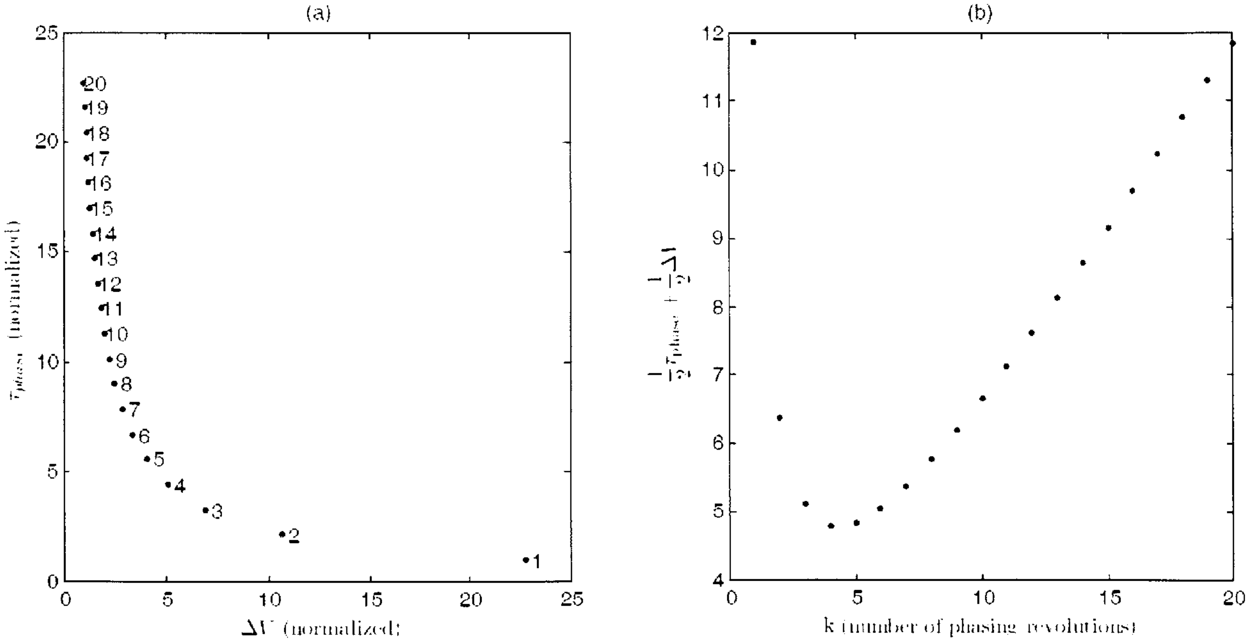


Figure 4.2 Determining Number of Phasing Revolutions – Baseline Servicing Architecture

One constraint on the number of phasing revolutions is the need select a number of revolutions for the target satellite that does not cause the perigee of the transfer orbit to impose a ΔV penalty due to atmospheric drag or to pass through the Earth. The high velocities and high drag characterizing extremely low altitude orbits imposes a ΔV penalty for orbit maintenance. So as to make this ΔV penalty trivial, a constraint is imposed on the servicing vehicle (in the case when it trails the target satellite) such that the perigee of the transfer orbit may not be less than 1000 km in altitude.

Upon reaching the target satellite, the servicing operations begin. The ΔV and time costs to the servicing vehicle for operations are assumed to be constants of 50 m/s and one day, respectively. The mission completes with the servicing vehicle assuming a parking orbit in GEO adjacent to the target satellite it just serviced. As such, the orientation of servicing vehicles in the simulation is dependent upon the location of the last set of target satellites. Total ΔV cost and time for each servicing mission is calculated with Equations 4-14 and 4-15:

$$\Delta V_{total} = \Delta V_{phase} + \Delta V_{proximity} \tag{4-14}$$

$$T_{total} = T_{phase} + T_{servicing} \tag{4-15}$$

4.2.3 Initial Conditions

Initial conditions for the target satellites in the model are based on the orbital elements provided on GEO spacecraft in the UCS satellite database. Four servicing vehicle are assumed to be parked in the GEO belt.

4.2.3.1 Target Satellites

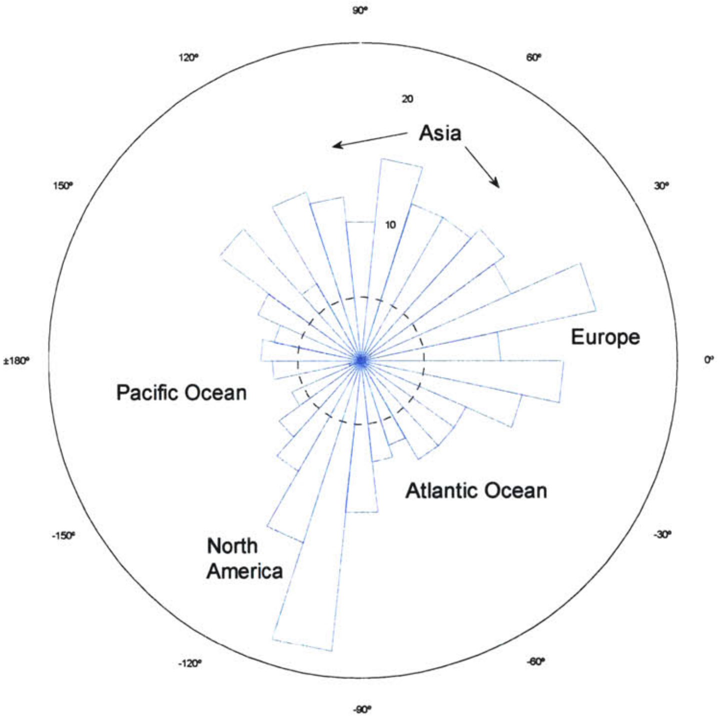


Figure 4.3 GEO Satellite Density

Target satellites are initialized based upon the UCS satellite database. Of the approximately 800 total spacecraft in the database, 335 are listed as being in GEO and contain true anomaly data. These 335 spacecraft comprise the target satellites used in the model and are assumed to be at GEO altitude with zero degree inclination (a close approximation of reality). NORAD identification tags are also tracked in the simulation to establish traceability to satellite attributes beyond orbital elements (*e.g.*, mission area, operator, payload) for later post-processing. Figure 4.3 depicts GEO satellite density as a function of longitude in thirty discrete bins (with bin magnitude representing the number satellites occupying a particular twelve-degree section of the GEO belt). Local maximums may be observed over Europe and North America.

4.2.3.2 Servicing Vehicles

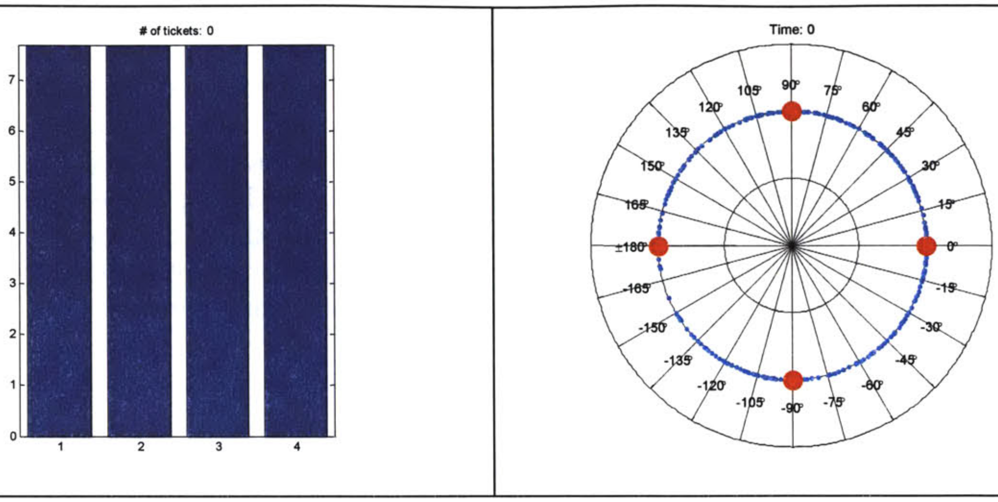
Although the purpose of the OOS model is not to design a servicing provider architecture, it is necessary to assume a baseline set of servicing vehicles from which the physical amenability of target satellites to rendezvous activities may be derived. For the provider architecture in the model, four servicing vehicles are assumed to be parked in the GEO belt with initial locations of 0, 90, 180, and 270 degrees around the globe.

Current robotic, launch, and propulsion technologies are assumed in the simulation. Each servicing vehicle is based on ESA's Geosynchronous Servicing Vehicle (GSV). With a dry mass of 1088 kg, the GSV consists of a conventionally designed bus, an augmented attitude maneuver and transfer capability, a sensor system for both rendezvous and docking and visual monitoring, and teleoperated robotic arms for mechanical manipulation (de Peuter, *et al.*, 1994). Assuming launch with a Delta IV Heavy, the wet mass of the GSV delivered to GEO is 6276 kg (Isakowitz, *et al.*, 2004). This leaves 5188 kg of fuel for each GSV maneuvering in GEO. Assuming H_2/O_2 (I_{sp} = 450 sec) propulsion for the GSV (Wertz and Larson, *et al.*, 1999), the rocket equation yields:

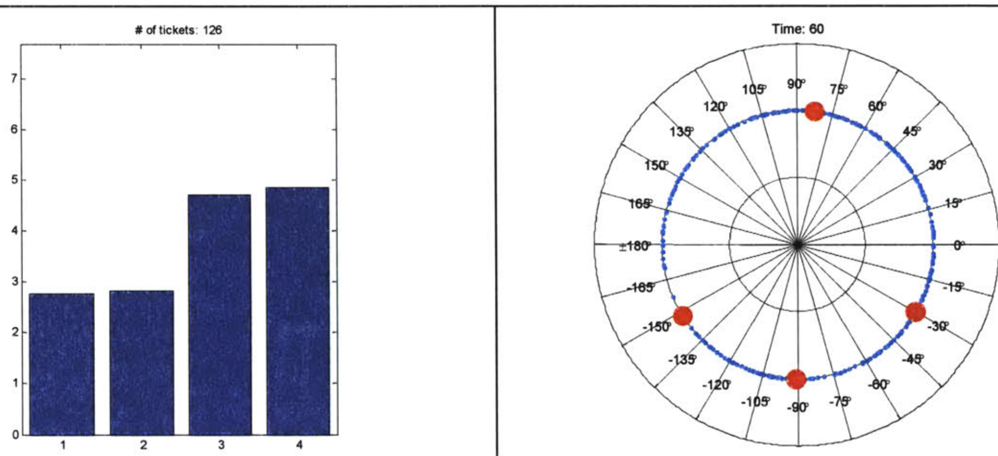
$$\Delta V_{total} = g(I_{sp})\ln\frac{M_p + M_f}{M_f} = 9.81(450)\ln\left(\frac{5188+1088}{1088}\right) \approx 7700\ \mathbf{m/s} \qquad \mathbf{(4\text{-}16)}$$

4.2.4 Results

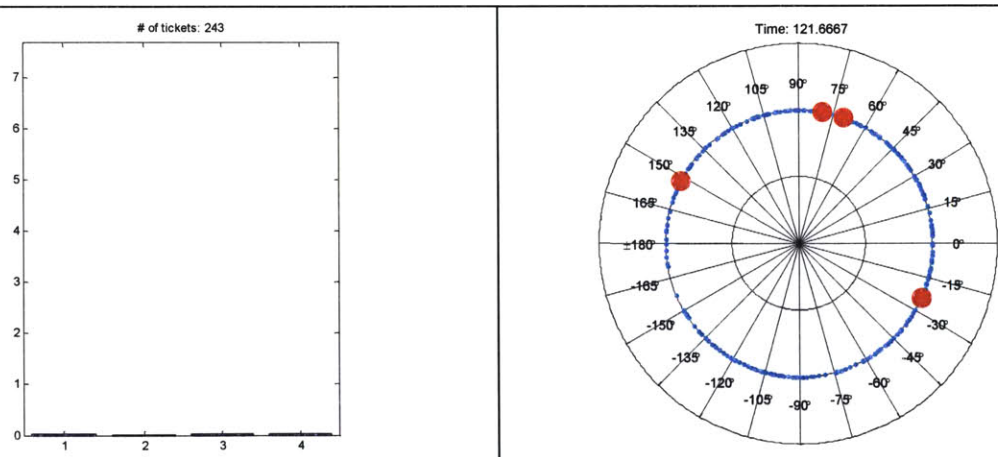
Figure 4.4 depicts a sequence of three snapshots taken of the OOS agent model "dashboard" over the course of a typical servicing simulation. The column on the left depicts remaining ΔV capability of each of the four servicing vehicles. The cumulative number of servicing tickets issued by target satellites is displayed above these "fuel bars." Polar views of the Earth are depicted in the right column. Small, blue dots represent GEO satellites and the four large, red dots each represent a servicing vehicle. Time is displayed above the polar view. While time steps in the model are tracked in hour increments, the time step depicted in the tool dashboard is 30 days. At t=0 (row one), each of the four servicing vehicles possess a full ΔV capability (i.e., 7700 m/s). No tickets have been issued and the servicing vehicles are evenly spaced in GEO parking orbits. At t=60 (row two), almost five years have passed and 126 tickets have been issued. Each servicing vehicle is parked in the slot of its last servicing operation and has between 2 and 5 km/s of ΔV capability remaining. After ten years have passed (row three), 243 servicing requests have been made. However, each servicing vehicle has run out of fuel so it is likely that some servicing requests have not have been satisfied. Each simulation terminates at the end of the 10th year (~122 30-day increments).



Time=0 years (ΔV=7700 m/s for each servicing vehicle, 90° spacing)



Time=~5 years (ΔV varies between 2 and 5 km/s for each servicing vehicle, variable spacing)



Time=10 years (ΔV~0 for each servicing vehicle, variable spacing)

Figure 4.4 Servicing Vehicle Evolution over Ten Years – Dashboard Snapshots of OOS Agent Model

Two ten-year OOS campaigns in GEO are investigated. In the first campaign, servicing vehicles use a constant number for phasing orbit revolutions (k=5). In the second campaign, the number of phasing orbit revolutions for the servicing vehicle varies as a function of servicing ticket urgency (k=5 for normal tickets, k=1 for urgent tickets). Since servicing tickets are issued probabilistically; and, since ΔV expenditures and response time are functions of both the location of the target satellite of the current servicing mission and the target satellite of the last servicing mission, calculations in the agent model are path dependent. As such, a Monte Carlo analysis, consisting of 1,000 runs of each servicing campaign, is performed to derive meaningful results.

The following two subsections explain the implications of the assumed k value(s) for their respective servicing vehicles and then show the results of the Monte Carlo analyses. The discussion is focused on two key "orbit serviceability" parameters: the availability of target satellites in a particular orbital slot for mission operations (where availability between target satellites is distinguished only by the response time of servicing vehicles) and the average ΔV expenditure for OOS missions to a particular orbital slot (where ΔV expenditure is driven only by the rendezvous activities).

4.2.4.1 Servicing Campaign #1 – Constant Response Time

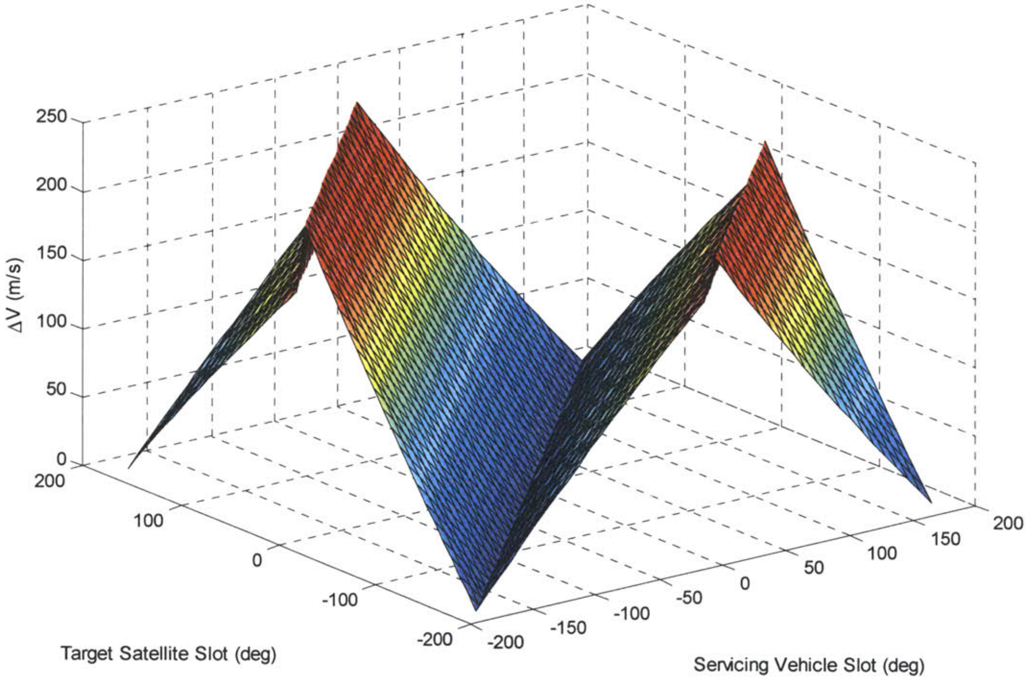


Figure 4.5 Distribution of ΔV Expenditures for Bi-Impulsive Phasing Maneuvers in GEO (k=5)

Figure 4.5 depicts the range of possible ΔV expenditures by servicing vehicles for bi-impulsive phasing maneuvers (assuming five revolutions). When the target satellite leads in the orbit (negative phase angle), the servicing vehicle must move into a lower orbit with a shorter period to account for the initial time displacement (Figure 4.1). Maximum ΔV expenditures of ~225 m/s occur when the servicing vehicle is displaced exactly 180° from the target satellite. When the target satellite trails the servicing vehicle (positive phasing angle), the phasing orbit is made higher than the target orbit to allow the target satellite to catch up.

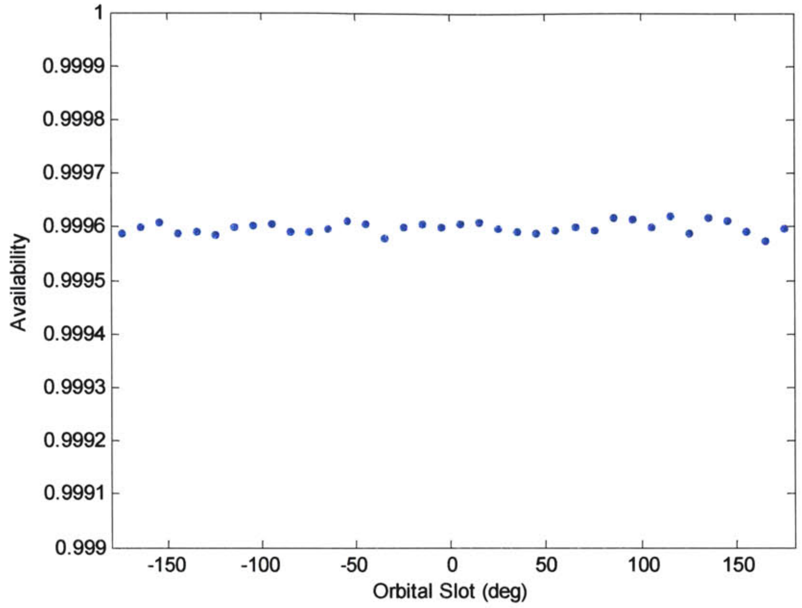


Figure 4.6 Target Satellite Availability (k=5)

Availability is defined as the percentage of the time in the simulation that a given satellite is able to perform its operational mission. Satellites issue urgent servicing tickets (for repair, relocation, or deployment assistance) when they are unable to perform their operational mission. Figure 4.6 displays the average availability for ten-degree clusters of GEO satellites over the course of 1,000 decade-long servicing campaigns. Availability is extremely high (around 0.9996%), and, as observed by the horizontal shape of the scatter plot, relatively constant across GEO orbital slots. Although more variation was expected, this result is not altogether surprising given the small probability of urgent servicing tickets being issued and the fact that servicing operations always succeed.

Figure 4.7 depicts the average ΔV expenditure for servicing missions to a particular orbital slot for each of the 1,000 simulation runs. Only nonzero ΔV averages are plotted.[3] Each vertical line of points (marked with a unique color) represents the distribution of average ΔV expenditures for one of the 335 GEO satellites included in the model. The spacing between vertical lines indicates the varying density of GEO satellites (e.g., light concentration over the Pacific Ocean at -160°) as depicted in Figure 4.3. Also evident in Figure 4.7 is the presence of numerous outliers in each vertical distribution. While average ΔV expenditure values appear to be concentrated starting at the lower limit (*i.e.*, 50 m/s, the minimum given the assumed fixed cost of proximity operations), a few average ΔV's are outliers with values as high as 280 m/s in some simulation runs.

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[3] If an orbital slot was not serviced over the course of a run of the ten-year simulation, average ΔV expenditure would be zero.

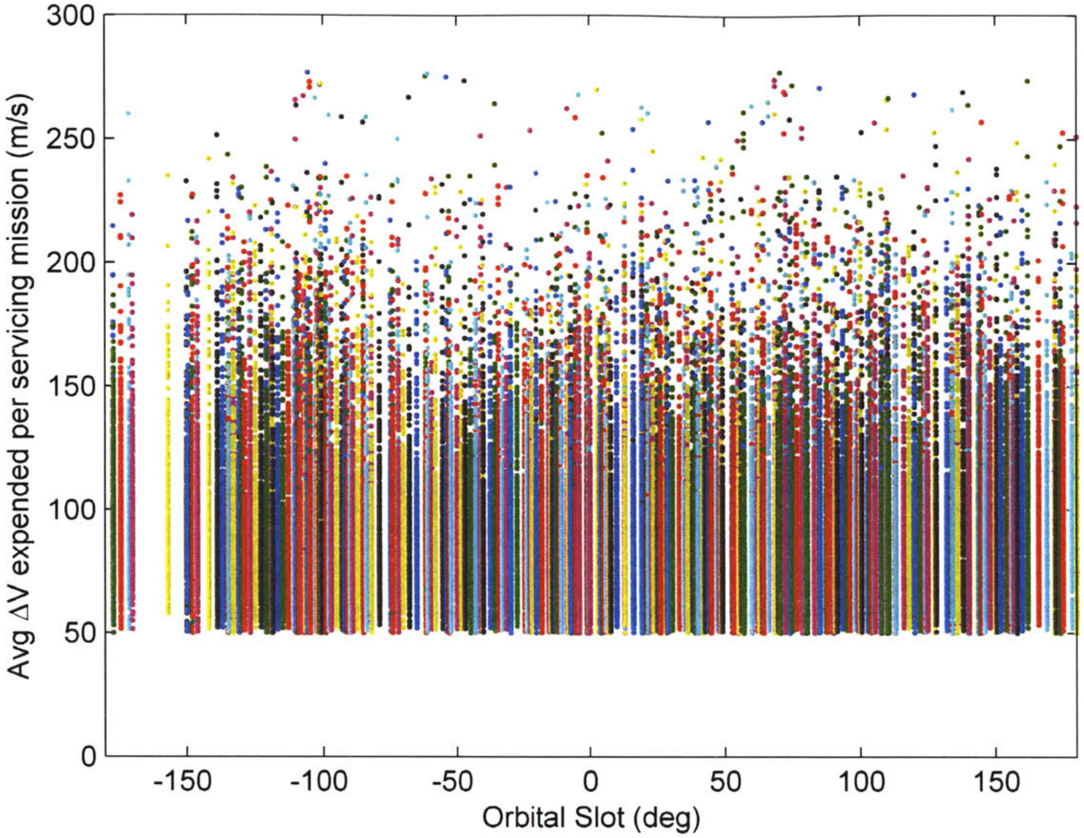

Figure 4.7 Average ΔV Expenditure for Servicing Missions in Each Simulation Run (k=5)

Figure 4.8 depicts a histogram of the average ΔV expenditure for servicing missions to the GEO slot located at -.75°. Representative of most average ΔV distributions, it may be observed that average ΔV expenditures are indeed concentrated at lower values with a few outliers on the high-end. This result is expected given the assumed concept-of-operations in which servicing missions are assigned to the servicing vehicle that will expend the least amount of ΔV.

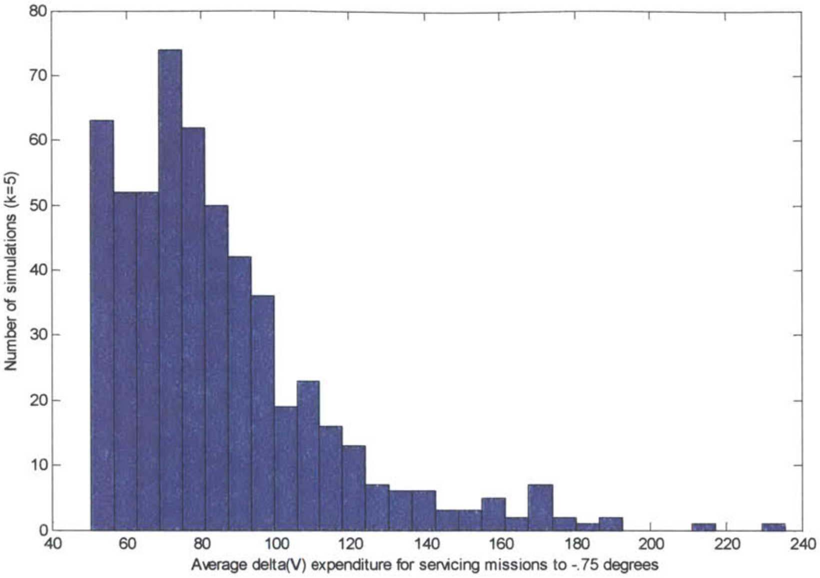

Figure 4.8 Sample Distribution of Average ΔV Expenditure (GEO #150 at -.75°)

Although Figure 4.7 contains lots of data, it is not useful for deriving general results. Further distillation of the data is required to understand how ΔV expenditure for servicing missions varies with respect to GEO orbital slot (if at all). However, one thing that Figure 4.7 does tell us is that simply taking the mean value of each distribution would be misleading given the effect of outliers on the high-end.

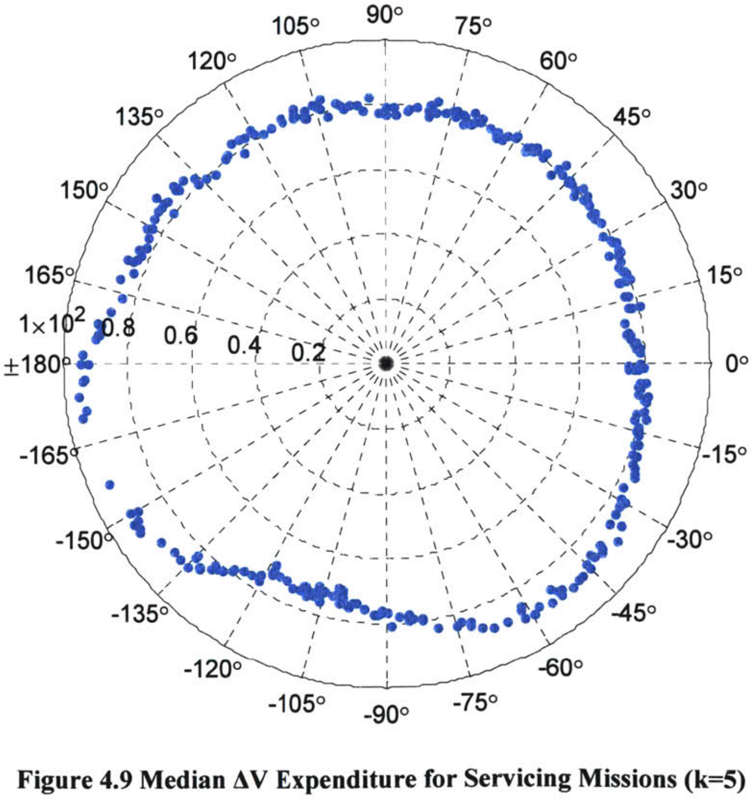

Figure 4.9 Median ΔV Expenditure for Servicing Missions (k=5)

Figure 4.9 plots the *median* ΔV expenditure for servicing missions in each GEO orbital slot. As observed in the polar view, most GEO satellites are expected to cost servicing vehicles around 80 m/s for each mission. Unlike availability, ΔV expenditure is not constant around the belt as North American values hover around 70 m/s with a spike to 95 m/s above the Pacific Ocean. European ΔV expenditures are expected to be around 75 m/s, rising irregularly to around 85 m/s in the Far East.

4.2.4.2 Servicing Campaign #2 – Variable Response Time

Performing a sensitivity analysis on the baseline provider architecture is important for understanding the extent to which assumptions regarding the servicing vehicles impact the serviceability results. Since the principal trade in the servicing architecture is between transfer time and ΔV efficiency, the number of allowed phasing orbit revolutions is treated as a parameter as a means to assess its impact on the relative performance of satellites in the serviceability metrics (*i.e.,* availability and ΔV expenditure per servicing mission).

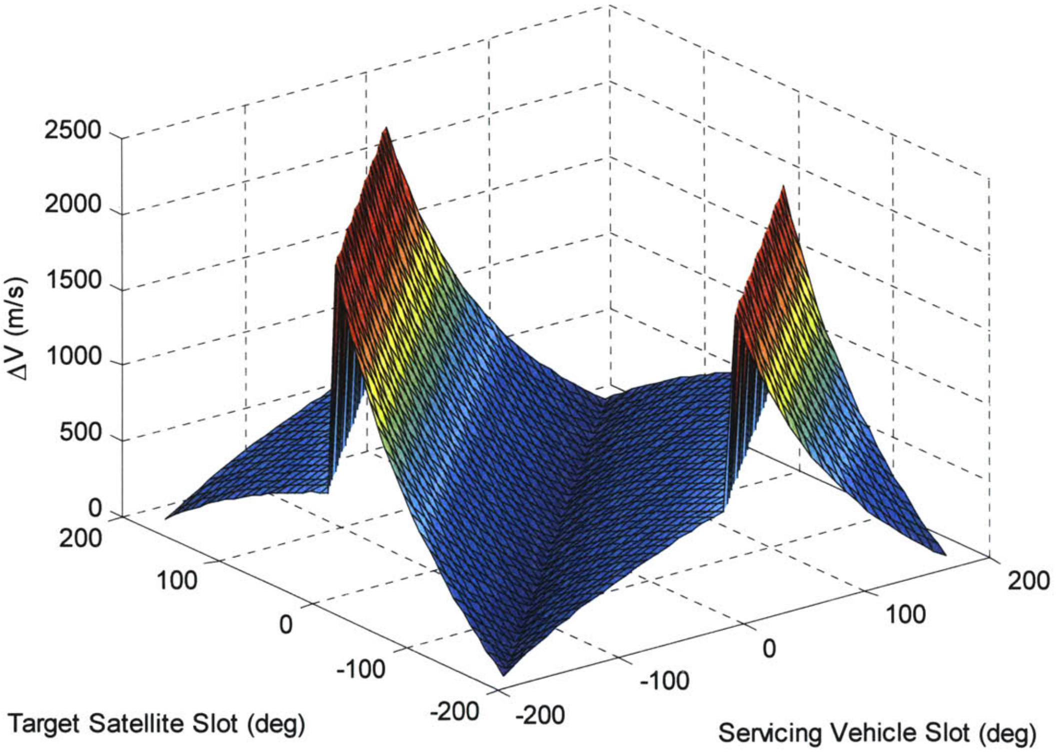

Figure 4.10 Distribution of ΔV Expenditures for Bi-Impulsive Phasing Maneuvers in GEO (k=1)

In contrast to the first servicing campaign in which k was assumed to be five across all servicing tickets, the number of phasing orbit revolutions for the servicing vehicle in the second campaign varies as a function of servicing ticket urgency (k=5 for normal tickets, k=1 for urgent tickets). Figure 4.10 depicts the range of possible ΔV expenditures by servicing vehicles for bi-impulsive phasing maneuvers in the case of k=1. Maximum ΔV expenditures of ~2 km/s occur when the servicing vehicle is displaced exactly 180° from the target satellite. These maximum ΔV expenditures are almost an order of magnitude greater than those in the case of k=5 (Figure 4.5).

Figure 4.11 displays the average availability for ten-degree clusters of GEO satellites over the full set of Monte Carlo runs. As in the first servicing campaign, availability is very high (around 0.998%) and effectively constant across GEO orbital slots. Although availability values are very high in Figure 4.11, they do not reach the extreme values of approximately 0.9996% observed in Figure 4.6. This is counterintuitive because a servicing architecture that rapidly responds to urgent tickets (which are generated when a target satellite is down) might be expected to achieve a higher availability than a servicing architecture which has a constant, slower response time. However, this outcome is an artifact of inactivity of servicing vehicles in the simulated time window. In the first campaign, servicing vehicles would typically retain around 2 km/s of ΔV capability after ten years of operation. In the second campaign, servicing vehicles frequently run out of fuel. In the case that all four vehicles lose operational capability, servicing tickets accumulate and target satellites remain down for the remainder of the simulation.[4]

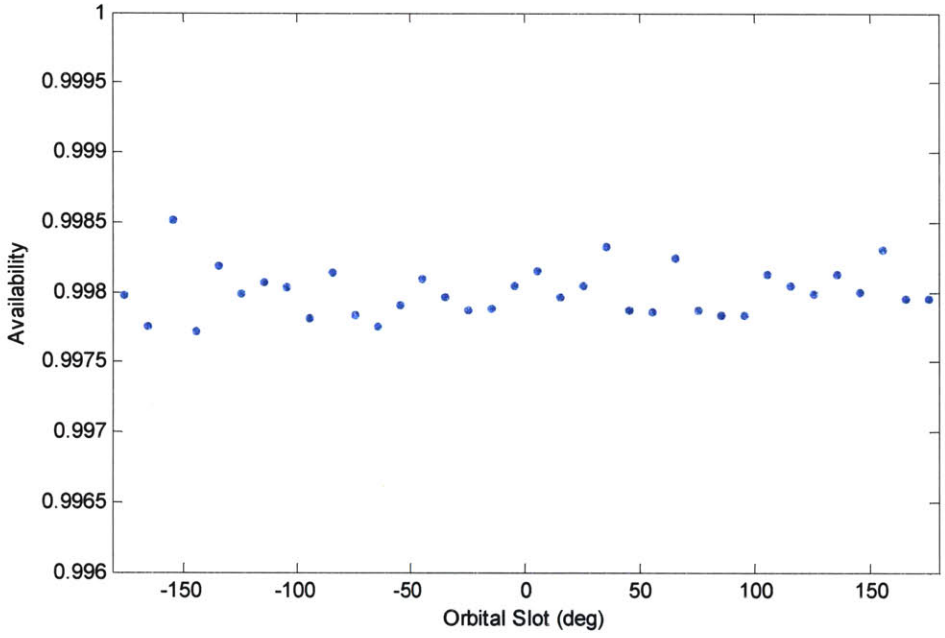

Figure 4.11 Target Satellite Availability (variable k)

Figure 4.12 depicts the average ΔV expenditure for servicing missions to a particular orbital slot for each of the Monte Carlo runs. As before, only nonzero ΔV averages are plotted. Average ΔV expenditures again appear to be concentrated starting at the lower limit. What distinguishes Figure 4.12 from the associated Figure 4.7 (from the first servicing campaign) is the magnitude of the numerous vertical outliers across the GEO slots. While average ΔV outliers in the first

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[4] Once a single servicing vehicle becomes inoperable, it not only adds to the number of missions for other servicing vehicles, increasing the rate of fuel consumption, but also raises average ΔV expenditures for each mission due to an increase in the average magnitude of the phasing angles.

campaign have values as high as 280 m/s, average ΔV outliers for some simulations in the second campaign reach 2300 m/s. The impact of rapid response times for urgent servicing requests (reducing mean transit time from approximately 5 days to around 24 hours) lowers fuel efficiency by around 88% for the most extreme missions.

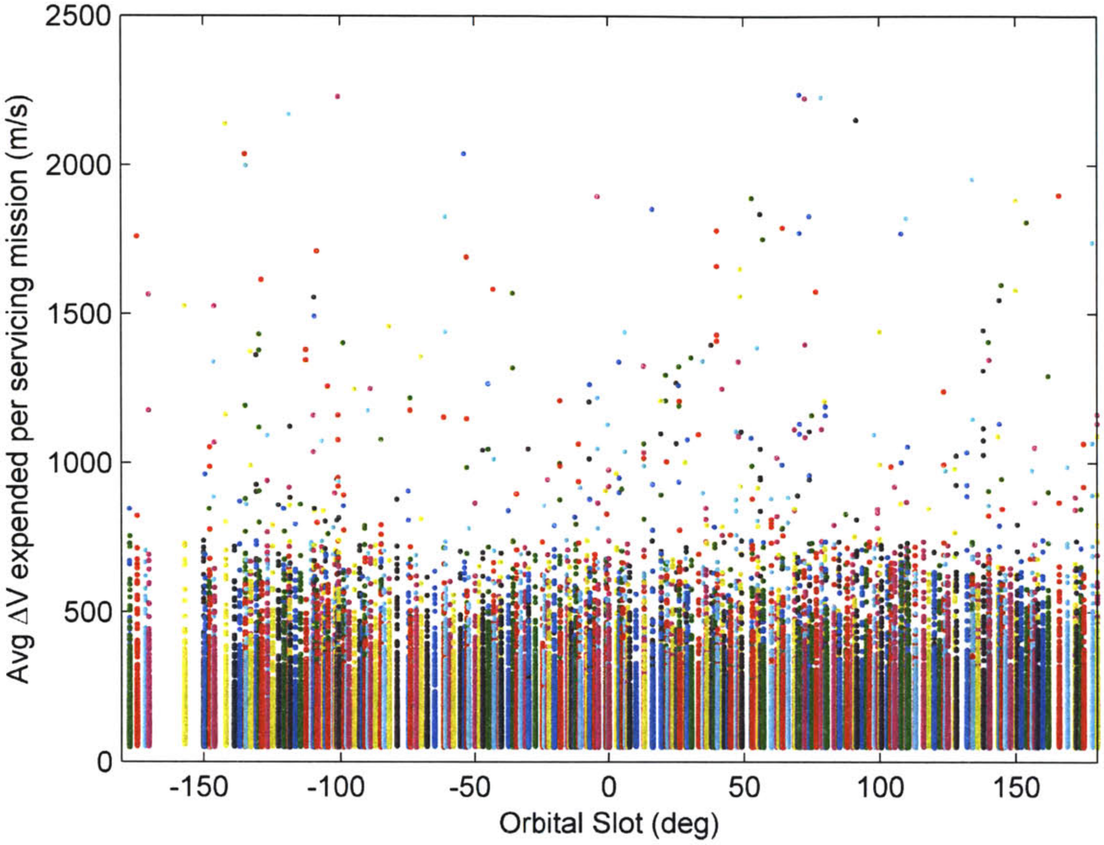


Figure 4.12 Average ΔV Expenditure for Servicing Missions in Each Simulation Run (variable k)

Figure 4.13 plots the median ΔV expenditure for servicing missions in each GEO orbital slot. As observed in the polar view, most GEO satellites are expected to cost servicing vehicles around 100 m/s for each mission, an increase of approximately 20 m/s from Figure 4.9. Again, ΔV expenditure varies between target satellites as a function of orbital slot. North American values constitute the minimum median ΔV expenditure at approximately 85 m/s. GEO slots are most costly above the Pacific Ocean with ΔV expenditures at 120 m/s. European ΔV expenditures are expected to be around 90 m/s, rising irregularly to around 100 m/s in the Far East. An important outcome of Figure 4.13 is that the general trend of ΔV expenditure for servicing missions to particular orbital slots is the same as in Figure 4.9. This allows statements to be made about the serviceability of target satellites independent of the servicing architecture. Another interesting outcome of Figure 4.13 is the roughly 25% increase in ΔV expenditure across orbital slots from the first servicing campaign. Given that approximately 25% of servicing tickets are urgent (Table 4.1), this suggests that reducing the number of allowed phasing revolutions from five to one roughly doubles the required ΔV expenditure for a typical servicing mission.

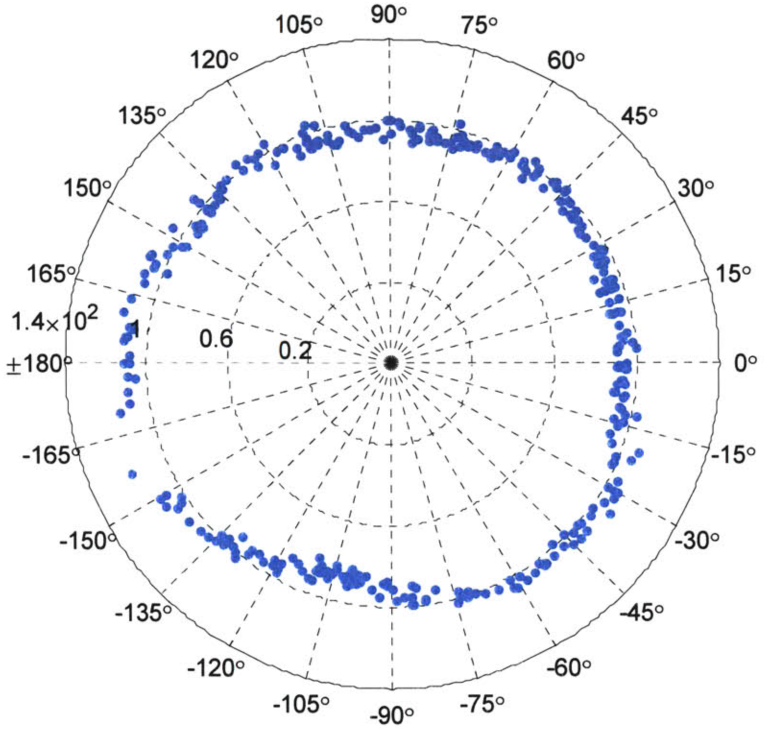


Figure 4.13 Median ΔV Expenditure for Servicing Missions (variable k)

4.2.5 Discussion

Many interesting lessons emerged from the agent-based model of OOS with implications for both serviceability assessments of target satellites and servicing provider architecture. Most fundamentally, the high availability of GEO satellites in the model (Figure 4.6, Figure 4.11) suggests that satellites work too well to stress a simple OOS system. Even in the first simulation with the intermediate response time, servicing vehicle availability exceeded 90%. This means that servicing provider utilization could have increased by an order of magnitude and there still would be overcapacity in terms of what four servicing vehicles can do at a given point in time. The probability of two or more servicing vehicles conducting servicing missions simultaneously was less than 1%. Underscoring this high availability of servicing vehicles is the fact that all servicing opportunities in the model initiated servicing tickets. Although the GEO servicing is the most lucrative with a high concentration of valuable spacecraft and friendly orbital dynamics, satellites launched over the past two decades are simply designed too well to stress a simple servicing system.

While availability is not a good metric for distinguishing between orbital slots, Figure 4.14 and Figure 4.15 illustrate that ΔV expenditure for servicing missions does vary across the GEO belt as a function of the concentration of other target satellites (note that the magnitude of the rose petals of satellite concentration in Figure 4.15 are increased by a factor of three so as to be visible along the m/s axis). By subjecting the baseline OOS system to sensitivity analysis, the value of the ΔV expenditure metric for performing serviceability assessments—independent of provider architecture—is affirmed given that varying response times does not affect the relative performance of the GEO slots.

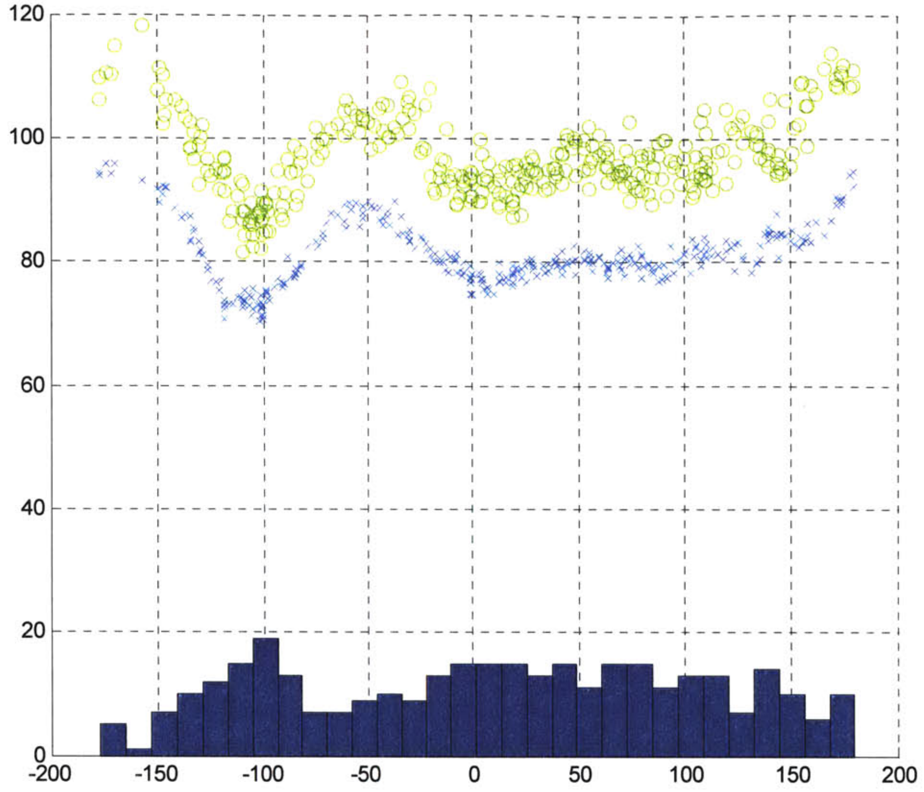


Figure 4.14 Histogram of Median ΔV Expenditure for Both Servicing Campaigns

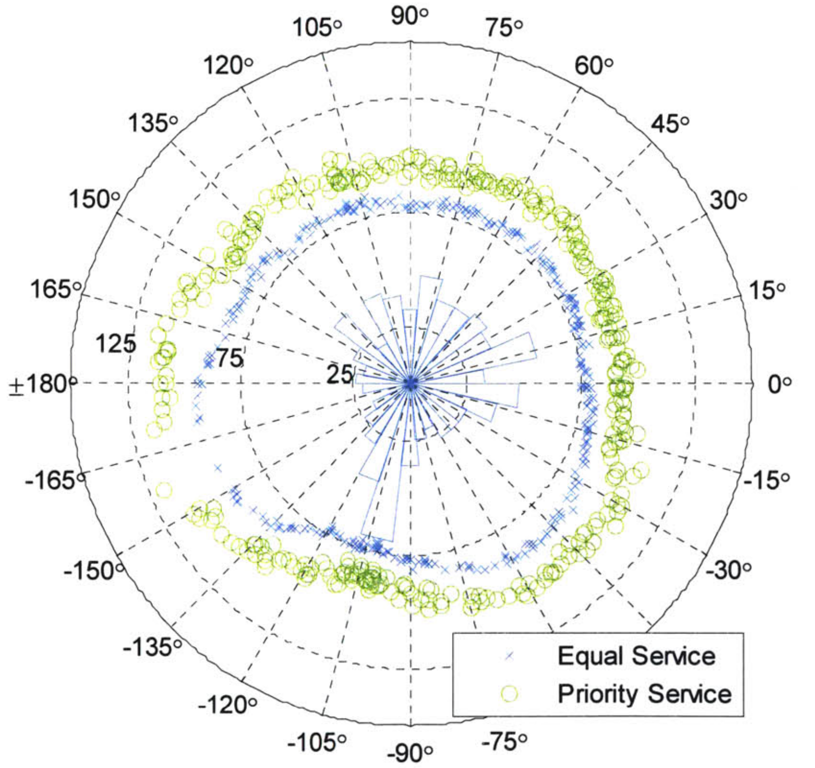


Figure 4.15 ΔV Expenditure for Both Servicing Campaigns with GEO Satellite Density

4.3 Framework for Conducting Serviceability Assessments

This section lays the theoretical foundation for a generalized framework for conducting on-orbit serviceability assessments. Other industries that perform remote servicing operations are surveyed as means to gather ideas for the construction of this framework. Having extracted lessons learned from servicing offshore oil platforms, knowledge, scale, precision, and timing are proposed as four elements for characterizing the complexity of servicing operations.

4.3.1 Lessons from Servicing Offshore Oil Platforms

After discussing the general problem of robotic servicing in high-risk environments, offshore oil platform maintenance activities are reviewed as a case study in the remote servicing of complex systems. The purpose of this investigation is to extract lessons from a well-established field which may be applied towards a general framework of serviceability.

4.3.1.1 Robotic Servicing in High-Risk Environments

Remote intervention in hostile environments is not a problem limited to the OOS domain. From deep-sea exploration and nuclear-reactor servicing (de Peuter, *et al.*, 1994) to toxic waste clean-up and improvised explosive device detection and removal in Iraq, remotely-controlled machines are employed in a variety of risky environments to limit losses to human life. As a first step in developing a framework for comparing the serviceability of satellite bus designs to OOS, lessons may be extracted from other servicing operations conducted by machines in harsh environments.

Five criteria inform the applicability of other servicing missions to assessing on-orbit serviceability. First, the system to be serviced must be complex and technologically enabled. Second, the system must be difficult to access and characterized by limited servicing opportunities. Third, the system must operate in a harsh environment and be subjected to component wear-out and degradation. Fourth, the system should operate over a period spanning years or decades. Fifth, the system should constitute critical infrastructure to the decision makers for the servicing operation. Off-shore oil platform maintenance meets all these criteria and is used in this analysis.

4.3.1.2 Overview of Offshore Oil Platforms

Offshore drilling operations extract oil and natural gas from beneath the ocean floor. Platforms are usually located on the continental shelf and may be attached to the ocean floor, to artificial island, or be floating. Typical platforms have thirty wellheads located on the platform and directional (or slant) drilling allows reservoirs to be accessed at positions up to 5 miles from the platform. Components in the oil/gas production process include wellheads, production manifolds, production separators, gas compressors, water injection pumps, metering equipment, and pumps. Most platforms are self-sufficient in energy and water needs with electrical generation and water desalination capabilities. Minimizing environmental impact and minimizing EOL disposal cost are both drivers in offshore oil platform design (disposal costs are measured in the tens of millions of dollars) (Parliamentary Office of Science and Technology, 1995). Off-shore drilling operations are supported by platform supply vessels during normal operations, emergency support vessels for unexpected contingencies, and anchor handling tug supply vessels which assist in a variety of functions including supply, towing, and emergency operations (*i.e.*, rescue and firefighting).

4.3.1.3 Servicing Operations

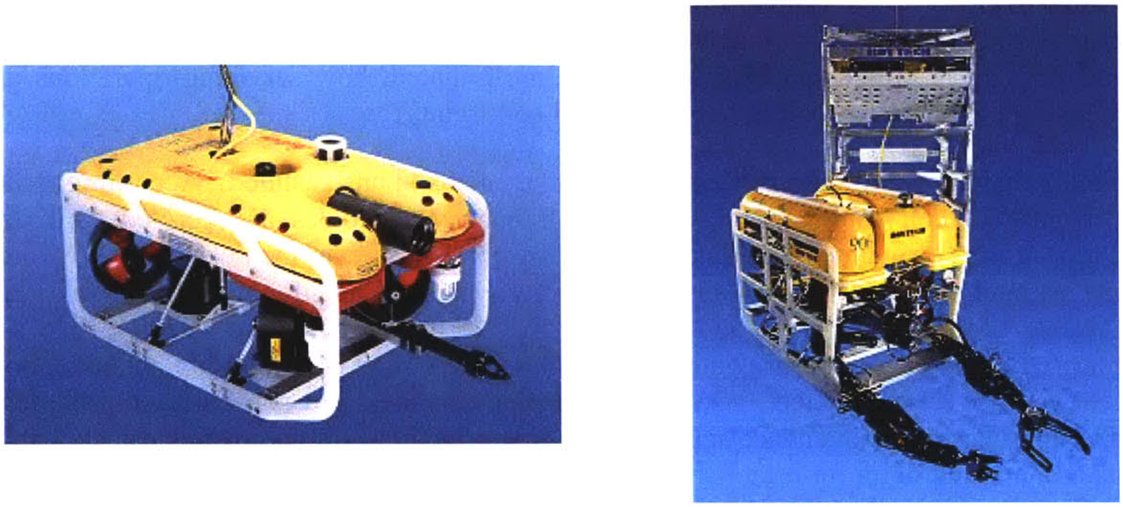
The key actors in any offshore oil platform servicing operation are the oil platform, remotely operated vehicles (ROV) which support maintenance and repair activities, and associated drilling infrastructure (*e.g.*, pipeline). As such, an understanding of serviceability necessitates an analysis of the way in which servicing operations are initiated, how servicing operations are conducted, and the associated context (*e.g.*, temporal constraints).

ROV servicing operations fall into two categories: scheduled and unscheduled. According to Dr. Robert Perrons of Shell International, servicing frequency schedules are derived from the extensive repositories of maintenance data complied by companies over the decades. "We know how often a pump breaks down, and how many years a length of pipe should last because...we've been extracting oil and gas from the North Sea since the 1970s. There's a statistic for pretty much every event you care to mention: how often people sprain an ankle, how often the waves rise above 30 feet, how quickly a pipe corrodes in a particular environment, *etc*." Rather than basing maintenance schedules on first principles, oil companies use statistical precedents as a starting point for establishing servicing policy. Dr. Perrons further explains how servicing schedules are implemented:

> For the most part, maintenance is handled by fairly rigorous schedules. On a Shell U.K. offshore platform, a computer automatically issues "job cards" that trigger a servicing or maintenance procedure on a particular component. Example: "It's now time for the annual non-destructive inspection of this section of pipe via x-ray to determine if there are any cracks forming inside of it." A procedure and checklist is then automatically issued, and the relevant operators are given specific instructions as to how they should tackle this problem. Any problems that arise are dealt with after this.

Servicing operations are also conducted as unscheduled activities. In this case, ROV servicing operations may be initiated when on-board health monitoring equipment indicates failed or failing components. A variety of sensors characterize the state of offshore oil platforms. These may be broken into two categories: sensors for monitoring the extraction process (*i.e.*, components that actually contain oil, gas, and water) and sensors for monitoring the structural integrity of the platform. In general, three pieces of information characterize the majority of segments in the extraction process: temperature, pressure, and flow rate. Pressure sensors are the first line of defense for monitoring the extraction process as pressure drops may indicate leaks. "Corrosion coupons" are also used as health monitoring equipment in flow lines. As sacrificial metal strips that are made of the same material as the flow line itself, corrosion coupons are inserted into flow lines and regularly removed and analyzed to assess the rate of corrosion occurring within the pipeline. Another method for monitoring the health of the systems involved in the extraction process is non-destructive testing (NDT). This method employs x-rays, eddy currents, and ultrasonic techniques to assess the integrity of pipes and load-bearing members without removing them.

The other major facet of offshore oil platform health is the integrity of the components not directly involved in extraction (*i.e.*, structure that holds up the platform and keeps everything in place). The ocean is a harsh environment with salt water continuously corroding steel components. Given that the construction of entire platforms out of stainless steel to prevent rusting is not economical, expensive materials are reserved for more critical or precise components for which corrosion isn't an option. While NDT may be employed for assessing the non-process components of oil platforms, visual inspection is the primary means by which structural health is monitored.



(a) Seaeye Falcon **(b) Seaeye Panther Plus**

The Seaeye Falcon (a) is a portable ROV weighing only 50 kg and rated to 300 meters depth. A wide range of standard tools and accessories can be fitted for survey applications in coastal and inshore waterways. The Seaeye Panther Plus (b) is a medium-work class ROV for survey and drill support operations. It designed for strong currents and depths of up to 1000 meters.

Figure 4.16 Remotely Operated Vehicles for Oil Platform Servicing (Photo Credit: Seaeye Marine Limited)

Remotely operated vehicles also support offshore servicing operations. Depending on the servicing operation, there is a wide range of ROV services available to offshore oil platform operators (Figure 4.16). There are a myriad of companies making ROV for underwater applications ranging from small ROVs that fit inside a suitcase for visual inspections to large ROVs for manipulating steel pipes on the sea floor. (Oil companies typically do not own ROVs for underwater servicing. These are usually procured from independent vendors who transport and operate the equipment.) Functionally, ROVs are capable of drill support, well workovers,[5] structural inspections, site surveys, pipeline inspections (visual and NDT), pipeline maintenance, and submerged construction.

4.3.1.4 Synthesis

In generalizing offshore oil platform servicing operations, determining the frequency of servicing events is a primary step. This is accomplished by monitoring how the state of the system evolves over time through a combination of historical data and health monitoring equipment. With a

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[5] A "workover" is any one of a broad range of operations on a producing well to restore or increase production. A workover may be performed to stimulate the well, remove sand or wax from the well bore, mechanically repair the well, or address other issues.

range of platform supply vessels and emergency support vessels available to conduct servicing operations, it is also necessary to determine the size and precision required of the servicing mission in order to deploy robotic vehicles with an appropriate range of capability.

4.3.2 Generalized Framework for Assessing System Serviceability

A four-element framework of serviceability is proposed (Table 4.2) as a means to assess the probability of success of a servicing mission: knowledge (K), scale (S), precision (P), and timing (T). Scale and precision represent the size and accuracy required in the spatial domain while timing captures the temporal characteristics of the servicing mission. Knowledge is critical as information regarding the state of the system defines a finite range of servicing scale, precision, and timing requirements.

Table 4.2 Serviceability Framework Definitions

Four Elements of Serviceability	
(K) Knowledge	Quality of information regarding state of system
(S) Scale	Size of the task to be performed (spatial domain)
(P) Precision	Accuracy level required for success (spatial domain)
(T) Timing	Time constraints required of servicing architecture (temporal domain)

Four Servicing Activities (μ)	
(1) Rendezvous	Movement of servicing vehicle from starting position to target vicinity
(2) Acquire	Transfer of servicing vehicle from vicinity to holding of target
(3) Access	Deployment of servicing tools from stowed position to area of interest of target
(4) Service	Operation of deployed servicer components for system improvement

Within this framework, serviceability is a function of sixteen parameters as each element is decomposed by the set of four servicing activities. For example, K^2 represents the quality of information regarding the system to be serviced for planning the docking activity.

$$Serviceability = f(K^{\mu}, S^{\mu}, P^{\mu}, T^{\mu}) \tag{4-17}$$

Implicit in the serviceability framework is the assumption that serviceability is a subjective definition (*e.g.*, as technology matures, serviceability of a system increases). Given the difficulty in divorcing the question of system serviceability from the capabilities of the servicing system, it is necessary to incorporate both into the framework.

One way to proceed is to consider the question of serviceability as a relationship between the range of the servicing vehicle's capabilities and the range of the system's potential states. Suh (2005) provides a theoretical foundation for this form of analysis in axiomatic design by defining functional requirements (*e.g.*, dock with satellite) within a specified range (*e.g.*, robotic arm end effector position accuracy of 0.2 to 0.4 mm/0.1°). There is uncertainty of satisfying a functional requirement within the specified accuracy or tolerance because the range of potential system states (represented as a probability density function in Figure 4.17) may not fully overlap with the accuracy or design range of the function provider (*e.g.*, robotic servicer). A functional requirement is only satisfied when the system range is within the design range, an area Suh refers to as the common range.

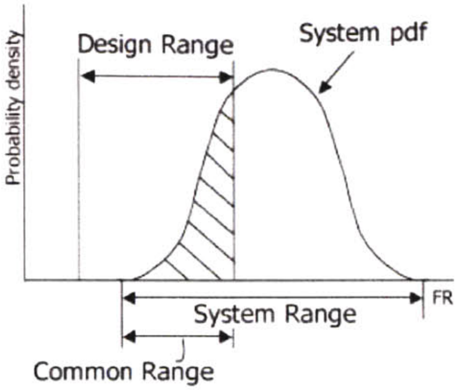

Figure 4.17 Probability Density Function of a Functional Requirement (Suh, 2005)

Applied to servicing, Suh's theory of relative complexities holds that when the system range is completely within the design range of the servicing vehicle, complexity is zero and the probability of success of the servicing mission is 100%. When the system range and design range do not overlap, complexity is infinite and the probability of servicing mission success is zero. If the system range partially overlaps the design range, the probability of success is finite. Suh's theory may be incorporated into the serviceability framework by considering each servicing activity as a functional requirement and calculating the common range between system state and servicer capability.

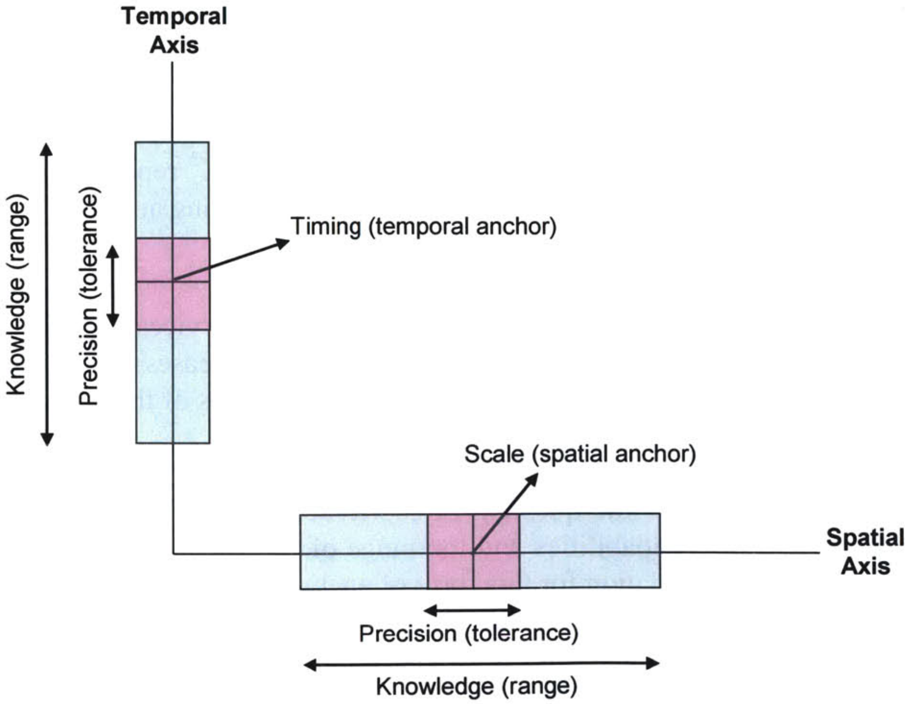

Figure 4.18 Dimensions of Servicing Mission Complexity

Figure 4.18 illustrates the temporal and spatial dimensions of a servicing mission and how the serviceability elements inform the system range in each dimension. Timing and scale are the temporal and spatial anchors, respectively. Each defines the target functional requirement (*e.g.*, refuel 200 m/s worth of fuel every four years). Precision refers to the tolerances of the system to deviations from this target functional requirement (*e.g.* within 10 m/s and within three months). Knowledge bounds the distribution of the system range along both axes from the perspective of the servicing provider. Without knowledge of the system, its range of potential states is unbounded and the common range with the servicing vehicle's design range is low.

4.4 Applying Framework to On-Orbit Servicing

This section surveys candidate serviceability metrics before selecting specific metrics for each serviceability parameter. These metrics are then mapped to the high level OOS functions identified in Chapter 1—inspect, relocate, restore, augment, and assemble.

4.4.1 Serviceability Metrics

The following four sections propose qualitative and quantitative methods for defining the serviceability elements across each servicing activity.

4.4.1.1 Knowledge

Knowledge is the element of serviceability representing the quality of information on the state of the system. Applied to OOS, knowledge is best described as the availability and extent of satellite design data and current telemetry. The knowledge available to a servicing provider is a driver for the amount of adaptable (as opposed to scripted) behavior required by the servicing vehicle. For example, the servicing vehicle and target satellite included on Japanese ETS-VII (Section 2.1.6.1) were designed to demonstrate autonomous rendezvous and docking. The sophistication of a servicing vehicle with analogous capabilities (but designed for a mission with less available knowledge on the system to be serviced, *e.g.*, removing unidentified pieces of orbital debris) would need to incorporate additional adaptable behavior. The lack of information necessitates adaptable behavior. There are three elements of an adaptable servicing architecture: information gathering (*e.g.*, design data from manufacturer, telemetry, ground-based sensing, *in-situ* inspection, on-board sensing), decision-making (telerobotic or autonomous), and execution. Perfect information allows for scripted behavior in which case the servicing architecture only is required to execute pre-planned activities.

- [K^1] Knowledge for OOS rendezvous activities is high across all satellites given space situational awareness capabilities. For example, the position of a satellite at geosynchronous altitude can be determined from the ground to within 24 km in the along-track direction, 17 km in the cross-track direction, and 2.6 km in range (Settelmeyer, 1997). If telemetry is available to supplement ground-based sensing or relative GPS, the orbital elements and orientation of the spacecraft may be determined to identify any constraints on proximity operations (*e.g.*, axis of rotation for a tumbling satellite). Given these two cases (*i.e.,* telemetry or no telemetry), [K^1] may be treated as a binary serviceability parameter. [K^1] may be boosted with proximity inspections.

- **[K^2]** Knowledge for docking activities is defined as the accuracy of data available to the servicing provider on the external structure of the target satellite. For example, knowledge of the structure of the apogee boost motor (as a first 'hook for temporary stabilization) and the launcher interface ring docking (for rigid attachment) would enable a servicing provider to incorporate docking mechanisms tailored for target satellites. Key factors in the analysis of docking performance include mass properties of the vehicles; initial lateral and angular misalignments; approach, lateral, and angular relative velocities; contact friction; contact damping; capture mechanism stiffness properties; capture mechanism damping properties; and contact geometry (Ma, *et al.*, 2002). High levels of [K^2] may improve docking performance as capture mechanism stiffness properties, capture mechanism damping properties, and contact geometry are under the control of the docking designer. Based on whether the servicing provider knows the satellite bus type, [K^2] may be treated as a binary serviceability parameter. As with [K^1], [K^2] may be boosted with proximity inspections.

- **[K^3]** Knowledge for the access servicing activity is defined as the accuracy of data available on the structure of the target satellite leading to the components requiring servicing. [K^3] includes knowledge on internal composition which may not be boosted by proximity inspections. Although manageable for adaptable servicing architectures, low [K^3] may cripple autonomous servicing as bent connector pins or even sagging insulation (blocking visibility) may disrupt scripted operations. A subjective measure such as Likert scales are probably needed to assess [K^3]. Discrete levels of [K^3] do not exist as [K^3] is a function of several factors including the extent of available satellite design data, the extent of internal sensors, configuration control during assembly, level of vibrations and shocks experienced during launch, and cumulative damage sustained while exposed to the space environment (*e.g.*, distortion due to thermal cycling).

- **[K^4]** Knowledge of the condition of the satellite components to be serviced (*e.g.*, payload, consumables) will be high if sensors are monitoring these items. (Degradation of supporting spacecraft infrastructure may be more difficult to measure; however, these components on the satellite are less likely to be serviced). Reliability analysis with empirical data may supplement telemetry sets. The best quantitative metric for [K^4] is probably the number of telemetry points monitored. It may be possible to boost [K^4] with proximity inspections.

4.4.1.2 Scale

Scale is the element of serviceability representing the size of the servicing task. Applied to OOS, scale is measured in different ways depending on the particular OOS activity be measured.

- **[S^1]** The scale of the rendezvous servicing activity is a function of the starting position of the servicing vehicle and the orbit of the target satellite. Quantity of required changes in the servicing vehicle's velocity vector is the best metric for assessing [S^1]. Modeling [S^1] is the subject of Section 4.2 and is not further addressed here.

- **[S^2]** The scale of the docking servicing activity drives the required capability of the docking subsystem of the servicing vehicle. Target satellite metrics for assessing [S^2]

may be the satellite mass, the principal moments of inertia, and the contact friction coefficient (Table 4.3).

Table 4.3 Conditions and Parameters for Docking (Ma, 2002)

Parameter	Value(s)
Target spacecraft mass and principal moments of inertia	50 to 3000 kg 1.5 to 1000 $kg.m^2$
Chaser spacecraft mass and principal moments of inertia	500 to 9000 kg 50 to 2000 $kg.m^2$
Lateral misalignment at contact	0.05 m
Roll misalignment at contact	5 deg
Tilt (pitch + yaw) misalignment at contact	5 deg
Approaching speed	0.03 to 0.05 m/s
Lateral drifting rates	0.005 m/s
Roll drifting rate	0.25 deg/s
Tilt (pitch + yaw) drifting rate	0.25 deg/s
Contact friction coefficient	0 to 0.3

- **[S^3]** The scale of the access servicing activity is defined as the distance between the docking location and the repair zone on the target satellite. [S^3] is a major driver of serviceability in GEO where the spacecraft subsystems likely to be serviced (payloads and antennae) are located on the Earth-pointing side of the satellite (five meters from projected docking locations on the back end of the spacecraft).

- **[S^4]** Servicing scale may be measured as the number of unique tasks to be performed. Serviceable spacecraft may incorporate modularity and commonality to enable functional periodicity, limiting the number of unique servicing tasks and the associated level of complexity required in the servicing vehicle. Other possible metrics for servicing scale are the mass and cost of the components being delivered or repaired.

4.4.1.3 Precision

Precision is the element of serviceability representing the accuracy level required of servicing tasks. Applied to OOS, precision is defined as the permitted tolerances for robotic operations in each activity.

- **[P^1]** Rendezvous precision is required during proximity operations near the target satellite (*e.g.*, approaches for docking, circumvention and hovering for damage assessment) to maintain proper relative position and orientation and to avoid thruster plume impingement. According to Wertz and Bell (2003), thruster plume impingement can damage sensitive optics, disturb thermal blankets and coating, and also impart large disturbance torques.[6] A possible proxy metric for assessing satellite sensitivity to thruster plume impingement (and hence [P^1]) is the satellite mission area with astronomical and

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[6] "The plume is likely to hit deployables and appendages such as the end of the solar array that can be a long way from the center of mass. With the long moment arm, even small forces can provide significant torque that can disturb or even tumble the target vehicle. This, in turn, can cause either thruster firings or a direct collision that could damage either or both spacecraft. When expanding into a vacuum, the thruster plume will have a component 90 deg or more from the line of thrust."

earth-sensing spacecraft requiring higher [P^1] than communications and navigation satellites.

- **[P^2]** Docking precision specifies the permitted tolerances for aligning the position and attitude of the servicing vehicle and target satellite. Table 4.4 specifies attributes of DARPA's Orbital Express docking system, including angular capture misalignment tolerances. Metrics for [P^2] include the relative position and attitude accuracy required of the robotic servicing vehicle (*e.g.*, ±5 cm and ±2 degrees, respectively. Due to time lags in supporting communications infrastructure, autonomous docking is typically required of robotic servicing vehicles. Another element of [P^2] is the combined spacecraft attitude control problem. Once docked, the two spacecraft have a combined moment of inertia and center of mass different from each separate spacecraft. Cargo or fuel transfer may further change attitude control properties over time. As performed on the Cassini mission, calibration firings may be performed whereby thrusters are fired on the new combined spacecraft and the new mass properties are determined based on responses measured by on-board gyros (Wertz and Bell, 2003).[7]

Table 4.4 Orbital Express Docking System Requirements (Stamm and Motaghedi, 2004)

Parameter	**Value**
Axial Capture Distance:	6 inches
Angular Capture Misalignment Tolerance	
Pitch/Yaw	+/-5 degrees
Roll	+/-5 degrees
Lateral Misalignment Tolerance*:	+/- 2 inches
Linear Contact Velocity Tolerance*:	3 cm/s
Preload:	2500 lbf
Capture Time:	< 10 s
Capture and Latch Time:	< 240 s
Interface Outer Diameter:	< 18 inches
Active Mass:	< 50 lbs
Passive Mass	< 25 lbs

- **[P^3]** Access precision specifies the permitted tolerances for transferring the servicing tools to the area of interest on the target satellite. Possible robotic concepts for accomplishing this include a large crane concept, a micro-macro manipulator, and innovative concepts such as truss-building robots (de Peuter, *et al.,* 1995). The large crane concept may be able directly to access the repair zone but suffers from low precision (on the order of centimeters) and poor local dexterity. The micro-macro manipulator is effective but requires a large mass budget. One method for assessing [P^3] is to categorize the location of the area of interest in terms of degree of integration. Three categories might be (1) externally mounted, (2) inside two layers of access doors, and (3) fully integrated and inaccessible. However, given the continuum across the range of possible component locations, a Likert scale is more appropriate.

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[7] Thruster plume impingement remains a concern because control anomalies or tumbling may occur if thrusters from either of the spacecraft face appendages from the other (Wertz and Bell, 2003).

- **[P^4]** Service precision refers to the ability to add value to the components requiring replacement or repair. [P^4] assessments may be informed by the degree of component integration. The Spacecraft Modular Architecture Design Study (Section 2.4.1.5) was conducted in 1999 and included an analysis of the replacement potential of satellite components. Collecting data on redundancy, reliability, weight, power, physical location, and electrical architecture, the replaceability of various satellite components was categorized. Table 4.5 documents some of the results with replaceability categories: (A) no design modifications required, (B1) minor design modifications required, (B2) major design modifications required. As with [P^3], [P^4] has a wide range of states and is best assessed with a Likert scale.

Table 4.5 Practically Replaceable Satellite Components (Reynerson, 1999)

Component Name	Replaceability Category
Intertial Reference Unit	A
Direct Down Link	A
Three Axis Magnetometer Sensor	B1
Star Tracker	B1
Reaction Wheel	B1
Electromagnetic Torque Rods	B1
GPS Receiver	B1
Payload Electronics	B1
Gimbal Control Electronics	B2
Digital Sun Sensor Electronics	B2
Three Axis Magnetometer Electronics	B2
Drive Control Units	B2
Power Distribution Unit	B2
Batteries	B2
Command Auto-Track Receiver	B2
Encoder Modulator Unit	B2

4.4.1.4 Timing

Timing is the element of serviceability representing the temporal constraints for the servicing architecture.

- **[T^1]** Rendezvous timing represents the duration and time constraints on servicing vehicles in-transit to target satellites. For example, rescue missions may have limited windows of opportunity. Modeling [T^1] is the subject of Section 4.2 (*e.g.*, phasing wait time) and is not further addressed here.

- **[T^2]** Acquire timing captures any time constraints which may exist for the docking activity. Timing requirements have been specified for servicing vehicles (*e.g.*, < 10 seconds) but it is not clear how this might inform serviceability assessments of the target satellite. [T^2] may be related to limited windows of opportunity for docking operations and to the question of satellite downtime while the servicing vehicle is docked.

- [T^3] Access timing is the duration of transporting the servicing tools to the area of interest on the target satellite. [T^3] is related to the issue of satellite downtime while the servicing vehicle is docked. Key potential OOS customers (*e.g.*, national security systems, direct broadcast) are strongly averse to satellite downtime.

- [T^4] Service timing is the duration of the value-added activities. Servicing activities may be time-critical, such as the need to replace the Hubble Space Telescope's gyroscopes before science operations are paused (projected September 2007) and Hubble's batteries before irreversible damage is sustained in the optical assembly due to thermal instability (projected May 2011) (Figure 2.5). Dynamic serviceability assessments are the focus of Chapter 5.

4.4.2 Mapping Metrics to Servicing Functions

Table 4.6 summarizes the previous section with a top-level view of serviceability parameters and associated metrics for on-orbit serviceability assessments. As observed, metrics are qualitative and quantitative with relative and absolute values.

Table 4.6 Metrics for Serviceability Assessments

Label	Parameter Names	Metric for Satellite Servicing	Unit
K1	Rendezvous knowledge	position/attitude telemetry	binary (yes/no)
K2	Acquire knowledge	bus type	binary (yes/no)
K3	Access knowledge	structure and composition (evolved)	Likert scale
K4	Service knowledge	telemetry points monitored	number
S1	Rendezvous scale	delta-v	m/s
S2	Acquire scale	principal moments of inertia	kg·m2
S3	Access scale	distance between docking and service zones	m
S4	Service scale	unique servicing tasks	number
P1	Rendezvous precision	mission area	discrete categories
P2	Acquire precision	angular misalignment tolerance	degree
P3	Access precision	service zone integration	Likert scale
P4	Service precision	component integration	Likert scale
T1	Rendezvous timing	phasing and transfer duration	time
T2	Acquire timing	window of opportunity	time
T3	Access timing	permitted satellite downtime	time
T4	Service timing	projected failures, value-added duration	time

Table 4.7 identifies the serviceability metrics to be used as input parameters for calculating the complexity of each OOS function. Each row informs the development of a unique serviceability function for each servicing function with a subset of relevant serviceability metrics.

Table 4.7 Mapping Satellite Serviceability Metrics to OOS Functions

	Knowledge				Scale				Precision				Timing			
	K1	K2	K3	K4	S1	S2	S3	S4	P1	P2	P3	P4	T1	T2	T3	T4
Inspect	X				X			X	X		X		X		X	
Relocate	X	X			X	X			X	X			X	X	X	X
Restore	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Augment	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Assemble	X	X			X	X	X	X	X	X	X		X	X		X

4.4.2.1 Inspect

Seven serviceability parameters were identified for the inspection function, the observation of a space object from an attached position or a remote surveillance vehicle. The availability of telemetry, ΔV expenditures, mission area (servicing as a proxy for the sensitivity of the satellite to thruster plume impingement), and phasing and transfer durations are fundamental (knowledge) parameters of serviceability across all OOS functions. The number of required inspection tasks is also relevant (*e.g.* in-track "hovering" requires no thrusting while any other position requires continuous thrust). Additionally, the level of integration of the areas of interest is related to the visibility of that area for the inspection function. Finally, permitted satellite downtime informs constraints on the inspection function (*e.g.*, circumnavigation around the Earth-pointing side of a GEO communications satellite will not be possible if transponders are left on).

4.4.2.2 Relocate

Ten serviceability parameters were identified for the relocate function, the modification of the orbit of a space object. In addition to the four fundamental parameters of serviceability, four serviceability parameters inform the complexity of docking operations: target satellite bus type, principal moments of inertia, permitted angular misalignment tolerance for capture, and docking timing constraints. Permitted satellite downtime is relevant as it informs the trade between the duration of transfer orbits and ΔV efficiency.

4.4.2.3 Restore

The restore function, returning a satellite to a previous state (or intended state), may require a wide range of servicing vehicle activities. Restoration activities include refueling for lifetime extension and maneuverable spacecraft, docking and providing stationkeeping to extend mission life, repairing or replacing faulty hardware, and deploying appendages which fail to reach operational orientations at BOL. Therefore, the full set of serviceability parameters is required. Using the relocate OOS function as a baseline, additional parameters are required, including knowledge of the internal state of the satellite, the number of telemetry points monitored, the distance between the docking and service zones, and the number of unique servicing tasks for the robotic vehicle. The level of integration of the service zone and components of interest are also relevant serviceability parameters.

4.4.2.4 Augment

The augment OOS function, increasing the capability of a satellite, consists of replacing or adding hardware to improve spacecraft performance. As with the restore function, augment complexity is informed by all sixteen serviceability metrics (Table 4.6).

4.4.2.5 Assemble

The assemble OOS function, mating modules, involves complex robotic operations. The primary difference between restore and augment is that servicing activities only occur around modules, not within. Therefore, knowledge of the internal satellite structure (*e.g.*, internal health monitoring telemetry, level of component) is not essential.

4.5 Synthesis

Developed in this chapter is a methodology for assessing both "orbit serviceability" (*i.e.*, rendezvous activity) and "satellite bus serviceability" (*i.e.*, acquire, access, and service activities). To assess orbit serviceability, an agent-based model of target satellites and servicing vehicles was developed in which OOS is treated as a multi-variable optimization problem with the principal trade of minimizing both ΔV expenditures and transfer time. This model was applied to the GEO belt with satellite failure behavior based on empirical data (Sullivan, 2005). It was found that, while availability is not a good metric for distinguishing between orbital slots, ΔV expenditure for servicing missions does vary across the GEO belt as a function of the concentration of other target satellites (*e.g.*, satellites in GSO above North America were found to be approximately 25% less expensive in terms of fuel than satellites above the Pacific). It was also found that ΔV expenditure was largely driven by response time (*e.g.*, up to an order of magnitude increase in fuel utilization in GEO when switching from the baseline intermediate response time to urgent response). To validate the "orbit serviceability" assessments, it was necessary to show that relative performance of orbital slots does not vary as a function of the assumed servicing provider architecture. Therefore, the concept-of-operations of the servicing provider was subjected to sensitivity analysis, and it was found that varying response times does not affect the relative performance of the GEO slots in terms of the ΔV serviceability metric.

In contrast to LEO satellites for which the high propulsive cost of maneuvering severely limits the number of target satellites which may be serviced, GEO orbital dynamics are relatively friendly with a concentration of high-value satellites in GSO. In terms of "orbit serviceability," physical amenability for GEO target satellites is high. With approximately 25 servicing opportunities in GEO each year, an OOS architecture consisting of four servicing vehicles parked in GEO is able to maneuver to virtually all satellites requiring servicing over the course of a decade. The high availability of satellites in the model suggests that satellites are too reliable to stress an OOS system. Servicing provider utilization could have increased by an order of magnitude, and there still would be overcapacity in terms of what four servicing vehicles can do (*e.g.*, the probability of two or more servicing vehicles conducting servicing missions simultaneously was less than 1%). As such, future work is needed to explore the trade between redundant, highly reliable space systems (current paradigm), and lower cost, less redundant systems that utilize an OOS system to achieve similar reliability.

Having focused on “orbit serviceability” in the first half of Chapter 4, a generalized framework for conducting serviceability assessments was developed. Based in part on lessons extracted from maintaining offshore oil platforms, the framework decomposed servicing mission complexity into four elements: knowledge (K) of the state of the target system, scale (S) and precision (P) required of the servicing operations, and timing (T) characteristics or constraints imposed on servicing operations. By further decomposing servicing missions into four sets of activities, sixteen serviceability parameters were proposed. The framework was then applied to the OOS domain by identifying metrics which characterize the performance of satellite bus attributes for each serviceability parameter. However, in contrast to “orbit serviceability” assessments which were performed across all operational GEO satellites, serviceability assessments at the satellite bus level cannot be performed for large numbers of spacecraft simultaneously due to the lack of comprehensive data on detailed satellite bus attributes. Therefore, it is deemed necessary to perform case studies of individual spacecraft to conduct “satellite bus serviceability” assessments. Chapter 5 builds on the serviceability framework developed here by analyzing how architecture frameworks might be used as a tool for assessing serviceability at the satellite bus level.

5 Development of a Dynamic Servicing Architecture Model

The goal of this chapter is to explore the value of architecture frameworks for conducting serviceability assessments.[1] The primary questions addressed in this chapter are:

- How can architecture frameworks inform dynamic serviceability assessments?
  - What forms of architecture description exist to expand the scope of OOS understanding to both the physical and functional domains?
  - Can static representations of space systems in the Department of Defense Architecture Framework be extended to incorporate time as a dimension in serviceability assessments?

Initially, architecture frameworks are introduced and illustrated as tools for managing space system complexity and tracking the state of satellites over time. Upon selecting the U.S. Department of Defense Architecture Framework (DoDAF) for describing space systems, desirable attributes of architecture framework development tools are identified and industry-leading software applications are surveyed. CORE,® a systems engineering modeling language with the ability to create executable models, is then applied to the construction of a high-level DoDAF representation of the Hubble Space Telescope.[2]

The value of the DoDAF and CORE software for conducting serviceability assessments is explored through the development of a discrete event simulation of Hubble servicing missions. Having investigated the temporal dimension of servicing in Chapter 4 for only the rendezvous OOS activity with a servicing simulation based on orbital transfers, the simulation described in this chapter incorporates all four OOS activities—rendezvous, acquire, access, and service—in a single executable model. In particular, a multi-year servicing campaign is modeled for Hubble, including behavioral threads that characterize the Orbiting Observatory, servicing architecture, and science customers. Preliminary results indicate that, when coupled with an executable model, the Department of Defense Architecture Framework can be utilized for dynamic quantitative evaluation of space system servicing architectures. The chapter concludes with lessons learned from constructing the Hubble DoDAF and the executable model. Ideas are offered for improving the DoDAF as are prescriptive considerations for users and developers of architecture frameworks.

5.1 Overview of Architecture Frameworks

Architecture frameworks are tools for managing complexity by establishing standards for the description of architectures. These standards define the system to be characterized as well as how the system is to be constructed and operated. Architecture frameworks serve as a communication tool by presenting a common set of information with multiple views (Figure 5.1). Each view reflects the perspective of a unique stakeholder (*e.g.*, customer, designer, user).

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[1] This chapter is based on a paper entitled "Managing Complexity with the Department of Defense Architecture Framework: Development of a Dynamic System Architecture Model" (Richards and Shah, *et al.*, 2006).

[2] CORE Workstation and associated training was provided by Vitech Corporation as part of an outreach program for academic research. The survey of architecture framework development tools was completed after work on the Hubble DoDAF in CORE had begun.

Maier and Rechtin (2002) identify five goals of architecture frameworks: (1) institutionalize best practices for architectural description, (2) ensure system sponsors receive information in the format they desire, (3) facilitate comparative evaluation of architectures, (4) improve the productivity of development teams, and (5) improve interoperability of information systems by requiring that critical interfaces are described. The third goal (*i.e.*, comparative evaluation of space system architectures) motivates the application of architecture frameworks to this research.

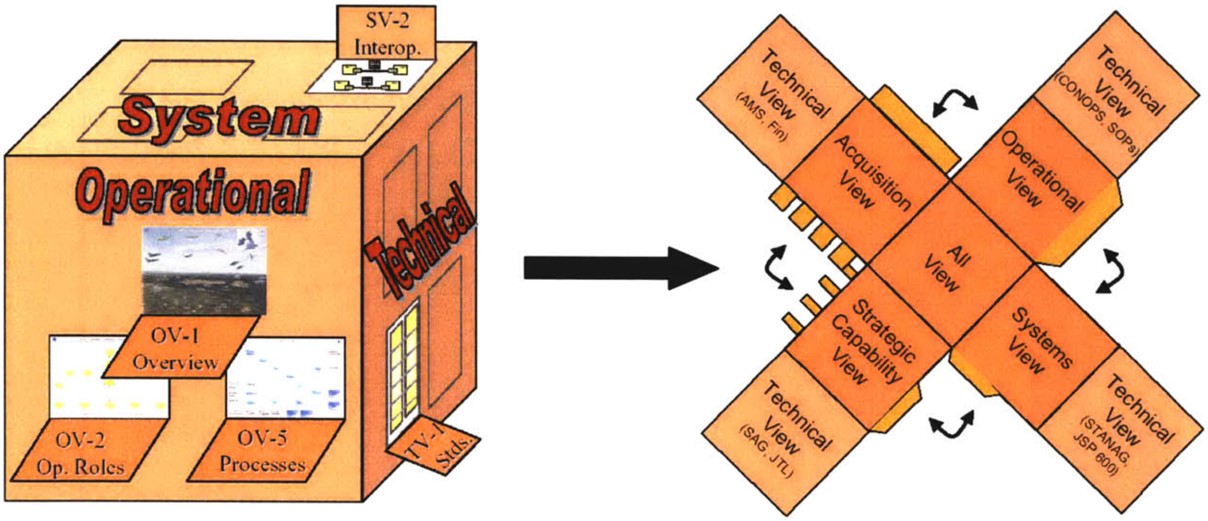
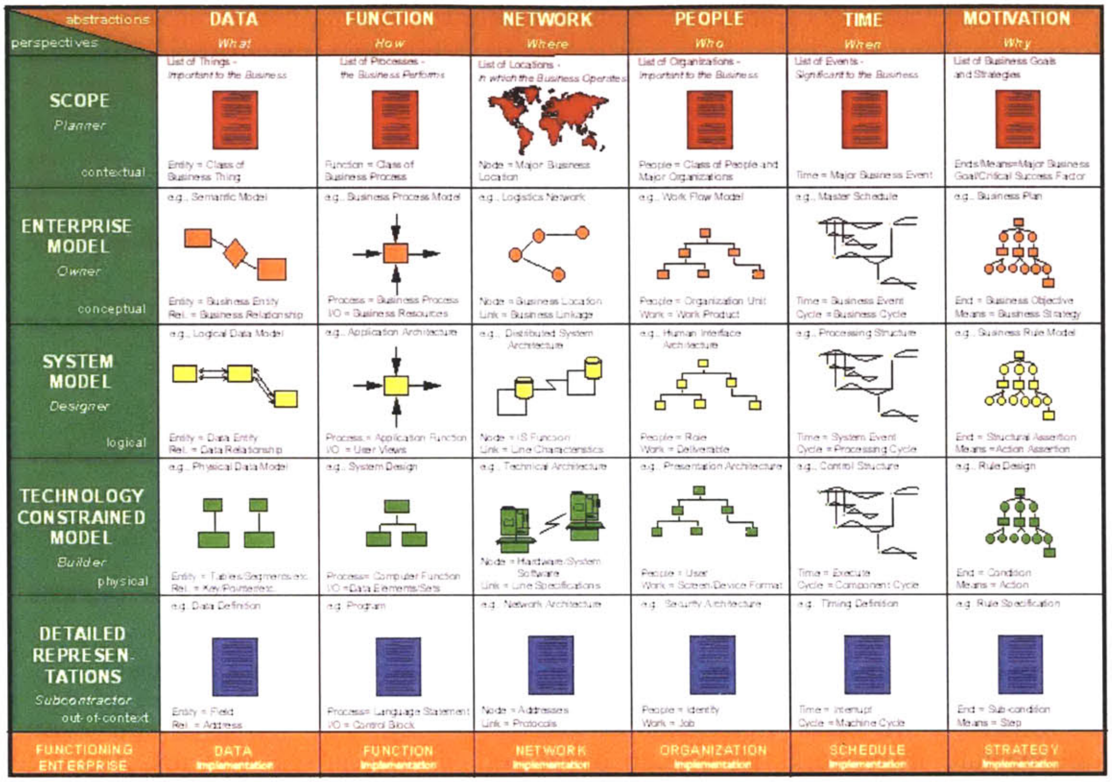


Figure 5.1 Architecture Framework "Unwrapped" (U.K. Ministry of Defence, 2005)

Several architecture frameworks have been developed for enterprises, systems, and software since the late 1980's. This section provides a brief overview of three enterprise architectures critical in the evolution of these tools: the Zachman Framework, The Open Group Architecture Framework (TOGAF), and Federal Enterprise Architecture Framework (FEAF). Two architecture frameworks for communicating system design concepts—the DoDAF and U.K. Ministry of Defence Architecture Framework (MoDAF)—are then evaluated for application to space systems. Major architecture frameworks excluded in this overview include the Computer Integrated Manufacturing Open Systems Architecture (CIMOSA), Integrated Architecture Framework (IAF), Architectural Descriptions of Software Intensive Systems (*i.e.*, IEEE 1471), and International Standards Organization Reference Model for Open Distributed Processing (ISO RM-ODP). A detailed analysis of architecture frameworks is outside the scope of this thesis and has been conducted elsewhere (Tang *et al.*, 2004).

5.1.1 Zachman Framework

The Zachman Framework was released in 1987 by IBM to provide a blueprint for an organization's information infrastructure (Figure 5.2). Embraced by the architecture community, the Zachman Framework has been incorporated into the four other architecture frameworks discussed in this section. The framework consists of populating a 6x6 matrix—establishing relationships of six elements of information systems (*i.e.*, data, function, network, people, time, motivation) across six perspectives (*i.e.*, planner, owner, designer, builder, subcontractor, and working system). Unlike the TOGAF, FEAF, DoDAF, and MoDAF, design tradeoffs are not captured (Tang *et al.*, 2004). Since the Zachman Framework was not developed by a professional organization, no explicit compliance rules have been published. No architectural development process is documented in publications and most prescriptive guidance is only offered through consulting services by the Zachman Institute (Schekkerman, 2004).



abstractions perspectives	DATA *What*	FUNCTION *How*	NETWORK *Where*	PEOPLE *Who*	TIME *When*	MOTIVATION *Why*
SCOPE *Planner* contextual	List of Things - *Important to the Business* Entity = Class of Business Thing	List of Processes - *the Business Performs* Function = Class of Business Process	List of Locations - *in which the Business Operates* Node = Major Business Location	List of Organizations - *Important to the Business* People = Class of People and Major Organizations	List of Events - *Significant to the Business* Time = Major Business Event	List of Business Goals and Strategies Ends/Means=Major Business Goal/Critical Success Factor
ENTERPRISE MODEL *Owner* conceptual	e.g., Semantic Model Entity = Business Entity Rel. = Business Relationship	e.g., Business Process Model Process = Business Process I/O = Business Resources	e.g., Logistics Network Node = Business Location Link = Business Linkage	e.g., Work Flow Model People = Organization Unit Work = Work Product	e.g., Master Schedule Time = Business Event Cycle = Business Cycle	e.g., Business Plan End = Business Objective Means = Business Strategy
SYSTEM MODEL *Designer* logical	e.g., Logical Data Model Entity = Data Entity Rel. = Data Relationship	e.g., Application Architecture Process = Application Function I/O = User Views	e.g., Distributed System Architecture Node = I/S Function Link = Line Characteristics	e.g., Human Interface Architecture People = Role Work = Deliverable	e.g., Processing Structure Time = System Event Cycle = Processing Cycle	e.g., Business Rule Model End = Structural Assertion Means = Action Assertion
TECHNOLOGY CONSTRAINED MODEL *Builder* physical	e.g., Physical Data Model Entity = Tables/Segments/etc. Rel. = Key/Pointer/etc.	e.g., System Design Process= Computer Function I/O =Data Elements/Sets	e.g., Technical Architecture Node = Hardware/System Software Link = Line Specifications	e.g., Presentation Architecture People = User Work = Screen/Device Format	e.g., Control Structure Time = Execute Cycle = Component Cycle	e.g., Rule Design End = Condition Means = Action
DETAILED REPRESENTATIONS *Subcontractor* out-of-context	e.g. Data Definition Entity = Field Rel. = Address	e.g. Program Process= Language Statement I/O = Control Block	e.g. Network Architecture Node = Addresses Link = Protocols	e.g. Security Architecture People = Identity Work = Job	e.g. Timing Definition Time = Interrupt Cycle = Machine Cycle	e.g. Rule Specification End = Sub-condition Means = Step
FUNCTIONING ENTERPRISE	DATA Implementation	FUNCTION Implementation	NETWORK Implementation	ORGANIZATION Implementation	SCHEDULE Implementation	STRATEGY Implementation

John A. Zachman, Zachman International

Figure 5.2 Zachman Framework

5.1.2 The Open Group Architecture Framework

The Open Group Architecture Framework is a freely-available industry standard for designing, evaluating, and building enterprise architectures. Although it does include documentation on architecture framework development and views for design rationale, TOGAF is principally a tool for business organization.

5.1.3 Federal Enterprise Architecture Framework

The Federal Enterprise Architecture Framework was first published in 1999 and represents the realization of the 1996 Clinger-Cohen Act, which requires federal agencies to develop, maintain, and facilitate integrated systems architectures. The FEAF structure borrows heavily from Zachman (Couretas, 2003) and is optimized for enterprise engineering and program and capital management.

5.1.4 Department of Defense Architecture Framework

In contrast to enterprise architectures which also connect organizational goals to business activities, system architectures relate operational concepts and capabilities to technical architectures. The Department of Defense Architecture Framework Version 1.0, released in 2003, defines a common approach for describing and comparing DoD architectures (Figure 5.3). The DoDAF evolved from the 1996 Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) Architecture Framework which was developed following lessons learned from the Persian Gulf War of 1991. A host of integration problems occurred during Desert Shield and Desert Storm as C4ISR systems were deployed for the first time in support of tactical operations for a large-scale conflict. Older platforms were used for missions for which they were not designed (*e.g.,* Defense Support Program satellites for Scud detection), new technologies were applied piecemeal, and interoperability problems hindered full exploitation of information technology (Spires, 2001). Some of these integration problems were solved during the six month build-up to war (*e.g.*, early warning satellites were used successfully for detection of tactical ballistic missiles) while others were not (*e.g.*, paper copies of air tasking orders had to be flown from the command center in Riyadh to the decks of aircraft carriers) (Zinn, 2004).

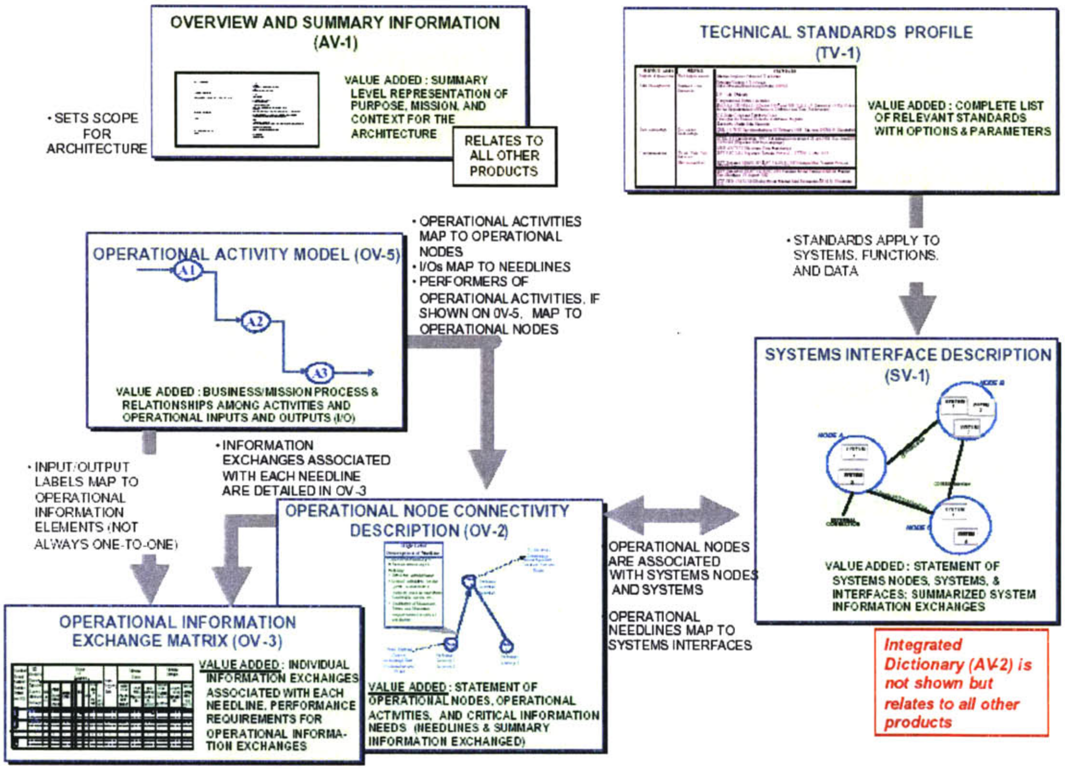


Figure 5.3 Sample Work Products from Department of Defense Architecture Framework (DoDAF, 2003)

In developing the C4ISR/DoD Architecture Framework to aid interoperability and system-of-systems integration, the Department of Defense selected three views (composed of multiple work products) to characterize major systems: Operational, Systems, and Technical. To first order, the Operational View may be thought of as a functional decomposition of the system, specifying mission-critical activities and information exchanges. The Systems View constitutes the form decomposition of the system, tracing the needs identified in the Operational View to resources and capabilities of the technical architecture. Taken together, the Systems View and the

Operational View fully describe the system and how it will operate. Since the two views are built simultaneously, the system architect allocates operational tasks to particular system components, whether physical or organizational. Conversely, knowledge of the system behavior can inform operational design. Finally, the Technical View captures standards and conventions for the architecture, prescribing the minimal set of rules governing the arrangement, interaction, and interdependence of system components (DoDAF Working Group, 2003).

Although developed for acquisition supervisors concerned with interoperability, the DoDAF in practice is primarily used to produce architecture descriptions during the early-stages of system development (Maier *et al.*, 2004). Maier further argues that the DoDAF is not necessarily well-suited for this application. Another criticism of DoDAF is that it does not provide analytical techniques or mechanisms for synthesizing the architecture information into "cogent, compelling conclusions" (French, 2005). No formal DoDAF development process is prescribed. A variety of tools, discussed in the following section, have been developed to aid in the construction of DoDAF work products.

5.1.5 Ministry of Defence Architecture Framework

The UK Ministry of Defence Architecture Framework, released in 2005, is an extension of the DoDAF with identical Operational, Systems, and Technical views to facilitate information exchange for interoperability analyses across US-UK systems. The MoDAF formalizes two perspectives not explicitly addressed in the DoDAF by adding two views: Strategic and Acquisitions (Figure 5.4). Both are aimed at improving portfolio management across MoD programs. The Strategic Viewpoint translates MoD policies into appropriate measures of effectiveness that can be used for capability audit and gap/overlap analysis. The Acquisitions Viewpoint incorporates programmatic details such as dependencies across development efforts (Ministry of Defence, 2005). Through these new views, the MoDAF intends to capture the perspectives of all MoD system stakeholders throughout the acquisitions process. This is consistent with the principles of enterprise architecture but at odds with the primarily technical approach prescribed in the DoDAF (Barrett, 2004).

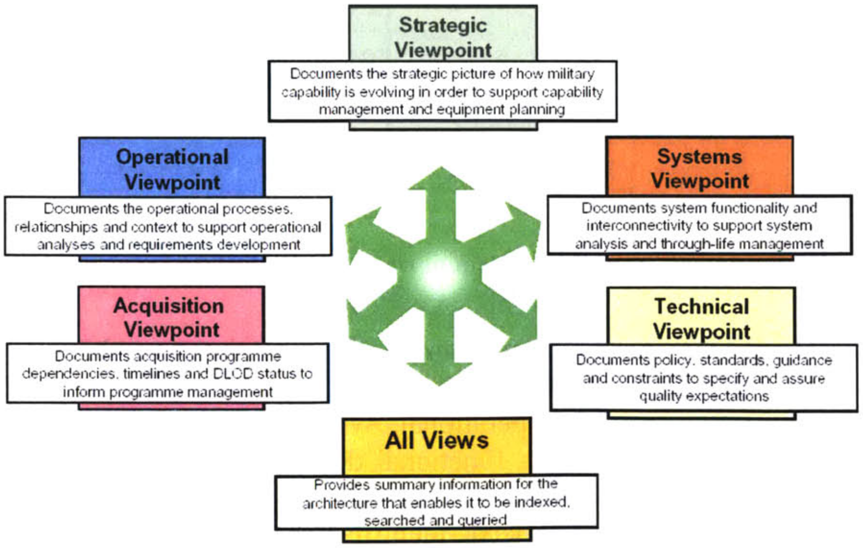


Figure 5.4 Six Views of UK Ministry of Defence Architecture Framework (Ministry of Defence, 2005)

For the application of comparative evaluation of architectures (*i.e.*, serviceability assessments of space systems), the DoDAF and MoDAF offer similar qualities. Both are oriented towards technical architecture with Operational and Systems views to enable structured analyses of satellite functions, physical attributes, and servicing activities. However, the DoDAF was selected for this research due to a variety factors exogenous to the frameworks themselves: industry experience with DoD architecture frameworks over the last decade, availability of literature and research on the DoDAF, and the existence of several tools supporting the DoDAF development process.

5.2 Tools Available for Constructing Architecture Frameworks

Table 5.1 Tools Supporting DoDAF Development (as of April 2006)

Product	Company	Key Features
Core Workstation	Vitech Corporation	• Modeling language with modifiable database schema • Executable behavior models with discrete event simulator • Automatically export DoDAF views from central data repository
DoDAF*Live!*	Wizdom Systems	• Niche DoDAF project management tool • Provides online data repository for all information and models
EA WebModeler	Agilense	• Central repository of data accessed via standard web browser • Supports Zachman, TOGAF, FEAF, and DoDAF development
Elements Repository	Enterprise Elements	• Web-based data management tool • Integrates DoDAF views from multiple modeling tools
Metis Client Tools	Troux Technologies (acquired from Computas)	• "Living Timeline" support for system evolution • Operational capabilities as objects • Architecture reuse via broad support for DoD reference models
netViz Enterprise	netViz	• Generic enterprise architecture tool with relationship modeling • Documents all 27 DoDAF work products
ProVision Modeling Suite	Proforma Corporation	• Only DARS-certified tool (July 2005) • Web-based repository for enterprise and system architectures • Discrete event simulator coupled with Monte Carlo analysis
Rhapsody	Telelogic (bought I-Logix)	• UML/SysML modeling and simulation tool • Includes "DoDAF pack" for outputting DoDAF views
System Architect	Telelogic (acquired from Popkin Software)	• First tool to offer a DoDAF extension (industry leader) • Integrated with Telelogic DOORS for requirements traceability • Supports Zachman, TOGAF, and DoDAF development
TAU	Telelogic	• UML/SysML modeling and simulation tool • Includes "Enterprise Architect for DoDAF" extension • Integrated with Telelogic DOORS for requirements traceability

While the views of the DoDAF are well-defined, little documentation is provided on how the views are to be constructed. This lack of documentation, coupled with a focus on final view outputs in early user training, led to a work product-centric approach to DoDAF development. As a result, many early DoDAF work products were pictures (many done in PowerPoint) that were neither internally consistent nor complete in capturing relevant data. In order to analyze the behavior of a system, it is essential to capture dependencies and parallelisms among activities, processes, and supporting technologies. However, these abilities are lacking in standard office automation programs that are often used to develop DoD architecture frameworks (Troche *et al.*, 2004). To fix this problem, DoD has made a significant push towards data-centric architecture development with the implementation of the DoD Architecture Repository System (DARS) for certified formal methods and modeling languages.

Ideally, a common process for constructing DoDAF views is followed to maintain consistency and enable comparisons across architectures. Several companies offer enterprise architecture tools with templates to construct DoDAF work products. In general, each tool offers relatively complete DoDAF support with certain tools offering unique capabilities (Table 5.1).

One of the shortcomings of architecture frameworks is that they rely on static pictures, diagrams, and textual descriptions—not necessarily adequate for conveying the logical, behavioral, and performance properties of the architecture (Levis and Wagenhals, 2000). To capture the dynamic properties of a system, an executable model is necessary to carry out simulations (Wagenhals *et al.*, 2000). Therefore, it is important to select a DoDAF development tool that can input the information contained in the static views to an executable model.

Five criteria were deemed essential for architecture framework development tools: (1) a hierarchical structure to enable high-level representations, (2) support for exporting operational and systems views, (3) modeling and simulation capabilities for dynamic performance analyses, (4) a learning curve consistent with an eight-month research project, and (5) affordability. Vitech Corporation's CORE® Workstation (Figure 5.5) meets these criteria and was used for this research.

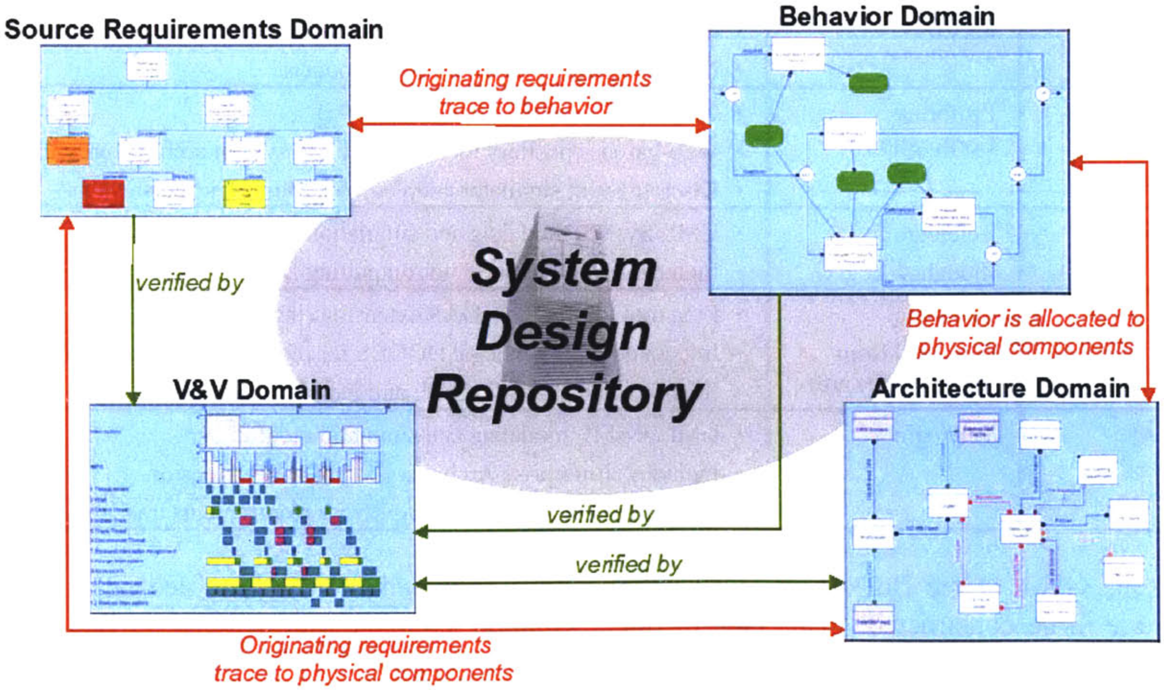


Figure 5.5 Domains of CORE Workstation (Vitech Corporation)

CORE is a systems engineering tool that couples requirements management with functional analysis and simulation. The tool accomplishes this by representing these domains with a common modeling language. Leveraging a central system design repository for rapid population of DoDAF views, CORE traces originating requirements to functions in the behavior domain. Behaviors are represented with Enhanced Functional Flow Block Diagrams (EFFBD) and then allocated to physical components in the architecture domain. One of the most interesting elements of CORE is a discrete event simulator that allows an EFFBD to be executed. Ascent Logic Corporation's RDD-100 tool offered a similar suite of capabilities but has been discontinued.

5.3 Sample DoDAF: Hubble Space Telescope

Given the large quantity of open-source data available (National Research Council, 2005; Nelson *et al.*, 2002) and its status as the only uninhabited space platform that is currently serviced, Hubble was a natural choice for exploring the value of the DoDAF and CORE. In scoping the problem, populating all DoDAF work products (Table 5.2) in full detail was found to be unnecessary and unrealistic. Completion of a DoDAF for a small uninhabited air vehicle with only 150 components took two person-years (Cooper and Ewoldt, 2005)—Hubble has 400,000 parts. Therefore, each DoDAF work product was studied and seven were found to be applicable to the problem of conducting serviceability assessments: (1) Overview and Summary Information (AV-1), (2) High-Level Operational Concept Graphic (OV-1), (3) Operational Node Connectivity Description (OV-2), (4) Operational Activity Model (OV-5), (5) Systems Interface Description (SV-1), (6) Systems Evolution Description (SV-8), and (7) Systems Technology Forecast (SV-9).

Source: DoDAF Deskbook

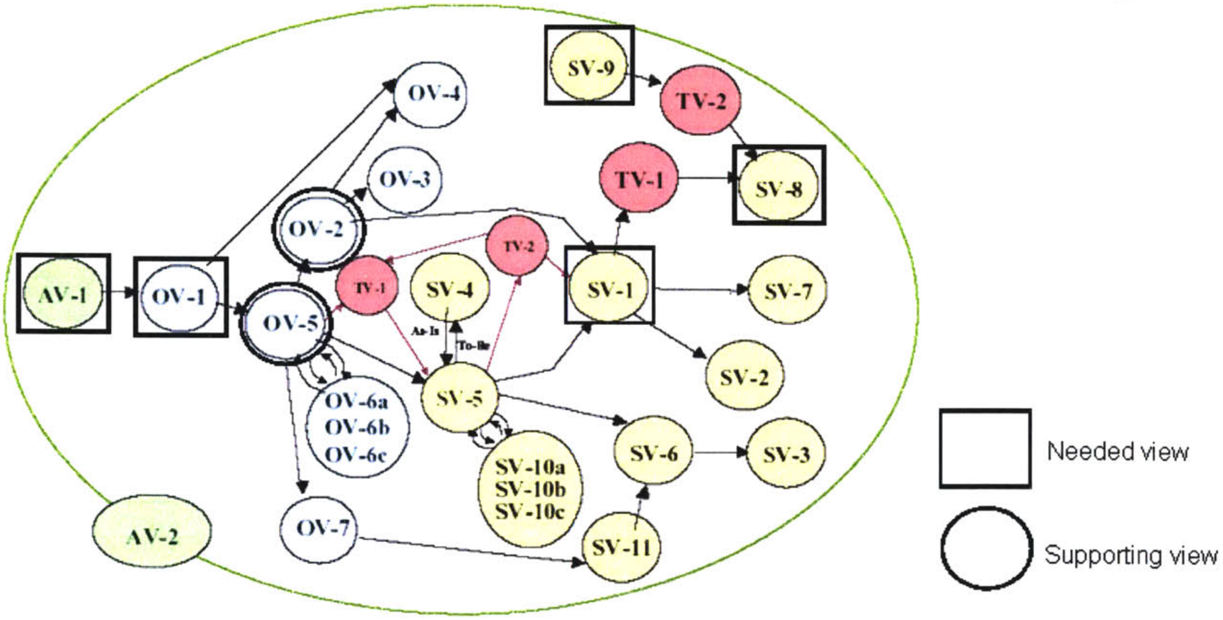


Figure 5.6 Data-Centric DoDAF Build Sequence

Table 5.2 Description of DoDAF Work Products (DoDAF Working Group, 2003)

Applicable View	Framework Product	Framework Product Name	General Description
All Views	AV-1	Overview and Summary Information	Scope, purpose, intended users, environment depicted, analytical findings
All Views	AV-2	Integrated Dictionary	Architecture data repository with definitions of all terms used in all products
Operational	OV-1	High-Level Operational Concept Graphic	High-level graphical/textual description of operational concept
Operational	OV-2	Operational Node Connectivity Description	Operational nodes, connectivity, and information exchange needlines between nodes
Operational	OV-3	Operational Information Exchange Matrix	Information exchanged between nodes and the relevant attributes of that exchange
Operational	OV-4	Organizational Relationships Chart	Organizational, role, or other relationships among organizations
Operational	OV-5	Operational Activity Model	Capabilities, operational activities, relationships among activities, inputs, and outputs; overlays can show cost, performing nodes, or other pertinent information
Operational	OV-6a	Operational Rules Model	One of three products used to describe operational activity—identifies business rules that constrain operation
Operational	OV-6b	Operational State Transition Description	One of three products used to describe operational activity—identifies business process responses to events
Operational	OV-6c	Operational Event-Trace Description	One of three products used to describe operational activity—traces actions in a scenario or sequence of events
Operational	OV-7	Logical Data Model	Documentation of the system data requirements and structural business process rules of the Operational View
Systems	SV-1	Systems Interface Description	Identification of systems nodes, systems, and system items and their interconnections, within and between nodes
Systems	SV-2	Systems Communications Description	Systems nodes, systems, and system items, and their related communications lay-downs
Systems	SV-3	Systems-Systems Matrix	Relationships among systems in a given architecture; can be designed to show relationships of interest, e.g., system-type interfaces, planned vs. existing interfaces, etc.
Systems	SV-4	Systems Functionality Description	Functions performed by systems and the system data flows among system functions
Systems	SV-5	Operational Activity to Systems Function Traceability Matrix	Mapping of systems back to capabilities or of system functions back to operational activities
Systems	SV-6	Systems Data Exchange Matrix	Provides details of system data elements being exchanged between systems and the attributes of that exchange
Systems	SV-7	Systems Performance Parameters Matrix	Performance characteristics of Systems View elements for the appropriate time frame(s)
Systems	SV-8	Systems Evolution Description	Planned incremental steps toward migrating a suite of systems to a more efficient suite, or toward evolving a current system to a future implementation
Systems	SV-9	Systems Technology Forecast	Emerging technologies and software/hardware products that are expected to be available in a given set of time frames and that will affect future development of the architecture
Systems	SV-10a	Systems Rules Model	One of three products used to describe system functionality—identifies constraints that are imposed on systems functionality due to some aspect of systems design or implementation
Systems	SV-10b	Systems State Transition Description	One of three products used to describe system functionality—identifies responses of a system to events
Systems	SV-10c	Systems Event-Trace Description	One of three products used to describe system functionality—identifies system-specific refinements of critical sequences of events described in the Operational View
Systems	SV-11	Physical Schema	Physical implementation of the Logical Data Model entities, e.g., message formats, file structures, physical schema
Technical	TV-1	Technical Standards Profile	Listing of standards that apply to Systems View elements in a given architecture
Technical	TV-2	Technical Standards Forecast	Description of emerging standards and potential impact on current Systems View elements, within a set of time frames

In constructing high-level views, a data-centric build sequence is followed whereby several DoDAF relationship and attribute classes for subsequent work products are automatically generated from core entities constructed in earlier work products. Figure 5.6 depicts the suggested build sequence derived from the relationships between DoDAF views. Given this suggested build sequence, two supporting views of Hubble Space Telescope are selected for completion along with the five needed views. It is important to note that a data-centric build sequence does not imply rigid sequencing as the highly related nature of the views necessitates an iterative work process.

5.3.1 Overview and Summary Information (AV-1)

Overview and Summary Information (AV-1) provides an executive-level summary of Hubble including scope, assumptions, constraints, and limitations of the architecture description (Figure 5.7). High-level features of the Orbiting Observatory are described (*e.g.,* 2.4 meter primary mirror, 11,110 kilogram weight).

- **Description**
  - The Hubble Space Telescope is a joint venture of the National Aeronautics and Space Administration (NASA) and European Space Agency (ESA). Launched into Low Ear Orbit on April 24, 1990 by the Space Shuttle Discovery (STS-31), Hubble's location above the Earth's atmosphere enables high resolution imaging of astronomical objects.
  - Hubble features a 2.4 meter primary mirror, is composed of more than 400,000 parts and contains 26,000 miles of electrical wiring. Total dimensions of the telescope are 13.3 meters in length and 4.3 meters in diameter. Hubble weighs 11,110 kg.
- **Purpose**
  - Hubble Space Telescope is a scientific instrument and its main scientific objectives are to determine:
    - The constitution, physical characteristics, and dynamics of celestial bodies.
    - The nature of processes which occur in the extreme physical conditions existing in and between astronomical objects.
    - The history and evolution of the universe.
    - Whether the laws of nature are universal in the space-time continuum.
- **Scope**
  - The Hubble Space Telescope program includes the orbiting observatory, the Space Telescope Science Institute, and the Space Telescope Operations Control Center. The system is supported by the Space Shuttle, the Tracking and Data Relay Satellite System, and the NASA Communications Network.

Figure 5.7 Hubble Overview and Summary Information (AV-1)

5.3.2 High Level Operational Concept Graphic (OV-1)

High Level Operational Concept Graphic (OV-1) depicts Hubble's interaction with its environment as well as with external systems (Figure 5.8). For the purposes of this research, OV-1 was deemed useful for rapidly communicating the missions of various space systems and their operational context—both of which might elicit constraints on servicing operations (*e.g.,* imaging payload sensitivity to thruster plume impingement).

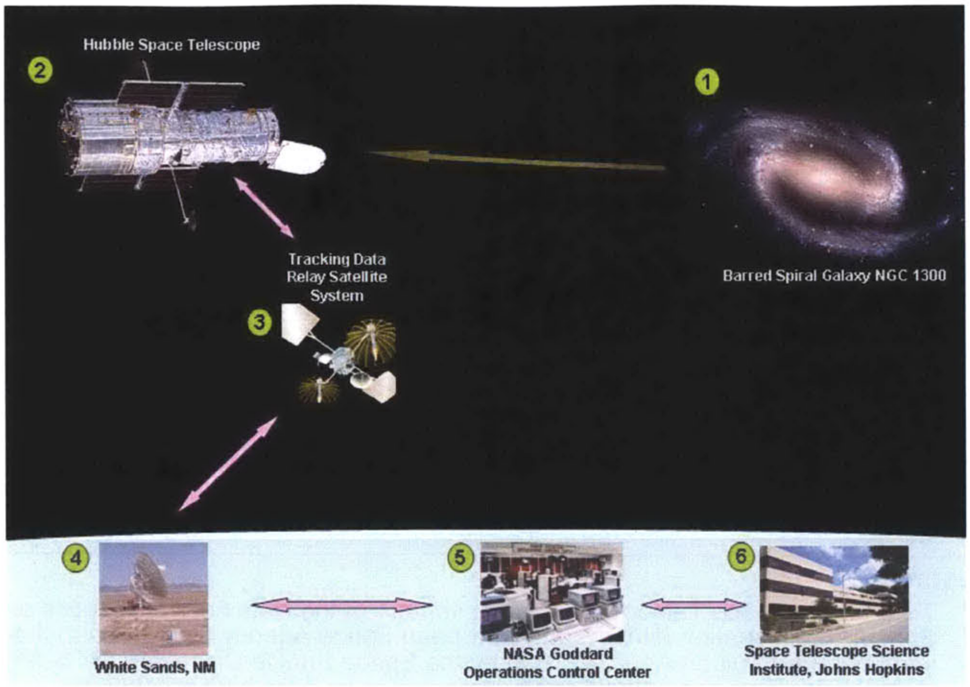


Figure 5.8 Hubble High-Level Operational Concept Graphic (OV-1)

5.3.3 Operational Node Connectivity Description (OV-2)

Operational Node Connectivity Description (OV-2) tracks the need to exchange information across nodes. This includes internal operational nodes as well as external nodes. OV-2 does not depict the connectivity between nodes. For example, Figure 5.9 shows that the Orbiting Observatory depends on the Space Telescope Operations Control Center (STOCC) for command and control, which in turn needs to downlink data to STOCC. The Tracking Data Relay Satellite System (TDRSS)—the communications pipeline between these two operational nodes—is not depicted. Understanding communication needlines for satellites is necessary for eliciting constraints on servicing operations (*e.g.,* aversion of fixed satellite service providers to transponder downtime).

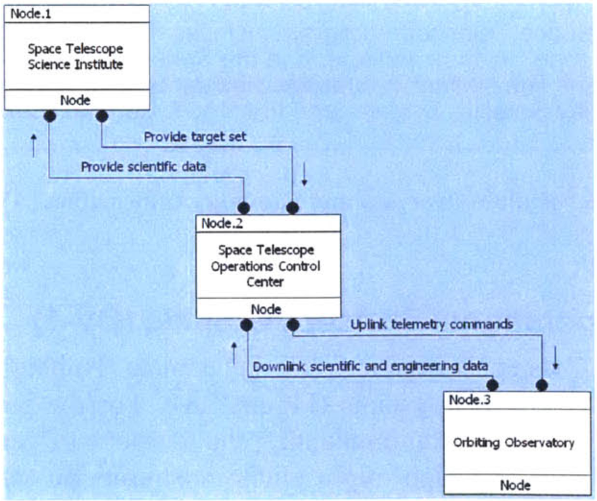


Figure 5.9 Hubble Operational Node Connectivity (OV-2)

5.3.4 Operational Activity Model (OV-5)

Operational Activity Model (OV-5) describes the operations that are normally conducted in the course of achieving a mission. It specifies activities and inputs and outputs between activities. OV-5 delineates lines of responsibility when coupled with OV-2 and is a necessary foundation for depicting activity sequencing and timing. Figure 5.10 is a high-level EFFBD representation of OV-5 for a typical Hubble science mission. Similar diagrams were constructed for other Hubble activities including monitoring spacecraft health, attitude determination and control, and Space Shuttle servicing operations (see Appendix B). In the next section, two Hubble servicing methods are simulated using an executable EEFBD—enabling comparison of two architectures in the behavioral domain.

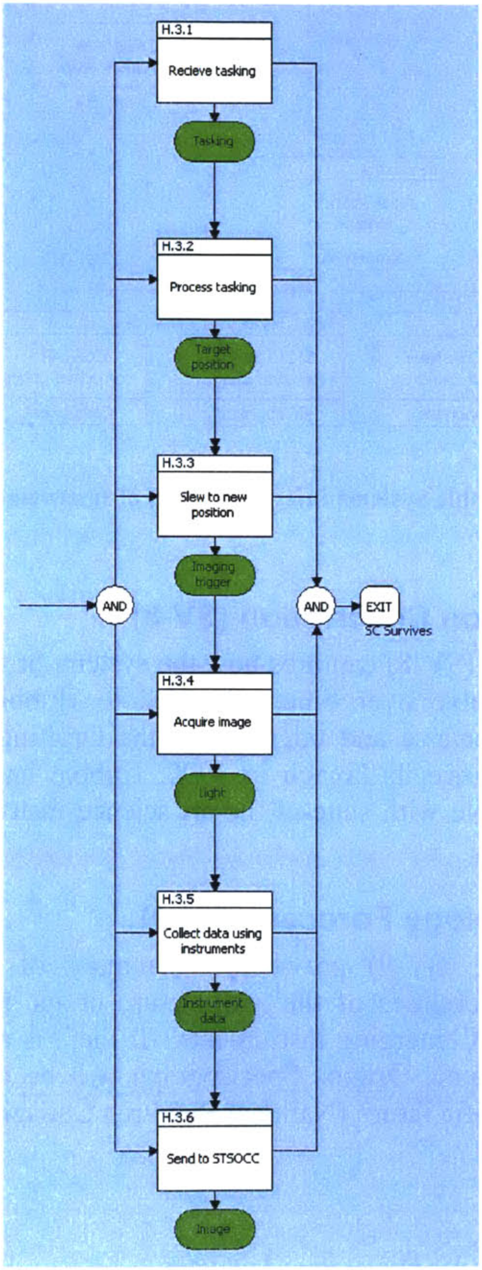


Figure 5.10 Hubble Operational Activity Model – Imaging (OV-5)

5.3.5 Systems Interface Description (SV-1)

Systems Interface Description (SV-1) identifies the systems nodes that support operational nodes. Detailed SV-1 work products may be used for specifying requirements and for interoperability assessments. For the Hubble architecture, SV-1 was used to show the physical decomposition of 42 components, including the TDRSS communications pipeline excluded in OV-2. Five levels are present in the constructed hierarchy. Figure 5.11 displays a sample of this decomposition—level IV-V components of the Telescope Instrument Assembly. Appendix B includes more views of the system decomposition.

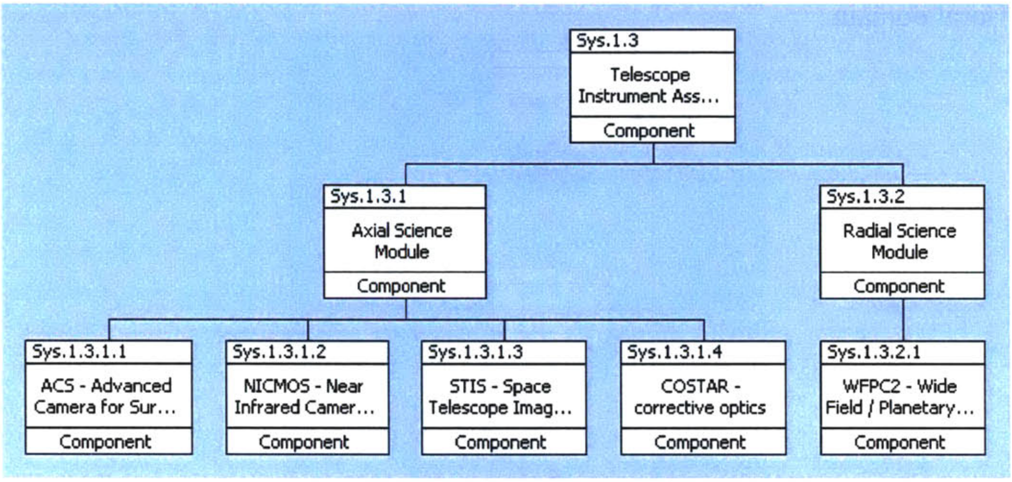


Figure 5.11 Hubble Systems Interface (SV-1) of Instrument Assembly

5.3.6 Systems Evolution Description (SV-8)

Systems Evolution Description (SV-8) captures how the system, or the architecture in which the system is embedded, will evolve over time. Applied to Hubble, SV-8 is used to record completed and planned maintenance and upgrades of the Orbiting Observatory during Space Shuttle servicing missions. Since its launch in 1990, Hubble has been serviced four times, enabling NASA to equip Hubble with state-of-the-art science instruments every few years and replace limited-life components.

5.3.7 Systems Technology Forecast (SV-9)

Systems Technology Forecast (SV-9) provides a summary of expected improvements in technology that affect the capabilities of the architecture or its systems. For Hubble, SV-9 principally involves a survey of emerging instruments. If there is a fifth servicing mission, the Wide Field Camera 3 and Cosmic Origins Spectrograph will be installed to allow Hubble to continue its high level of scientific return (National Research Council, 2005).

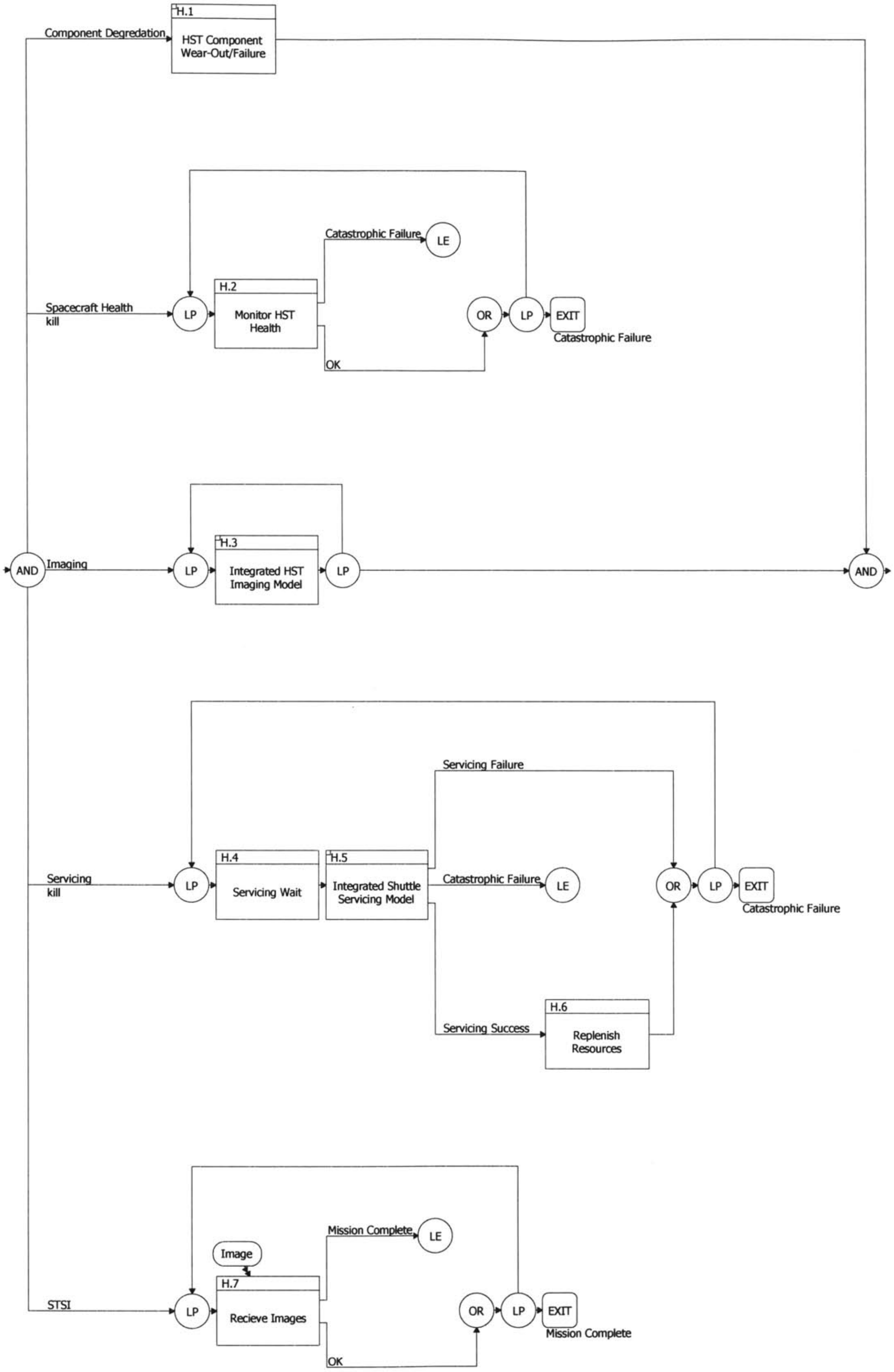


Figure 5.12 Integrated Hubble Servicing Model

5.4 Hubble Servicing Simulation

Upon developing static DoDAF work products, the value of architecture frameworks for conducting serviceability assessments was explored through the development of an executable model that captures the dynamic properties of Hubble at a level of detail consistent with conceptual design. In particular, the performance of two servicing architectures was compared using the discrete event simulator packaged with CORE. Figure 5.12 is a top-level view of the multi-layered behavioral model developed of Hubble performance in the context of a multi-year servicing campaign. The behavioral model is depicted as an EFFBD and shows the interactions of three key actors in the simulation: the Orbiting Observatory, servicing architecture, and science customers. System behaviors are represented using sequential, parallel, repetitive, and decision logic. Five parallel threads are modeled: (1) Hubble Component Failure and Degradation, (2) Hubble Health, (3) Hubble Imaging, (4) Shuttle/Robotic Servicing, (5) Science Dissemination.

5.4.1 Component Failure and Degradation Thread

Hubble Component Failure and Degradation Thread models the wear-out of various critical Hubble components (*i.e.*, batteries, avionics, gyroscopes, reactions wheels, and fine-guidance sensors). Hubble has a battery capacity of 540 ampere-hours (Ah) with energy storage requirements of 160 Ah to support science operations and 40 Ah to maintain thermal stability of the optical assembly. Gradual loss of charge capacity may be projected and is modeled deterministically at 5 Ah each month. The state of the avionics system is modeled as a binary whereby it is either functioning or broken. If broken, no science operations are conducted and Hubble waits for the next successful servicing mission to restore the avionics system.

Table 5.3 Key Assumptions in Servicing Simulation

Component Wear-Out	
Probabilistic Failures	Monthly Rate
gyroscopes	0.036
reaction wheels	0.022
fine-guidance sensors	0.025
avionics system	0.006
Deterministic Degradation	Monthly Rate
solar panels	0
battery capacity	5 Ah

Servicing Missions		
Probabilistic Failures	Space Shuttle	Robotic Vehicle
launch and rendezvous	0.02	0.10
dock (catastrophic)	0.01	0.05
dock (non-catastrophic)	0.01	0.05
access	0.05	0.15
service	0.02	0.10
mission frequency	36 months	36 months
services avionics?	yes	yes

Gyroscopes, reaction wheels, and fine-guidance sensors failure is both probabilistic and deterministic. For simplicity, these three components are assumed to fail probabilistically (Table 5.3) with half-lives mapped to most-likely failure projections (National Research Council, 2005). Three gyroscopes are required to sense drift rates during normal pointing and slewing operations. At launch and following successful servicing operations, six healthy gyroscopes are on the telescope—offering "three for six" redundancy. Fine-guidance sensors, used for precision pointing of the observatory, are modeled similarly and have "two for three" redundancy. Reaction wheels provide three-axis control of the telescope and incorporate "three for four" redundancy.

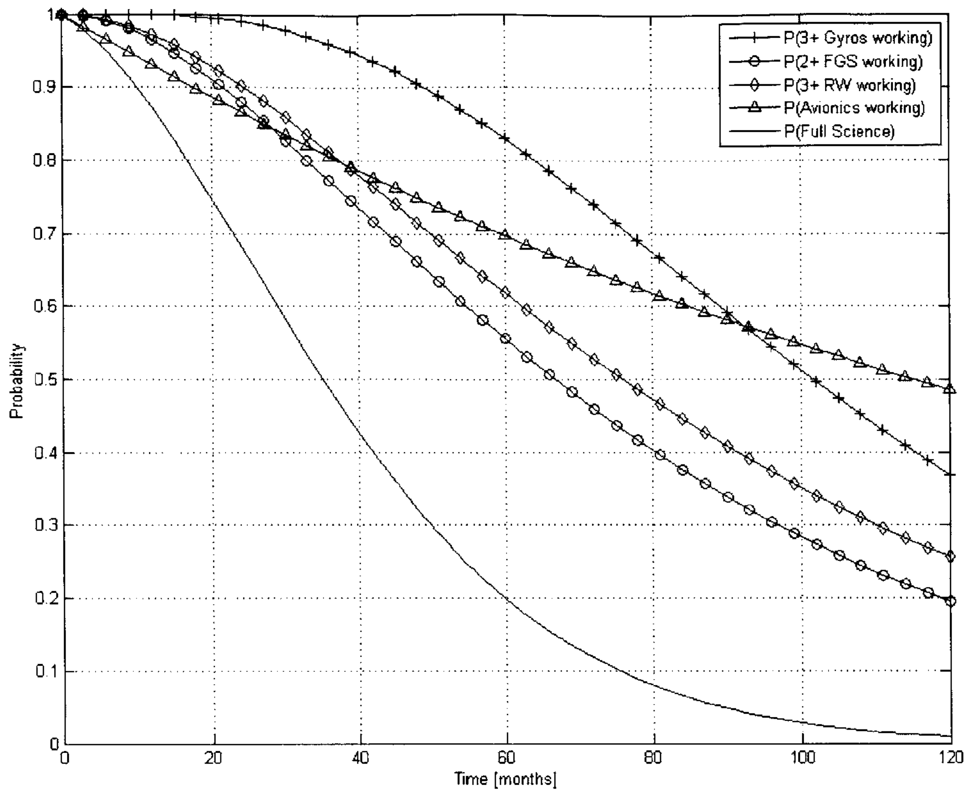


Figure 5.13 Assumed Reliability of Critical Subsystems over Time (no servicing)

5.4.2 Health Thread

Hubble Health Thread monitors the overall state of Hubble. Three states are possible: fully functional for conducting science operations, survival mode during which no science is conducted, and dead. To be fully functional, Hubble must possess a working avionics system and at least 160 Ah of battery capacity, three healthy gyroscopes, two healthy fine-guidance sensors, and three healthy reaction wheels. Figure 5.13 plots the probability of each of these conditions being met (in isolation) as a function of time (if no servicing missions were carried out). Once one of these conditions is not met (*e.g.*, four of the six gyroscopes fail), Hubble enters into a survival mode, pausing science operations until the next successful servicing or the occurrence of a catastrophic failure. Catastrophic failures may be caused by docking collisions during attempted servicing operations or degradation of battery capacity below 40 Ah (minimum energy required to prevent irreversible structural deformation of the optical assembly).

5.4.3 Imaging Thread

Hubble Imaging Thread tracks science operations (Figure 5.10). The imaging thread is triggered by the sequence of images sent by a fully functioning Hubble. Science operations are conducted in one-month increments. In the simulation, Hubble's target science goal is 120 months of successful imaging operations. In its first ten years of operation, the actual Hubble system took approximately 350,000 exposures of 14,000 astronomical targets (Nelson *et al.*, 2002).

5.4.4 Shuttle/Robotic Servicing Thread

Shuttle/Robotic Servicing Thread tracks the implementation of the servicing architecture. Two servicing threads were created—one representative of the Space Shuttle and the other of a robotic servicing vehicle. Four servicing activities are included in each model: (1) Launch and Rendezvous, (2) Dock, (3) Access, and (4) Service. Launch is defined as the movement of a servicing vehicle from a starting position (*i.e.,* launch pad) to a position where relative navigation is possible with laser ranging, radar, and cameras (< 500 meters). Rendezvous positions the servicing vehicle for docking (< 3 meters). Docking is defined as the mating of the servicing vehicle to Hubble. In the case of a robotic servicing vehicle, autonomous execution is required for proximity operations because of a two-second communications delay in routing signals through TDRSS (National Research Council, 2005). Access constitutes all activities required to deploy the stowed tools, upgrades, and replacement parts of the servicing vehicle to the Hubble components which require servicing. Finally, Service entails operation of the servicing vehicle to improve Hubble and return it to full operation. All four servicing activities must be completed for servicing to be successful. Differences between Space Shuttle and robotic vehicle servicing activity success probabilities are outlined in Table 5.3. Figure 5.14 shows the sequential servicing activities for Shuttle. If servicing is successful, all subsystems are replenished to beginning-of-life levels, restoring Hubble to a "like new" condition.

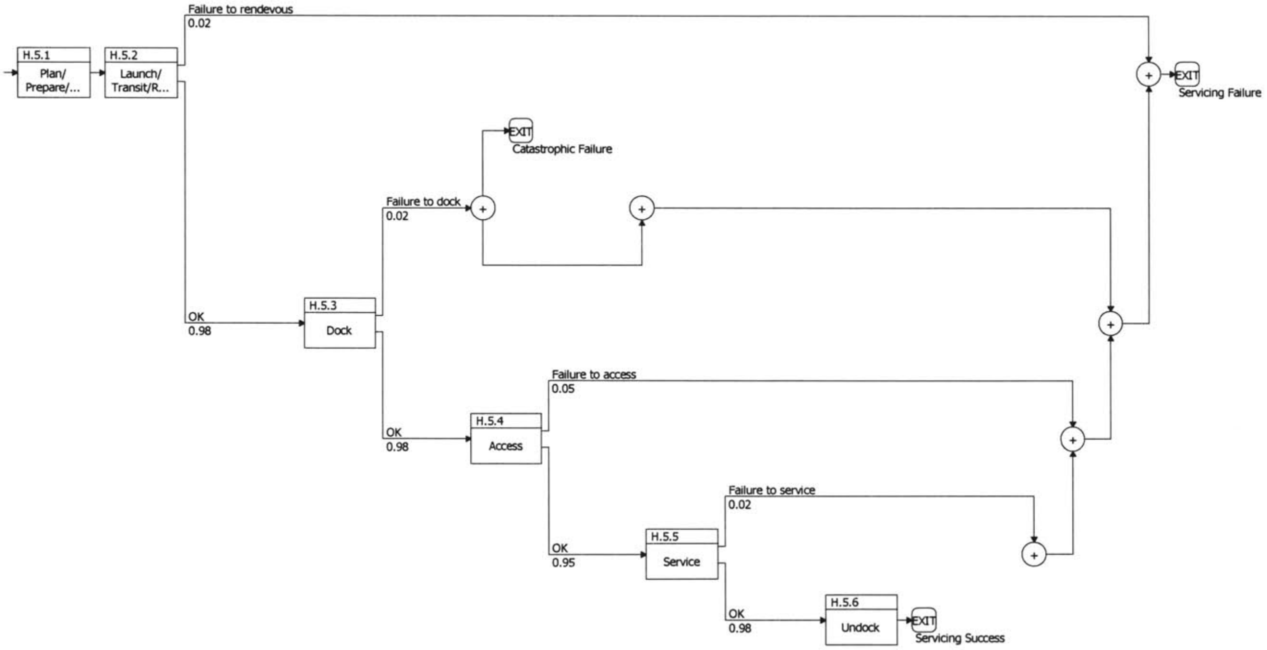


Figure 5.14 Space Shuttle Servicing Thread

5.4.5 Science Dissemination Thread

Science Dissemination Thread tracks the transfer of images to the Space Telescope Science Institute (STScI) and terminates the simulation upon STScI receipt of 120 months of science data. The simulation terminates earlier if a catastrophic failure occurs.

5.4.6 Results

Upon developing the multi-layered Integrated Servicing Model, the dynamic performance and functional behavior of Hubble was analyzed using CORE's discrete event simulator. The simulator outputs a timeline of functional activation, execution, and duration. Wait states, resource inventory history, and queuing triggers (items waiting to be processed by functions) are all depicted. Colored duration bars are used to represent different types of events. Grey specifies the amount of resources available, teal indicates the execution of a function, yellow indicates that a function is enabled but waiting for a trigger, and magenta indicates that a function is enabled but waiting for resources.

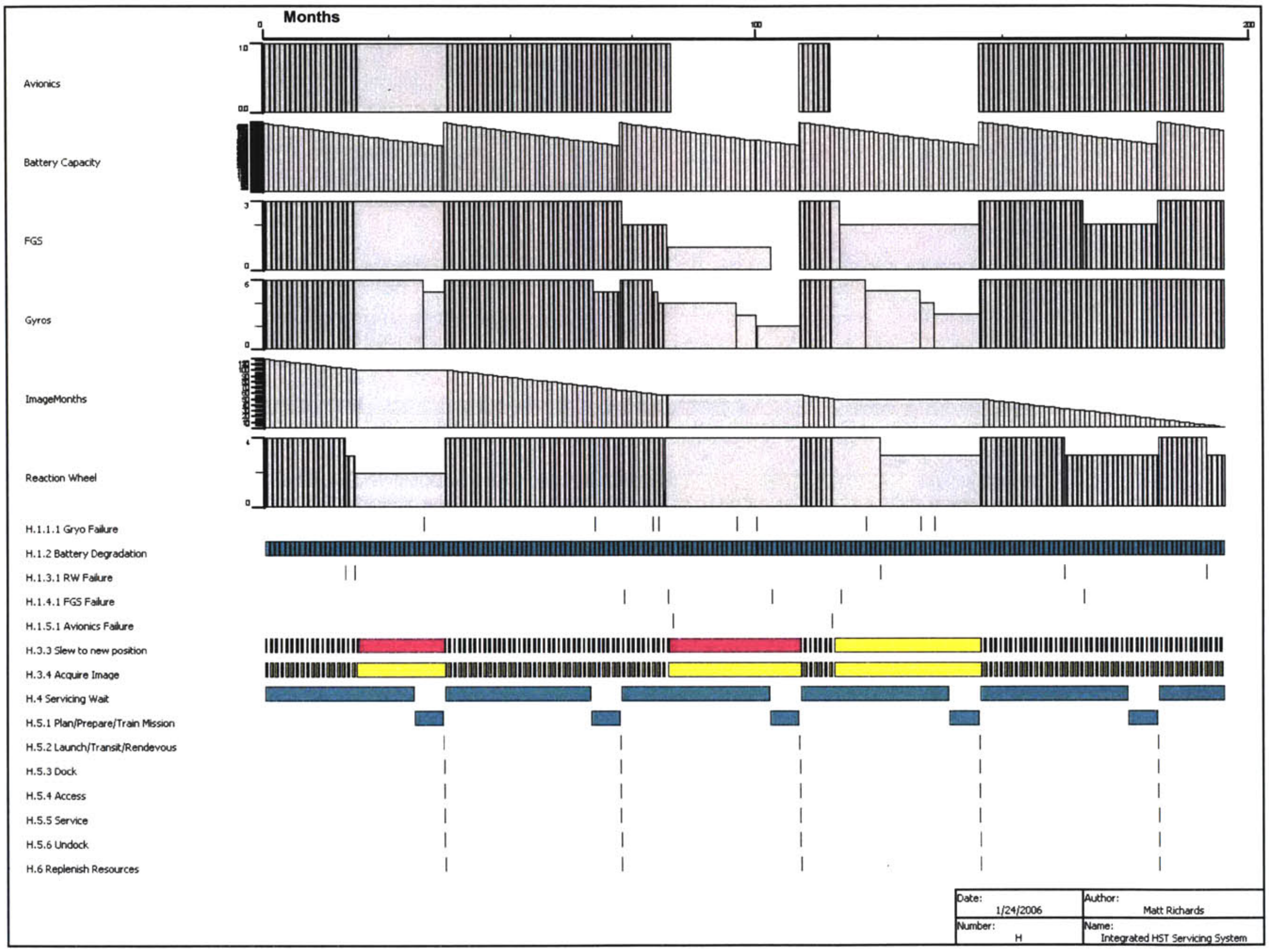


Figure 5.15 Hubble Servicing Simulation – Space Shuttle

Figure 5.15 shows a sample run of the Integrated Hubble Servicing Model for a Space Shuttle servicing campaign. Rows depict resource levels and function states with a horizontal axis of time (measured in months). It can be observed that in the 20th month the reaction wheel resource had fallen from four to two (below the required level of three). This resource change initiated a state change in Hubble from fully functional to survival mode, pausing science operations until successful Shuttle servicing during the 37th month. The "ImageMonths" resource continued to count down successfully from 120 until the 85th month when the fine-guidance sensor resource fell to one (below the required level of two), followed by a failure of the avionics system a month later. Science operations were put on hold again until the third servicing mission succeeded in replenishing all of the resources. In total, five servicing missions were attempted, and all were successful. Once 120 months worth of science had been collected and disseminated, the simulation terminated during Hubble's 17th year of operation.

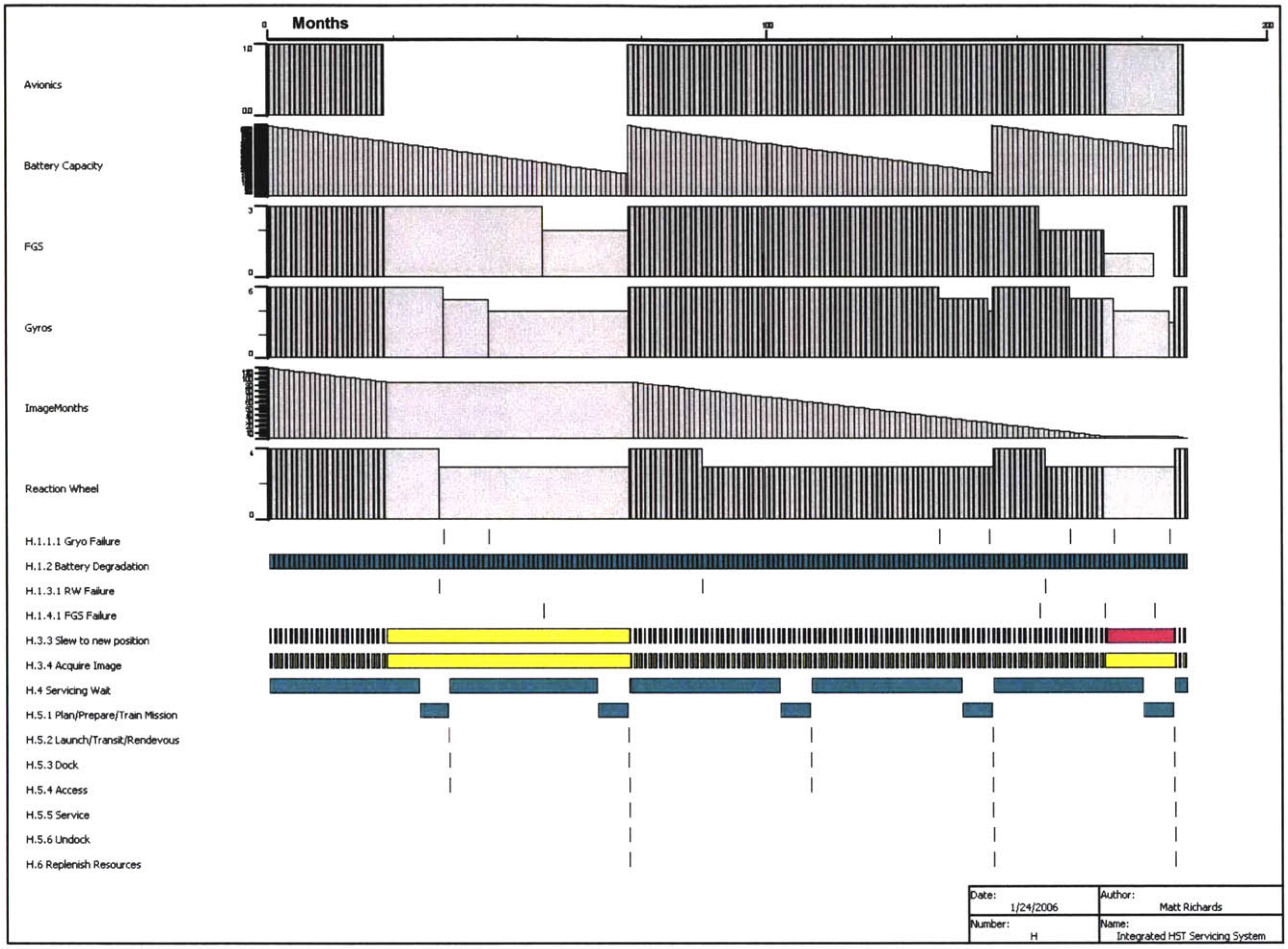


Figure 5.16 Hubble Servicing Simulation – Robotic Vehicle

Figure 5.16 shows a sample run of the Integrated Hubble Servicing Model with a robotic servicing vehicle. In this particular run, an initial two years of science operations were followed by nearly four years of survival mode due two events: an early failure of the avionics system and a failure of the Access servicing activity during the first attempted servicing mission. The second attempted servicing mission was successful in restoring, among other things, energy storage capacity before battery degradation caused a catastrophic loss.[3] Of the five robotic

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[3] With servicing scheduled once every three years, Hubble will not survive if there are two consecutive servicing failures. After six year without servicing, the battery capacity will have degraded below the necessary level to maintain the optical assembly.

servicing missions that were attempted, three were successful. The simulation terminated during the 16th year after 120 months of science data had been returned.

One metric for comparing the relative performance of the two servicing architectures is availability, the percentage of time in the simulation that Hubble was able to perform its science mission. (If a catastrophic failure occurs during the first 120 months of operation, 120 months is used in the denominator of the availability calculation.) Given that each run of the discrete event simulator produces a unique outcome, a Monte Carlo analysis was performed to calculate availability across multiple Space Shuttle and robotic vehicle servicing campaigns (Appendix C and Appendix D, respectively). Table 5.4 shows the results of this preliminary analysis. The higher probability of success assumed for Shuttle in all four servicing activities is evident with the 17% average availability advantage.

Table 5.4 Monte Carlo Comparison of Two Servicing Architectures

	Number of Simulations	Average # of Successful Servicing Missions	Average Availability
Space Shuttle	25	4.12	72.8%
Robotic Vehicle	25	2.24	56.0%

Although these preliminary results imply the superiority of a Shuttle servicing architecture, it is important to keep in mind the impact of assumptions, the simplicity of the model, and the limitations of the availability metric. Aggregating the assumed probabilities of servicing success across the four servicing activities, the Space Shuttle only fails one out of ten missions while the robotic vehicle fails nearly four out of ten missions. These assumptions were not subjected to sensitivity analysis and also may need to be modified as teleoperated and autonomously controlled vehicle technology improves. Regarding simplicity of the model, the executable portion only describes the functional aspects of Hubble's operation and servicing as the physical architecture of Hubble does not inform the success or failure of servicing. With another layer of detail, the linkages in CORE between the physical architecture and functional behavior domains can be leveraged to model the impact of physical design choices on serviceability. The model also does not allow on-demand servicing to supplement the shortcomings of the scheduled servicing campaign (*e.g.*, four-year pause in science operations observed in Figure 5.16). Most importantly, the availability metric captures only one of many attributes of a servicing architecture. The added utility of instrument upgrades, servicing cost trades, and the risk to astronaut life all need to be incorporated into the value proposition.

5.5 Key Findings

This chapter addressed the question of how architecture frameworks may inform dynamic serviceability assessments. It was found that while architecture frameworks bring structure to describing complex systems, the DoDAF views alone are insufficient for characterizing the dynamic behavior inherent in a satellite servicing architecture. However, when such views are constructed using a system engineering modeling tool such as CORE, both the DoDAF work products and an executable behavior model are created simultaneously. The executable model can then be used for quantitative evaluation of the dynamic system behavior.

5.5.1 Implications for Serviceability Assessments

Over the course of this chapter, lessons emerged how the DoDAF and systems engineering modeling tools may be applied to dynamic serviceability assessments at the satellite bus level. It was found that the process of constructing the static DoDAF work products and building an executable model enabled rapid understanding of the structure and operation of the larger Hubble system (*i.e.,* Orbiting Observatory, Space Telescope Operations Control Center, and Space Telescope Science Institute). On its own, the model of Hubble does not provide insights into whether Hubble is more or less physically amenable to servicing than other space systems. However, other space systems can rapidly be incorporated into the same overall servicing architecture to allow for comparison. Once these models for candidate target satellites are in place, judgments will become possible about the relative amenability of spacecraft to on-orbit servicing over time.

5.5.2 Implications for DoDAF

Lessons also emerged regarding the DoDAF and its development process. Emphasis is placed on final architecture products rather than process. Work products are frequently too complex to present to senior leadership without modification. Most fundamentally, weaknesses in the DoDAF have been identified as it undergoes transition from a static, descriptive tool to a tool that attempts to characterize dynamic system properties. Little guidance is provided on how to translate requirements into the design of the work products. As promulgated, the DoDAF does not have a companion architecture development process to take advantage of its interconnected views. As a result, many developers of DoDAF have treated it as a contract deliverable as opposed to a central communications tool in the design process. While it is not the business of DoD to stipulate how contractors conduct system design, it is in the interest of DoD to require architectures that are internally consistent and support dynamic performance analysis. Architecture development software with DoDAF extensions and integrated modeling and simulation capabilities is available to fill this void. In practice, however, 70% of DoDAF developers are not building executable architectures (Office of the Assistant Secretary of Defense for Networks and Information Integration, 2005).

Finally, the existence of a clear purpose for building the high-level Hubble architecture framework (*i.e.*, serviceability assessment) was a critical element in the construction of views that were both compliant with the static DoDAF taxonomy and useful for understanding dynamic system properties. For the value of the DoDAF to be fully realized, its construction must be mission-driven, focused on providing information that supports decision-making processes.

6 Architecting for Satellite Servicing: Prescriptive Technical Considerations

This chapter synthesizes lessons from Space Shuttle servicing missions, previous studies, and research described in Chapters 2 through 5 to determine how the design of future satellites may be affected by an OOS requirement. First, previous studies on the modification of existing satellites to enable OOS are reviewed. Second, the technical challenges facing OOS providers are surveyed as a means to understand the drivers of servicing mission complexity. Third, the serviceability framework proposed in Chapter 4 is used as a lens through which serviceability lessons are discussed. The following questions are addressed:

- What are the "architectural principles" for developing serviceable spacecraft?
  - What are the technical challenges facing servicing providers?
  - What are prescriptive technical considerations for enabling serviceability?

6.1 Background

> At present most spacecraft are not designed for on-orbit servicing. The electrical architecture does not allow for function replacement of many components.... All of the electrical components are interconnected by a combination of data buses (digital and optical fiber), power lines, and discrete digital lines. In order to be replaceable, any component that is interconnected with discrete lines will need to have all of these connections wired to the docking interface.... Current spacecraft designs do not have the basic hardware which is needed to cooperatively interface with a servicer spacecraft.... The physical layout of current spacecraft do not lend themselves to serviceability. Almost all external surface area and surrounding space is occupied by components that have a range of motion or field of view which cannot be blocked (Reynerson, 1999).

Such statements were extracted from the findings of the 1999 Spacecraft Modular Architecture Design Concept. As a historical context for this chapter on the design of future serviceable spacecraft, this section overviews two previous studies done on the modification of existing satellite bus designs to enable OOS: the Nimbus satellite configuration study (1969) and the GPS structural modification study (1999).

6.1.1 Nimbus Satellite Configuration Study

Representative of a class of complex research and development satellites in the late 1960's, Kiersarsky (1969) discusses how the Nimbus satellite was selected as a candidate satellite for determining how accessibility of components for an on-orbit servicing requirement would affect configuration. Like many satellites, Nimbus was designed for accessibility during fabrication, testing, and evaluation in the factory—not in-orbit. While a modular approach was employed with equipment mounted in separate bays and with removable panels to assist in system orientation and installation, the structure was designed as compact and dense and possible to meet launch vehicle weight and fairing constraints.

In addition to evaluating the transport of Nimbus to an on-orbit hangar facility for "shirt-sleeve" servicing, the effect of increasing the volumetric size of Nimbus was investigated with a particular focus on the sensor ring and attitude control system (which are enclosed areas with densely packed equipment). While the design modifications proposed to make the Nimbus satellite more serviceable are only applicable to satellites in operation decades ago, the study did derive a few heuristics, some of which may apply to modern spacecraft:

- Equipment should be configured to modular type containers
- Decrease in volume utilization (*i.e.*, low density packaging) appears to be unavoidable
- Access panels, either hinged or readily removable, are required
- All fasteners should be "captive" type
- Areas of access should be free of cabling and harnesses
- Cabling and harnesses should be routed in areas where no disassembly is required
- Connectors should be readily accessible through equipment access doors
- Insulation should be segmented and fixed to access panels

6.1.2 GPS Structural Modification Study

Hall and Papadopoulos (1999) document a preliminary assessment of the structural modifications necessary to enable servicing of GPS spacecraft. Two scenarios were considered, component addition and component replacement. Five serviceable GPS spacecrafts were studied in depth with two providing standardized slots for upgrade components and three providing hardware for both upgrades and replacements: basic bus with upgrade compartment, basic bus with upgrade boom, removable equipment panels, drawer equipments panels, and access doors. Depending on the level of serviceability, the study found that the mass impact on GPS spacecraft ranges from 100 to 700 lb. Table 6.1 shows the distribution of the mass penalty across these five bus types as a function of robotic servicer capability.

Table 6.1 Structure Mass Impact for Serviceability (Hall and Papadopoulos, 1999)

Satellite Config.	High Capability RS	Medium Capability RS	Low Capability RS
	Mass Impact, lb	Mass Impact, lb	Mass Impact, lb
Basic Bus with 20 inch Upgrade Compartment	99	127	103
Basic Bus with 40 inch Upgrade Compartment	152	180	157
Basic Bus with Upgrade Boom	37	65	37
Reconfigured Equipment Panels Removable Subpanels	184	212	200
Reconfigured Equipment Panels Drawers	287	314	N/A
Reconfigured Equipment Panels Access doors	200	227	N/A

6.2 *Key Technical Challenges Facing Servicing Providers*

Having reviewed two previous studies on the modification of existing satellites to enable OOS, the technical challenges facing servicing providers are surveyed as a means to understand the drivers of servicing mission complexity.

Numerous technical challenges face OOS providers. For one, the available telemetry points may be inadequate to determine the exact cause of on-orbit failure. Second, line loss issues make analog and radio frequency connections weak candidates for functional replacement. A third challenge is the replacement of attitude and determination control components which require alignment to the reference coordinate system of the target satellite—or need to be designed for on-orbit calibration—either of which impacts the design of the servicing vehicle's structure and docking interface (Reynerson, 1999).

Figure 6.1 depicts Orbital Express's prototype servicing vehicle, ASTRO, and its key enabling technologies, such as the 3.3 meter robotic arm and fluid transfer system. With plans for a flight test in 2006, ASTRO may serve as a baseline for the development of future robotic vehicle technology. More generally, Hollander (2000) identifies five key features of space robotics: (1) autonomy, (2) intelligence, (3) interface, (4) machine vision, and (5) reliability.

Key ASTRO Elements

- Spacecraft Processing
  - Open architecture and modular design
  - RAD hard 750 Power PC processor
  - 1394 fire wire plug & play embedded network
  - Sun safe mode
  - Distributed telemetry data acquisition
  - SGLS & TDRSS command & control links
- Electric Power
  - Deployable gimbaled solar arrays
  - Lithium-ion battery, 2 x 33 A-hr
- Robotic Arm
  - MDR arm and end effector
  - Camera on end effector
  - Maximum reach ~3.3m
- Fluid Transfer & Propulsion System
  - 72 kg monoprop hydrazine based on TRW heritage
  - 37 kg propellant transfer quantity
  - Propellant & pressurant transfer mechanisms
- Attitude Determination, Control & Navigation
  - Star camera & GPS receiver
  - Inertial measurement unit & sun sensors (4x)
- Structures & Mechanisms
  - Low cost Al honeycomb panel construction w/ central cylinder backbone
  - Load and stiffness for mated ASTRO/NEXTSat launch configuration
  - Built-in thermal radiators
- Communications
  - AFSCN SGLS & TDRSS S-Band
  - Crosslink subsystem
  - Encryption & decryption
- Rendezvous / Prox Ops
  - Boeing RPO Suite
    - 3 visible cameras
    - 1 IR camera
    - 1 long range LIDAR
  - AVGS sensor (NASA MSFC sensor)

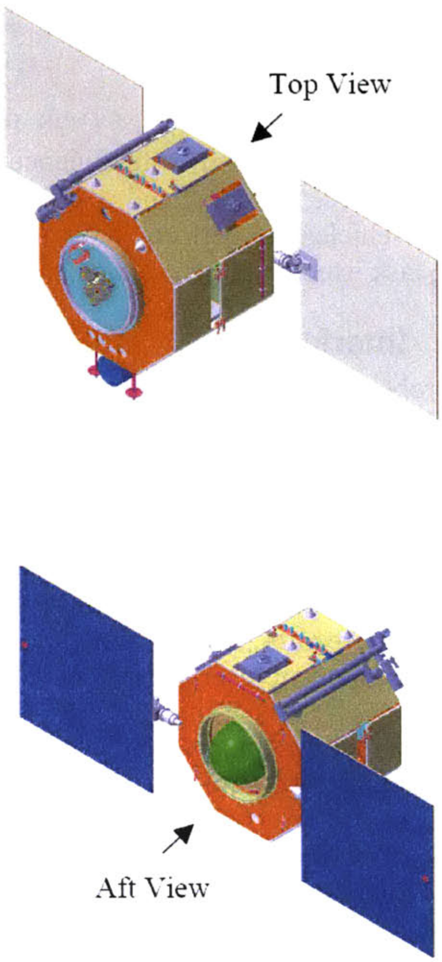

Figure 6.1 Orbital Express's Demonstration ASTRO (Shoemaker and Wright, 2004)

6.2.1 Autonomy

Robotic servicing vehicles should incorporate some degree of self-reliance but also keep a human operator in the loop for tasking, notification, monitoring, and problem resolution. It is highly desirable to automate most servicing tasks. For time-critical tasks such as final capture and docking, autonomous control may be essential due to telemetry delays of an estimated 2 to 5 seconds (Ianni, *et al.*, 2002).

While it is important for robotic vehicles to execute specific, pre-programmed tasks on their own, it is also important that robotic vehicles do not proceed with servicing activities when dangers to a target satellite or themselves arise. Given that lower-cost satellites are the least likely to be serviced, OOS is expected to be performed on expensive satellites for which the stakes will be too high to blindly trust an autonomous system. Through military research in uninhabited vehicles, it has been found that it is arduous and costly to develop software that is flexible enough to deal with the full set of possible outcomes (Ianni, *et al.*, 2002). Furthermore, even the most sophisticated pre-planned logic sequences may not be adequate to deal with the host of potential surprises which may arise, such as software errors, incorrect sensor calibration, solar weather, and space debris.

6.2.2 Intelligence

Another enabling technology of OOS from the provider perspective is intelligence. Closely associated with autonomy, intelligence is best described as a decision-making capability. Through sensors, memory, and a predetermined set of rules, intelligent software may enable servicing vehicles to perform a variety of tasks: planning, rendezvous, object recognition, docking, task execution, fault diagnosis, and anomaly resolution (Hollander, 2000).

6.2.3 Interface

Ideally, robotic vehicles would impose no requirements upon the objects or systems they service. Applied to OOS, this ideal would mean that the target satellite would not need to cooperate other than to enter into a quiescent mode while being serviced.

The burden of interfacing with target satellites translates to several design requirements for the servicing vehicle: an inter-satellite communications link to command the target satellite, an autonomous rendezvous and docking capability, an ability to take over attitude control for the combined spacecraft, and an ability to establish couplings with the target satellite including electrical component insertion and fluid transfer.

Future satellites might incorporate standard mechanical and electrical interfaces to ease the burden on servicing vehicles, particularly for complex OOS missions. One model for OOS interface standards is the set of standards imposed on spacecraft by launch vehicles: a mechanical interface consisting of a bolt pattern to accommodate a separation device and an electrical interface consisting of an umbilical cord for pre-launch satellite testing and connections to activate the separation system (Miller, *et al.,* 2002).

6.2.4 Machine Vision

Robotic servicing vehicles need to be able to recognize complex three-dimensional objects that vary in terms of orientation, distance, and lightening. Hollander (2000) documents two options for automating machine vision for OOS, the process of determining range and orientation of one spacecraft relative to another: two-dimensional scene analysis and three-dimensional surface imaging and analysis.

In a typical scene analysis, edge detection methods are applied to develop a silhouette of the target satellite. Corner points or edge shapes are compared to a three-dimensional model of the target satellite to determine range and orientation. Weaknesses of edge detection include ambiguity problems for symmetric objects and loss of capability once the camera's field of view (FOV) is filled. Recognition may be aided through the placement of fiducial marks on the exterior of the target satellite which impose no weight or cost penalty. However, fiducial marks do require surface area which may already be allocated to solar cells and thermal blankets. They also require the servicing vehicle to carry an illumination source during eclipse.

In contrast to scene analysis, three-dimensional range imaging determines current distance to an array of points distributed over the portion of the target satellite within the ranging instrument's FOV. These three-dimensional surface images are then compared to three-dimensional models of the target satellite taken prior to launch. No markings are required and objects may be recognized from any aspect. Several range imaging sensors based on laser radar techniques exist. A competing technology being developed at NRL employs cameras and a correlation code projector for structured light triangulation.[1]

It is important to note that the machine vision technologies discussed here only support proximity operations. Radar and beacons will be required for rendezvous. At altitudes below 7400 km, GPS may also be employed.

6.2.5 Reliability

As highly complex electromechanical devices which require extensive servicing in terrestrial environments, robotic systems deployed into the inaccessible and extreme environment of space impose design challenges. Furthermore, given the need to amortize the cost of sophisticated servicing vehicles over multiple missions, a design life exceeding a decade may be required. Long operational lives impose significant burdens on lubricants, high throughput thrusters, relays, and other active components (Hollander, 2000).

6.3 Architectural Heuristics for Designing Serviceable Spacecraft

Having reviewed the technical challenges facing servicing vehicles, we now turn to the question of the design of future spacecraft that are serviceable. Table 6.2 lists the maintainability lessons that were stated by the crew of STS-61, the first Hubble servicing mission. Although referring to human servicing operations, these heuristics apply to enabling robotic servicing operations.

This section integrates lessons from Space Shuttle servicing missions and findings from previous chapters to derive prescriptive technical considerations for satellite designers. Considerations are divided into four broad categories: (1) maximize knowledge of target satellite, (2) manage scale of servicing activities, (3) minimize precision of servicing activities, and (4) minimize temporal constraints.

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[1] A structured light module emits sequentially pulsed illuminations from a light-emitting diode, and digital images are synchronized with light source flashes.

Table 6.2 Lessons Learned from Hubble Space Telescope Repair (Shishko, *et al.*, 1995)

- For spacecraft in LEO, don't preclude a servicing option; this means, for example, including a grapple fixture even though it has a cost and mass impact.
- When servicing is part of the maintenance concept, make sure that it's applied throughout the space craft. (The HST Solar Array Electronics Box, for example, was not designed to be replaced, but had to be nevertheless.)
- Pay attention to details like correctly sizing the hand holds and using connectors and fasteners designed for easy removal and reattachment.
- Make sure ground-based mock-ups and drawings exactly represent the "as-deployed" configuration.
- Verify tool-to-system interfaces especially when new tools are involved.
- Make provision in the maintainability program for high-fidelity maintenance training.

6.3.1 Maximize Knowledge of Target Satellite

Maximizing knowledge regarding the state of the target satellite is critical to reduce uncertainty in servicing operations. If a servicing vehicle has perfect information, operations may be scripted. The less knowledge available on the target satellite, the more operations need to be adaptable which adds complexity. Two mechanisms are available for maximizing knowledge of the target satellite: extensive spacecraft health monitoring and a mission operations profile that minimizes spacecraft deviance from the original design state.

First, serviceable spacecraft should incorporate extensive fault detection, isolation, and diagnostic capabilities. When an anomaly occurs, operators on the ground need to be able to determine exactly which components have failed. Inspections may also boost knowledge of the external structure of the target satellite. To lower the cost of inspections, orbits which are amenable to remote-sensing or accessible to free-flying proximity inspectors should be considered.

Second, serviceable spacecraft need to minimize deviance from the design documents used to plan the servicing operation. According to former Astronaut Jeffrey Hoffman, the crew of STS-41C encountered difficulties during the repair of the Solar Max satellite due to the placement of thermal insulation on the bus exterior that was not captured in design documents. While difficulties such as these may not have compromised Shuttle servicing missions, robotic servicing vehicles may not be as well-disposed to adapt to emergent requirements. One way to prevent this problem is to strictly enforce configuration control during manufacturing, assembly, and pre-launch operations.

Minimizing spacecraft deviance from design documents extends beyond configuration control. Minimizing damage sustained in post-assembly operations is important as well. While it is impossible to prevent all on-orbit anomalies, the concentration of radiation, thermal cycling, and debris in certain orbits may inform architecture-level trades in planning mission operations for serviceable satellites. In addition to evaluating orbits in terms of the potential for satellite degradation, it may also be valuable to consider the loads placed on spacecraft by various launch vehicles.

6.3.2 Manage Scale of Servicing Activities

Managing the scale of servicing activities is critical for controlling the complexity of servicing operations. If the scale of a servicing is too great, it may be impossible with current technology or require multiple servicing vehicles (likely crippling the economic justification). Three general recommendations are discussed: reducing ΔV expenditures for servicing missions by considering the concentration of other potential OOS targets in orbit selection, minimizing the distance between docking ports and servicing zones, and minimizing the number of unique tasks for robotic vehicles.

First, target satellites should be within propulsive reach of servicing vehicles such that multiple spacecraft can be reached by an individual servicer over the course of its design life. In terms of orbital dynamics, this means that LEO satellites should be within 1 to 2 degrees inclination and 100 km in altitude of other target spacecraft (see Figure 3.4). GEO satellites are relatively amenable to the rendezvous OOS activity with servicing vehicle ranges extending to 5 degrees inclination and 1,000 km in altitude (Galabova, *et al.*, 2003). As illustrated in Figure 4.9 and Figure 4.13, ΔV expenditures for servicing missions vary not only as a function of orbit but also as a function of orbital slot.

Minimizing the distance between the mating zone of the servicing vehicle and the area of interest on the target satellite is a second mechanism for managing the scale of servicing activities. To be serviceable, the robotic arm of the servicing vehicle must be able to access the necessary components. Electrical interfaces, fluid transfer modules, and ORU storage bays should be collocated with docking ports. This may constitute a major departure from the current architecture of some GEO communications spacecraft in which the spacecraft subsystems likely to be serviced (payloads and antennas) are located on the Earth-pointing side of the satellite (five meters from projected docking locations on the back end of the spacecraft).

Third, target satellites should minimize number of unique tasks required of the servicing operation. One method for reducing the number of unique servicing tasks is through functional periodicity whereby functional requirements of servicing operations are repeated as much as possible (Suh, 2005). Component commonality (*e.g.*, use of limited number of bolt sizes throughout satellite structure) is one mechanism for achieving functional periodicity.

Including margin on the spacecraft in terms of both functional capability and spatial volume is another architectural heuristic for minimizing the number of unique servicing tasks. For example, if the thermal control system is designed *a priori* for operation before servicing and after servicing (*e.g.*, when a payload module is docked), the impacts of varying radiative surfaces and heat sources will not add the requirement of augmenting the thermal control system to the servicing operation. Designing with capability margin for loads of additional payload modules may also prevent modifications to the electrical power and attitude control subsystems. Reducing the utilization of spatial volume in areas of the target satellite most likely to be serviced may also improve accessibility for servicing operations.

6.3.3 Minimize Precision of Servicing Activities

Minimizing the required precision of OOS involves designing target satellites such that tolerances are permitted during servicing operations. Three general recommendations are made for minimizing required precision: designing "safe modes" of satellite operation to mitigate thruster plume impingement, tightly controlling interfaces with the servicing vehicle, and employing loose coupling for serviceable components.

First, target satellites might incorporate "safe modes" of operation when servicing vehicles are in close proximity. Thruster plume impingement can have serious detrimental effects on satellites including disturbance torques, unwanted heating of components, and surface contamination. The instrumentation of remote-sensing satellites is particularly sensitive to impingement damage.

Second, target satellites should tightly control interfaces such that interfaces are amenable to robotic intervention. For example, satellites might incorporate a docking port with retro reflectors to assist in autonomous rendezvous and docking maneuvers. Similar interfaces should be designed to assist in disassembly and assembly tasks, the opening and closing of panels, and instrument change-out.

Third, target satellites should avoid highly-integrated designs. Loose coupling is one mechanism for enabling a modular architecture (*e.g.*, "plug-n-play" avionics).

DARPA's NEXTSat from the Orbital Express program is the prototype for a future generation of satellites designed for OOS. As observed in Figure 6.2, NEXTSat's servicing elements both manage the scale of servicing activities and minimize the precision required of the servicing provider.

NEXTSat Servicing Elements

- Rendezvous / Prox Ops Aids
    - Passive docking sensor
    - Retro reflectors
    - Grapple fitting for alternate docking
- Crosslink Antenna
- ASTRO Servicing Interfaces
    - Starsys passive latch
        - Triangular wedge design guides and positions active side arms
    - Electrical coupler interfaces
    - Fluid / pressurant transfer coupling
        - Self-sealing design
        - Quick disconnect
- Separation Ring
    - Transfers launch loads
- ORUs and Storage Bays
    - Lithium-ion battery ORU
    - Processor ORU
- Fluid Transfer Module
    - Modular transfer system
    - 34 kg fuel tank capacity

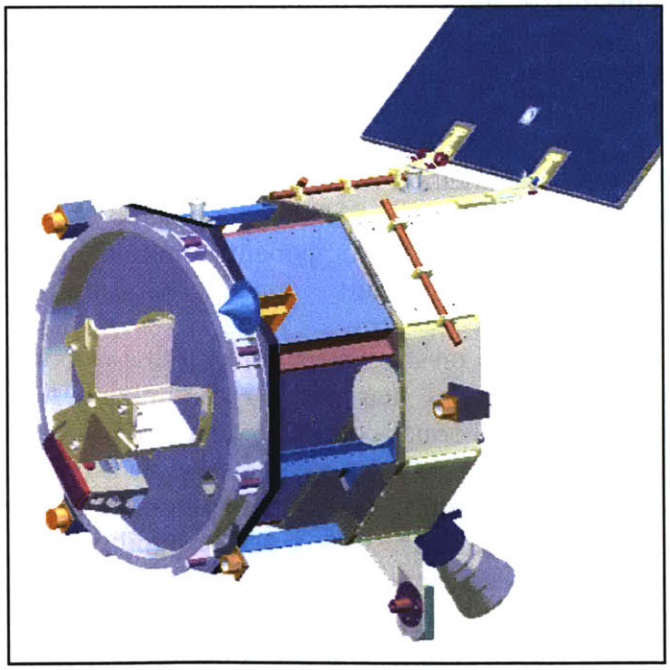

Figure 6.2 Orbital Express's Demonstration NEXTSat (Shoemaker and Wright, 2004)

6.3.4 Minimize Temporal Constraints

Two general areas are suggested for minimizing the temporal constraints imposed by the target satellite on the servicing architecture: enhancing the predictability of servicing missions and mitigating timing constraints during servicing missions.

Compiling empirical data on satellite component degradation is critical for understanding servicing frequency and hence a mechanism for minimizing temporal constraints on the OOS provider. An analogy drawn from the oil industry pertains to the maintenance of offshore oil platforms. Rather than basing maintenance schedules on first principles, oil companies use statistical precedents as a starting point for establishing servicing policy (see Section 4.3.1). As predictability of satellite servicing improves, servicing missions may be scheduled in advance of component failure (*e.g.*, Hubble). This will not only improve satellite availability but also may reduce ΔV expenditures for servicing missions by an order of magnitude (Section 4.2.4).

OOS may also cause operational downtime (on the order of hours) for target satellites during operations of a service mission. Following the considerations under the knowledge, scale, and precision categories (discussed in the previous three sections) will reduce the duration of servicing operations. If possible, functions of the serviceable vehicle should be replicated by another means (*e.g.*, temporarily rent transponder capacity on another satellite) to serve end-users during this period.

6.4 Summary

Table 6.3 summarizes the architectural heuristics derived in this chapter for designing serviceable spacecraft.

Table 6.3 Architectural Heuristics for Designing Serviceable Spacecraft

Maximize knowledge of target satellite	**Manage scale of servicing activities**
• Incorporate extensive fault detection, isolation, and diagnostic capabilities • Enforce configuration control during manufacturing, assembly, and pre-launch operations • Limit structural deformation from launch, radiation, and thermal cycling	• Consider the proximity of other potential OOS targets in orbit selection • Collocate electrical interfaces, fluid transfer modules, and ORU storage bays with docking ports • Use common components • Design electrical, thermal, and attitude control subsystems with margin for loads of additional payload modules
Minimize precision of servicing activities	**Minimize temporal constraints**
• Design "safe modes" of satellite operation to mitigate thruster plume impingement • Control servicing interfaces tightly • Substitute highly-integrated designs with modular, loosely-coupled configurations	• Compile empirical data on component degradation to enable scheduled servicing • Allow for temporary outsourcing of functions to shield end-users from operational downtime

7 On-Orbit Servicing Implementation

This chapter addresses OOS issues located at the interface of technology and policy. Perfect technical solutions are useless unless they can be implemented. Iridium was a technical marvel (*e.g.*, 48-hour assembly time, dynamic crosslinks) but failed economically with the collapse in the projected demand for personal satellite communications (due to an extraordinary installation of fiber optics cables and proliferation of cell phone service during the late 1990's). An example related to OOS is STS-51C in which the Shuttle retrieved the Palapa and Westar VI satellites. Stuck in LEO because of upper stage failures, Hughes Aircraft Company and NASA engineers worked out a technical solution for a Shuttle rescue mission in six weeks. However, it took over six months to resolve the legal questions concerning ownership, salvage rights, insurance coverage, and the release of liability between the insurance carriers before the recovery effort began (Wertz and Larson, *et al.*, 1999). Fortunately, this time window was consistent with the preservation of the Palapa and Westar VI satellites. Other on-demand rescue operations may not afford such temporal flexibility.

This chapter unifies the political, legal, and financial aspects of on-orbit servicing and highlights the challenges that stand in the way of an operational servicing vehicle.[1] Implementation strategies are proposed for the realization of a national servicing infrastructure in space. The following questions are addressed:

- What are the non-technical challenges facing OOS implementation?
    - What are the political issues and legal constraints for OOS?
    - What economic themes characterize OOS? What financial models make sense for servicing providers?

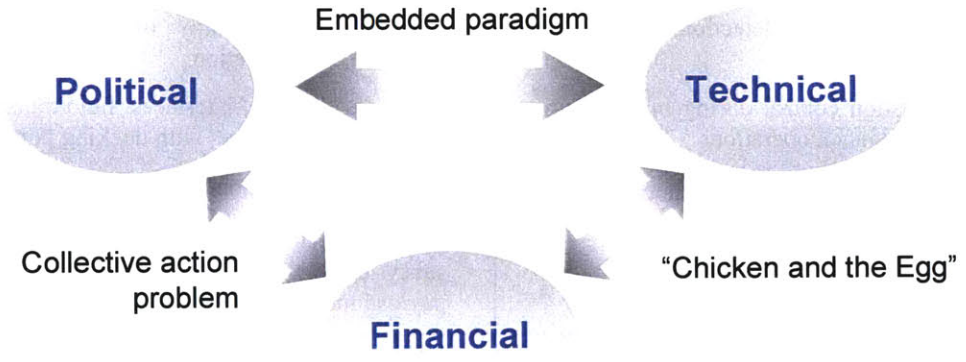

Figure 7.1 Challenges Facing On-Orbit Servicing Providers

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[1] Portions of this chapter are based on a paper entitled "Assessing the Challenges to a Geosynchronous Space Tug System" (Richards, Springmann, and McVey, 2005).

First, U.S. Space Transportation Policy is reviewed, and OOS is recognized as an enabler of emerging national space transportation requirements. Second, customary international and United States laws are then explored as potential constraining forces on future servicing missions. Third, potential financing models and the issue of insurance for OOS are discussed and identified as the principal challenges facing implementation of a servicing system. This chapter offers a positive forecast for the future of OOS and endorses continued government support for proof-of-concept missions.

7.1 Policy Rationale

As the foundation for future government capabilities in space, it is necessary to consult national space policy to justify government on-orbit servicing operations. In the post-Cold War, development of a servicing capability was consistent with national space policy directives but not explicitly addressed. In a victory for proponents of OOS, the recently released U.S. Space Transportation Policy outlines a next-generation technology development program and specifically endorses development of OOS capabilities. In addition to discussing the evolution of U.S. space policy, this section will also address other important stakeholders of OOS and the challenges these stakeholders might impose on implementation of a space tug system.

7.1.1 Post-Cold War National Space Policy

Until recently, the only published post-Cold War statement of U.S. space policy was the 1996 Presidential Decision Directive (PDD) guidelines for national space security (White House Office of Science and Technology Policy, 1996). Developed by the National Science and Technology Council (NSTC), PDD/NSTC 8 provides a direction for U.S. space activities that is consistent with the development of an OOS capability. Although servicing operations are not mentioned specifically in PDD/NSTC 8, a servicing system might constitute a means of accomplishing many of the guidelines outlined in the directive. For example, in the guidelines for civil space activities, NASA is instructed to develop "new and innovative space technologies…to improve the performance and lower the cost of future space missions." The potential space tug capabilities of relocation and refueling of satellites—which otherwise will fail to perform their mission—are certainly "new and innovative space technologies" that come at a lower cost than the replacement option. Indeed, NASA's Hubble Telescope provides not only a dramatic precedent for future servicing missions but also an excellent example of a space system remaining state-of-the-art through a series of servicing missions—at a fraction of the cost of launching new systems (see Section 2.2.1). By automating a process currently only performed by astronauts and Shuttle, OOS offer the potential to expand the benefits of servicing enjoyed by Hubble to many government and commercial satellites.

7.1.2 New National Space Policy

The new U.S. Space Transportation Policy, authorized by President Bush in December 2004 and released by the White House Office of Science and Technology on January 6, 2005, extends and clarifies the 1996 Presidential Decision Directive in the area of OOS by explicitly endorsing space tug technology development (White House Office of Science and Technology Policy, 2005). The new policy emphasizes a technology development program "that dramatically improves the reliability, responsiveness, and cost of access to, transport through, and return from space." This transformation of the U.S. space transportation infrastructure is found essential both to augment "space-based capabilities in a timely manner in the event of increased operational needs," and minimize "disruptions due to on-orbit satellite failures, launch failures, or deliberate actions against U.S. space assets." As a means to these improvements, U.S. Space Transportation Policy directs a sustained research and development effort that includes "automated rendezvous docking, and the ability to deploy, service, and retrieve payloads or spacecraft in Earth orbit."

7.1.3 Policy Challenges

Although OOS technology will likely be developed in accordance with U.S. Space Transportation Policy, the actual deployment of such a system is uncertain due to the nature of its potential customers. The primary policy challenge facing implementation of a servicing system is gaining the trust of satellite operators to fund missions such as lifetime extension or orbital transfer. This challenge is particularly great in the Air Force, where program managers of national space assets are traditionally risk-adverse and might hold a short-term outlook of satellite operations given that the tenure of many program managers is less than two years (Defense Science Board/Air Force Scientific Advisory Board, 2003). To overcome this barrier, it might be necessary to review the incentive structure of Air Force program managers. Lengthening tours-of-duty of program managers or providing career incentives to program managers who extend mission life of space assets are possible improvements. Another alternative is to make mission life extension a requirement for high-value space assets.

All space-faring nations are stakeholders in the development of a OOS system. Foreign nations might welcome the development of a servicing vehicle as an enabling tool for flexible mission profiles or might fear the new capability on safety or strategic grounds. The potential for negative international reaction to a U.S. orbital correction capability is one of the key challenges facing OOS implementation. What if space tugs are perceived as a space weapon and the U.S. government faces stiff international resistance? In the eyes of U.S. policymakers, will the political capital required to gain international acceptance of this capability outweigh the extended lifetimes of national space assets? During the Cold War, the Soviet Union viewed the Space Shuttle as a weapon in Low Earth Orbit, capable of docking and manipulating a variety of sensitive on-orbit assets. In light of these concerns, one strategy to improve international acceptance of OOS is to describe in detail what the functions of a servicing system are *(e.g.*, orbital transfer, lifetime extension) and what they are not (militarization of space). Another mechanism to increase international acceptance of an OOS system is to offer a notification protocol whereby mission profiles of servicing vehicles such as space tugs are shared with other space-faring nations. The issue of bringing transparency to OOS operations is discussed further in Section 7.2.1.2 On-Orbit Liability and Registration.

7.2 Legal Constraints

Legal constraints for space tug operations can be divided into three categories: customary international law, U.S. law, and the U.S. International Traffic in Arms Regulations (ITAR). Since its establishment in 1959, the United Nations Committee on Peaceful Uses of Outer Space (COUPOS) has launched five major international legal instruments that form the bulk of laws governing space. Other customary international space laws are derived from bilateral arms control treaties between the U.S. and U.S.S.R. National legal principles relevant to space tug operations include U.S. criminal law pertaining to interference with the operation of a satellite, export control policy which may prevent international OOS, and classification concerns which may limit the size of OOS markets.

Table 7.1 Relevant International and National Legal Instruments

1967 Outer Space Treaty	Article VIII: Provides a state jurisdiction and control over its registered space objects
1972 Liability Convention	Article II: Holds a state liable for damage caused by its launched space objects
	Article III: Determines liability by fault
	Article IV: Holds states jointly liable if a collision of their space objects causes third party damage
1973 Telecommunication Convention	Bans harmful interference to the communications of other states
1975 Registration Convention	Requires states to maintain a registry of objects launched into space
US Criminal Law Title 18, Section 1367	Makes interference with satellite communications a federal offense
1976 US Arms Export Control Act	Created ITAR and the United States Munitions List which regards all satellites and most space systems as munitions subject to export control

7.2.1 International Legal Principles

Three COUPOS treaties—the 1967 Outer Space Treaty, the 1972 Convention on International Liability for Damage Caused by Space Objects, and the 1975 Convention on Registration—contain provisions which may set forth legal constraints for OOS operations. In addition to the COUPOS treaties, the 1973 International Telecommunication Convention also has implications for space tug parking orbits and phasing maneuvers.

7.2.1.1 Jurisdiction and Control of Space Objects

According to Article VIII of the Outer Space Treaty, a country retains jurisdiction and control over its registered space objects. Additionally, Article VI provides that states bear international responsibility for government and private space activities and must supervise and regulate national activities in space whether conducted by government agencies or non-governmental entities.

A servicing capability in GEO would enable a variety of missions including the relocation of functioning space objects and the retrieval or salvage of nonfunctioning space objects. However, customary international law strictly limits missions of this variety to national space assets. Peacetime retrieval, alteration of orbit, or any other form of interference with foreign space objects would be unlawful without prior consent.

The retrieval or removal of nonfunctioning foreign space objects is also banned by customary international law. Article VIII of the Outer Space Treaty clearly holds that state property remains state property unless relinquished. The case of non-functioning satellites on-orbit is analogous to the case of sunken ships. The United States and most other countries have consistently upheld the principle that sunken ships remain the property of the flag state unless rights are transferred or explicitly abandoned (where abandonment cannot be implied from the absence of acts demonstrating interest in such property, even over long periods of time). Therefore, although a servicing capability such as a space tug near the geostationary belt would make possible a variety of relocation, retrieval, and salvage missions, customary international law would limit such operations to strictly national space objects.

7.2.1.2 On-Orbit Liability and Registration

The issue of liability in space has drawn attention since the dawn of the space age. Orbital transfer vehicles designed to dock with multiple space objects such as space tugs are likely to attract further attention to this area of international concern. Although the Outer Space Treaty provides that states bear international responsibility for all national space activities, it does not provide any mechanism for resolving liability disputes that may arise.

The 1972 Convention on International Liability for Damage Caused by Space Objects fills the void left by the Outer Space Treaty by clearly defining customary international legal principles in the areas of fault and liability and by establishing a dispute settlement mechanism for damage caused by collisions in space. Article II of the Liability Convention provides that a launching state is absolutely liable for damage caused by its space objects in space, and Article III provides that this liability is determined by fault. In cases where diplomatic negotiations fail, the Liability Convention enables signatories to request the formation of a Claims Commission to rule on the issue of fault and to determine the amount of compensation due. However, in the history of the Liability Convention, a Claims Convention has never been established due to the low frequency of incidents of damage in space from collisions between spacecraft or with space debris. The most serious collision in space—the 1996 collision of a French Cerise military satellite with an Ariane upper stage—involved two French space objects, so the question of international liability never arose (Schildge, 2003).

Space tug operations would require new interpretations of the Liability Convention and could serve as the impetus for innovative contractual relationships between space tug operators and operators of target satellites. A worst-case scenario illuminates why the assignment of fault in the course of space tug operations may not be a clear decision. Suppose a tug fails to safely rendezvous with a target satellite and instead crashes into the satellite. Then, suppose debris from the fractured satellite damages a third-party satellite. Which party is at fault for the third-party damage, the tug operator or the operator of the fractured satellite that physically caused the damage?

The Liability Convention holds the launching state responsible for damage caused by its space objects and offers insight into the case of third-party damage. According to Article IV, in the event of damage being caused in space to a space object of one launching state by a space object of another launching state, and of damage thereby being caused to a third state, the first two states are jointly liable. Furthermore, in cases of joint liability, the burden of compensation for the damage is divided between the first two states in accordance with the extent to which they were at fault. Finally, if the extent of the fault of each of these states cannot be established, the burden of compensation shall be divided equally between them.

The uncertainty associated with liability claims would need to be addressed contractually between space tug service providers and satellite operator customers prior to space tug operations. The Liability Convention is not sufficient in itself to resolve liability. The Convention has already become outmoded in other areas, such as commercial launch, where fault is assigned to launching states despite the frequent practice of packaging a payload from one state inside a launch vehicle of another. Just as liability for multi-party commercial launches are resolved contractually, so, too, might liability issues be resolved for space tug operations.

The 1975 Convention on Registration of Space Objects requires a state to maintain a registry of objects it launches into space. Information on each registered object—including date and location of launch, basic orbital parameters, and the general function of the space object—is to be provided in timely manner to the United Nations register for full and open access to the international community.

Current customary international law pertaining to registration and liability does not assign direct legal constraints to space tugs but may be amended in the future as satellite servicing operations mature. A significant exemption to the Registration Convention is the lack of a requirement for states to provide updated orbital properties if space objects move from original orbits as functioning space tugs certainly would. Although national security space assets currently move to unreported orbits without issue, the high frequency of phasing maneuvers inherent to space tugs may prompt calls for eliminating this gap in the Registration Convention. Liability concerns could drive calls for strict notification requirements of changing space tug orbital properties. For example, in the case of a space tug operating in undisclosed orbit and accidentally colliding with another state's space object, the injured party would want accurately to attribute fault for a liability claim to the offending tug, not be led to believe that orbital debris is the cause of damage.

7.2.1.3 Noninterference with Communications

The 1973 International Telecommunication Convention holds that all space objects must be operated so as not to cause harmful interference to the radio services or communications of others. Traditionally, this interference is linked to issues of limited bandwidth and frequency. For space tug operations in the highly-populated GEO belt, it is also necessary to avoid physical blockage of communication beams. Appropriate parking orbits and rendezvous maneuvers for avoiding communication beams of GEO spacecraft during space tug operations are discussed in Appendix F – Space Tug Concept-of-Operations.

7.2.2 U.S. National Law

U.S. national law and regulations which may constrain future OOS operations include Title 18, Section 1367, of U.S. Criminal Law, the International Traffic in Arms Regulations maintained by the U.S. Department of State, and classification of government spacecraft.

7.2.2.1 U.S. Criminal Law

U.S. criminal law Title 18, Section 1367, pertains to interference with the operation of a satellite. This statute makes it a federal criminal offense for anyone who, "without the authority of the satellite operator, intentionally or maliciously interferes with the authorized operation of a communications or weather satellite or obstructs or hinders any satellite transmission." Title 18, Section 1367, specifically exempts U.S. government agencies involved in lawfully authorized investigative, protective, and intelligence activities. For space tug operations in the GEO belt, this statute serves to reinforce the international requirement of noninterference with communications.

7.2.2.2 International Traffic in Arms Regulations

Would ITAR prevent international on-orbit servicing? Fear of export control violations might deter entry of OOS providers into a global satellite servicing market. The relative scientific advantage of the United States to other countries is recognized as a critical enabler of U.S. military capabilities. Space technology in particular has become a vital component of the United States military. The U.S. military utilizes space for many key aspects of military operations: communications; navigation; missile warning; weather forecasting; and intelligence, surveillance, and reconnaissance. Satellites are efficient means to collect, transmit, and distribute information to the warfighter (Fernandez, 2004). Foreign entities employ a variety of techniques to glean militarily applicable knowledge from the United States. Knowledge transfer may occur through covert actions as well as overt methods. Whether channeled through illegal purchases of equipment from third party nations and industrial espionage by foreign agents or through academic exchanges and open literature, technology transfers can be militarily significant. Regulations must, therefore, uphold the national security interests of the United States.

The Arms Export Control Act of 1976 is the legal foundation of United States export control policy—manifested in the International Traffic in Arms Regulations. Recognizing the need for the United States to control the spread of weapons technologies, the Arms Export Control Act (*i.e.*, 22 U.S.C. § 2778(a)(1)) grants the Executive Branch the authority to designate items—comprising the United States Munitions List (USML)—considered defense articles or services. The USML is administered on behalf of the President by the Department of State's Directorate of Defense Trade Controls. In principle, ITAR serves as a mechanism by which the U.S. government may limit the export of technology and information to foreign nations and nationals who might use those exports against U.S. interests. Examining the USML provides insight into the scope of exports that are prohibited by ITAR. Divided into 21 categories, the USML includes everything from firearms and assault weapons to protective personnel equipment and shelters. Category IV, "Launch Vehicles, Guided Missiles, Ballistic Missiles, Rockets, Torpedoes, Bombs and Mines," and Category XV, "Spacecraft Systems and Associated Equipment," are of particular interest to potential OOS providers as they include such items as ground control stations for telemetry, tracking, and control; radiation-hardened microelectronics; rockets; all satellites; launch vehicles and their power plants; and all related technical data. The breadth of the USML leaves room for individual interpretations by enforcement agents within the State Department and, hence, may cause uncertainty in the minds of those who are engaged in the increasingly global space industry (Broniatowski, Jordan, Long, Richards, and Weibel, 2005).

In general, ITAR requires a license for the export of military information, technologies, and equipment to some foreign nations, organizations, and citizens and prohibits outright the transfer of such technology to others. Projects which employ foreign nationals from any country are therefore subject to added scrutiny with respect to international arms export restrictions. In order to export an item that appears on the USML, one must obtain an ITAR export license from the State Department unless one qualifies for a licensing exemption. As published in the Federal

Register on March 29, 2002, licensing exemptions for spacecraft systems and associated equipment may be available to members of the North American Treaty Organization (NATO), the European Union, the European Space Agency, and major non-NATO allies for fundamental research (Broniatowski, Jordan, Long, Richards, and Weibel, 2005).

In reviewing the primary documents comprising export control policy, it is not clear if the sharing of technical information (*e.g.*, satellite bus structure for docking operations) between an OOS provider of one national and an OOS customer of another nation would be allowed under ITAR. Empirical evidence suggests it might not be. In April 1998, the Justice Department began a criminal investigation into whether Loral Space and Communications, Ltd., and Hughes Electronics Corp. violated export control law during launch accident investigations. Both cases involve proliferation concerns with the mating of U.S.-built satellites to Chinese launch vehicles. In 1995, a Long March rocket exploded and destroyed the Hughes-built Apstar-2 satellite. A year later, another Long March exploded, destroying the Loral-built Intelsat-708 satellite. At the insistence of insurance companies, the launch accidents were reviewed, during which time U.S. expertise was allegedly transferred to China that could enhance the guidance and control systems of its nuclear ballistic missiles.[2] In 2002, Loral agreed to a civil settlement of $20 million. In early 2003 Hughes and Boeing Satellite Systems settled for $32 million (Kan, 2003).

The threat of violating export control policy might deter entry of U.S. OOS providers into a global satellite servicing market. As observed in Table 7.2 and Figure 7.2, potential customer satellite operators are distributed globally. Perhaps only the United States possesses enough satellites to construct a commercially viable servicing model. However, economic analyses of OOS viability under even the most favorable circumstances—GEO lifetime extension—is already questionable given the need for compatibility between the provider and customer across several dimensions including value, technology, and timing. Splicing OOS markets further by limiting servicing to domestic satellites will not help already fragile business models.[3]

Table 7.2 Distribution of Active Satellites by Country of Operator

	Civil	Commercial	Military	Total
United States	58	265	71	394
Russia	7	26	57	90
China	17	10	8	35
Rest of World	96	128	30	254

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[2] After suffering satellite launch failures in 1992, 1995, and 1996, China reportedly had 27 consecutive, successful launches through 2002 (Kan, 2003).

[3] Of active GEO communications satellites, 102 will reach their EOL between 2005 and 2016 (Long and Hastings, 2005). However, only 42% are owned/operated by the United States (UCS Satellite Database, 2006).

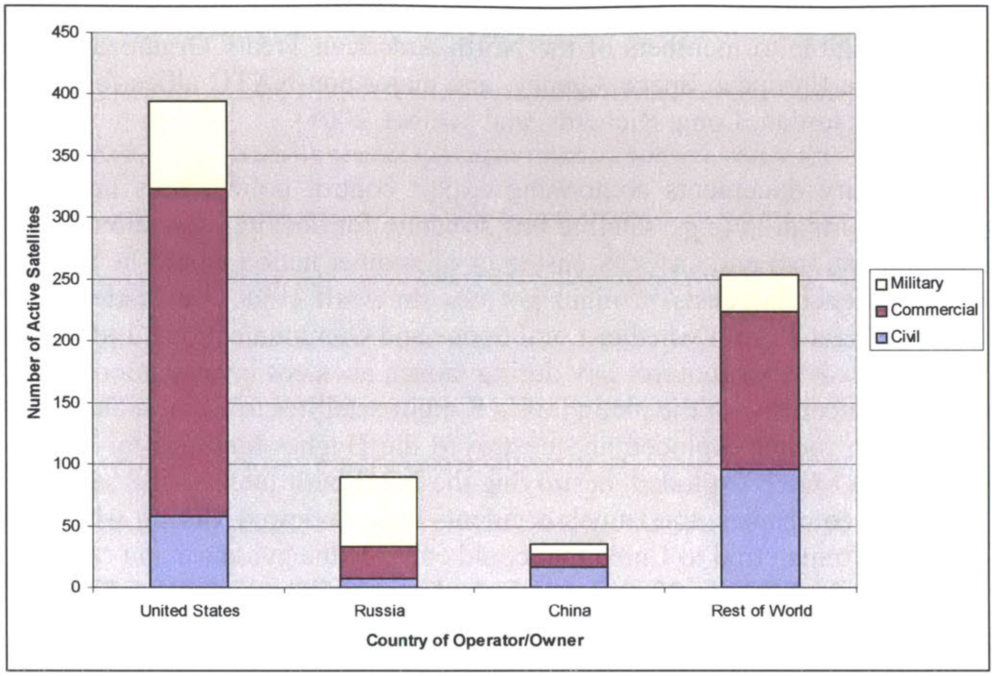

Figure 7.2 Distribution of Satellites by Country of Operator

7.2.2.3 Classification

Another concern related to the sensitivity of satellite designs facing OOS providers is the classification of various government spacecraft. Would classification prevent a country's military and intelligence spacecraft from using a shared servicing vehicle? Would it be legally possible for a commercial satellite to use a servicing vehicle that also services classified government spacecraft? The issue of government-commercial collaboration in space is addressed from a financing perspective in Section 7.3.

7.3 Financial Challenges

A variety of civil and military programs to verify technologies needed for space tug operations and on-orbit servicing are in development. While technological breakthroughs are necessary before OOS becomes a reality, this is only one aspect of the problem. Perhaps the greatest challenge to implementation of space tug systems is financial. A number of papers have made a strong business case for OOS (see Section 2.4.2). However, little work has been done in the areas of financing and insuring OOS operations. After highlighting the themes characterizing the financial challenges facing OOS, this section reviews candidate financing models for an OOS provider and analyzes the issue of insuring servicing vehicles.

7.3.1 Economic Themes

In addition to enabling unique missions, on-orbit servicing has been proposed as a tool for improving the economic efficiency of space systems. However, economic barriers stand in the way of the development of servicing vehicles themselves. The reason for this is that the OOS market offered by any one satellite operator is probably not a commercially viable proposition, thus necessitating an OOS provider to serve multiple satellite customers. Multiple satellite customers with unique requirements are a barrier to the commoditization (and affordability) of serviceability. Five economic themes characterize the set of challenges that must be overcome to achieve a robust OOS industry: the "chicken and the egg," an embedded paradigm, a collective action dilemma, problems with market definition, and unstable property rights.

7.3.1.1 "Chicken and the Egg"

The "chicken and the egg" problem constitutes one of the most fundamental hurdles to OOS implementation. From the customer perspective, satellite design will not change to accommodate servicing vehicles until they are built and flight-tested. On the provider side, investments will not be made in OOS technology until a demand exists for OOS—a demand driven to a large extent by the existence of satellites designed to be serviced. With demand required to justify the provider's investment and the provider infrastructure required to generate demand, the "chicken and the egg" problem leads to a circular argument (Joppin, 2004). Without external forces affecting supply and demand (*e.g.*, government-sponsored proof-of-concept missions, tax incentives), market forces themselves may not be adequate to foster an OOS industry.

7.3.1.2 Embedded Paradigm

Another OOS implementation challenge is the embedded paradigm of satellite design. The need to get satellite manufacturers to accept the concept of OOS is a potential impediment to satellite servicing. Assuming the economic case has been made for satellite operators to invest in serviceable spacecraft due to lifecycle cost savings, it is not clear what incentive satellite manufacturers have to offer serviceable designs. Would the added revenue from marginally increased price for serviceable spacecraft offset the development costs of new, modular satellite bus designs? More importantly, if a market shift to serviceable satellites occurs, what are the implications for satellite demand? Satellite manufacturers will be against OOS if they believe the ability for satellite operators to perform in-orbit maintenance will only increase satellite lifetime and not open new business opportunities.

Lessons learned from the automobile industry indicate that OOS may create new business opportunities for satellite manufacturers. In the automobile industry, substantial revenue comes from both the initial sale of cars as well as an aftermarket of sales and maintenance services (Long, 2004). Satellite manufacturers may invest in OOS if they believe they can leverage their traditional expertise in capturing a potential satellite aftermarket.

7.3.1.3 Collective Action Dilemma

Another economic challenge facing OOS implementation is the question of who pays for the initial research and development as well as infrastructure. While numerous government and commercial organizations stand to benefit from OOS when provided at marginal cost, few organizations can contemplate developing a satellite servicing infrastructure on their own. The U.S. government is one such organization, and precedents exist for the funding of projects with both government and commercial benefits (*e.g.*, Intelsat).

7.3.1.4 Problems with Market Definition

Defining the market to serve is a fundamental problem facing OOS providers. First, potential target satellites are distributed in numerous orbital zones. Second, different services are available (*i.e.*, inspect, relocate, restore, augment, assemble). Third, the price charged for servicing must cover provider costs and also be an attractive value proposition to the target satellite operator. Fourth, the servicing vehicle must be compatible with the target satellite for proximity and docking operations. Fifth, time horizons must be aligned such that a servicing request occurs during the operational life of a servicing vehicle. Sixth, for the case of a U.S. servicing provider, the scope of the OOS market may need to be limited to U.S. satellites to prevent export control violations. Seventh, servicing market size may be further reduced due to classified government spacecraft. A robust OOS business plan must address all seven of these issues when defining the target market.

7.3.1.5 Unstable Property Rights

The utilization of a common resource (*e.g.*, GEO space tug) by multiple users may bring about a situation of unstable property rights. In one hypothetical scenario, a servicing vehicle with a finite set of customers performs two types of missions: scheduled maintenance and on-demand emergency repairs. If a scheduled maintenance and an on-demand emergency repair are requested at the same time, what mission should the servicing provider conduct first? What if two on-demand emergency repairs are requested simultaneously, forcing a servicing provider to choose which satellite to save?

In another hypothetical scenario, the U.S. government may develop and deploy servicing vehicles on-orbit as part of a national infrastructure in space. As part of a campaign to boost the servicing market, the government encourages commercial satellite operators to incorporate less redundancy in their designs and instead rely on a government OOS capability provided at marginal cost. One question likely to be asked by commercial industry is what the concept of operations will be for a government servicing vehicle with competing commercial and government servicing requests. Given the lessons learned in the wake of the Challenger accident—when the U.S. government limited use of the Shuttle to the launch of communications satellites with national security or foreign policy implications (after previously undercutting the commercial expendable launch vehicle market)—commercial satellite operators may not be persuaded to rely on a government-provided OOS infrastructure.

Another economic theme falling within the category of unstable property rights is the tragedy of the commons. A tragedy of the commons occurs when a freely-available shared resource is overused to the point where it is no longer useful to anyone. Like the high seas, space is a commons shared by all space-faring nations. Utilization of space deposits orbital debris (*e.g.*, dead satellites, spent upper stages, separation devices, bolts, and paint chips). Orbital debris is a tragedy of the commons problem in that the marginal cost of "littering" in space is nil, yet the cumulative degradation of the space environment due to debris deposits may hinder space utilization in the long-term. One possible mission of OOS is orbital debris cleanup. However, organizing the diverse set of space-faring nations beyond agreeing to voluntary orbital debris mitigation standards is a challenge. As such, the potential OOS mission of orbital debris cleanup may be underfunded due to the lack of space environment "ownership."

7.3.2 Financing Models

Government-commercial cost sharing precedents exist for space assets and other shared resources. However, it is unclear what type of financing model space tug operations will assume or how the issue of proprietary development will impact financing. The Commercial Space Competitiveness Act of 1992 authorized NASA and other agencies to make their facilities available to private entities. This provides a number of options for ownership, operation, and use of a satellite servicing system. Four financing models are discussed below.

7.3.2.1 Government Owned and Operated with No Commercial Use

This most restrictive case would entail U.S. government development, ownership, and operation of an OOS capability with no cost-sharing or use by private industry. An example is the Milstar satellite communication system. Although the most simplistic financing model with near-term potential, an all-government system would limit the benefits of space tug operations to civil, military, and intelligence space systems.

If only owned and operated by the U.S. government, the organizational structure of the OOS provider is an open question. The servicing provider might be an existing government agency, a coalition of government agencies, or a new government agency.

7.3.2.2 Government Owned and Operated with Commercial Use

The United States has a history of developing systems for government purposes that end up being utilized as shared resources. For example, the interstate highway system was constructed to satisfy a defense policy of moving troops around the country more efficiently.

An example of government ownership and operation in space with commercial use is the Tracking and Data Relay Satellite System (TDRSS). TDRSS is owned by NASA and supports near real-time communications between low Earth orbit satellites and Earth. Under the Commercial Space Competitiveness Act of 1992, NASA allows the private firm SpaceData International (SDI) of the marine seismic industry to operate four underutilized TDRSS satellites on a time-share basis. SDI provides per-minute payments to NASA for use of the TDRSS satellites in frequency bands allocated to US government use (Federal Communications Commission, 2001). Similarly, if the Air Force were to develop a space tug system, it may make sense to allow commercial use at marginal cost.

A public-private partnership (PPP) is a financing scheme whereby OOS would be funded and operated through a combination of government and one or more private companies. These partnerships range from public-oriented arrangements (*e.g.*, public authority in which a public organization is created to act like a private company, contract-based relationships where government is able to outsource work) to private sector-oriented arrangements (*e.g.*, buy-build-operate, build-own-operate). The PPP financing model leverages the ability of the government to bear risk and supply a market with the ability of industry to provide flexibility and superior managerial skills (McConnell, 2003).

The PPP financing model is well-suited to OOS implementation due to its ability to provide the necessary capital base for OOS technology development with the flexibility to allow the commercialization of services and products that would not occur with a strictly government OOS capability.

7.3.2.3 Commercially Owned and Operated for Commercial and Government Use

Commercial ownership and operation of a space system for commercial and government users (*e.g.*, the Iridium Satellite System) is another financing option for OOS. Currently, Orbital Recovery Corporation is developing an "orbital tugboat" concept, Spacecraft Life Extension System (SLES), to supply propulsion, navigation and guidance to maintain a satellite in its orbital slot for 10+ years (Section 2.2.3). Exploratory commercial ventures such as SLES will gain credibility as the government invests in a sustained research and development program of autonomous rendezvous and docking technology.

The private sector in the United States is particularly adept at developing commercially-viable systems once the government has bridged the gap between fundamental research and deployable technology by funding high-risk research and development. For example, the origins of the internet can be traced to the "ARPANET" project of the Defense Advanced Research Projects Agency during the Cold War which aimed to create a distributed communications network that could survive a nuclear strike. Satellite servicing and space tug technology investment, such as continued funding of DARPA's Orbital Express and SUMO programs, may have equivalent implications for the satellite industry.

7.3.3 Insuring Servicing Vehicles

The TDRSS-SDI relationship is a good example of a government owned and operated space system with commercial use. However, the liability issue associated with the government-commercial sharing of TDRSS bandwidth is not of the same magnitude as the liability issues associated with a spacecraft approaching and docking with another spacecraft. Sharing excess bandwidth certainly does not entail the same level of risk as docking two spacecraft. In addition to the utilization of safe approach maneuvers (*e.g.*, see Zero Closing Speed Guidance in Appendix F), mitigation of the risk associated with OOS operations can also be accomplished through financial instruments such as on-orbit insurance.

Space insurance providers are typically large multinational conglomerates with large premium bases. The space insurance industry is characterized by volatile market conditions. Current premiums are closely tied to recent returns. In recent years, the space insurance market has "hardened" after the "soft" market of the late 1990's that featured low premiums and coverage often extending from launch plus five years of mission life (Federal Aviation Administration, 2002).

Given that it is often difficult for satellite operators to secure reasonable premium for in-orbit insurance policies for normal operations, obtaining affordable insurance for space tug missions is a significant challenge. During the assessment process for space mission coverage, underwriters scrutinize the intended mission profile and conduct detailed reliability analyses of the launch vehicle and satellite. With an underwriting process that places great weight on past performance, obtaining reasonable insurance for OOS missions in the near-term may be impossible. As such, it is critical for the government to support standard-setting and proof-of-concept satellite servicing missions to provide commercial space tug operators access to insurance.

7.4 Meeting the Challenges

Challenges exist across political, legal, operational, and financial dimensions for potential on-orbit servicing providers. However, the financial aspect poses the greatest hurdle.

From the political and legal perspective, the greatest difficulty in rolling out an OOS system will be overcoming resistance from the international community. Despite the functional intentions of a servicing provider, having a capability to arbitrarily move space object around on orbit is sure to generate some objections as the Space Shuttle did during its development. Avenues exist for mitigating this concern. The U.S. military is adept at summarizing its core functionalities in language that is readily understood in the international community. For instance, military OOS operations could be framed in terms of "freedom of space." A commercial space tug provider might frame its operations in terms of reducing the liability of companies responsible for space junk.

On the operational side, the technical hurdles that remain in the way of OOS are not insurmountable. In fact, as has been noted, the major remaining technology developments are under way. The most significant of these is an arbitrary docking capability. One area that needs to be studied in more detail is the potential for electromagnetic interference between the servicing vehicle and the target satellite. Although this will probably not present any major problems, it warrants further study. A larger problem for an operational servicing system will be maintaining its capability across changing satellite architectures, which could eventually be very different than what is in orbit presently.

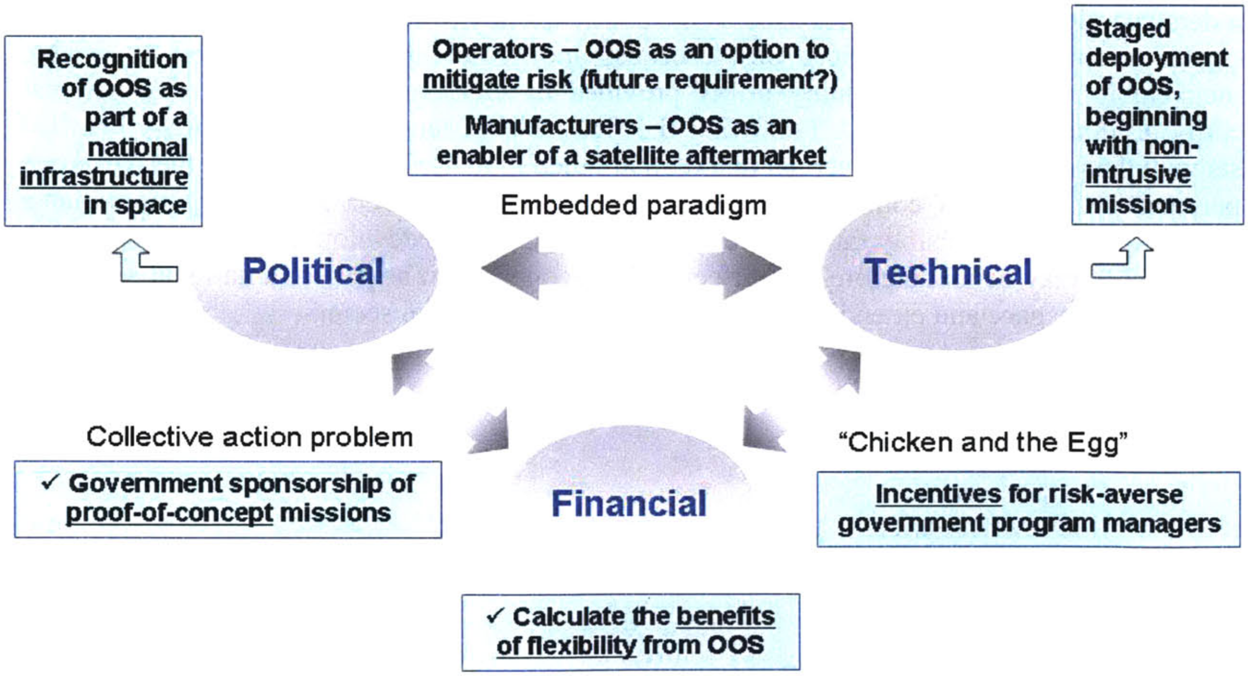

Figure 7.3 Challenges and Solutions for On-Orbit Servicing Implementation

The greatest barrier to an OOS system is the financial challenge. Collective action problems exist in government, and economic viability has not been demonstrated to potential commercial servicing providers. Although U.S. Space Transportation Policy endorses on-orbit servicing technology development, risk-adverse military space program managers are unlikely to pay for servicing capabilities individually; and the research and development costs, combined with the risk, appear to be too high for the commercial sector to undertake development on its own. Innovative financing arrangements between government and industry may be possible once an operational servicing vehicle exists (*e.g.*, public-private partnership). Initially, however, the "chicken and the egg" problem—the facts that satellites will not be designed for serviceability before a servicing vehicle is developed and that no commercial provider will invest in OOS before a servicing market exists—indicates that the government will need to continue to bear the brunt of unmanned on-orbit servicing technology development through programs such as Orbital Express. Overcoming the "chicken and the egg" problem is also achievable technically through the development of non-intrusive servicing technology that requires no modifications to currently active satellites (*e.g.*, Spacecraft for Universal Modification of Orbits, GEO lifetime extension[4]).

One of the first steps towards overcoming the embedded paradigm of traditional satellite design is convincing satellite manufacturers that they have incentives to offer serviceable designs. One of these incentives is a potential commercial satellite aftermarket based upon the automobile industry model whereby manufacturers generate revenue from an aftermarket of used car sales and maintenance services.

Given the applications of OOS to enhance space system availability, performance, and capability, the most likely implementation route for OOS is to satisfy military missions. If OOS can demonstrate unique capabilities such as the ability quickly to repair failed satellites, perform upgrades to prevent technological obsolescence, and refuel spacecraft on-orbit to enable maneuverable satellites, the military utility provided by OOS might allow a strong national security argument for servicing. Following the Shuttle experience, in which NASA justified costs with the promise of a commercial market that failed to materialize (as well as the Air Force experience with the EELV commercial market), attempts to defend OOS as anything more than a defense program will probably fail. However, if the military does develop a servicing capability, that capability may be made more cost-effective by recognizing it as part of a national servicing infrastructure in space and extending its use to civil and commercial sectors.

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[4] In some cases, GEO retirement missions could extend operational life of spacecraft by as much as four years due to inaccurate fuel gauges which force operators to be very conservative in the timing of maneuvers to super-synchronous orbit (McVey, 2004). Typical extensions can be expected to be approximately one year, translating to roughly $100M in additional transponder revenue for GEO communications spacecraft.

8 Discussion

This thesis is focused on fostering an understanding of the attributes which characterize the physical amenability of satellites to OOS. In the previous chapters, a three-step process was followed to perform serviceability assessments. First, an ordered taxonomy of space systems was constructed to add structure to the problem and to identify satellite attributes that drive servicing mission complexity (Chapter 3). Second, a methodology was proposed to assess serviceability across the four servicing activities of rendezvous, acquire, access, and service (Chapter 4). This included development of an agent-based model based on orbital transfers in the GEO belt as well as a framework in which serviceability was decomposed into four elements: (1) knowledge of target satellite state, (2) scale of servicing activities, (3) precision required, and (4) temporal constraints. Third, the value of architecture frameworks and systems engineering modeling languages for conducting serviceability assessments was explored through the development of a discrete event simulation of the Hubble Space Telescope (Chapter 5). The technical portion of the thesis concluded with prescriptive technical considerations for designing serviceable satellites (Chapter 6) followed by a discussion of the political, legal, and financial challenges facing servicing providers (Chapter 7).

This chapter discusses the implications of the research, related ongoing work at MIT, and possible extensions of the thesis. In particular, the following questions are addressed:

- What are the contributions and extensions of this thesis?
    - What are the implications of this research?
    - What related work is currently being conducted at MIT?
    - What opportunities exist for future research?

8.1 Implications of Research

This section discusses the applicability, limitations, and unique contributions of the research.

8.1.1 Applicability

The general goal of this research is to address the problems and limitations associated with traditional design, acquisition, and operation of space systems by proposing and demonstrating the value of a more flexible approach. In particular, this thesis aims to improve the state of knowledge regarding on-orbit servicing and the practice of systems engineering as it relates to system architecture and design. As this work integrates and builds on many previous OOS studies, it is hoped that this thesis will allow one to rapidly survey the breadth of previous work done on OOS as well as identify related technical, economic, and social factors.

Although focused on the space systems domain, this work may be extended to other domains. In this thesis, the serviceability framework has been applied to satellites, yet nothing in this methodology is unique to space systems or robotic servicing vehicles. Derived from lessons extracted from the servicing of offshore oil platforms, the serviceability framework may be applied to assessing the complexity of servicing operations of systems in any environment by any means (*e.g.*, nuclear reactors, toxic waste clean-up, improvised explosive device detection and removal in Iraq). While metrics for assessing each of the serviceability parameters are domain-dependent, the serviceability parameters themselves apply across servicing missions.

8.1.2 Limitations

The principal limitation of this work was the lack of comprehensive data on satellite bus characteristics across space system architectures. While a methodology was developed to assess serviceability across both "orbit serviceability" (*i.e.*, rendezvous activity) and "satellite bus serviceability" (*i.e.*, acquire, access, and service activities), the availability of data limited the implementation of the methodology to "orbit serviceability" assessments.

Another limitation of this work is that only one case study (*i.e.*, Hubble Space Telescope) was conducted to explore the value of architecture frameworks and associated executable models for dynamic serviceability assessments. On its own, the DoDAF and discrete event simulation of Hubble does not provide insights into whether Hubble is more or less physically amenable to servicing than other space systems.

8.1.3 Unique Contributions

Many previous studies have addressed the issue of OOS customer architecture through valuation studies and point designs of future serviceable space system architectures. Therefore, much of the content of this thesis is based on existing knowledge (*e.g.*, Sullivan's empirical data on satellite failures which informs the agent model of OOS in Section 4.2). However, two factors that make this work unique are: (1) the focus on serviceability for existing satellites and (2) integration of a wide range of disciplines—from astrodynamics and robotics to architecture frameworks and systems engineering modeling languages—that breaks the paradigm of tightly-scoped studies which address only a limited set of OOS issues.

8.2 Ongoing Related Research

This section discusses the relationship between this thesis and ongoing research at MIT by Jason Bartolomei on screening for real options, Spencer Lewis on functional emergence, Charlotte Mathieu on distributed spacecraft, Adam Ross on system changeability, and Nirav Shah on system-of-systems.

8.2.1 Bartolomei – Screening for Real Options

Air Force Captain Jason Bartolomei (ESD Ph.D., expected 2007) is developing an analytical framework for screening for real options in engineering systems.[1] Documenting the need to develop flexible systems in order to improve operational, technical, and programmatic effectiveness, he is applying real options thinking to weapons acquisitions as a means to "deftly avoid downside consequences or exploit upside opportunities" (Bartolomei, *et al.*, 2006). On-orbit servicing is effectively a manifestation of real options for satellites. As such, Bartolomei's framework might be useful for screening for OOS opportunities.

Captain Bartolomei is employing a two-phase process to capture knowledge about the physical and non-physical aspects of systems, insight into sources of change, and the ability to examine the dynamic behavior of a system: (1) create a lifecycle representation of engineering systems

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[1] Real options are defined as the right, but not the obligation, to take an action at a predetermined cost at a predetermined time. These are referred to as 'real options' because they apply to physical (tangible) assets rather than financial instruments.

using coupled Design Structure Matrices that includes endogenous interactions across system views and interactions with system environment and (2) model the evolution of engineering systems in order to identify opportunities for real options. He is currently constructing an end-to-end system representation of a mini-air vehicle.

8.2.2 Lewis – Functional Emergence

Spencer Lewis (ESD Ph.D., expected 2007) is investigating what allows or encourages people to utilize objects for applications beyond their original concepts while other objects remain unmodified. He hopes to establish a link between functional emergence and a complex system's architecture. Currently investigating GPS, Lewis is focused on the following research questions.

1) What architectural characteristics encourage functional emergence in complex engineering systems?
2) What architectural characteristics allow systems to transfer from military sectors into civilian markets?
3) What are the lifecycle characteristics of complex engineering systems?

OOS might encourage functional emergence in space systems. Furthermore, Lewis's detailed case study of the 24+ GPS satellites might inform serviceability assessments.

8.2.3 Mathieu – Distributed Spacecraft

Charlotte Mathieu (Master of Science in Technology and Policy, 2006) is analyzing the use of distributed spacecraft, a network of elements consisting of a free-flying payload supported by a nearby free-flying infrastructure. As a means to improve the flexibility of traditional monolithic spacecraft, the motivation driving spacecraft fractionation is very similar to the rationale for OOS.

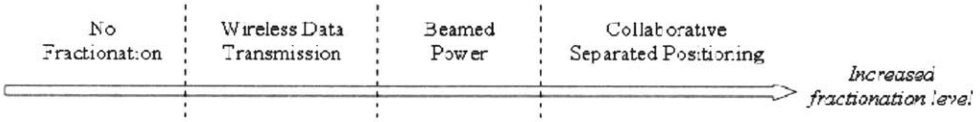


Figure 8.1 Spacecraft Fractionation (Mathieu and Weigel, 2005)

To assess fractionation, Mathieu has developed utility functions characterizing customer preferences and coupled these with models consisting of spacecraft design parameter such as subsystem fractionation level and the number of infrastructure modules. Subsystems considered "fractionable" are communications, control and data handling, power, attitude determination and control, and propulsion. Mathieu has found that fractionation makes sense when non-traditional attributes—maintainability, scalability, flexibility, and responsiveness—are valued highly (Mathieu and Weigel, 2005).

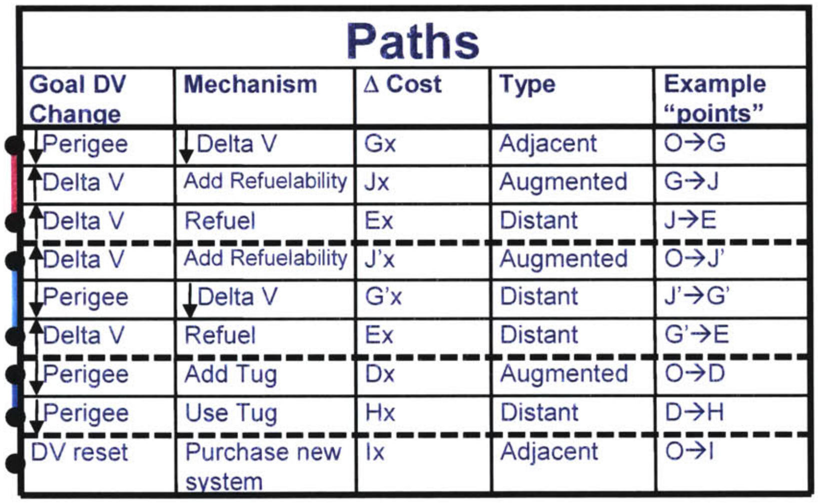
8.2.4 Ross – System Changeability

Adam Ross's doctoral dissertation (ESD Ph.D., 2006) is focused on the management of unarticulated stakeholder value (*i.e.,* derived needs which emerge from the system in operation). Unarticulated needs include those that are not explicitly communicated because the stakeholder has forgotten them, or does not know them yet, or cannot express them in words. Ross highlights problems with the optimization approach to system design, noting that changing objective functions and operational environments mean that systems will not necessarily remain "best" over time. In fact, recent research suggests that highly optimized designs are fragile to changing objectives and contexts (Carlson and Doyle, 2000).

As a representation of system modification, Ross introduces transition paths as a mechanism for capturing the time and cost of system change. Traditional designers focused on enumerating static system tradespaces might also include considerations for system change by creating transition mechanisms. As an example, Ross discusses how this framework might be applied to an OOS problem:

> Consider a system design for a satellite in low earth orbit whose orbit must be changed, for whatever reason, but whose fuel must remain at pre-orbit change levels. Possible transition rules include: 1) burning on-board fuel to maneuver to a new orbit, followed by an on-orbit refuelability modification, and on-orbit refueling to bring the on-board fuel back to pre-burn levels, 2) adding the refuelability modification prior to launch, burning the on-board fuel to maneuver to a new orbit, followed by on-orbit refueling to bring the on-board fuel back to pre-burn levels, 3) using a space tug to grab the satellite, move it to the new orbit, and release, 4) purchase a new satellite that is inserted into the correct new orbit. The following two figures [Table 8.1, Figure 8.2] show how these four path mechanisms result in different costs for having a system change from the same state 1 to state 2.

Table 8.1 Sample Transition Paths for Perigee Lowering (Ross, 2006)



Paths

Goal DV Change	Mechanism	Δ Cost	Type	Example "points"
↓Perigee	↓Delta V	Gx	Adjacent	O→G
↑Delta V	Add Refuelability	Jx	Augmented	G→J
↑Delta V	Refuel	Ex	Distant	J→E
↑Delta V	Add Refuelability	J'x	Augmented	O→J'
↓Perigee	↓Delta V	G'x	Distant	J'→G'
↑Delta V	Refuel	Ex	Distant	G'→E
↓Perigee	Add Tug	Dx	Augmented	O→D
↓Perigee	Use Tug	Hx	Distant	D→H
DV reset	Purchase new system	Ix	Adjacent	O→I

Table 8.1 and Figure 8.2 depict the application of transition paths to perigee lowering. In particular, Figure 8.2 illustrates the path dependency of architecture transitions with a horizontal axis of change in cost and a vertical axis of utility.

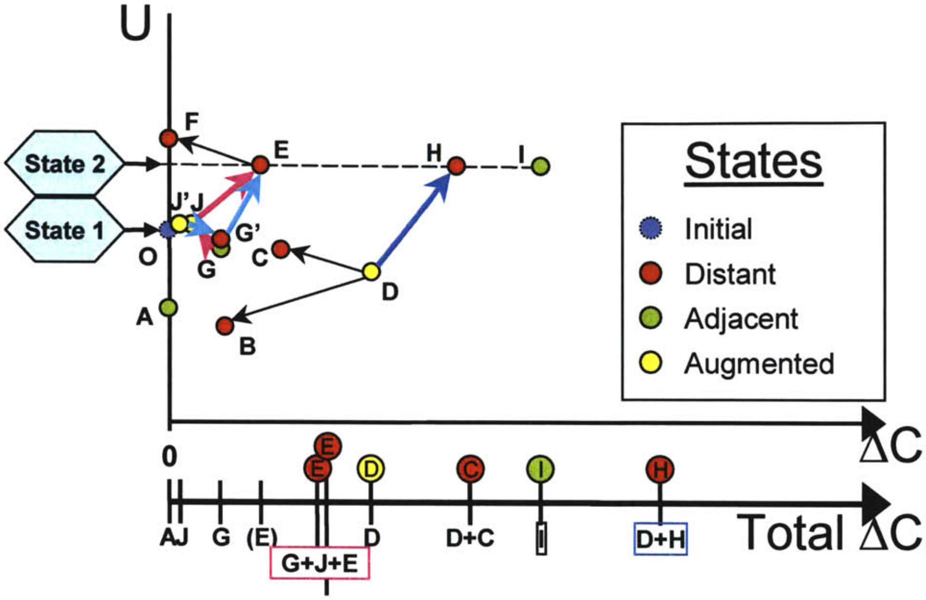


Figure 8.2 Sample Transition Paths for Perigee Lowering (Ross, 2006)

8.2.5 Shah – Systems-of-Systems

Nirav Shah's research (Aeronautics and Astronautics Ph.D., expected 2007) is focused on systems-of-systems, collections of systems which work together for a common purpose and exhibit operational and managerial independence. Given that space capabilities are often provided by systems-of-systems (*e.g.,* SBIRS), Shah's work informs analysis of many potential OOS customers. Furthermore, architecting principles that enable systems-of-systems (*e.g.*, modularity, loose couples) are applicable to serviceable spacecraft design.

8.3 Ideas for Future Research

This section proposes five research projects for extending this research: investigate redundancy trades in the design of future spacecraft, extend the agent-based servicing model of orbital transfers, populate the serviceability framework, analyze the tradespace of servicing provider architectures, and explore serviceability as a case study in emergent behavior of complex systems.

8.3.1 Investigate Spacecraft Redundancy Trades

Future work is needed to explore the trade between redundant, highly reliable space systems (current paradigm), and lower cost, less redundant systems that utilize an OOS system to achieve similar reliability. Lowering mission costs has been offered as a motivation for OOS such that operators may choose to rely on servicing as a means to incorporate less redundancy into spacecraft. Other proposals involve reducing upfront costs by designing satellites for shorter lives and delaying the decision either to allocate funds for servicing or to abandon at a later date. Although these justifications make intuitive sense, a rigorous analysis of the costs to incorporate varying levels of redundancy in spacecraft would be a valuable contribution to OOS research.

8.3.2 Extend Agent Model of Satellite Servicing

Although the focus of the agent-based model of OOS in Chapter 4 is on serviceability assessments of target satellites, the model is readily adapted to the design of concept-of-operations for servicing vehicles. With OOS is treated as a multi-variable optimization problem between minimizing ΔV expenditures and transfer time, the model might be extended to parking orbit selection, servicing architecture tradeoffs (*e.g.*, number of servicing vehicles, whether to include on-orbit supply depots), and analyzing servicing cost as a function of response time.

Further work might also incorporate innovative servicer-serviced relationships. For example, Tsiotras and de Nailly (2005) have explored a decentralized, peer-to-peer refueling approach in which there is no a priori designated refueling satellite. Instead, all satellites in the constellation can assume the role of the refueling spacecraft.

8.3.3 Populate Serviceability Framework

Future work might build on this thesis by fully populating the serviceability framework (developed in Chapter 4) with data from all operational satellites. While the UCS Satellite Database was a good source for data on the orbital elements of satellites, it did not provide enough technical data on the satellite bus for utilizing all of the serviceability metrics (Table 4.6). Satellite data on bus composition might be derived from integrating databases such as those in Table 8.2. Detailed case studies might further validate the serviceability metrics.

Table 8.2 Satellite Databases (Sullivan, 2001)

Source	Start	Records	Fields
Aerospace Source Book	1984	672	23
Celestrak Satellite Catalog	1957	5,383	7
Hibbard	1976	125	14
Hughes	1963	195	11
Intelsat	1980	30	15
Isakowtiz	1965	2,967	21
Jonathan's Space Report	1957	6,407	11
Mission Spacecraft Library	1957	5,107	19
NSSDC Master Catalog	1957	5,604	16
PanAmSat	1985	22	17
Satellite Today Database	1980	247	8
AGI Spacecraft Digest	1960	595	24
The Satellite Encyclopedia	1957	2,043	64

8.3.4 Analyze Provider Architecture Tradespace

The focus of this thesis was on the architecture of the supply side of on-orbit servicing. To fully understand the on-orbit servicing marketplace, this analysis needs to be coupled with economic valuation studies and modeling of the provider architecture tradespace. As a rapid and scalable conceptual design process that applies decision theory to model and simulation-based design, Multi-Attribute Tradespace Exploration (MATE) (Ross, 2003) is a strong candidate for the concept generation and selection of commercially-viable on-orbit servicing architectures. Guiding research questions for the proposed OOS provider architecture study are:

1) What on-orbit servicing architecture maximizes the provider's profit?
    a. From the provider's perspective, what is the best way to divide up the market? What attributes characterize each market segment?
    b. What design variable vector(s) represent the most profitable architecture for each market segment?
2) How might MATE be employed to manage a dynamic OOS tradespace?
    a. What are the costs and benefits of designing for extensibility and market uncertainty?
    b. What is the expansion path for an OOS provider? In what order should an OOS provider reach out to the different market segments?
3) What value can MATE add to the staged deployment of systems with multiple stakeholders?
    a. How do you merge preferences of multiple stakeholders into system requirements?

Implementing the MATE approach to system design involves three steps. First, Multi-Attribute Utility Theory is used to aggregate stakeholder preferences (attributes) into a single utility function. Second, a design vector is input to parametric models that enumerate a tradespace of design solutions. Third, the utility function is used to assess the tradespace such that a pareto-efficient set of designs may be selected for more rigorous analysis.

One of the principal challenges in architecting an OOS system is the diverse set of customers such a system would need to target for economic viability. The potential OOS market is divided by satellite operators with various risk tolerances, by nation, and by user type (*e.g.*, civil, commercial, military). One approach to this problem would be to divide up the serviceable satellite market into multiple market segments, identify the attributes that characterize each market segment, and then use MATE to select OOS designs that represent profitable business model for each market segment. (Appendix E provides MATLAB code developed to perform a MATE analysis on a space tug design vector). A more complete method might employ the latter approach as a first step towards the development of a "product family" of servicing vehicles that leverages common platforms and technology to tap the entire servicing market.

Table 8.3 Proposed MATE Design Vectors

Design Vector 1	Proximity Inspector	a free-floating vehicle or attached surveillance instrument which characterizes a space object without physical contact
Design Vector 2	Space Tug	a vehicle designed to rendezvous and dock with a space object; make an assessment of its current position, orientation, and operational status; and then either stabilize the object in its current orbit or move the object to a new location with subsequent release
Design Vector 3	Pre-Planned Servicer	a vehicle that is able to improve the state of target satellites that has been designed for servicing
Design Vector 4	All-Purpose Servicer	a vehicle that is able to improve the state of target satellites, regardless of whether they have been designed for servicing

While a family of servicing vehicles would involve evaluation of multiple design vectors (*e.g.*, Table 8.3) across a suite of OOS functions (decomposed by separate multi-attribute utility functions), past MATE studies have involved system design with one design vector for specific missions. As such, one contribution of this provider architecture study would be an extension of the MATE methodology to system design across multiple design vectors and utility functions (Figure 8.3).

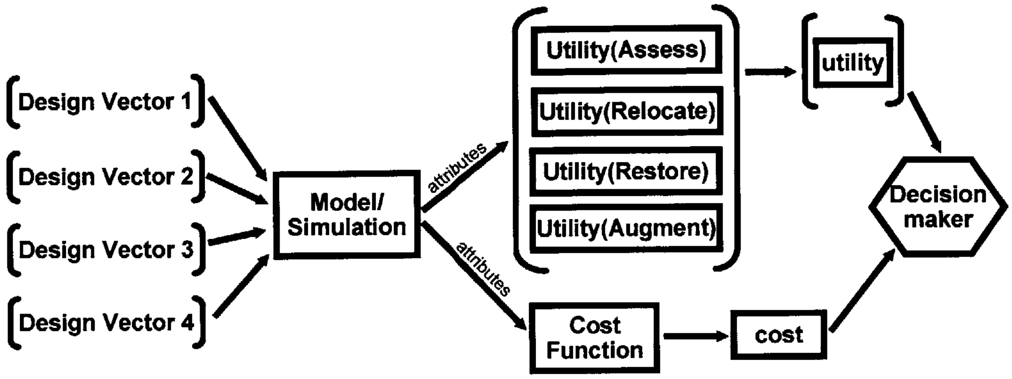


Figure 8.3 MATE with Multiple Design Vectors and Utility Functions

One of the issues this proposed study might address is how uncertainty is managed in the design process. Understanding the costs and benefits of designing for extensibility would help the OOS provider plot the expansion path for evolving system capabilities and tapping an increasing number of market segments. Ongoing research focused on dynamic tradespaces (Ross, 2006) provides insights into how MATE can add value to the development of systems that strategically investigate expansion path strategies (*e.g.*, evolutionary acquisition, P3I, spiral development) during preliminary design.

8.3.5 Study Serviceability as a Case Study in Emergent System Behavior

Emergent behavior involves the discovery of new uses for systems following operational deployment. A fundamental property of complex systems, emergent behavior may result from nonlinear interactivity during the process of self-organization or from macro-level patterns arising in systems of interacting agents. Emergence is neither predictable nor deductible from individual components. As such, emergent behavior must be analyzed with a global system perspective. Emergent behavior is of interest to systems engineers because such behavior is often unexpected and nontrivial. However, its inherent properties pose a challenge to system engineers as traditional “divide and conquer” approaches do not apply.

Future research is proposed to investigate the on-orbit serviceability of existing space systems as a case study in functional emergence. Given that most satellites were not designed for servicing, serviceability represents an emergent property of satellites. The following steps comprise one possible methodology for this research: (1) identify the architectural elements in satellites which foster serviceability, (2) investigate other systems for emergent behavior, tracing emergence to architectural characteristics, (3) generalize the results to classes of emergent behavior in engineering systems, and (4) calculate the costs and benefits associated with emergent capabilities. Other case studies candidates include the Air and Space Operations Center Weapons System, the Theater Battle Management Core System, GPS, and the B-52 Stratofortress.

The emphasis during the case studies of the first phase would be to identify emergent properties, emergent functions, and the architectural elements that aid emergence. The second phase would consist of small-scale studies including agent-based modeling for studying emergence in dynamic situations and design structure matrices for understanding the static structure that might give rise to emergent behavior. Other fields of study have well established tools for understanding and exploiting local emergent behavior. For example, conventional physics employs thermodynamics and statistical mechanics to study the pressure and temperature of gas. A central goal of research on emergence is to explore and develop methodologies which may offer analogous insights into emergent behavior in complex engineering systems.

By defining and modeling the elements of systems architecture that enable emergent behavior, designers of complex engineering systems will be better equipped to understand the implications of building-in latent capability, exploit emergent functionality, and evaluate system properties such as robustness, adaptability, and flexibility. Aided with tools to understand emergence, designers will be free to build emergent functionality into future systems. In particular, the military may exploit complex system behavior for a variety of applications including data fusion in large arrays of micro-sensors, optimizing performance of networks under overload conditions, and implementing social behavior of collaborating robots. Understanding how to architect *a priori* for different classes of emergence will also enable design of future systems capable of adapting to new missions and operational environments. Both flexibility and robustness will be measurable as functions of emergence in beyond-equilibrium conditions. More generally, understanding of emergent phenomena will minimize uncertainty in the process of complex systems engineering.

9 Conclusions

This chapter returns to the research questions identified in Chapter 1 and draws general conclusions regarding the future of OOS.

9.1 Guiding Questions

The guiding questions discussed in the Problem Statement (Section 1.2) are revisited here:

1) In what areas might original contributions be made to the study of OOS?
2) How might a taxonomy of space systems for serviceability be constructed?
3) What is the amenability of existing satellites to OOS?
4) How can architecture frameworks inform dynamic serviceability assessments?
5) What are the "architectural principles" for developing serviceable spacecraft?
6) What are the non-technical challenges facing OOS implementation?

In what areas might original contributions be made to the study of OOS?

In reviewing contemporary government, industry, and academic studies, it was found that much OOS work has been done on servicing provider architecture and some on customer valuation. However, little work was found on the satellite architecture of the customer. Furthermore, the work that does exist on serviceable spacecraft was found to focus on implementing design changes in future satellites. Although understanding the amenability of different orbits to OOS and the degree of complexity associated with servicing various satellite bus designs is a necessary precursor to evaluating servicing missions, no studies were found that address these questions for existing satellites. The central goal of this thesis was to build on previous OOS studies by developing and implementing a framework to assess the serviceability of spacecraft currently in orbit around the Earth. The first step taken towards this goal was to add structure to the problem through the construction of a taxonomy for space systems and servicing activities.

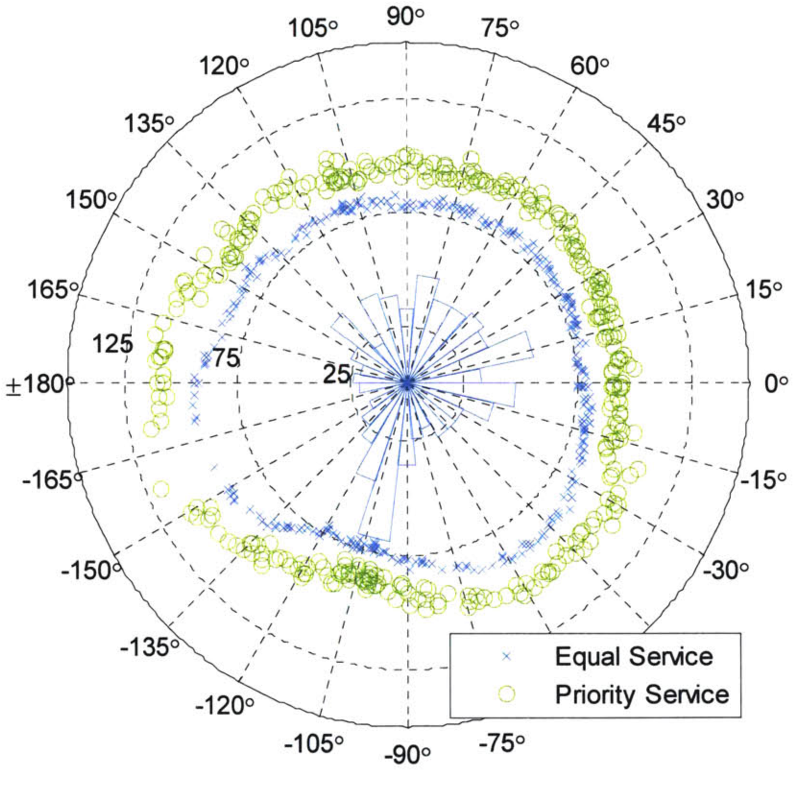
How might a taxonomy of space systems for serviceability be constructed?

Three sets of definitions form the taxonomy used to structure this thesis. First, five generic servicing functions were defined in the functional domain—inspect, relocate, restore, augment, and assemble—to characterize the scope of potential OOS missions. Second, servicing missions were decomposed by four unique activities—rendezvous, acquire, access, and service—which define the phases of an OOS operation. Third, five elements of satellites architecture were deemed relevant to serviceability: (1) mission area, (2) orbital elements, (3) attitude control system, (4) bus structure, and (5) payload configuration. Attributes of the fourth element, bus structure, were decomposed further into attributes of bus shape and size, solar array configuration, antenna placement, and launch vehicle mating interface. With a servicing taxonomy in place, the thesis turned to the question of serviceability assessments of existing satellites.

What is the amenability of existing satellites to OOS?

A two-step methodology was followed to determine the amenability of existing satellites to OOS: (1) "orbit serviceability" assessments through the development of an agent model of OOS based on orbital transfers and (2) "satellite bus serviceability" assessments as a function of servicing mission complexity. The first step assesses amenability for the rendezvous servicing activity while the second step considers amenability across all four servicing activities.

For orbit serviceability assessments, target satellites and servicing vehicles are modeled as agents, and OOS is treated as a multi-variable optimization problem with the principal trade of minimizing both ΔV expenditures and transfer time. Applied to the GEO belt with satellite failure behavior based on empirical data (Sullivan, 2005), it was found that ΔV expenditures for servicing missions varies across orbital slots as a function of the proximity and concentration of other target satellites (*e.g.*, satellites in GSO above North America were found to be approximately 25% less expensive in terms of fuel than satellites above the Pacific). A sensitivity analysis was performed on the assumed servicing provider architecture to validate the relative performance of orbital slots in terms of the ΔV serviceability metric (see figure below). In contrast to LEO satellites, for which the high propulsive cost of maneuvering severely limits the number of target satellites which may be serviced, it was found that the "orbit serviceability" of GEO satellites is high. With approximately 25 servicing opportunities in GEO each year, an OOS architecture consisting of four servicing vehicles parked in GEO is able to maneuver to virtually all satellites requiring servicing over the course of a decade.



ΔV Expenditure for Both Servicing Campaigns with GEO Satellite Density

Turning to the question of satellite bus serviceability, it was proposed that servicing mission complexity may be decomposed into four elements: information available on the state of the target satellite (knowledge), size of the servicing tasks to be performed (scale), accuracy requirements or permitted tolerances of servicing tasks (precision), and temporal constraints on the servicing mission (timing). It was further proposed that each of these elements of complexity applies to each servicing activity (*i.e.*, rendezvous, acquire, access, and service). As such, sixteen serviceability parameters were proposed, and a combination of quantitative and qualitative metrics were identified to assess of the performance of satellite bus attributes for each serviceability parameter (see table below). Notional serviceability functions for each of the five generic servicing functions were then proposed from subsets of the sixteen serviceability metrics.

Metrics for Serviceability Assessments

Label	Parameter Names	Metric for Satellite Servicing	Unit
K1	Rendezvous knowledge	position/attitude telemetry	binary (yes/no)
K2	Acquire knowledge	bus type	binary (yes/no)
K3	Access knowledge	structure and composition (evolved)	Likert scale
K4	Service knowledge	telemetry points monitored	number
S1	Rendezvous scale	delta-v	m/s
S2	Acquire scale	principal moments of inertia	kg·m2
S3	Access scale	distance between docking and service zones	m
S4	Service scale	unique servicing tasks	number
P1	Rendezvous precision	mission area	discrete categories
P2	Acquire precision	angular misalignment tolerance	degree
P3	Access precision	service zone integration	Likert scale
P4	Service precision	component integration	Likert scale
T1	Rendezvous timing	phasing and transfer duration	time
T2	Acquire timing	window of opportunity	time
T3	Access timing	permitted satellite downtime	time
T4	Service timing	projected failures, value-added duration	time

In contrast to "orbit serviceability" assessments, which were performed across all operational GEO satellites, serviceability assessments at the satellite bus level were not performed for large numbers of spacecraft simultaneously due to the lack of comprehensive data on detailed satellite bus attributes. Therefore, a case study methodology for analyzing satellite bus attributes was deemed more appropriate. To add structure to the analysis of individual spacecraft, system architecture frameworks (*e.g.*, DoDAF, MoDAF) were turned to as candidate tools for assisting in serviceability assessments.

How can architecture frameworks inform dynamic serviceability assessments?

It was found that, while architecture frameworks bring structure to describing complex systems, the three views of the Department of Defense Architecture Framework alone are insufficient for characterizing the dynamic behavior inherent in a satellite servicing architecture. Static DoDAF work products in the Systems View do not include enough technical detail of relevant satellite attributes (*e.g.*, health status of gyroscopes, reaction wheels, and fine-guidance sensors). However, when such work products are constructed using a system engineering modeling tool such as CORE, it is possible to build executable models that may be used for quantitative evaluation of system behavior over time.

Over the course of building DoDAF work products and a servicing model of the Hubble Space Telescope, lessons emerged how the DoDAF and systems engineering modeling tools may be applied to dynamic serviceability assessments at the satellite bus level. The process of constructing the static DoDAF work products and building an executable model enabled rapid understanding of the structure and operation of the larger Hubble system (*i.e.,* Orbiting Observatory, Space Telescope Operations Control Center, and Space Telescope Science Institute). Although the model of Hubble (on its own) did not provide insights into whether Hubble is more or less physically amenable to servicing than other space systems, other space systems can rapidly be incorporated into the same overall servicing architecture to allow for relative serviceability assessments.

Having conducted static and dynamic serviceability assessments for both orbital zones and satellite buses, the next question addressed in the thesis seeks to inform the design of future satellites.

What are the "architectural principles" for developing serviceable spacecraft?

In considering how an OOS requirement might affect the design of future serviceable satellites, twelve "architectural principles" were identified across four general categories: maximize knowledge of the target satellite, manage the scale of servicing activities, minimize the precision required of servicing activities, and minimize temporal constraints.

Architectural Heuristics for Designing Serviceable Spacecraft

Maximize knowledge of target satellite	**Manage scale of servicing activities**
• Incorporate extensive fault detection, isolation, and diagnostic capabilities • Enforce configuration control during manufacturing, assembly, and pre-launch operations • Limit structural deformation from launch, radiation, and thermal cycling	• Consider the proximity of other potential OOS targets in orbit selection • Collocate electrical interfaces, fluid transfer modules, and ORU storage bays with docking ports • Use common components • Design electrical, thermal, and attitude control subsystems with margin for loads of additional payload modules
Minimize precision of servicing activities	**Minimize temporal constraints**
• Design "safe modes" of satellite operation to mitigate thruster plume impingement • Control servicing interfaces tightly • Substitute highly-integrated designs with modular, loosely-coupled configurations	• Compile empirical data on component degradation to enable scheduled servicing • Allow for temporary outsourcing of functions to shield end-users from operational downtime

The final research question broadens the scope of the thesis to include non-technical issues associated with OOS.

What are the challenges facing OOS implementation?

OOS challenges exist across technical, political, and financial dimensions. Critical technology areas, including autonomous rendezvous and capture, control algorithms and software, and robotic operations, have not yet been flight-tested. Politically, the deployment of OOS systems may give rise to international resistance (*e.g.*, concerns regarding the militarization of space). Customary international laws may constrain the operational flexibility of servicing providers while U.S. regulations such as ITAR may limit servicing to domestic markets.

The greatest hurdles to OOS implementation fall into the general categories of financing and economics. Collective action problems exist in government for funding OOS, and economic viability has not been demonstrated to potential commercial servicing providers. Although U.S. Space Transportation Policy endorses on-orbit servicing technology development, risk-adverse military space program managers are unlikely to pay for servicing capabilities individually; and the research and development costs, combined with the risk, appear to be too high for the commercial sector to undertake development on its own. Innovative financing arrangements between government and industry may be possible once an operational servicing vehicle exists (*e.g.*, public-private partnership). Initially, however, the "chicken and egg" problem—the facts that satellites will not be designed for serviceability before a servicing vehicle is developed and that no commercial provider will invest in OOS before a servicing market exists—indicates that the government will need to continue to bear the brunt of unmanned on-orbit servicing technology development through such programs as Orbital Express.

In addition to government sponsorship of proof-of-concept missions, several strategies were proposed to overcome OOS implementation challenges. The best technical solution identified to overcoming the "chicken and egg" problem is for servicing providers to initially target low-risk, non-intrusive servicing missions which do not require modifications to the existing fleet of satellites. For example, staged deployment of a GEO "space tugging" capability for retirement missions—extending transponder life of communications satellites by approximately a year (generating an extra ~$100M revenue) by allowing them run out of propellant in their operational slots—would only require external grappling with legacy interfaces. Furthermore, given that target satellites are at EOL, operators may be more willing to utilize an OOS system having already achieved returns on investments.

Overcoming embedded paradigms in government and addressing stakeholder concerns in industry were also discussed. Given the current state of government acquisitions and the notion that the government "self-insures," it is unlikely that program offices will opt to pay for an OOS capability. Acquisitions officials do not want to be perceived as allowing for the option of failure, and "R&D non-essentials" are frequently the first elements in an acquisitions budget to be phased out. Therefore, decisions to incorporate OOS capabilities into government space programs will require stakeholder buy-in at levels above system program offices. This requires that OOS is endorsed not just as a technology development program in national space policy but also potentially added as a requirement in future programs (*e.g.*, Space Radar). Another step towards overcoming the embedded paradigm of traditional spacecraft design is providing incentives to satellite manufacturers to offer serviceable designs (*e.g.*, commercial satellite aftermarket).

9.2 *General Conclusions*

The U.S. experience with the Space Shuttle demonstrated that on-orbit servicing by humans is technically possible (*e.g.*, Solar Maximum repair, Intelsat 603 rescue) though economically infeasible. NASA's human servicing architecture failed to deliver on the promise of a high-frequency (60 times a year), low-cost (less than $20 million) OOS capability. As a means to bring the benefits of OOS to space systems beyond flagship programs such as Hubble and ISS, robotic servicing is promising. Having explored the serviceability of existing space system architectures to robotic vehicles, five general conclusions are offered:

Robotic on-orbit servicing is technically feasible but requires further technology development before it may be considered an operational capability.

Several robotic systems with minimal capabilities have been successfully flight-tested, including the AFRL series of XSS microsatellites and NASA's AERCam. Future military systems are in development by DARPA as well as the commercial SLES by ConeXpress. Although technology successes for robotic OOS far outnumber failures, more hardware must be flight-qualified before robotic servicing technology can be considered an operational capability. Critical technologies requiring further maturation include (1) control algorithms and software for autonomous rendezvous and docking and (2) robotic operations for internal manipulation of satellite components.

Many existing satellites are amenable to inspection, relocation, and attitude stabilization missions.

On-orbit servicing missions that are possible with the current generation of satellites include inspection, relocation, and restore missions that are limited to interaction with external interfaces. While the returns for inspection missions are relatively low, rescuing satellites stranded by upper stage failures, restoring attitude control for tumbling satellites through external stationkeeping, and reconfiguring constellations to meet emergent commercial markets and threat environments are higher-value OOS applications. Retirement missions for communications satellites constitute an intermediate-value OOS mission with opportunities for multiple missions in GEO.

Marginal costs to modify future satellites for refueling and component change-out missions are low.

More lucrative servicing missions are possible with value-added modifications to the internal components of satellites. Although the subsystem modules of existing satellites are electrically integrated into the satellite architecture with connectors requiring human-in-the-loop assembly, the modular bus interface utilized in modern spacecraft design (allowing for the concurrent development of subsystems) is a step towards modularity at the component level. Furthermore, empirical evidence from DARPA's Orbital Express technology development program suggests that the mass penalties for docking and refueling interfaces on target satellites are relatively low (*i.e.*, 32 kg and 50 kg, respectively).

With the existing value proposition of communications satellites, regular servicing missions do not make sense.

The commercial viability of robotic OOS is an open question. Lucrative missions seem to require either dedicated servicing vehicles (*e.g.*, rescue, attitude stabilization) or modifications to the current fleet of operational satellites. Customer valuation research suggests that servicing providers should focus on medium volatility markets, low-risk servicing missions, and satellite components incorporating fast-evolving technologies. However, one of the most lucrative markets identified (*i.e.*, GEO lifetime extension) is poised to shrink due to the shift of GEO communications satellites to electric propulsion.

In analyzing the physical amenability of satellites to OOS, it was found that the current generation of spacecraft is simply too reliable to ensure a steady revenue stream for potential OOS providers. Grounded in empirical data of annual servicing opportunities, the agent model of OOS applied to GEO found that servicing provider utilization could have increased by an order of magnitude without stressing the utilization factor of four servicing vehicles. Given the current inaccessibility of space systems, no trade has been performed between redundant, highly reliable satellites (current paradigm), and lower cost, less redundant satellites that utilize OOS to achieve similar reliability.

The development of a servicing infrastructure in space is dependent on whether new value propositions are incorporated into the operation of satellites.

In the short-term, the most promising OOS opportunities fall into the "space tugging" category. Two OOS markets particularly attractive across technical and economic dimensions are: (1) low-risk efficiency improvements for large numbers of satellites in zones characterized by friendly orbital dynamics (*e.g.*, GEO retirement missions) and (2) rescue of individual spacecraft that have failed at BOL (*e.g.*, orbital re-boosts due to failed upper stages and deployment assistance). Space tugs may also be employed to enable new, highly-valued capabilities in future constellations (*e.g.*, extremely low-altitude orbits for Space Radar).

Looking ahead, development of an OOS infrastructure will be driven by changes in the existing paradigm of the acquisition and operation of space systems. On-orbit servicing relaxes the constraint of inaccessibility during operational life and opens up the tradespace for less redundant satellite designs. Most importantly, the responsiveness offered by OOS provides flexibility to capitalize on emergent opportunities and robustness to mitigate risks, better equipping the space industry to deliver value in changing contexts.

Glossary

all-purpose servicer	a vehicle that is able to improve the state of target satellites, regardless of whether they have been designed for servicing; incorporates the functionality of space tugs and pre-planned servicers in a vehicle that also is able to repair faulty spacecraft components and conduct assembly operations
access	servicing activity involving the deployment of servicing tools from stowed position to area of interest of target; OOS activity involves the positioning of the servicer tools next to the satellite components to be serviced
acquire	servicing activity involving the transfer of a servicing vehicle from the target vicinity to the holding of the target; OOS activity involves the docking of a servicing vehicle to a target satellite
architecting	process of conducting system development with a focus on interfaces and associated operational, technical, and environmental contexts
architecture	integrated description of the operations, components, and technical standards of system; consists of a functional decomposition (from originating requirements) in the behavioral domain and an allocation of functions to components in the physical domain, all occurring within an environmental context
architecture framework	tools for managing complexity by structuring data in a common language and format, consisting of views tailored to the perspectives of different stakeholders (*e.g.*, designer, user)
assemble	on-orbit servicing function in which modules are mated
augment	on-orbit servicing function in which the capability of a satellite is increased
engineering system	a technologically-enabled system characterized by non-trivial (*i.e.*, requiring design changes in the technical system) feedback from a heterogeneous stakeholder set
inspect	on-orbit servicing function in which a space object is visually observed from an attached position or a remote surveillance vehicle
modularity	consisting of modules with tightly controlled interfaces
on-orbit servicing	the process of improving a space-based capability through a combination of in-orbit activities which may include inspection;

	rendezvous and docking; and value-added modifications to a satellite's position, orientation, and operational status
pre-planned servicer	a vehicle that is able to improve the state of target satellites that has been designed for servicing; incorporates most of the functionality of space tugs (with arbitrary docking capability being a key exception) in a vehicle that is also capable of fluid transfer and change-out of orbital replacement units
proximity inspector	a free-floating vehicle or attached surveillance instrument which characterizes a space object without physical contact
restore	on-orbit servicing function in which a satellite is returned to a previous state (or brought to an intended state)
relocate	on-orbit servicing function in which the orbit of a space object is modified
rendezvous	servicing activity involving the movement of servicing vehicle from starting position to target vicinity; OOS activity involves the positioning of the servicer for relative navigation with lidar, radar, or cameras
service	value-added servicing activity involving the operation of deployed servicer components for system improvement; OOS activity involving the repair, replacement, upgrade, addition, and/or removal of satellite components
serviceability	cooperativeness of a technical system to *in-situ*, value-added modifications
space tug	a vehicle designed to rendezvous and dock with a space object; make an assessment of its current position, orientation, and operational status; and then either stabilize the object in its current orbit or move the object to a new location with subsequent release
target satellite	spacecraft upon which servicing activities are to be performed

References

Air Force Science and Technology Board. (2004). *Evaluation of the National Aerospace Initiative. National Academy of Sciences.*

Akin, D., Lane, J., et al. (2001). "Robotic Capabilities for Complex Space Operations". *AIAA Space 2001*, Albuquerque, NM.

Akin, D., Roberts, B., et al. (2003). "Robotic Augmentation of EVA For Hubble Space Telescope Servicing." *AIAA Space 2003*, Long Beach, CA.

Ang, A. and Tang, W. (1975). Probability Concepts on Engineering Planning and Design. New York: John Wiley & Sons.

Aon Space. (2002). "Satellite Dies Another Day." *DLR Workshop on On-Orbit Servicing*, Cologne, Germany.

Apollo 13 Review Board. (1970). *Report of Apollo 13 Review Board.* National Aeronautics and Space Administration.

Arrow, K. J. (1963). Social Choice and Individual Values. New Haven: Yale University Press.

Baker, D. (2005). Jane's Space Directory 2005-06. Surrey, UK: Jane's Information Group.

Baldwin, C. and Clark, K. (2000). Design Rules: The Power of Modularity. Cambridge, MA: MIT Press.

Barrett, J., Hartkey, K., et al. (2004). "Improving requirement modelling and traceability within an enterprise architecture framework." *Command and Control Research and Technology Symposium*, San Diego, CA.

Bartolomei, J., Hastings, D., et al. (2006). "Screening for Real Options "In" an Engineering System: A Step Towards Flexible Weapon System Development." *Conference on Systems Engineering Research*, Los Angeles, CA.

Belew, L. (1977). *Skylab: Our First Space Station.* NASA Scientific and Technical Information Office.

Bell, R., Morphopoulos, T., et al. (2003). "Hardware-in-the-Loop Tests of an Autonomous GN&C System for On-Orbit Servicing". *AIAA Space 2003*, Long Beach, CA.

Berger, B. (2005). "Fender Bender: NASA's DART Spacecraft Bumped Into Target Satellite." *Space.com*, April 2005.

Bluth, B. and Helppie, M. (1986). *Soviet Space Stations as Analogs.* NASA Headquarters.

Bonds, T., Mattock, M., et al. (2000). *Employing Commercial Satellite Communications: Wideband Investment Options for DoD.* RAND Project AIR FORCE.

Bosse, A., Barnds, W., et al. (2004). "SUMO: Spacecraft for the Universal Modification of Orbits." *Proceedings of SPIE*, Vol. 5419, pp. 36-46.

Brisibe, T. (2002). "Servicing Satellites On-Orbit by Automation and Robotics: Potential Legal and Regulatory Considerations." *DLR Workshop on On-Orbit Servicing*, Cologne, Germany.

Broniatowski, D., Jordan, N., et al. (2005). "Balancing the Needs for Space Research and National Security in the ITAR." *AIAA Space 2005*, Long Beach, CA.

Brown, O. (2004). *Reducing Risk of Large Scale Space Systems Using a Modular Architecture. Defense Advanced Research Projects Agency.*

Caceres, M. (2006). "Cost overruns plague military satellite programs." *Aerospace America*, January 2006, 18-23.

Caceres, M. (2005). "Creating a space exploration industry." *Aerospace America*, August 2005, pp. 10-12.

Carlson, J. and Doyle, J. (2000). "Highly Optimized Tolerance: Robustness and Design in Complex Systems." *Physical Review Letters*, 84(11): 2529-2532.

Chaize, M. (2003). *Enhancing the Economics of Satellite Constellations via Staged Deployment and Orbital Reconfiguration.* Department of Aeronautics and Astronautics, Master's thesis. Massachusetts Institute of Technology, Cambridge, MA.

Chato, D. (2000). "Technologies for Refueling Spacecraft On-Orbit". *AIAA Space 2000*, Long Beach, CA.

Christensen, C. (2003). The Innovator's Dilemma. New York: HarperBusiness Essentials.

Clubb, J. and Ingels, F. (1987). "An Overview of the Hubble Space Telescope Command and Data Management System." *International Telemetering Conference*, San Diego, CA.

Collins, J., Meissinger, H., et al. (2001). "Small Orbit Transfer Vehicle for On-Orbit Satellite Servicing and Resupply". *AIAA Conference on Small Satellites*, Logan, UT.

Cooper, C. and Ewoldt, M. (2005). *A Systems Architectural Model for Man-Packable/Operable Intelligence, Surveillance, and Reconnaissance Mini/Micro Aerial Vehicles.* Department of Aeronautics and Astronautics, Master's Thesis. US Air Force Institute of Technology, Wright Patterson Air Force Base, OH.

Couretas, J., Adrounie, V., et al. (2003). "Enterprise Architectures as a Catalyst for System-of-Systems Development: A Global ISR Perspective." *AIAA/ICAS International Air and Space Symposium*, Dayton, OH.

Cuplin, L. and Chun, W. (2000). "Satellite Servicing and Space Logistics". *AIAA Space 2000*, Long Beach, CA.

Dam, S. and Willis, J. (2002). *Defensible C4ISR Architectures Require the Application of Good System Engineering Practice.* Systems and Proposal Engineering Company.

David, L. (2005). "Air Force Satellite Shows Off Rendezvous Skills." *Space.com*, 12 September 2005.

Davinic, N., Arkus, A., et al. (1998). "Cost-Benefit Analysis of On-Orbit Satellite Servicing." *Journal of Reducing Space Mission Cost*, Vol. 1: pp. 27-52.

Davis, T. (2003). *XSS-10 Microsatellite Flight Demonstration Program.* AFRL Space Vehicles Directorate.

de Neufville, R. (1990). Applied Systems Analysis: Engineering Planning and

Technology Management. New York: McGraw-Hill Co.

de Peuter, W., Visentin, G., et al. (1994). "Satellite Servicing in GEO by Robotic Servicing Vehicle." *ESA Bulletin*, Issue 78: pp. 33-39.

de Weck, O., Chang, D., et al. (2003). "Quantitative Assessment of Technology Infusion in Communications Satellite Constellations". *AIAA International Communications Satellite Systems Conference*, Yokohama, Japan.

de Weck, O., de Neufville, R., et al. (2003). "Enhancing the Economics of Communications Satellites via Orbital Reconfigurations and Staged Deployment". *AIAA Space 2003*, Long Beach, CA.

de Weck, O., de Neufville, R., et al. (2004). "Staged Deployment of Communications Satellite Constellations in Low Earth Orbit." *AIAA Journal of Aerospace Computing, Information, and Communication*, Vol. 1: pp. 119-136.

Defense Science Board/Air Force Scientific Advisory Board. (2003). *Report of the Joint Task Force on Acquisition of National Security Space Programs*. Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics.

Derleth, J. (2003). *Multi-Attribute Tradespace Exploration and Its Application to Evolutionary Acquisition*. Department of Aeronautics and Astronautics, Master's thesis. Massachusetts Institute of Technology, Cambridge, MA.

DeStefano, G. (2004). *Agent Based Simulation: SEAS Evaluation of DoDAF Architecture*. Department of Operational Sciences, Master's thesis. Air Force Institute of Technology, Wright-Patterson Air Force Base, OH.

Diller, N. (2002). *Utilizing Multiple Attribute Tradespace Exploration with Concurrent Design for Creating Aerospace Systems Requirements*. Department of Aeronautics and Astronautics, Master's thesis. Massachusetts Institute of Technology, Cambridge, MA.

DoD Architecture Framework Working Group. (2003). *DoD Architecture Framework: Version 1.0*.

Ellery, A. (2002). "Handling Technology for On-Orbit Servicing." *DLR Workshop on On-Orbit Servicing*, Cologne, Germany.

FAA Office of Commercial Space Transportation Licensing and Safety Division. (1992). *On-Orbit Collision Hazard Analysis in Low Earth Orbit Using the Poisson Probability Distribution.*

Federal Communications Commission. (2001). *Application of SpaceData International to Operate on a Time Share Basis NASA's Tracking and Data Relay Satellite System*.

Fehse, W. (2003). Automated Rendezvous and Docking of Spacecraft. New York: Cambridge University Press.

Fernandez, A. (2004). *Military Role in Space Control: A Primer*. Congressional Research Service.

Fredrickson, S., Wagenknecht, J., et al. (2002). *Miniature Autonomous Extravehicular Robotic Camera (Mini AERCam)*. NASA Johnson Space Center.

French, S. (2005). "DoDAF Lessons Learned." *Conference on Systems Engineering Research*, Hoboken, NJ.

Future Concepts and Transformation Division. (2003). *The U.S. Air Force Transformation Flight Plan.* United States Air Force.

Futron Corporation. (2002). *Commercial Space and Launch Insurance: Current Market and Future Outlook.* Fourth Quarter Launch Report.

Futron Corporation. (2002). *Launch Activity and Orbital Debris Mitigation.* Second Quarter Launch Report.

Futron Corporation. (2003). *GEO Commercial Satellite Bus Operations: A Comparative Analysis.*

Galabova, K. (2004). *Architecting a Family of Space Tugs Based on Orbital Transfer Mission Scenarios.* Department of Aeronautics and Astronautics, Master's thesis. Massachusetts Institute of Technology, Cambridge, MA.

Galabova, K., Bounova, G., et al. (2003). "Architecting a Family of Space Tugs Based on Orbital Transfer Mission Scenarios". *AIAA Space 2003*, Long Beach, CA.

Gruhl, W. (1992). *Lessons Learned, Cost/Schedule Assessment Guide.* Internal presentation, NASA Comptroller's Office.

Hacker, B. and Grimwood, J. (1977). *On The Shoulders of Titans: A History of Project Gemini.* NASA Scientific and Technical Information Office.

Hall, E. and Papadopoulos, M. (1999). "GPS Structural Modifications for On-Orbit Servicing." *AIAA Space Technology Conference*, Albuquerque, NM.

Hastings, D., de Weck, O., et al. (2002). *System Architecting for Space Tugs.* DARPA Research Proposal.

Hastings, D., Lamassoure, E., et al. (2001). *Policy Enablers for the Development of a Space-Based Infrastructure.* Massachusetts Institute of Technology.

Hazelrigg, G. (1996). Systems Engineering: An Approach to Information Design. Upper Saddle River: Prentice Hall.

Heiney, A. (2005). *Lending a Hand, an Arm, and a Boom: STS-114 Press Release.* National Aeronautics and Space Administration.

Hollander, S. (2000). "Autonomous Space Robotics: Enabling Technologies for Advanced Space Platforms". *AIAA Space 2000*, Long Beach, CA.

Honour, E. (2004). "Understanding the Value of Systems Engineering." *INCOSE Symposium*, Toulouse, France.

Horsham, G. (2003). *Envisioning a 21st Century, National Spacecraft Servicing and Protection Infrastructure and Demand Potential: A Logical Development of the Earth Orbit Economy.* Glenn Research Center, National Aeronautics and Space Administration.

Ianni, J., Repperger, D., et al. (2002). "Human Interfaces For Robotic Satellite Servicing." *Proceedings of SPIE*, Vol. 4632, Paper #14.

Iannotta, B. (2006). "SUMO wrestles satellites into new orbits." *Aerospace America*, February 2006, 26-30.

Inter-Agency Space Debris Coordination Committee. (2002). *IADC Space Debris Mitigation Guidelines.*

Isakowitz, S., Hopkins, J., et al. (2004). International Reference Guide to Space Launch Systems. Reston: American Institute of Aeronautics and Astronautics.

Joppin, C. (2004). *On-Orbit Servicing for Satellite Upgrades*. Technology and Policy Program, Master's thesis. Massachusetts Institute of Technology, Cambridge, MA.

Joppin, C. and Hastings, D. (2003). "Evaluation of the Value of the Flexibility Offered by On-Orbit Servicing: Case of Satellite Upgrade." *AIAA Space 2003*, Long Beach, CA.

Kan, S. (2003). *China: Possible Missile Technology Transfers from U.S. Satellite Export Policy - Actions and Chronology.* Congressional Research Service.

Kaplan, M. (2002). "The Road to OOS: Enabling Architecture." *DLR Workshop on On-Orbit Servicing*, Cologne, Germany.

Kawano, I. (2001). "Results of Autonomous Rendezvous Docking Experiment of Engineering Test Satellite-VII." *Journal of Spacecraft and Rockets*, 38(1): 105-111.

Keeney, R. and Raiffa, H. (1976). Decisions with Multiple Objectives: Preferences and Value Tradeoffs. Cambridge: Cambridge University Press.

Kiersarsky, A. (1969). *Effects of In-Orbit Servicing on Nimbus Configuration.* Bellcomm, Inc.

Koo, B. (2005). *A Meta-Language for Systems Architecting.* Engineering Systems Division, doctoral dissertation. Massachusetts Institute of Technology, Cambridge, MA.

Lamassoure, E. (2001). *A Framework to Account for Flexibility in Modeling the Value of On-Orbit Servicing for Space Systems.* Department of Aeronautics and Astronautics, Master's thesis. Massachusetts Institute of Technology, Cambridge, MA.

Lamassoure, E. and Hastings, D. (2000). "Generalized Metrics for Optimization of Space Systems Cost-Effectiveness." *AIAA Space 2000*, Long Beach, CA.

Lamassoure, E., Saleh, J., et al. (2002). "Space Systems Flexibility Provided by On-Orbit Servicing: Part 2." *Journal of Spacecraft and Rockets*, 39(4): 561-570.

Leisman, G. (2000). "Analysis of On-Orbit Servicing Architectures Using Microsatellites, Advanced Propulsion, Secondary Payload Opportunities and the Military Spaceplane Concept." *AIAA Space 2000*, Long Beach, CA.

Leisman, G. and Wallen, A. (1999). *Design and Analysis of On-Orbit Servicing Architectures for the Global Positioning System Constellation.* Department of Aeronautics and Astronautics, Master's thesis. US Air Force Institute of Technology, Wright Patterson Air Force Base, OH.

Leisman, G., Wallen, A., et al. (1999). "Analysis and Preliminary Design of On-Orbit Servicing Architectures for the GPS Constellation." *AIAA Space Technology Conference*, Albuquerque, NM.

Lethbridge, C. (1998). *STS-51I Fact Sheet.* Spaceline, Inc.

Levis, A. and Wagenhals, L. (2000). "C4ISR Architectures: I. Developing a Process for C4ISR Architecture Design." *Systems Engineering*, Vol. 3(4): 225-247.

Long, A (2005). *Framework for Evaluating Customer Value and the Feasibility of Servicing Architectures for On-Orbit Satellite Servicing.* Department of Aeronautics and Astronautics, Technology and Policy Program, dual Master's thesis. Massachusetts Institute of Technology, Cambridge, MA.

Long, A and Hastings, D. (2004). "Catching the Wave: A Unique Opportunity for the Development of an On-Orbit Satellite Servicing Infrastructure." *AIAA Space 2004*, San Diego, CA.

Long, A. and Hastings, D. (2005). "The Effect of Uncertainties in Architectural Design Elements on Potential Non-Commercial On-Orbit Satellite Servicing Markets." *AIAA Space 2005*, Long Beach, CA.

Ma, O., Crabtree, D., et al. (2002). "Development and Applications of a Simulink-Based Satellite Docking Simulatory with Generic Contact Dynamic Capabilities." *IAF World Space Congress*, Houston, TX.

Maier, M., Emery, D., et al. (2004). "ANSI/IEEE 1471 and Systems Engineering." *Systems Engineering*, 7(3): 257-270.

Maier, M. and Rechtin, E. (2000). The Art of Systems Architecting. Boca Raton: CRC Press.

Maley, J., Long, J., et al. (2003). *Systems Engineering and CORE: A Natural Approach to C4ISR/DoDAF.* Vitech Corporation.

Malik, T. (2004). "NASA engineers refine Robonaut." *CNN.com*, 23 August 2004.

Mathieu, C. and Weigel, A. (2005). "Assessing the Flexibility Provided by Fractionated Spacecraft." *AIAA Space 2005*, Long Beach, CA.

Mattice, J. (2004). *Hubble Space Telescope Systems Engineering Case Study.* Air Force Institute of Technology.

McConnell, M. (2005). *An Approach for Optimizing the On-Orbit Servicing Architecture for a Given Client Satellite Constellation.* Department of Operational Sciences, Master's thesis. Air Force Institute of Technology, Wright-Patterson Air Force Base, OH.

McInnes, C. (2000). "Autonomous Path Planning for On-Orbit Servicing Vehicles." *Journal of the British Interplanetary Society*, Vol. 53: pp. 26-23.

McManus, H., Hastings, D., et al. (2004). "New Methods for Rapid Architecture Selection and Conceptual Design." *Journal of Spacecraft and Rockets*, 41(1): 10-19.

McManus, H. and Schuman, T. (2003). "Understanding the Orbital Transfer Vehicle Tradespace". *AIAA Space 2003*, Long Beach, CA.

McVey, M. (2004). *DARPA Space Tug.* Internal presentation.

McVey, M. (2002). *Valuation Techniques for Complex Space Systems: An Analysis of a Potential Satellite Servicing Market.* Department of Aeronautics and

Astronautics, Master's thesis. Massachusetts Institute of Technology, Cambridge, MA.

McVey, M. and Warmkessel, J. (2003). "Valuation Techniques for Complex Space Systems: An Analysis of a Potential Satellite Servicing Market." *AIAA Aerospace Sciences Meeting and Exhibit*, Reno, NV.

Meissinger, H. and Collins, J. (1999). "Mission Design and System Requirements for a Multiple-Function Orbital Transfer Vehicle." *AIAA Space Technology Conference*, Albuquerque, NM.

Miller, J., Guerrero, J., et al. (2002). "SpaceFrame: Modular Spacecraft Building Blocks for Plug and Play Spacecraft". *AIAA Conference on Small Satellites*, Logan, UT.

Mirmina, S. (2004). "The Regulation of Orbital Debris through National Measures." *Air & Space Law*, 29(2): 137-146.

MODAF Partners. (2005). MOD *Architecture Framework*. Ministry of Defence, United Kingdom.

Moynahan, S. and Tuohy, S. (2000). "Development of a Modular On-Orbit Serviceable Satellite Architecture". *IEEE Aerospace Conference*, Big Sky, MT.

Murman, E., Allen, T., et al. (2002). Lean Enterprise Value: Insight's from MIT's Lean Aerospace Initiative. Wales, UK: Palgrave.

NASA. (1984). *STS 41-G National Space Transportation Systems Mission Report.*

NASA. (1992). *STS-49 Mission Report.*

NASA Advisory Council. (1992). *Report of the Group Task Force on Satellite Rescue and Repair*. National Aeronautics and Space Administration.

NASA Office of Space Flight. (1988). *Satellite Servicing: A NASA Report to Congress.*

National Business Review. (2006). Sky TV knocked off air as satellite goes 'missing'. 31 March 2006.

National Research Council. (2005). *Assessment of Options for Extending the Life of the Hubble Space Telescope: Final Report*. National Academies Press.

Nelson, B. (2002). *Hubble Space Telescope: Servicing Mission 3B Media Reference Guide*. Lockheed Martin Corporation.

Nilchiani, R. (2005). *Measuring the Value of Space Systems Flexibility: A Comprehensive Six-Element Framework.* Department of Aeronautics and Astronautics, doctoral dissertation. Massachusetts Institute of Technology, Cambridge, MA.

Nilchiani, R. and Hastings, D. (2003). "Measuring Flexibility in Design of an Orbital Transportation Network." *AIAA Space 2003*, Long Beach, CA.

Norman, C. (2005). *U.S. House of Representatives Committee on Science Hearing on Options for the Hubble Space Telescope.*

Office of the Assistant Secretary of Defense for Networks and Information Integration. (2005). *Architecture Development and Analysis Survey: The State of DoD Architecting.*

O'Keefe, W., Henderson, R., et al. (1998). *International Space Station Familiarization.* Mission Operations Directorate, Space Flight Training Division, NASA.

Orbital Recovery Corporation. (2005). *Orbital Recovery Group Signs a Reservation for the First Satellite Servicing Mission Using its CX-OLEV Space Tug.* Company Press Release.

Parliamentary Office of Science and Technology. (1995). *Oil Rig Disposal.* United Kingdom.

Partch, R., Baker, V., et al. (2004). *Autonomous Proximity Microsatellites.* AFRL TECH CONNECT.

Pelton, J. (2003). "New Satellite Communications Architecture for the Post 2010 Time Period." *AIAA International Communications Satellite Systems Conference and Exhibit*, Yokohama, Japan.

Perroton, G. and Busson, M. (1999). "Enhancement of the European ATV for Logistics Missions to ISS." *AIAA Space Technology Conference*, Albuquerqe, NM.

Phister, P., Williamson, D., et al. (2001). "Space On-Board "Servicer": A Key to Space Vehicle Longevity." *AIAA Space 2001*, Albuquerque, NM.

Pielke, R. (1993). "Space Shuttle Value Open to Interpretation." *Aviation Week and Space Technology*, 26 July 1993.

Polites, M. (1999). "Technology of Automated Rendezvous and Capture in Space." *Journal of Spacecraft and Rockets*, 36(2): 280-291.

Potter, S. (2003). *Orbital Express: Leading the Way to a New Space Architecture.* The Boeing Company.

Pratt, T., Bostian, C., et al. (2003). Satellite Communications. Hoboken: John Wiley & Sons.

Reynerson, C. (1999). "Spacecraft Modular Architecture Design for On-Orbit Servicing." *AIAA Space Technology Conference*, Albuquerque, NM.

Reynerson, C. (2001). "Spacecraft Servicing - First Order Model for Feasibility and Cost Effectiveness." *AIAA Space 2001*, Albuquerque, NM.

Richards, M., Shah, N., Hastings, D., and Rhodes, D. (2006). "Managing Complexity with the Department of Defense Architecture Framework: Development of a Dynamic System Architecture Model." *Conference on Systems Engineering Research*, Los Angeles, CA.

Richards, M., Springmann, P., and McVey, M. (2005). "Assessing the Challenges to a Geosynchronous Space Tug System." *SPIE Defense and Security Symposium*, Orlanda, FL.

Ring, S., Nicholson, D., et al. (2004). "An Activity-Based Methodology for Development and Analysis of Integrated DoD Architectures." *Command and Control Research and Technology Symposium*, San Diego, CA.

Roberts, C. (2003). *Architecting Evolutionary Strategies Using Spiral Development for Space Based Radar.* Technology and Policy Program, Massachusetts Institute of Technology, Cambridge, MA.

Rocco, E., Prado, A., et al. (1998). "Bi-Impulsive Orbital Transfers Between Coplanar Orbits with Time Limit." *AIAA Astrodynamics Conference*, Boston, MA.

Ross, A. (2006). *Managing Unarticulated Value: Changeability in Multi-Attribute*

Tradespace Exploration. Engineering Systems Division, doctoral dissertation. Massachusetts Institute of Technology, Cambridge, MA.

Ross, A. (2003). *Multi-Attribute Tradespace Exploration with Concurrent Design as a Value-Centric Framework for Space System Architecture and Design.* Department of Aeronautics and Astronautics, Technology and Policy Program, dual Master's thesis. Massachusetts Institute of Technology, Cambridge, MA.

Ross, A., Hastings, D., et al. (2004). "Multi-Attribute Tradespace Exploration as Front End for Effective Space System Design." *Journal of Spacecraft and Rockets*, 41(1): 20-28.

Saleh, J. (2002). *Weaving Time into System Architecture: New Perspectives on Flexibility, Spacecraft Design Lifetime, and On-Orbit Servicing.* Department of Aeronautics and Astronautics, doctoral dissertation. Massachusetts Institute of Technology, Cambridge, MA.

Saleh, J., Hassan, R., et al. (2005). "Impact of Subsystem Reliability on Satellite Revenue Generation and Present Value." *Journal of Spacecraft and Rockets*, 42(6): 1122-1129.

Saleh, J., Lamassoure, E., et al. (2002). "Space Systems Flexibility Provided by On-Orbit Servicing: Part 1." *Journal of Spacecraft and Rockets*, 39(4): 551-560.

Saleh, J., Lamassoure, E., et al. (2003). "Flexibility and the Value of On-Orbit Servicing: New Customer-Centric Perspective." *Journal of Spacecraft and Rockets*, 40(2): 279-291.

Saleh, J., Torries-Padilla, J., et al. (2005). "Utilization Rates of GEO Communication Satellites: Statistical Analysis of Loading Dynamics." *AIAA Space 2005*, Long Beach, CA.

Schildge, H. (2003). "Legal Implications of Collisions in Space." *Satellite Operations and Safety Workshop*, MIT Lincoln Laboratory.

Science Applications International Corporation. (1987). *Satellite Servicing Mission Preliminary Cost Estimation Model.* NASA Contract Number NAS9-17207.

Scott, M. and Antonsson, E. (2000). "Arrow's Theorem and Engineering Design Decision Making." *Research in Engineering Design*, 11(4): 218-228.

Seshasai, S. (2002). *A Knowledge Based Approach to Facilitate Engineering Design. Department of Electrical Engineering and Computer Science*, Master's degree. Massachusetts Institute of Technology, Cambridge, MA.

Settelmeyer, E. (1997). The Experimental Servicing Satellite - ESS. *Preparing for the Future*, 7(2).

Shah, N. (2004). *Modularity as an Enabler for Evolutionary Acquisition. Department of Aeronautics and Astronautics*, Master's thesis. Massachusetts Institute of Technology, Cambridge, MA.

Shaw, A. (2002). "The Chicken and Egg of On-Orbit Servicing." *DLR Workshop on On-Orbit Servicing*, Cologne, Germany.

Shen, H. and Tsiotras, P. (2002). "Optimal Scheduling for Servicing Multiple Satellites in a Circular Constellation." *AIAA*

Astrodynamics Specialist Conference, Monterey, CA.

Shen, H. and Tsiotras, P. (2002). "Optimal Two-Impulse Rendezvous Between Two Circular Orbits Using Multiple-Revolution Lambert's Solutions." *AIAA Guidance, Navigation, and Control Conference*, Monterey, CA.

Shishko, R., Chamberlain, R., et al. (1995). *NASA Systems Engineering Handbook.*

Shoemaker, J. and Wright, M. (2004). "Orbital Express Space Operations Architecture Program." *Proceedings of SPIE*, Bellingham, WA. Vol. 5419, 57-65.

Space Daily. (2006). "Russian Telecom Satellite Fails After Sudden Impact." 30 March 2006.

Space Systems Division. (1984). *Space Telescope Mission Operations Functional Requirements*. Lockheed Missiles and Space Company, Inc. Prepared for NASA Marshall Space Flight Center.

Space Systems/Loral. (1990). *Satellite Servicing Economic Study: Final Technical Report*. NASA Marshall Space Flight Center.

Spaulding, T. (2003). *Tools for Evolutionary Acquisition: A Study of Multi-Attribute Tradespace Exploration (MATE) Applied to the Space Based Radar (SBR)*. Department of Aeronautics and Astronautics, Master's thesis. Massachusetts Institute of Technology, Cambridge, MA.

Spires, D. (2001). Horizons: A Half Century of Air Force Space Leadership. Maxwell Air Force Base: Air University Press.

Stagney, D. (2003). *The Integrated Concurrent Enterprise*. Department of Aeronautics and Astronautics, Sloan School of Management, dual Master's thesis. Massachusetts Institute of Technology, Cambridge, MA.

Stamm, S. and Motaghedi, P. (2004). "Orbital Express Capture System: Concept to Reality." *Proceedings of SPIE*, Bellingham, WA. Vol. 5419, 78-91.

Suh, Nam P. (2005). Complexity: Theory and Applications. New York: Oxford University Press.

Sullivan, B. (2005). *Technical and Economic Feasibility of Telerobotic On-Orbit Satellite Servicing*. Department of Aerospace Engineering, doctoral dissertation. University of Maryland, College Park, MD.

Sullivan, B. and Akin, D. (2001). "A Survey of Serviceable Spacecraft Failures". *AIAA Space 2001*, Albuquerque, NM.

Tang, A., Han, J., et al. (2004). "A Comparative Analysis of Architecture Frameworks." *Asia-Pacific Software Engineering Conference*, Busan, Korea.

Troche, C., Eiden, G., et al. (2004). *Architecture Development Lessons-Learned: A Three-Year Retrospective*. MITRE Corporation.

Tsiotras, P. and de Nailly, A. (2005). "Comparison Between Peer-to-Peer and Single Spacecraft Refueling Strategies for Spacecraft in Circular Orbits." *AIAA Infotech@Aerospace*, Arlington, VA.

Turner, A. (2001). "Cost-Effective Spacecraft Dependent Upon Frequent Non-

Intrusive Servicing." *AIAA Space 2001*, Albuquerque, NM.

Turner, A. (2002). "Orbital Fueling Benefits for Geosynchronous Spacecraft." *AIAA International Communication Satellite Systems Conference*, Montreal, Canada.

Turner, A. (2002). "Use of a Staging Orbit for Geosynchronous Orbit-Raising Involving Servicing." *AIAA Astrodynamics Specialist Conference*, Monterey, CA.

Ulitsky, A. and King, D. (2002). "Enabling the Future: Lidar Space Vision Systems for Next Generation On-Orbit Servicing." *DLR Workshop on On-Orbit Servicing*, Cologne, Germany.

Union of Concerned Scientists. (2006). *UCS Satellite Database.*

Vallado, D. and McClain, W. (2001). Fundamentals of Astrodynamics and Applications. El Segundo: Microcosm Press.

von Neumann, J. and Morgenstern, O. (1953). Theory of Games and Economic Behavior. Princeton: Princeton University Press.

Wagenhals, L., Shin, I., et al. (2000). "C4ISR Architectures: II. A Structured Analysis Approach for Architecture Design." *Systems Engineering*, 3(4): 248-286.

Walton, M. (2002). *Managing Uncertainty in Space Systems Conceptual Design Using Portfolio Theory.* Department of Aeronautics and Astronautics, doctoral dissertation. Massachusetts Institute of Technology, Cambridge, MA.

Walton, M. and Hastings, D. (2004). "Applications of Uncertainty Analysis to Architecture Selection of Satellite Systems." *Journal of Spacecraft and Rockets*, 41(1): 75-84.

Waltz, D. (1993). On-Orbit Servicing of Space Systems. Malabar: Krieger Publishing Company.

Weigel, A. (2002). *Bringing Policy into Space Systems Conceptual Design: Qualitative and Quantitative Methods.* Engineering Systems Division, doctoral dissertation. Massachusetts Institute of Technology, Cambridge, MA.

Welch, J. and Brown, W. (1987). "Hubble Space Telescope Servicing: Experience Base for a New Era." *38th Congress of the International Astronautical Federation*, Brighton, United Kingdom.

Wertz, J. and Bell, R. (2003). "Autonomous Rendezvous and Docking Technologies: Status and Prospects." *Proceedings of SPIE*, Vol. 5088, pp. 20-30.

Wertz, J., Larson, W., et al. (1999). Space Mission Analysis and Design. El Segundo: Microcosm Press.

Wheelon, A. (1988). *Space Policy: How Technology, Economics and Public Policy Intersect.* Working paper, MIT Program in Science, Technology and Society.

Whekan, D., Adler, E., et al. (2000). "The DARPA Orbital Express Program: Effecting a Revolution in Space-Based Systems." *Proceedings of SPIE*, Vol. 4136, pp. 48-56.

White House Office of Science and Technology Policy. (1996). *U.S. Space Policy Fact Sheet.*

White House Office of Science and Technology Policy. (2005). *U.S. Space Transportation Policy Fact Sheet.*

Whittington, D. (2004). "Challenging the DoDAF Paradigm: Improving Requirements Modeling and Traceability within an Enterprise Architecture Framework." *Command and Control Research and Technology Symposium*, San Diego, CA.

Wingo, D. (2004). "Orbital Recovery's Responsive Commercial Space Tug for Life Extension Missions." *AIAA Responsive Space Conference*, Los Angeles, CA.

Wright, D., Grego, L., et al. (2005). *The Physics of Space Security.* Union of Concerned Scientists.

Yasaka, T. and Ashford, E. (1996). "GSV: An Approach Toward Space System Servicing." *Earth Space Review*, 5(2): 9-17.

Yoshida, K. (2003). "Engineering Test Satellite VII Flight Experiments For Space Robot Dynamics and Control: Theories on Laboratory Test Beds Ten Years Ago, Now in Orbit." *International Journal of Robotics Research*, 22(5): 321-335.

Zehner, M. (2002). *Legal Principles Relevant to Military Activities in Outer Space*. Air Force Office of the General Counsel.

Zinn, A. (2004). *The Use of Integrated Architectures to Support Agent Based Simulation: An Initial Investigation.* Department of Aeronautics and Astronautics, Master's thesis. Air Force Institute of Technology, Wright-Patterson Air Force Base, OH.

Appendix A. Agent-Based Model of Satellite Servicing

This appendix documents portions of the MATLAB code developed with Nirav Shah for the agent-based model of OOS in the GEO belt. Results of the multi-objective optimization problem (*i.e.*, target satellite availability, ΔV expenditure per servicing mission) are included in Chapter 4.

OOSim

```
numTrials = 1000;
drawDashboard = 0;
if drawDashboard
    figure(1);
    figure(2);
end;
totalDV = zeros(numTrials,1);
numTics = zeros(numTrials,1);
load_state_names;
OmegaAltIncUCS = OmegaAltInc;
mkdir(['monte-' num2str(numTrials,'%04d')]);
monteResultsDir = ['monte-' num2str(numTrials,'%04d') filesep];
save('UCSGEODATA','OmegaAltIncUCS');
diary([monteResultsDir 'monte-OOS-' num2str(numTrials,'%04d') '-Trials-
diary.txt']);
diary on;
for monte = 1:numTrials
    clear time satellite servicer ticket;
    [satellite,servicer,ticket] = initialization;
    numSats = length(satellite.ID);
    numServ = length(servicer.ID);

    Dtime = 60;
    Tstop = 10*365*24*60;
    timeV = 0:Dtime:Tstop;
    numTsteps = length(timeV);
    numOperSat = zeros(1,numTsteps,'uint16');
    numOpenTickets = zeros(1,numTsteps,'uint32');

    for i = 1:numTsteps
        time = timeV(i);
        [satellite,ticket]=satellite_update(time,satellite,ticket);

[servicer,ticket,satellite]=servicer_update(time,servicer,satellite,ticket);
        numOperSat(i) = sum(satellite.state == satOPERATING);
        numOpenTickets(i) = ticket.numTickets - sum(ticket.state ==
ticCLOSED);
%         if (mod(time,30*24*60) == 0) || time == Tstop
%             S = whos;
%             disp(['Time: ' sprintf('%5.3g',time/(60*24*30)) ' | '...
%                   '# of tickets: ' sprintf('%5d',ticket.numTickets) ' |
'...
%                   'Bytes Used: ' num2str(sum([S.bytes]))]);
%             if drawDashboard
%                 figure(1);
```

```
%                 mmpolar(satellite.slot,ones(1,numSats),'b.')
%                 hold on;
%                 deadSats = find(satellite.state == satDOWN);
%                 if ~isempty(deadSats)
% %
mmpolar(satellite.slot(deadSats),ones(1,length(deadSats)),'ko');
%                 end;
%                 h = mmpolar(servicer.slot,ones(1,numServ),'r.');
%                 set(h,'MarkerSize',24);
%                 title(['Time: ' num2str(time/(60*24*30))]);
%                 hold off;
%                 figure(2);
%                 bar(servicer.DVavailable);
%                 set(gca,'YLimMode','manual');
%                 set(gca,'YLim',[0 7.7]);
%                 title(['# of tickets: ' num2str(ticket.numTickets)]);
%                 drawnow;
%             end;
%         end;
    end;
    disp(monte);
    save([monteResultsDir 'monte-OOS-Trial-' num2str(monte,'%04d')]);
end;
diary off;
```

---

load_state_names

```
serPARKED = uint8(0);
serTRANSIT = uint8(10);
serSERVICING = uint8(20);
serOUTOFGAS = uint8(30);
serCAPTUREMODE = uint8(11);
serRETURNMODE = uint8(12);

satOPERATING = uint8(0);
satDOWN = uint8(1);

ticINQUEUE = uint8(0);
ticPROCESSING = uint8(1);
ticCLOSED = uint8(2);
ticNONE = uint8(99);
```

---

initialization

```
function [satellite,servicer,ticket] = initialization
load_state_names;
% init servicers
servicer.numServicers = 4;
for i = 1:servicer.numServicers
    servicer.ID(i) = uint16(i);
    servicer.parkAlt(i) = 35786; %km
    servicer.incl(i) = 0; %rad
    servicer.state(i) = serPARKED;
    servicer.DVavailable(i) = 7.7; % km/sec
    servicer.slot(i) = (i-1) * 2*pi/servicer.numServicers;
```

```
end;

% init satellite
% reading from the database
load('UCSGEODATA','OmegaAltIncUCS');
satellite.numSatellites = length(OmegaAltIncUCS);
for ptrSat = 1:satellite.numSatellites;
    satellite.ID(ptrSat) = uint16(ptrSat);
    satellite.incl(ptrSat) = 0; %OmegaAltIncUCS(ptrSat,3);
    satellite.alt(ptrSat) = 35786; %OmegaAltIncUCS(ptrSat,2);
    satellite.slot(ptrSat) = OmegaAltIncUCS(ptrSat,1);
    satellite.downTime(ptrSat) = 0;
    satellite.state(ptrSat) = satOPERATING;
    satellite.NORADID(ptrSat) = OmegaAltIncUCS(ptrSat,4);
    satellite.DVexpended(ptrSat) = 0;
end;

ticket.numTickets = int16(0);
ticket.state = ticNONE;

% put them into orbit
% for i = 1:length(inclinationBinsCntr)
%     for j = 1:length(altitudeBinsCntr)
%         if numOperSC(i,j) ~= 0
%             for k = 1:numOperSC(i,j)
%                 ptrSat = ptrSat + 1;
%                 satellite(ptrSat).ID = ptrSat;
%                 satellite(ptrSat).alt = altitudeBinsCntr(j);
%                 satellite(ptrSat).incl = inclinationBinsCntr(i);
%                 satellite(ptrSat).state = 'operating';
%             end;
%         end;
%     end;
% end;
```

---

satellite_update

```
function [satellite,ticket]=satellite_update(time,satellite,ticket)

load_state_names;

%Sullivan (2005)
probRefuel = 20;
probORU = 4.4;
probRepair = 3.8;   %unpredictable
probGEORelocate = 13;   %half unpredictable
probDeploy = .3;    %unpredictable

%UCS Database (2006)
numGEOSats = 345;
numSats = 773;

numServiceRequests = (numGEOSats/numSats)*(probRefuel + probORU +...
    probRepair + probDeploy) + probGEORelocate; %average in GEO per year
```

```
numUrgentRequests = (numGEOSats/numSats)*(probDeploy + probRepair) +
probGEORelocate*(.5);

probUrgent = numUrgentRequests/numServiceRequests;

probService = numServiceRequests/(365*24*numGEOSats);

opSet = find(satellite.state == satOPERATING);
servInd = find(rand(1,length(opSet)) < probService);

for i = opSet(servInd)%1:numSats
%    if satellite(i).state == satOPERATING
%        if reqRand(i)
            if rand(1)<probUrgent
                satellite.state(i) = satDOWN;
                ticket=generate_ticket(time,satellite,i,ticket);
            else
                ticket=generate_ticket(time,satellite,i,ticket);
            end;
%        end;
%    end;
end;

% increment down time;
downSet = find(satellite.state == satDOWN);
if ~isempty(downSet)
    satellite.downTime(downSet) = satellite.downTime(downSet) + 1;
end;
```

---

generate_ticket

```
function ticket=generate_ticket(time,satellite,satID,ticket)

load_state_names;

ticINQUEUE = uint8(0);

ptr = ticket.numTickets;

% add the ticket to the queue
% advance ptr
ptr = ptr + 1;
% fill in the new ticket
ticket.requestTime(ptr) = time;
ticket.satelliteID(ptr) = satID;
% urgency
switch satellite.state(satID)
    case satDOWN
        ticket.urgent(ptr) = 1;
    case satOPERATING
        ticket.urgent(ptr) = 0;
end;
ticket.state(ptr) = ticINQUEUE;
```

```
ticket.timeToService(ptr) = 24*60; % mins
ticket.ID(ptr) = ptr;
ticket.numTickets = ptr;
```

---

servicer_update

```
function
[servicer,ticket,satellite]=servicer_update(time,servicer,satellite,ticket)

numServicers = length(servicer.ID);
serPARKED = uint8(0);
serTRANSIT = uint8(10);
serSERVICING = uint8(20);
serOUTOFGAS = uint8(30);
serCAPTUREMODE = uint8(11);
serRETURNMODE = uint8(12);

satOPERATING = uint8(0);
satDOWN = uint8(1);

ticINQUEUE = uint8(0);
ticPROCESSING = uint8(1);
ticCLOSED = uint8(2);
ticNONE = uint8(99);

for i = randperm(numServicers)
    switch servicer.state(i)
        case serPARKED
            availTickets = find(ticket.state == ticINQUEUE);
            if ~isempty(availTickets)
                serviceableTickets =
tickets_can_service(servicer,i,satellite,ticket,availTickets);
                if ~isempty(serviceableTickets)
                    ticketToGrab = serviceableTickets(1);
                    [ticket,servicer] =
grab_ticket(time,ticket,ticketToGrab,servicer,i,satellite);
                end;
            end;
        case serTRANSIT
            if time>servicer.transitDone(i)
                ticketBeingServiced = servicer.currTicketID(i);
                satelliteBeingServiced =
ticket.satelliteID(ticketBeingServiced);
%                 switch servicer(i).transitMode
%                     case serCAPTUREMODE
                        servicer.slot(i) =
satellite.slot(satelliteBeingServiced);
                        servicer.state(i) = serSERVICING;
%                         servicer(i).totalDV = servicer(i).totalDV + ...
%                             DV_transit(satelliteBeingServiced.incl -
servicer(i).incl, ...
%                                        servicer(i).incl, ...
%                                        0, ...
%                                        servicer(i).parkAlt, ...
%                                        satelliteBeingServiced.alt) + ...
```

```
%                             DV_proximity;
%                         servicer(i).state = serSERVICING;
%                     case serRETURNMODE
%                         servicer(i).totalDV = servicer(i).totalDV + ...
%                             DV_transit(satelliteBeingServiced.incl -
servicer(i).incl, ...
%                                        satelliteBeingServiced.incl, ...
%                                        0, ...
%                                        servicer(i).parkAlt, ...
%                                        satelliteBeingServiced.alt);
%                         servicer(i).state = serPARKED;
%                 end;
            end;
        case serSERVICING
            if time>servicer.servicingDone(i)
                ticketBeingServed = servicer.currTicketID(i);
                [ticket,servicer,satellite] =
release_ticket(time,ticket,ticketBeingServed,servicer,i,satellite);
                if servicer.DVavailable(i) < DV_proximity
                    servicer.state(i) = serOUTOFGAS;
                end;
            end;
    end;
end;
```

---

tickets_can_service

```
function serviceableTickets =
tickets_can_service(servicer,servicerUsed,satellite,ticket,availTicket)

serPARKED = uint8(0);
serTRANSIT = uint8(10);
serSERVICING = uint8(20);
serOUTOFGAS = uint8(30);
serCAPTUREMODE = uint8(11);
serRETURNMODE = uint8(12);

satOPERATING = uint8(0);
satDOWN = uint8(1);

ticINQUEUE = uint8(0);
ticPROCESSING = uint8(1);
ticCLOSED = uint8(2);
ticNONE = uint8(99);


% Compute DV for each available ticket

serviceableTickets = [];
serviceableTicketsDV = [];


for ticketBeingChecked = availTicket
    targetSatID = ticket.satelliteID(ticketBeingChecked);
    DVcost = 1000*ones(1,servicer.numServicers);
```

```
    slot_tgt = satellite.slot(targetSatID);
    alt = satellite.alt(targetSatID);
    if ticket.urgent(ticketBeingChecked)
        k = 5;
    else
        k = 5;
    end;
    for j=1:servicer.numServicers
        slot_int = servicer.slot(j);
        if servicer.state(j) == serPARKED
            [transitTime,transitDV] = time_dv_phase_slot(slot_int,
slot_tgt,alt,k);
            if servicer.DVavailable(j) > transitDV + DV_proximity
                DVcost(j) = transitDV + DV_proximity;
            end;
        end;
    end;
    [minDV,minDVCI] = min(DVcost);
    if minDV ~= 1000
        if servicerUsed == minDVCI
            serviceableTickets = [serviceableTickets ticketBeingChecked];
            serviceableTicketsDV = [serviceableTicketsDV DVcost(minDVCI)];
            [ans,I] = sort(serviceableTicketsDV);
            serviceableTickets = serviceableTickets(I);
        end;
    end;
end;
```

---

time_dv_phase_slot

```
function [Tphase,dv] = time_dv_phase_slot(slot_int,slot_tgt,alt,k)

Re=6378.13649; % km from SMAAD
Mu=398600.5; %km^3/s^2

Ptgt = 2*pi*sqrt((alt+Re)^3/Mu);

if abs(slot_int-slot_tgt) > pi
    delta_slot = 2*pi - abs(slot_tgt-slot_int);
    if slot_tgt < slot_int
        delta_slot = -delta_slot;
    end;
else
    delta_slot = slot_int-slot_tgt;
end;

% sign of delta_slot indicate direction of phasing
%    (-) means moving prograde
%    (+) means moving retrograde
[Tphase,dv,aphase] = circCoplanerPhasing(alt+Re,delta_slot,k);
if aphase < alt+Re
    while 2*aphase - (alt+Re) < Re + 1000
        k = k+1;
        [Tphase,dv,aphase] = circCoplanerPhasing(alt+Re,delta_slot,k);
    end;
```

```
end;
Tphase = Tphase / 60; % minutes

% determine elements of phasing orbit
%
% k = 1:20;
% [Tphase,dv,aphase] = circCoplanerPhasing(alt+Re,delta_slot,k);
% vlambda = 0:0.1:1;
% minDV = zeros(length(vlambda),1);
% minT = zeros(length(vlambda),1);
% for i = 1:length(vlambda)
%     lambda = vlambda(i);
% %    J = lambda*dv*Ptgt/(alt+Re) + (1-lambda)*Tphase/Ptgt;
%     J = lambda*dv/min(dv) + (1-lambda)*Tphase/min(Tphase);
%     [minJ,minJI] = min(J);
%     if lambda == 0.5
%         aa=minJI;
%     end;
%     minDV(i) = dv(minJI)*Ptgt/(alt+Re);
%     minT(i) = Tphase(minJI)/Ptgt;
% end;
% %plot(minDV,minT,'.');
% plot(dv/mean(dv),Tphase/mean(Tphase),'.');
% text(dv/mean(dv),Tphase/mean(Tphase),num2str([1:20]'));
% [minJ,minJI] = min(hypot(dv/mean(dv),Tphase/mean(Tphase)))
% xlabel('{\Delta}V');
% ylabel('\tau_{phase}');
% keyboard;
```

---

circCoplanerPhasing

```
function [Tphase,dv,aphase] = circCoplanerPhasing(atgt,dphase,k)
% Vallado Alg. 44
Re=6378.13649; % km from SMAAD
Mu=398600.5; %km^3/s^2

ktgt = k; kint = k;

wtgt = sqrt(Mu./atgt.^3);
Tphase = (2*pi*ktgt+dphase)./wtgt;
if Tphase < 0
    disp(' *** negative Tphase ***');
    keyboard;
end;
aphase = (Mu*(Tphase./(2*pi*kint)).^2).^(1/3);
dv = 2*abs(sqrt(2*Mu./atgt - Mu./aphase) - sqrt(Mu./atgt));
```

DV_proximity

```
function out = DV_proximity
 out = 50/1000;
```

---

grab_ticket

```
function [ticket,servicer] =
grab_ticket(time,ticket,ticketToGrab,servicer,assignedServicer,satellite)

load_state_names;

% change the ticket sates

ticket.state(ticketToGrab) = ticPROCESSING;
ticket.servicerID(ticketToGrab) = assignedServicer;
ticket.grabTime(ticketToGrab) = time;
servicer.currTicketID(assignedServicer) = ticketToGrab;

% compute and record transit time

% alt_ini = servicer(assignedServicer).parkAlt;
% alt_fin = satellite(ticket(ticketToGrab).satelliteID).alt;

slot_int = servicer.slot(assignedServicer);
slot_tgt = satellite.slot(ticket.satelliteID(ticketToGrab));

servicer.state(assignedServicer) = serTRANSIT;
servicer.transitMode(assignedServicer) = serCAPTUREMODE;
if ticket.urgent(ticketToGrab)
    k = 5;
else
    k = 5;
end;
[transitTime,transitDV] = time_dv_phase_slot(slot_int, slot_tgt,
satellite.alt(ticket.satelliteID(ticketToGrab)),k); % time_hohmann(alt_ini,
alt_fin); % +time_phasing(alt_ini, alt_fin)
servicer.transitDone(assignedServicer) = time + transitTime;
servicer.servicingDone(assignedServicer) =
servicer.transitDone(assignedServicer) + ticket.timeToService(ticketToGrab);
ticket.DVcost(ticketToGrab) = transitDV + DV_proximity;
```

release_ticket

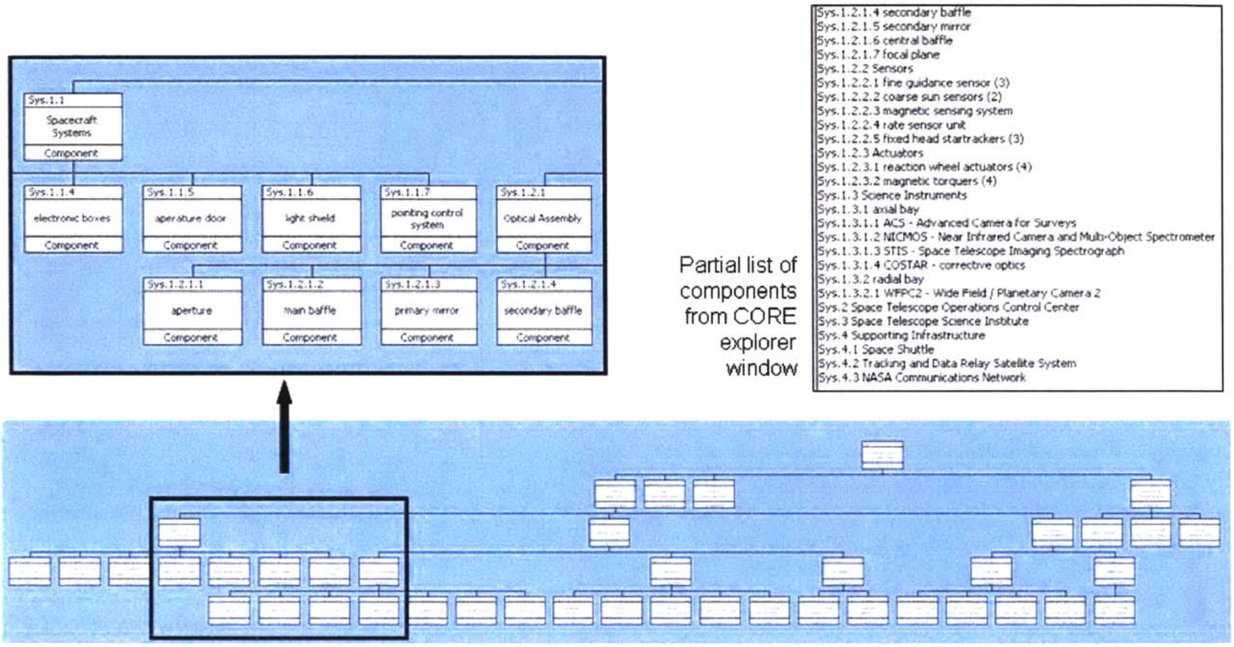
```
function [ticket,servicer,satellite] =
release_ticket(time,ticket,ticketBeingServed,servicer,assignedServicer,satell
ite)

load_state_names;

% change the ticket states

ticket(ticketBeingServed).state = ticCLOSED;
ticket(ticketBeingServed).closeTime = time;

% change satellite state
if ticket(ticketBeingServed).urgent

    satellite(ticket(ticketBeingServed).satelliteID).state = satOPERATING;
end;
```

```
% compute and record transit time
% alt_fin = servicer(assignedServicer).parkAlt;
% alt_ini = satellite(ticket(ticketBeingServed).satelliteID).alt;
% servicer(assignedServicer).state = serTRANSIT;
% servicer(assignedServicer).transitMode = serRETURNMODE;
% transitTime = time_hohmann(alt_ini, alt_fin); % +time_phasing(alt_ini,
alt_fin)
% servicer(assignedServicer).transitDone = time + transitTime;

servicer(assignedServicer).DVavailable =
servicer(assignedServicer).DVavailable - ticket(ticketBeingServed).DVcost;

% record DV expended for this ticket
satellite(ticket(ticketBeingServed).satelliteID).DVexpended = ...
    satellite(ticket(ticketBeingServed).satelliteID).DVexpended +
ticket(ticketBeingServed).DVcost;

servicer(assignedServicer).state = serPARKED;
```

Appendix B. Architecture Framework Work Products

This appendix includes additional CORE diagrams and DoDAF work product constructed for the Hubble Space Telescope as well as an EEFBD tracing the activities in a proposed robotic Hubble servicing mission for Hubble. This appendix concludes with two operational view work products for a space tug architecture.

Hubble Systems Interface Description

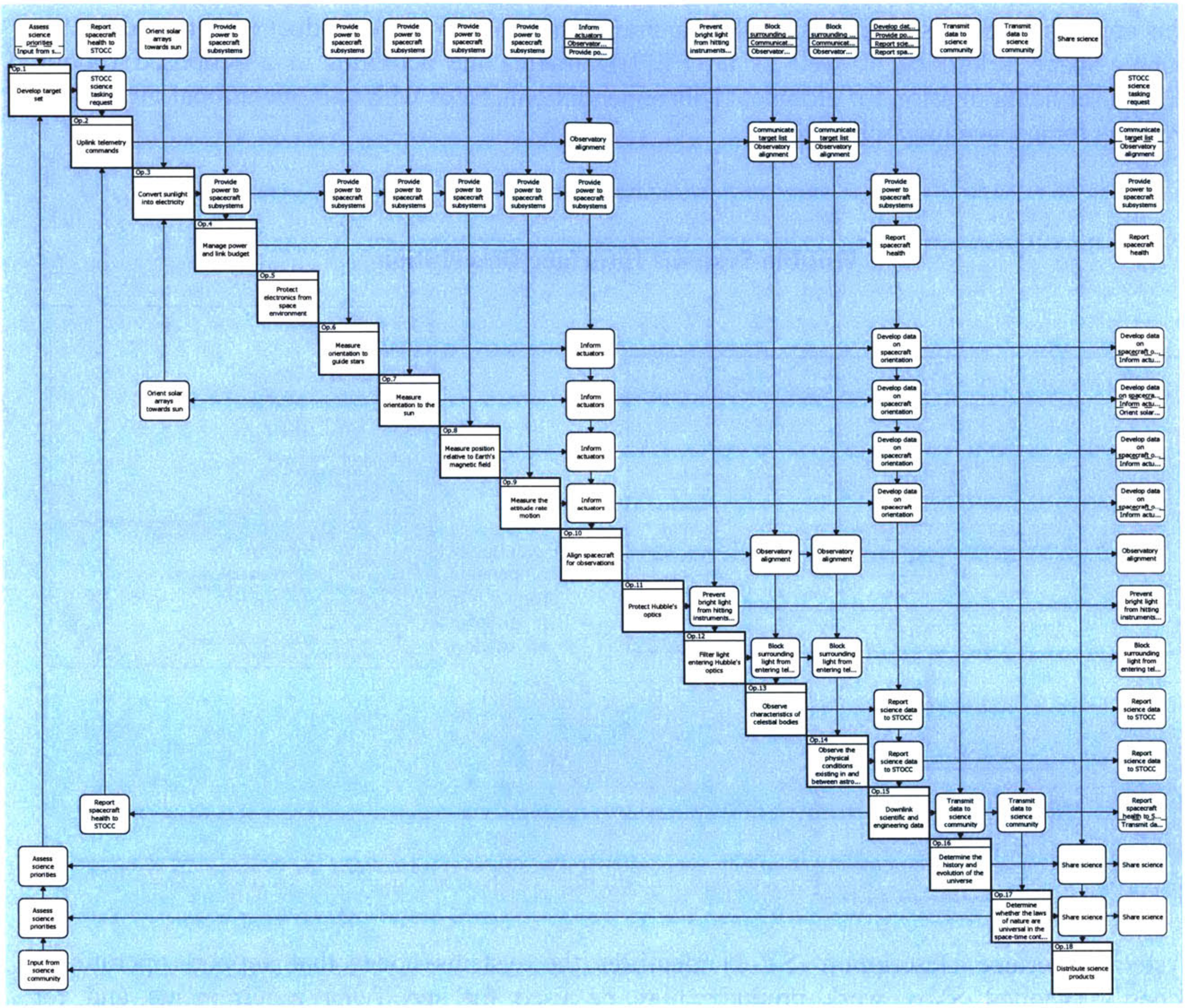


Partial list of components from CORE explorer window

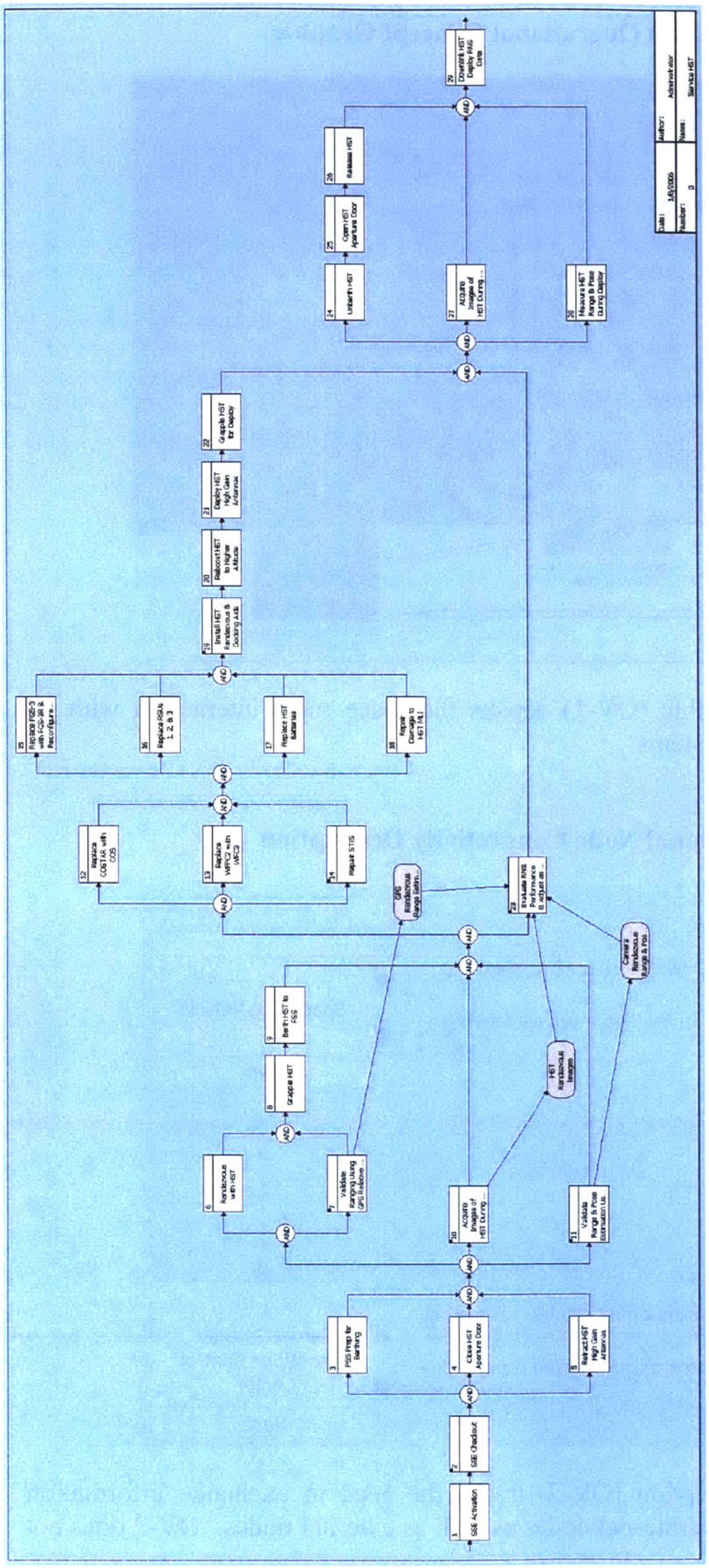
Sys.1.2.1.4 secondary baffle
Sys.1.2.1.5 secondary mirror
Sys.1.2.1.6 central baffle
Sys.1.2.1.7 focal plane
Sys.1.2.2 Sensors
Sys.1.2.2.1 fine guidance sensor (3)
Sys.1.2.2.2 coarse sun sensors (2)
Sys.1.2.2.3 magnetic sensing system
Sys.1.2.2.4 rate sensor unit
Sys.1.2.2.5 fixed head startrackers (3)
Sys.1.2.3 Actuators
Sys.1.2.3.1 reaction wheel actuators (4)
Sys.1.2.3.2 magnetic torquers (4)
Sys.1.3 Science Instruments
Sys.1.3.1 axial bay
Sys.1.3.1.1 ACS - Advanced Camera for Surveys
Sys.1.3.1.2 NICMOS - Near Infrared Camera and Multi-Object Spectrometer
Sys.1.3.1.3 STIS - Space Telescope Imaging Spectrograph
Sys.1.3.1.4 COSTAR - corrective optics
Sys.1.3.2 radial bay
Sys.1.3.2.1 WFPC2 - Wide Field / Planetary Camera 2
Sys.2 Space Telescope Operations Control Center
Sys.3 Space Telescope Science Institute
Sys.4 Supporting Infrastructure
Sys.4.1 Space Shuttle
Sys.4.2 Tracking and Data Relay Satellite System
Sys.4.3 NASA Communications Network

Systems Interface Description (SV-1) identifies the systems nodes that support operational nodes. Detailed SV-1 work products may be used for specifying requirements and for interoperability assessments. The SV-1 DoDAF representation identified 42 system components of Hubble. Decomposition ranged across five levels.

Hubble Operational Activity Model (OV-5) – N2 Representation



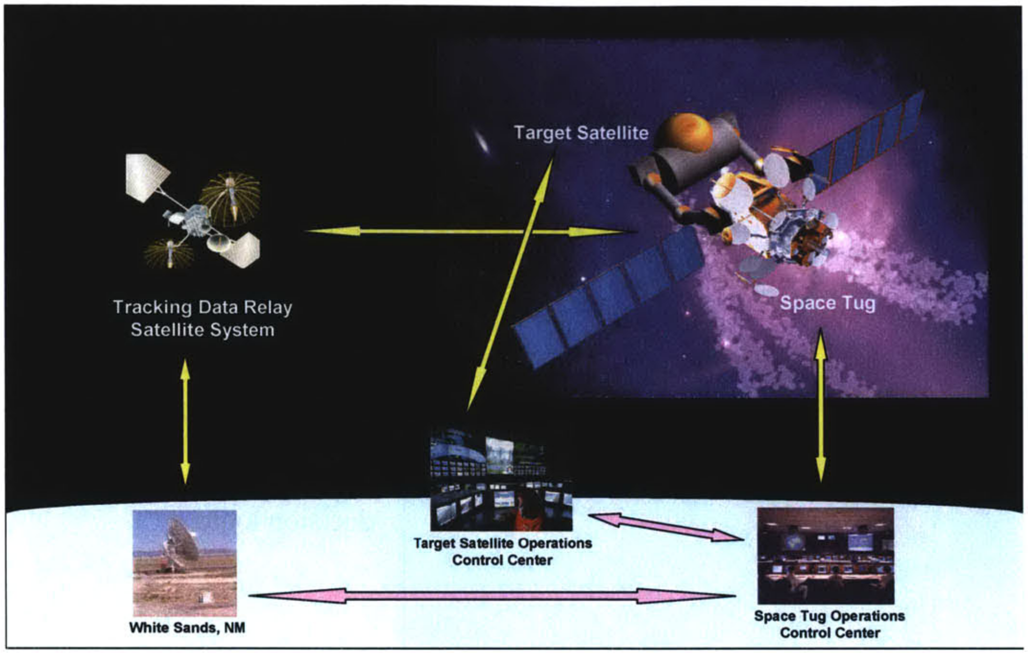
1. Develop target set
2. Uplink telemetry commands
3. Convert sunlight into electricity
4. Manage power and link budget
5. Protect electronics from space environment
6. Measure orientation to two guide stars
7. Measure orientation to the sun
8. Measure position relative to Earth's magnetic field
9. Measure the attitude rate motion
10. Align spacecraft for observations
11. Protect Hubble's optics
12. Filter light entering Hubble's optics
13. Observe characteristics of celestial bodies
14. Observe the physical conditions existing in and between astronomical objects
15. Downlink scientific and engineering data
16. Determine the history and evolution of the universe
17. Determine whether the laws of nature are universal in the space-time continuum
18. Distribute science products



Enhanced Functional Flow Block Diagram of Hubble Robotic Servicing Mission

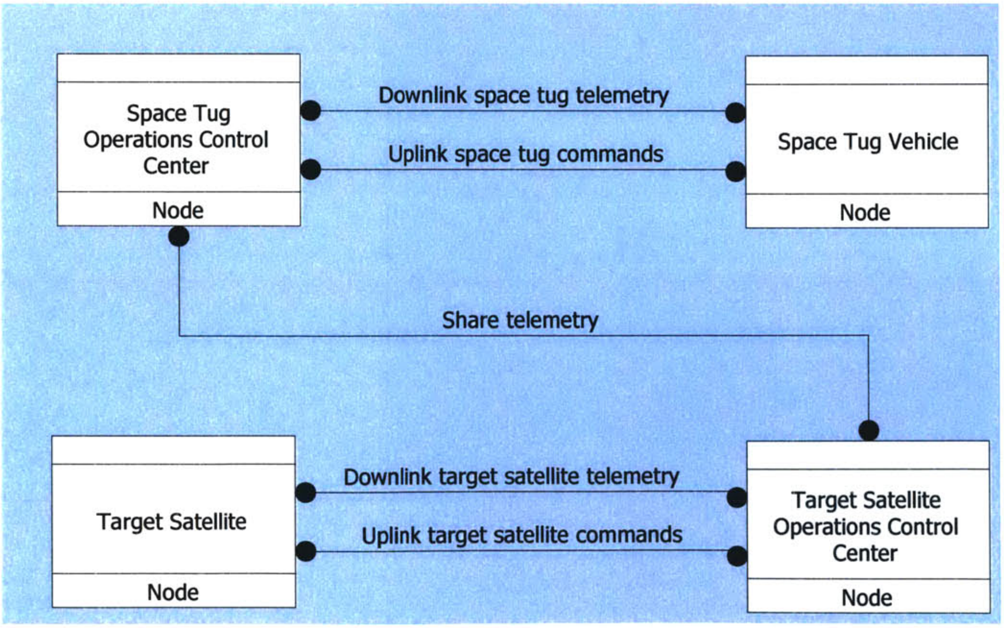
This alternative EEFBD representation of a hypothetical Hubble robotic servicing mission was developed by Rich Fink at NASA Goddard Space Flight Center. It was received shortly after completing the CORE servicing simulation. System behaviors are represented using sequential, parallel, repetitive, and decision logic.

Space Tug High Level Operational Concept Graphic



High Level Operational Concept Graphic (OV-1) depicts the space tug's interaction with its environment as well as with external systems

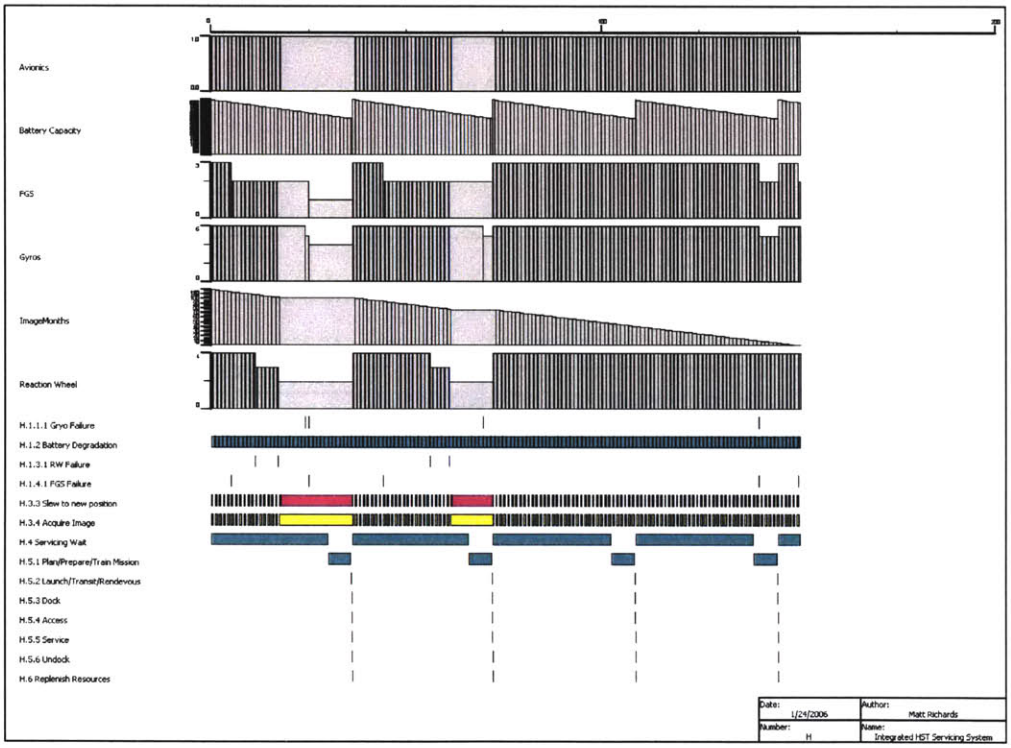
Space Tug Operational Node Connectivity Description



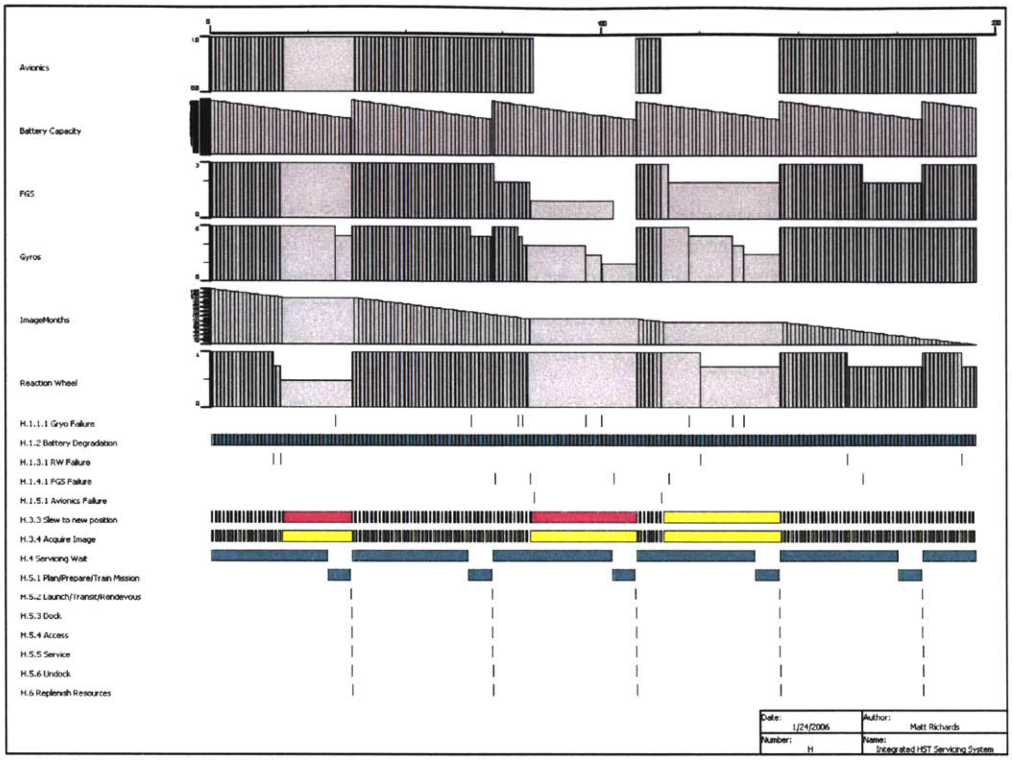
Operational Node Connectivity Description (OV-2) tracks the need to exchange information across nodes. This includes internal operational nodes as well as external nodes. OV-2 does not depict the connectivity between nodes.

Appendix C. Hubble Servicing Simulation – Space Shuttle

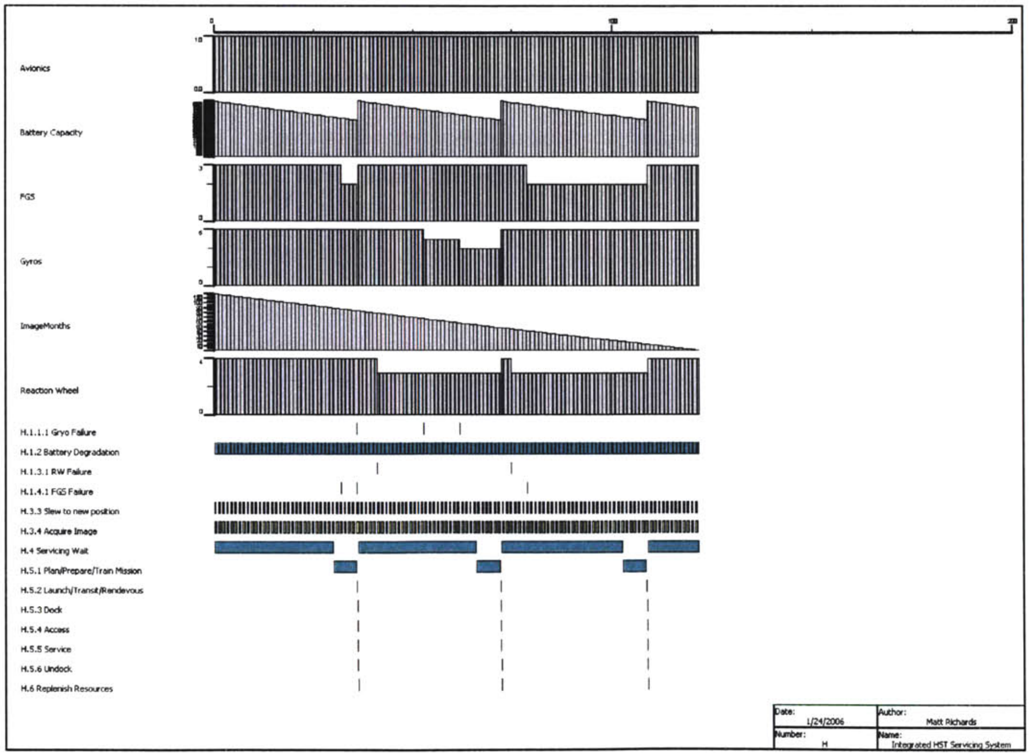
Using CORE's discrete event simulator, the dynamic performance and functional behavior of Hubble was analyzed. The simulator outputs a timeline of functional activation, execution, and duration. Wait states, resource inventory history, and queuing triggers (items waiting to be processed by functions) are all depicted. Colored duration bars are used to represent different types of events. Grey specifies the amount of resources available, teal indicates the execution of a function, yellow indicates that a function is enabled but waiting for a trigger, and magenta indicates that a function is enabled but waiting for resources. Given the probabilistic outcomes of any given simulation, a Monte Carlo analysis was performed with 25 simulation runs to characterize Shuttle performance.



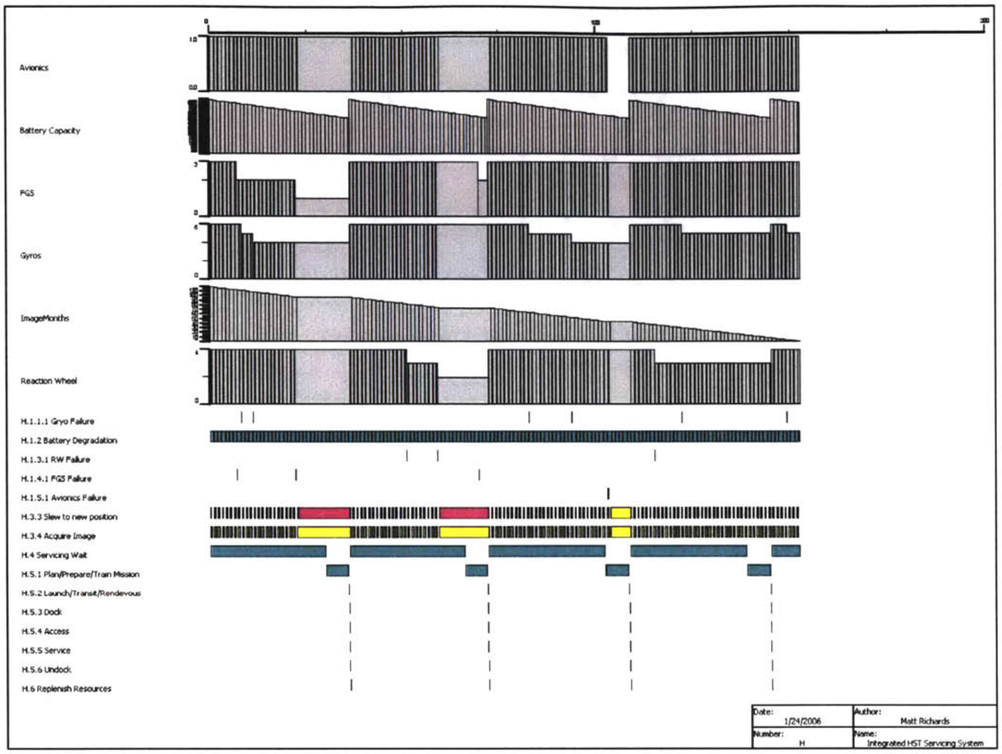
Hubble Servicing Simulation – Space Shuttle Run #1



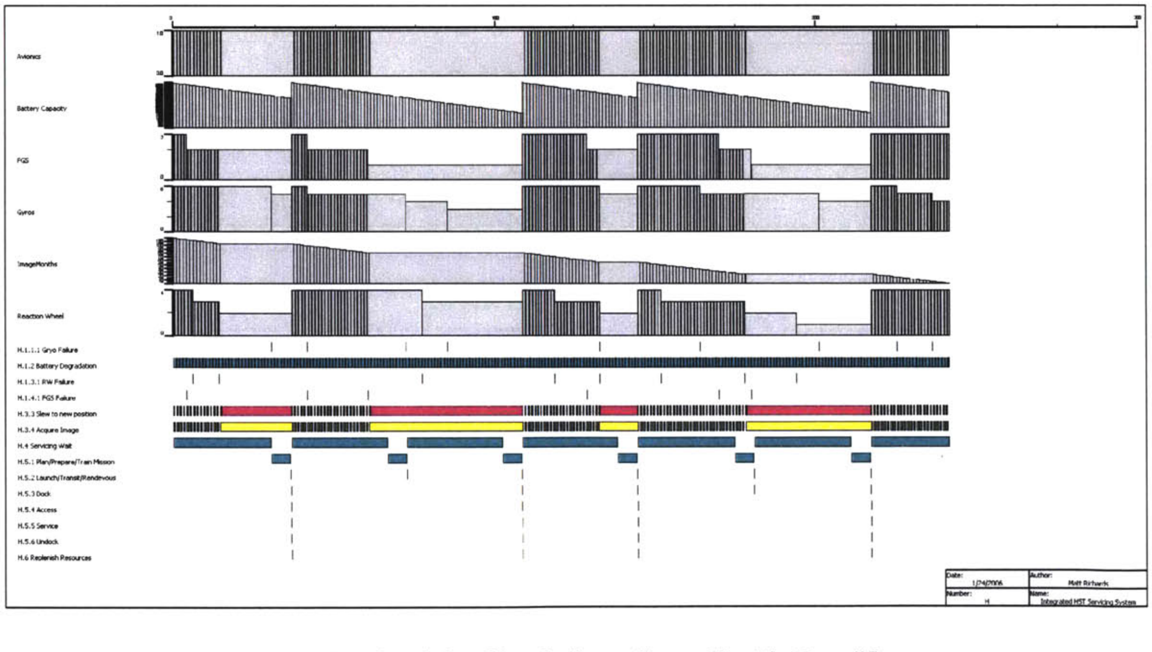
Hubble Servicing Simulation – Space Shuttle Run #2



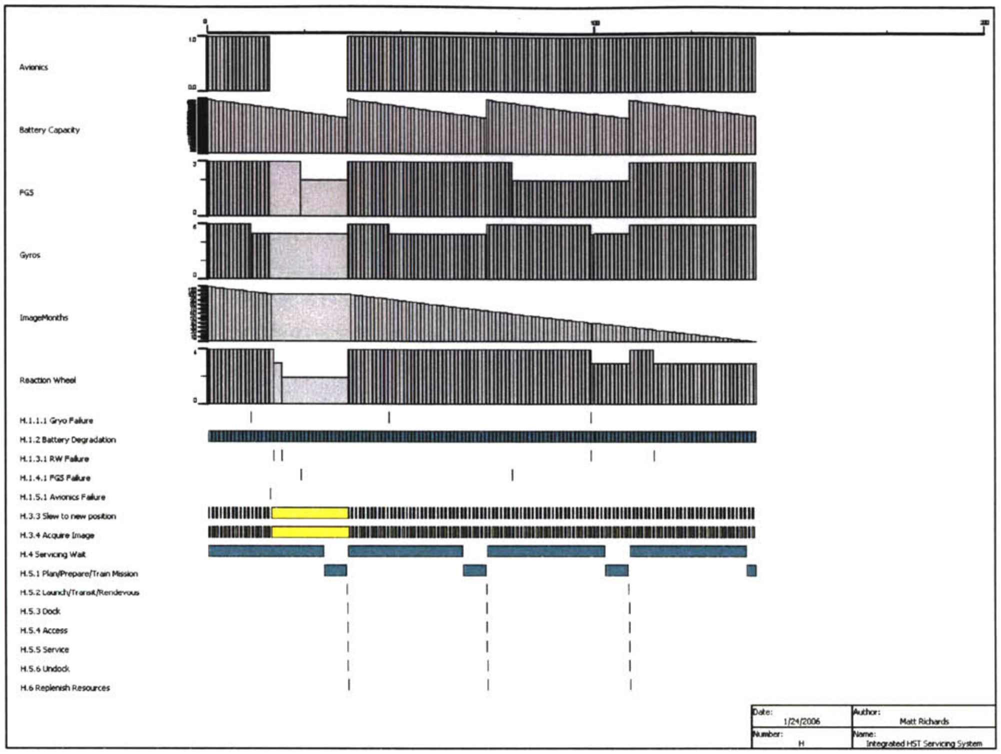
Hubble Servicing Simulation – Space Shuttle Run #3



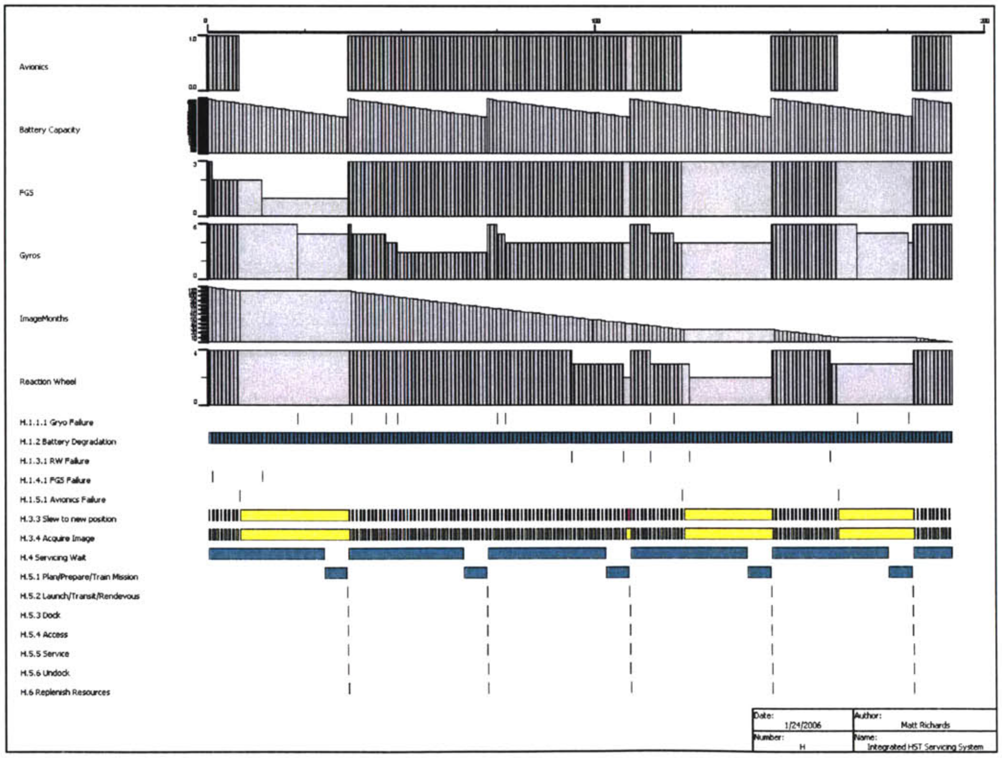
Hubble Servicing Simulation – Space Shuttle Run #4



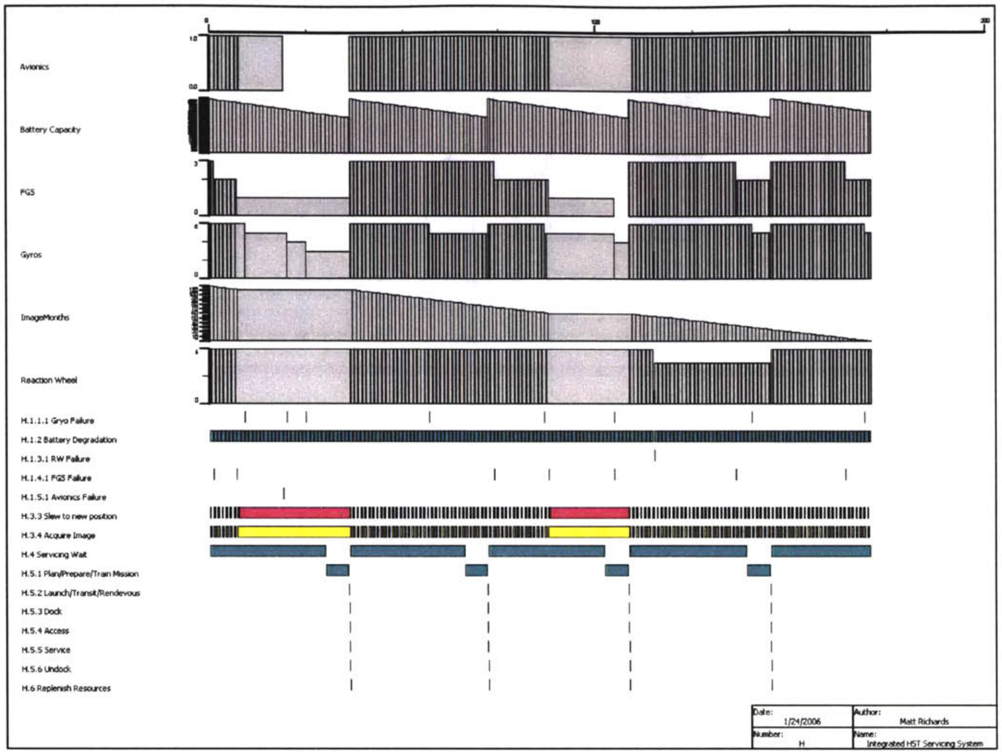
Hubble Servicing Simulation – Space Shuttle Run #5



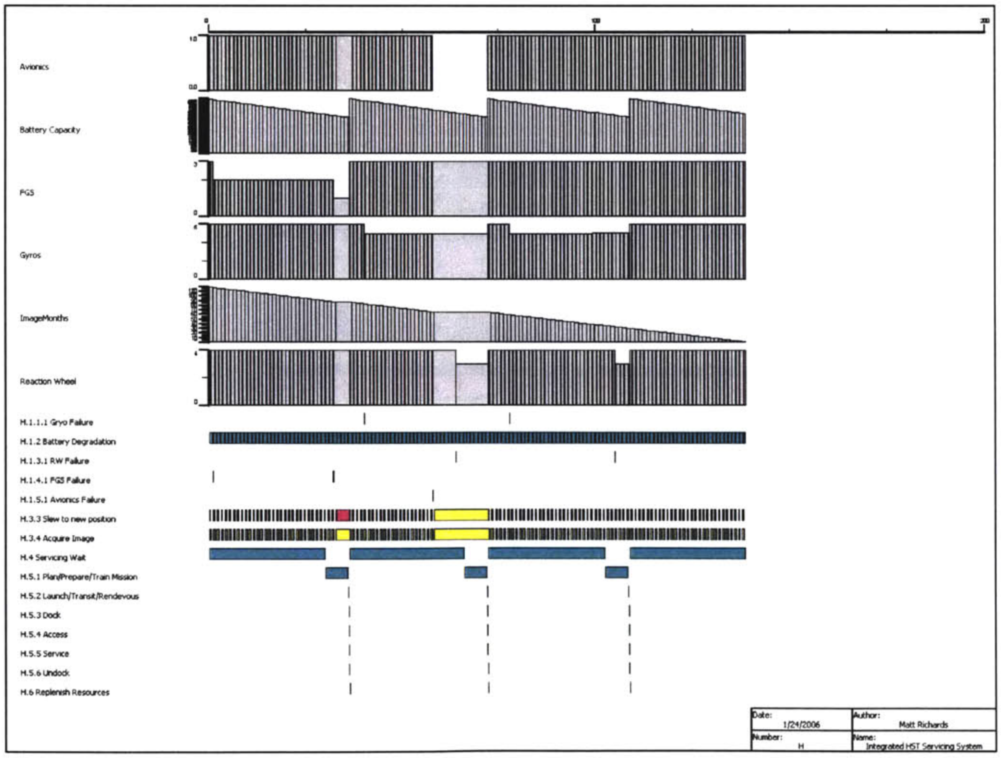
Hubble Servicing Simulation – Space Shuttle Run #6



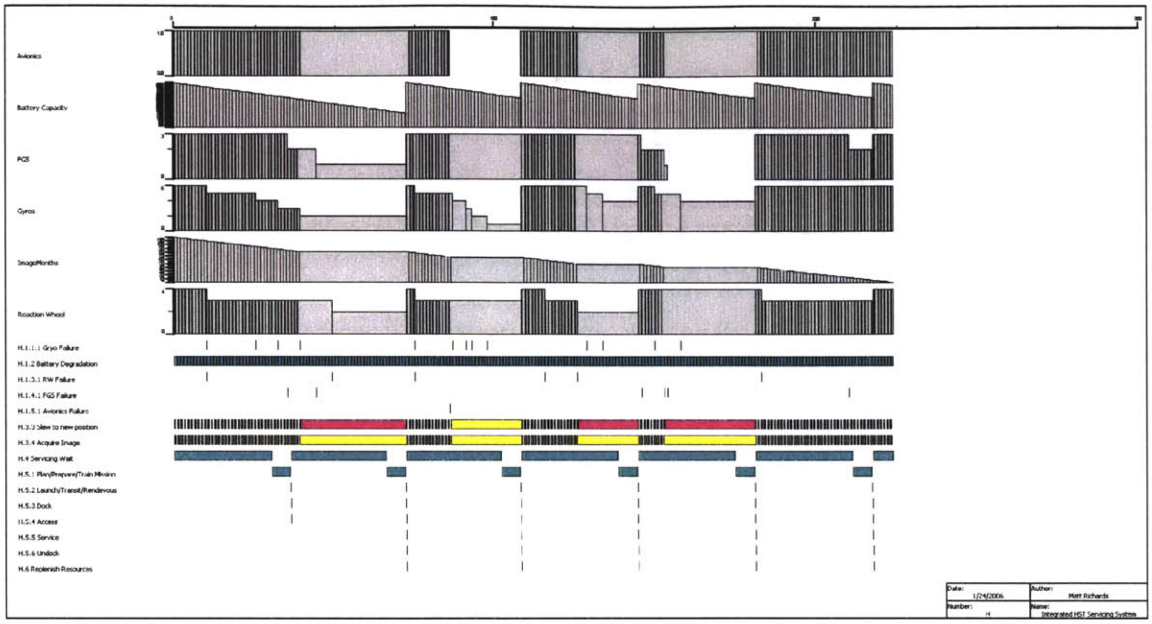
Hubble Servicing Simulation – Space Shuttle Run #7



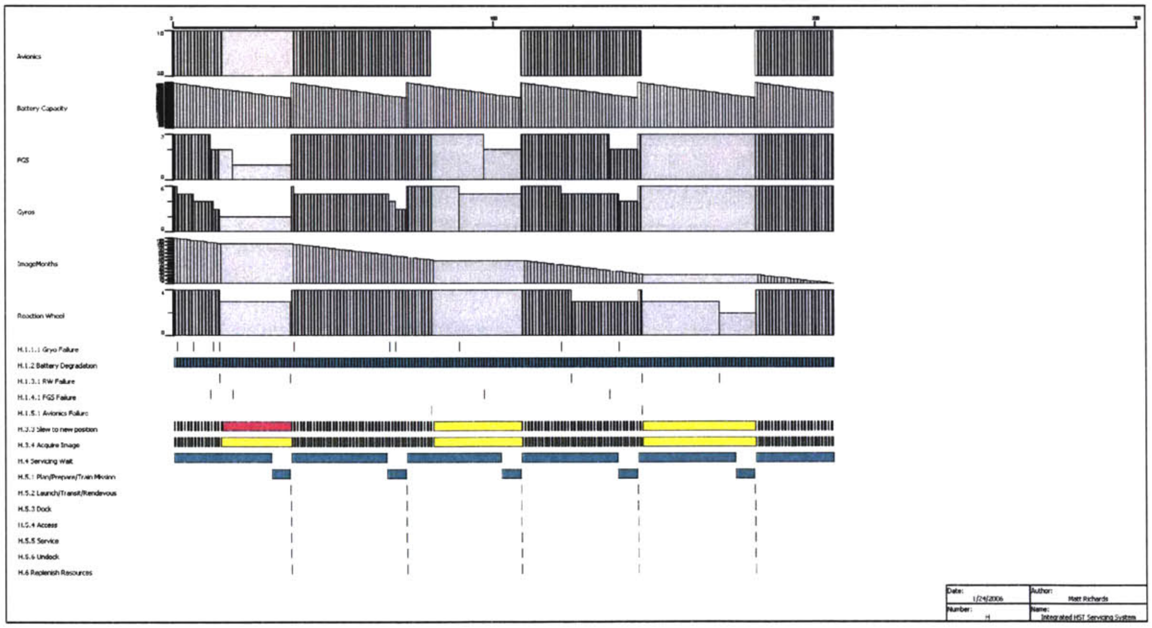
Hubble Servicing Simulation – Space Shuttle Run #8



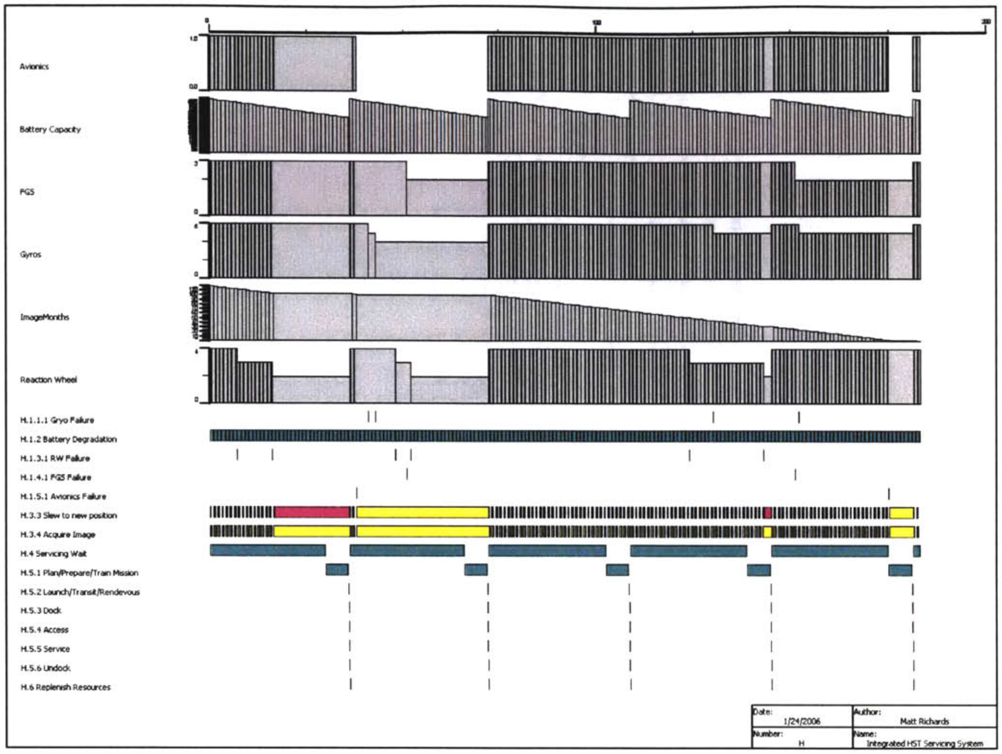
Hubble Servicing Simulation – Space Shuttle Run #9



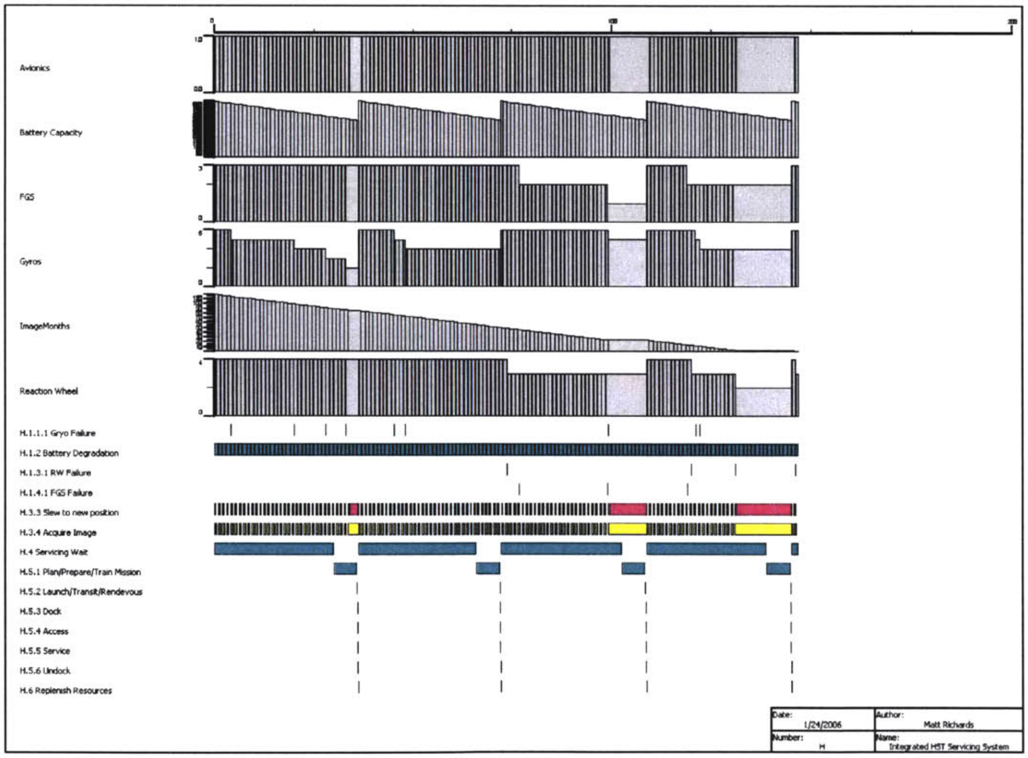
Hubble Servicing Simulation – Space Shuttle Run #10



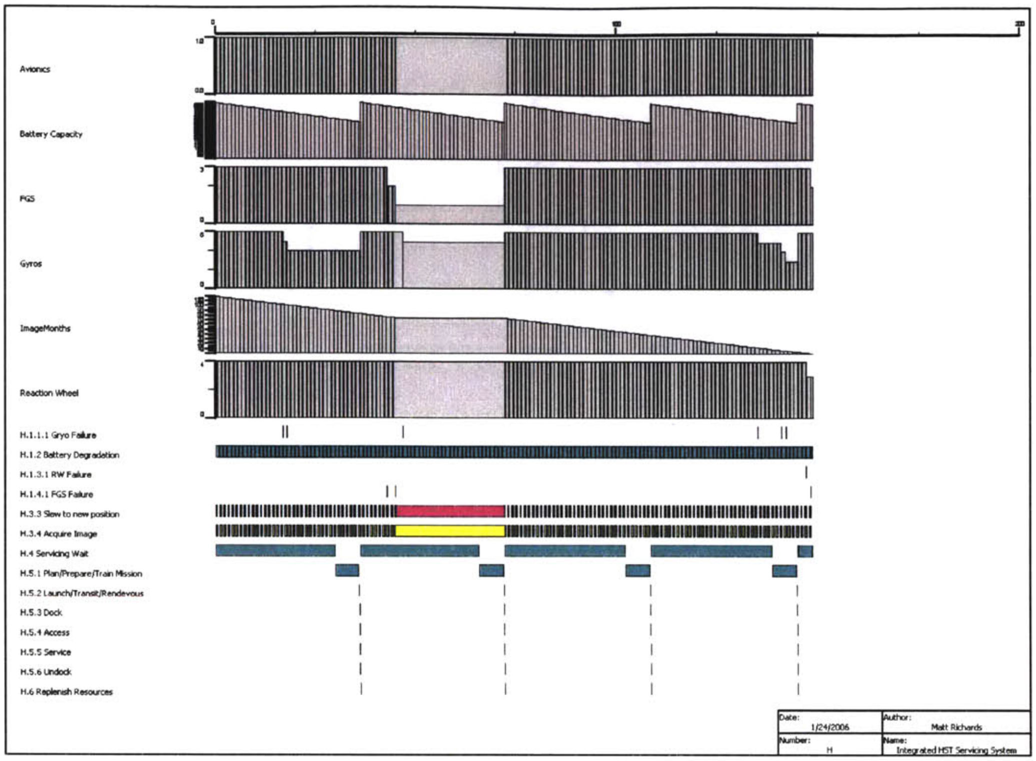
Hubble Servicing Simulation – Space Shuttle Run #11



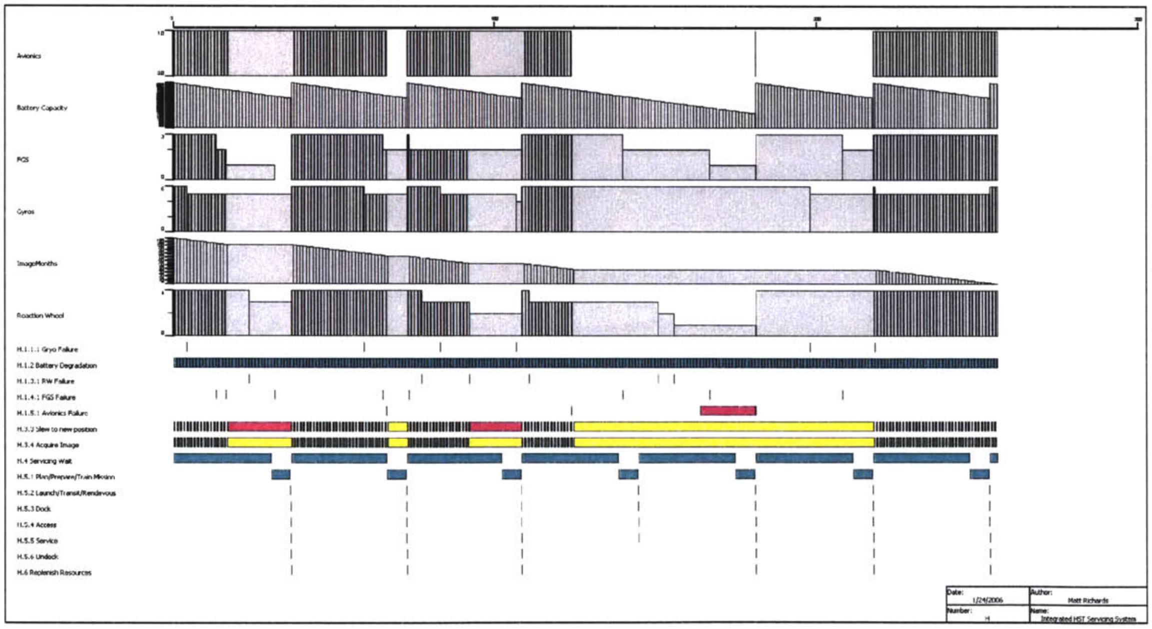
Hubble Servicing Simulation – Space Shuttle Run #12



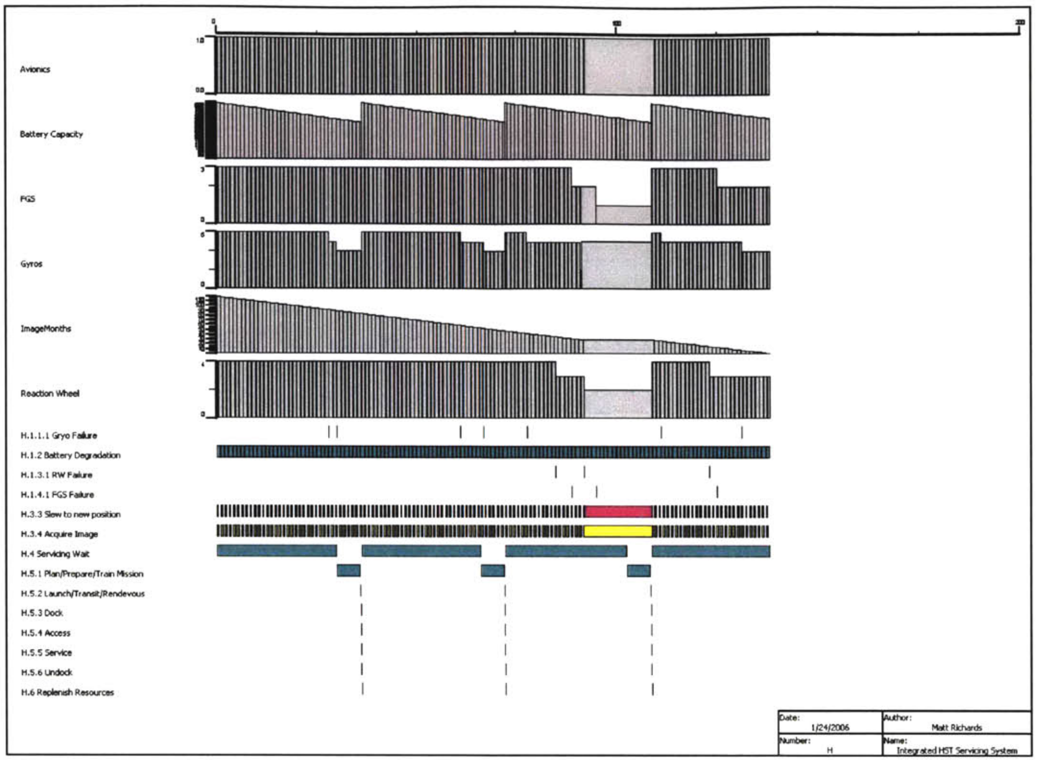
Hubble Servicing Simulation – Space Shuttle Run #13



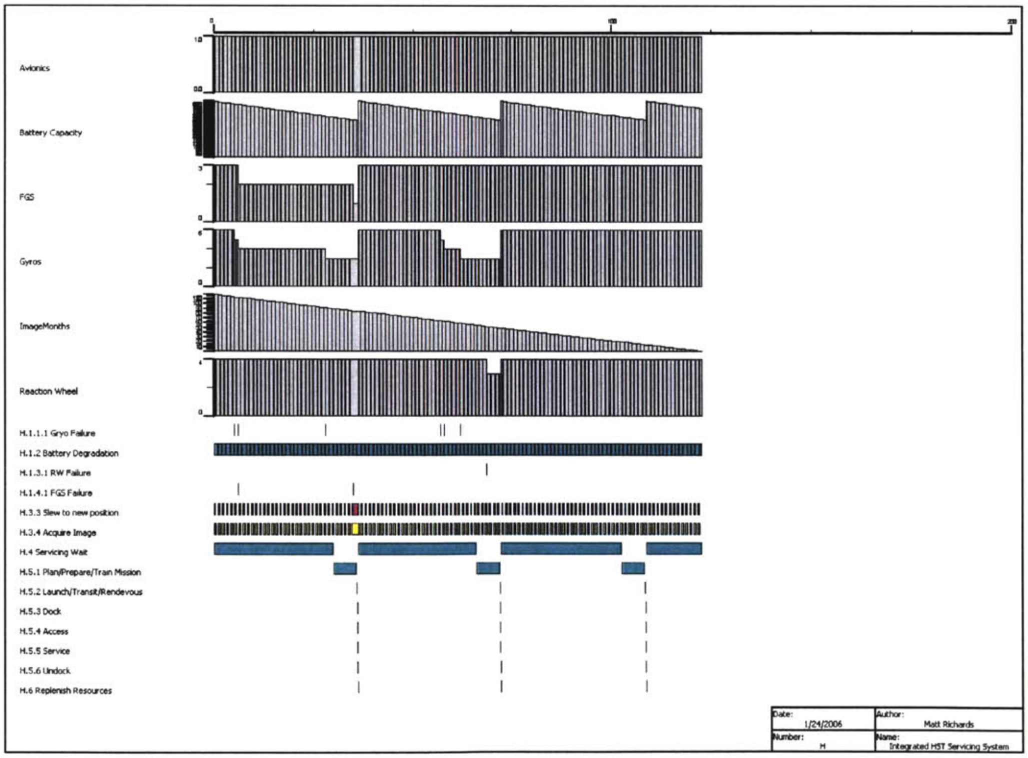
Hubble Servicing Simulation – Space Shuttle Run #14



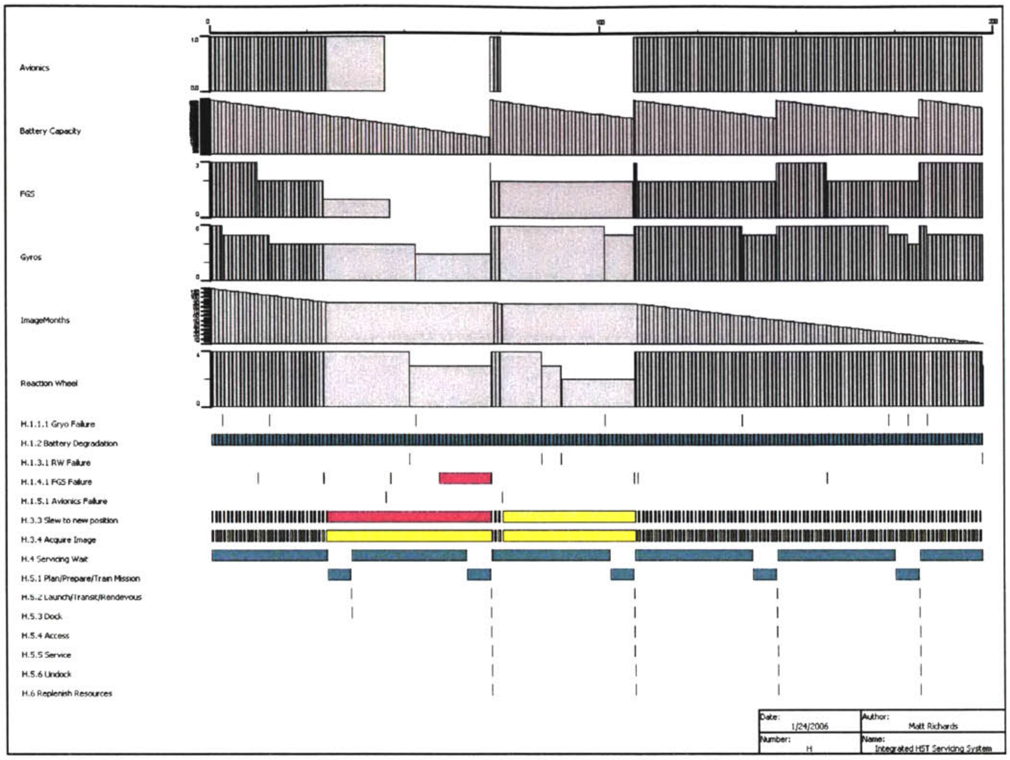
Hubble Servicing Simulation – Space Shuttle Run #15



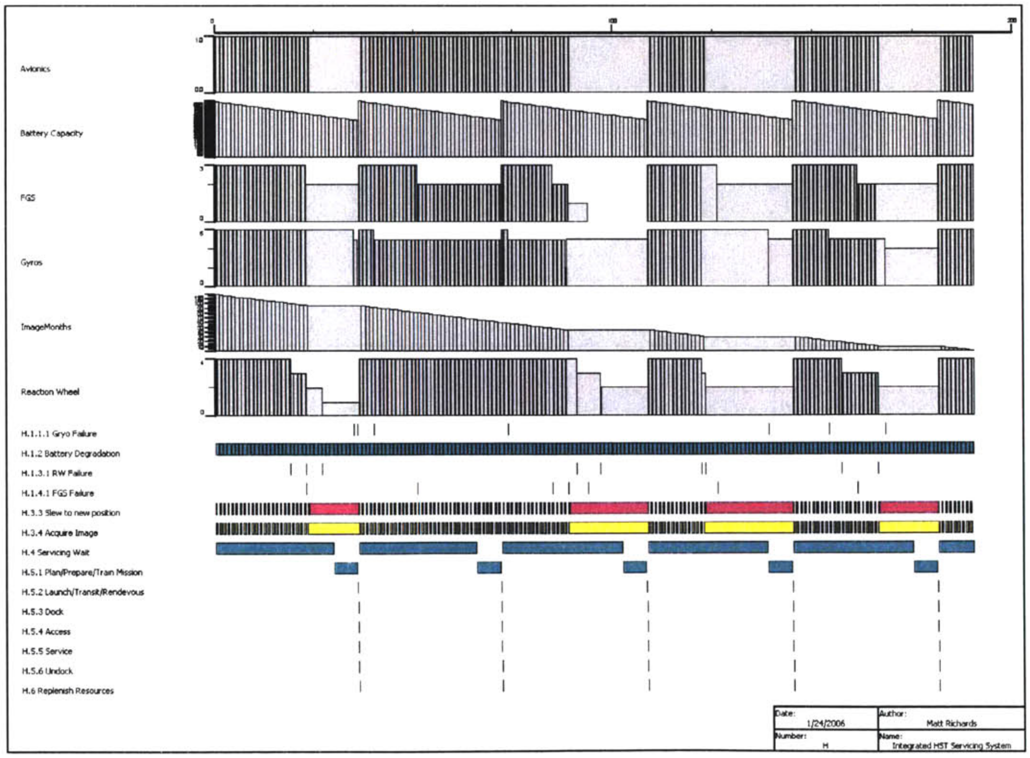
Hubble Servicing Simulation – Space Shuttle Run #16



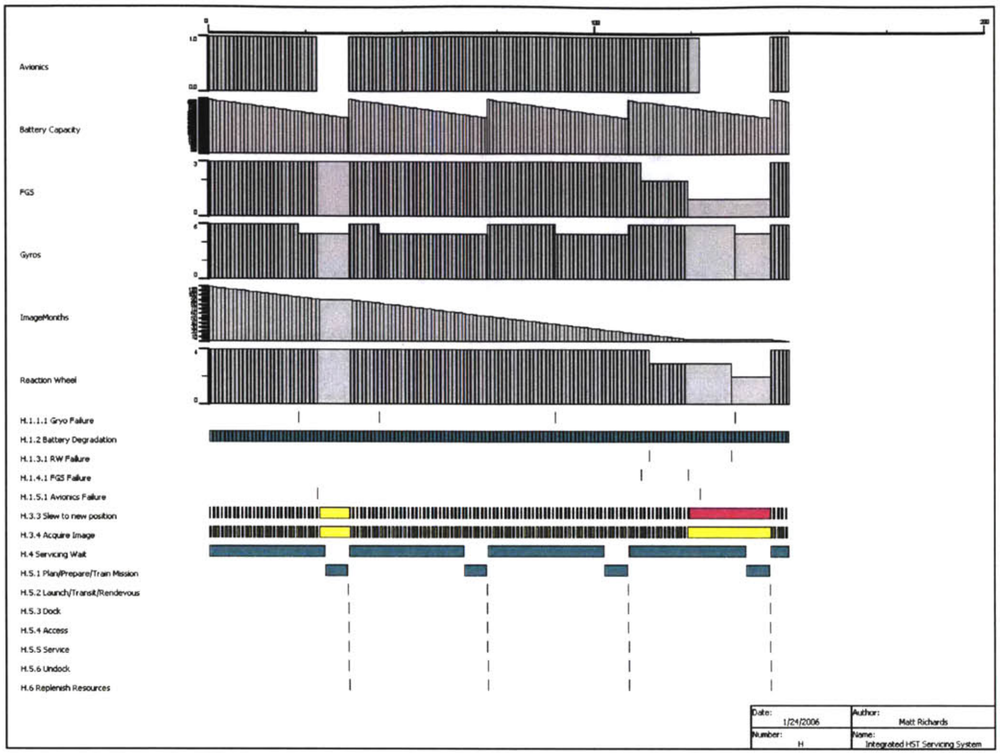
Hubble Servicing Simulation – Space Shuttle Run #17



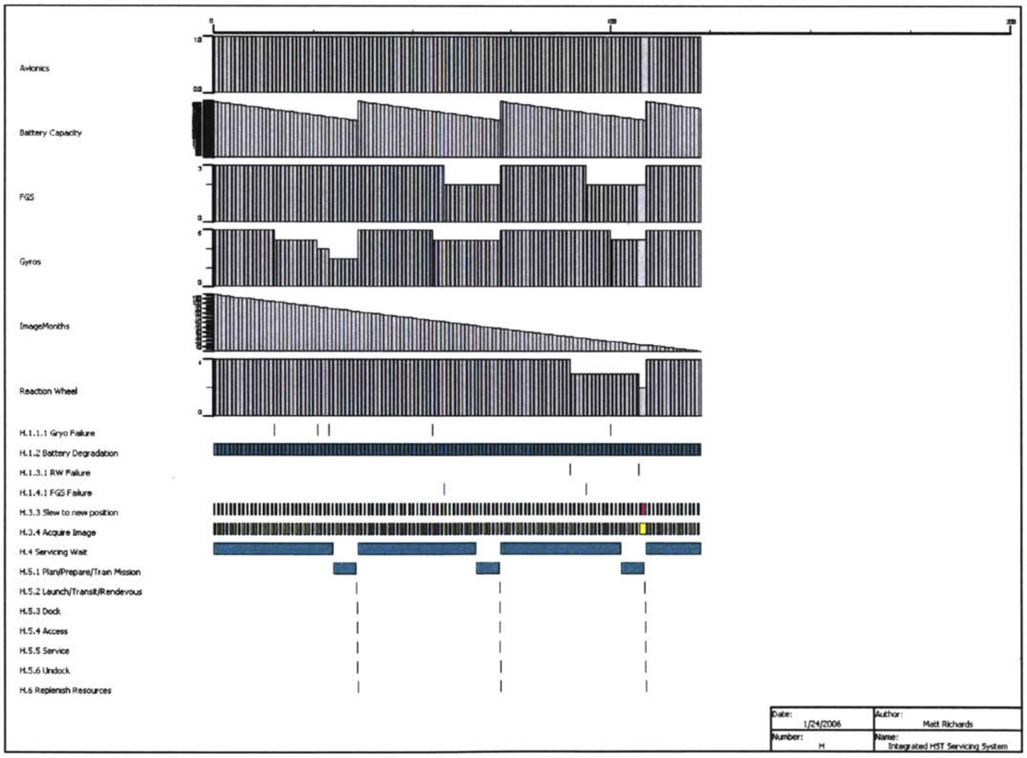
Hubble Servicing Simulation – Space Shuttle Run #18



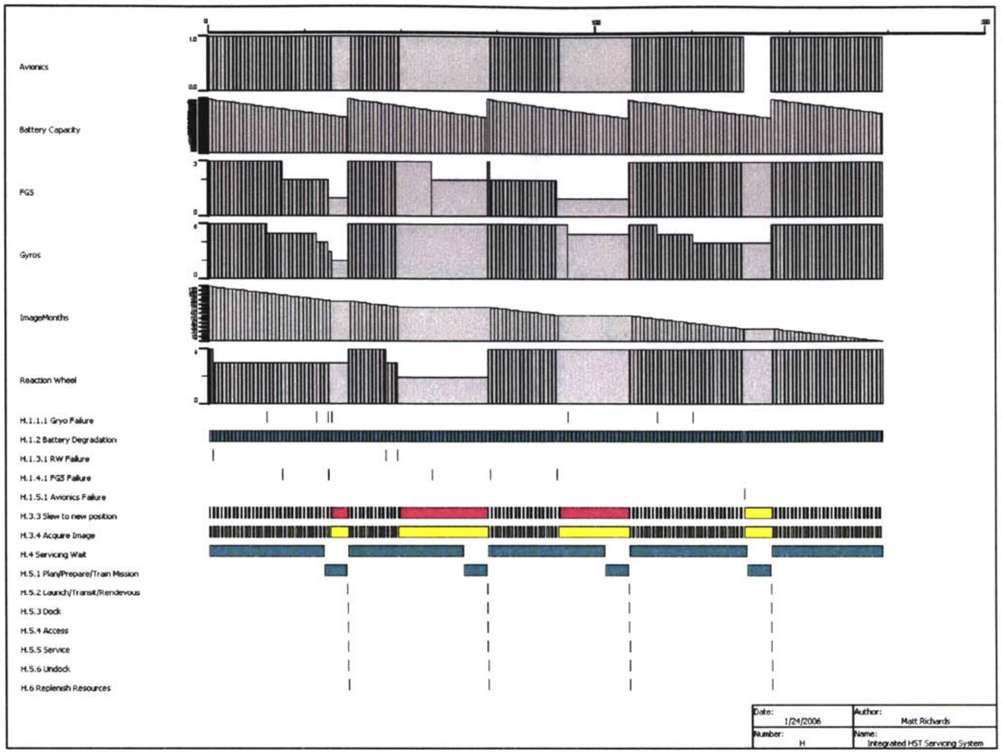
Hubble Servicing Simulation – Space Shuttle Run #19



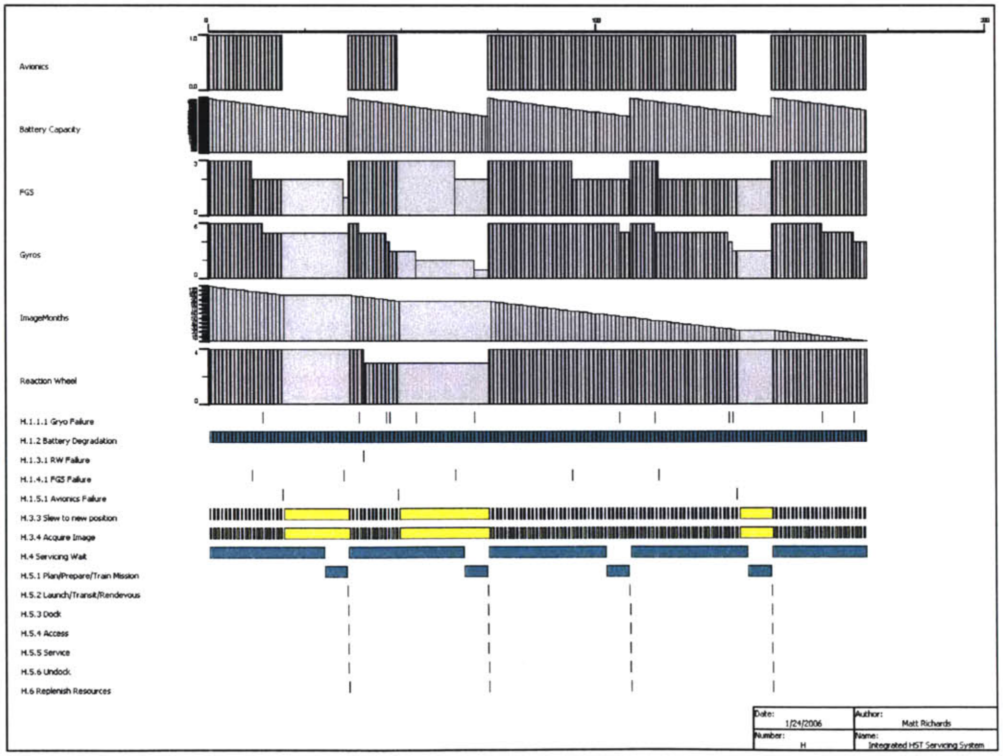
Hubble Servicing Simulation – Space Shuttle Run #20



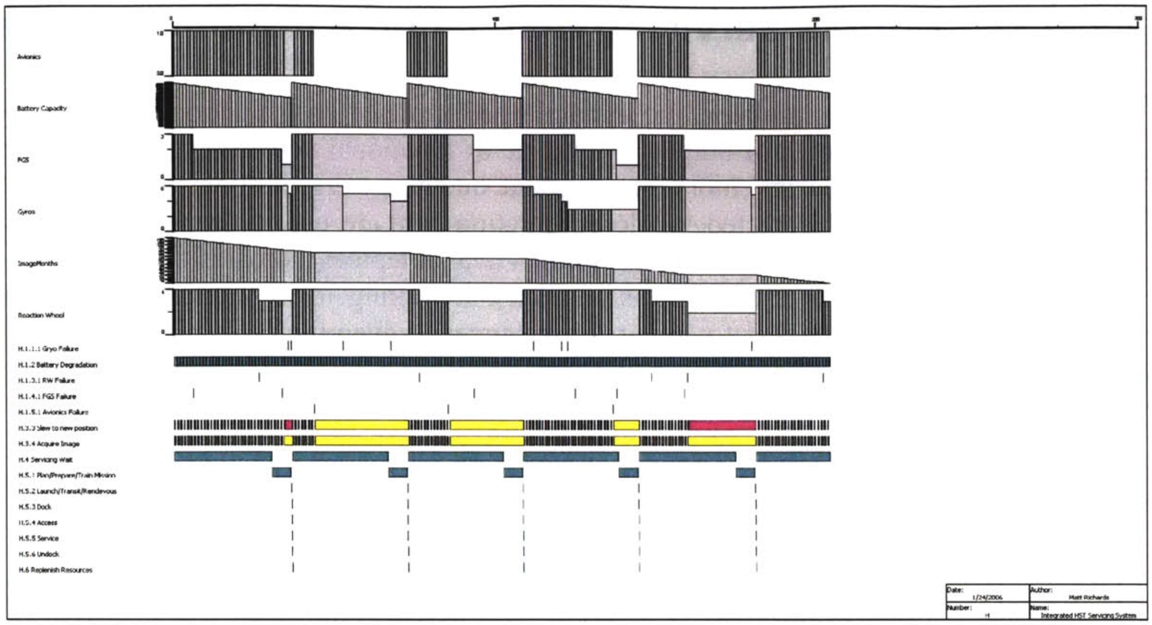
Hubble Servicing Simulation – Space Shuttle Run #21



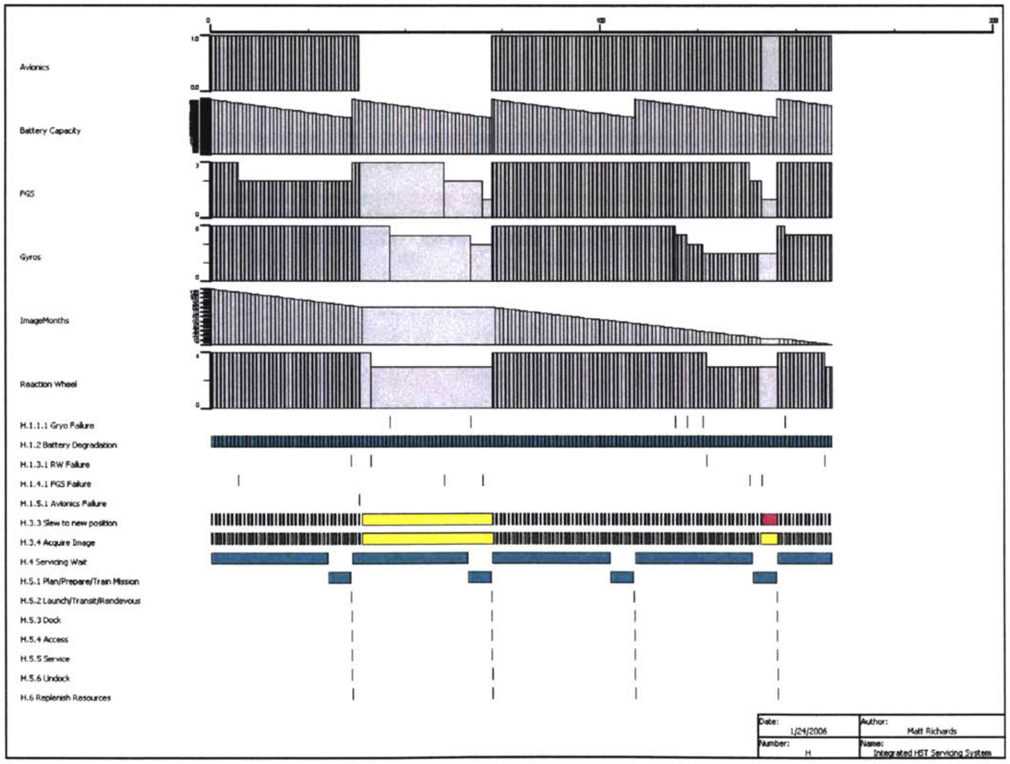
Hubble Servicing Simulation – Space Shuttle Run #22



Hubble Servicing Simulation – Space Shuttle Run #23



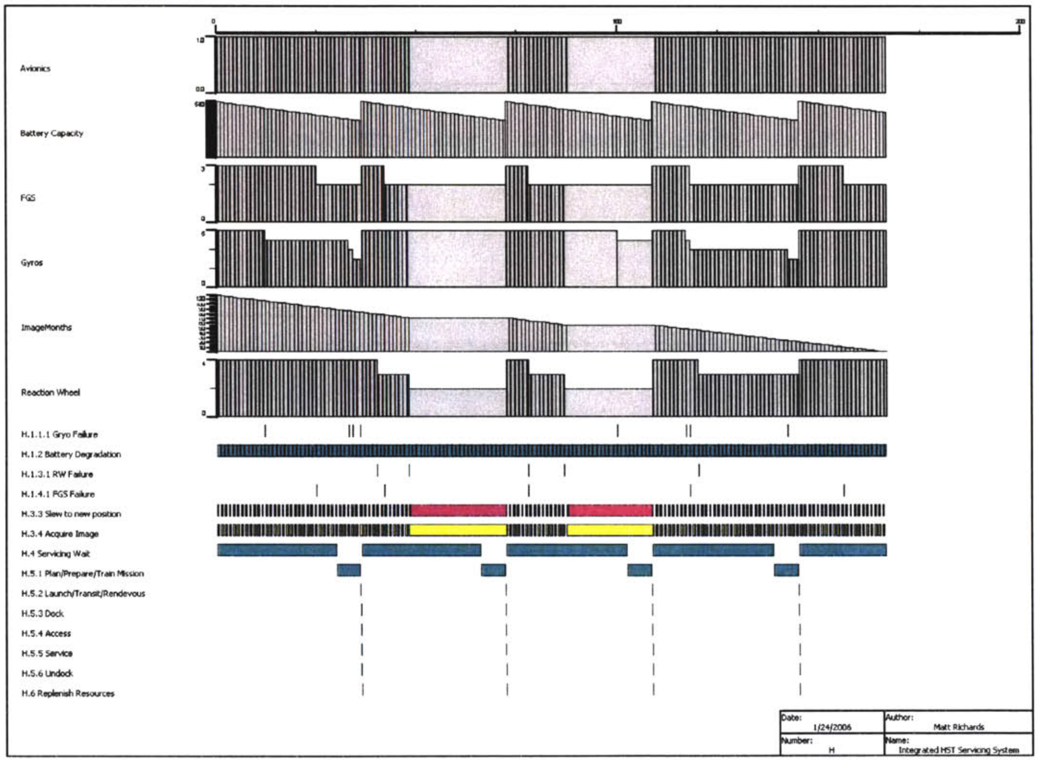
Hubble Servicing Simulation – Space Shuttle Run #24



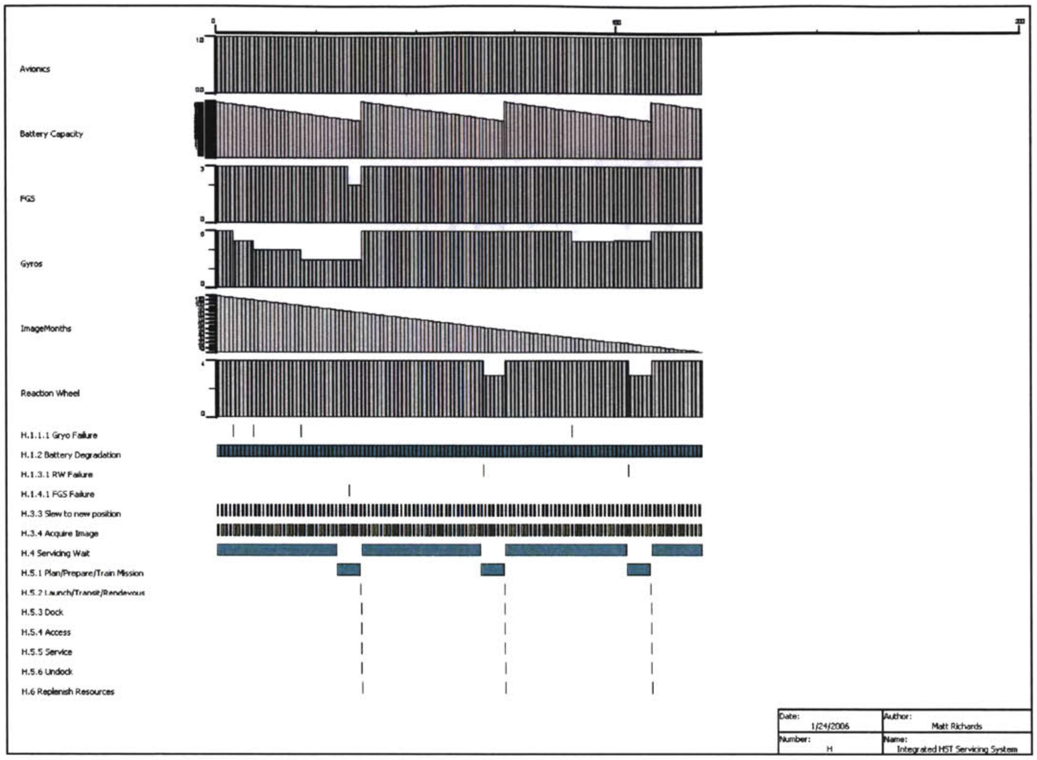
Hubble Servicing Simulation – Space Shuttle Run #25

Appendix D. Hubble Servicing Simulation – Robotic Vehicle

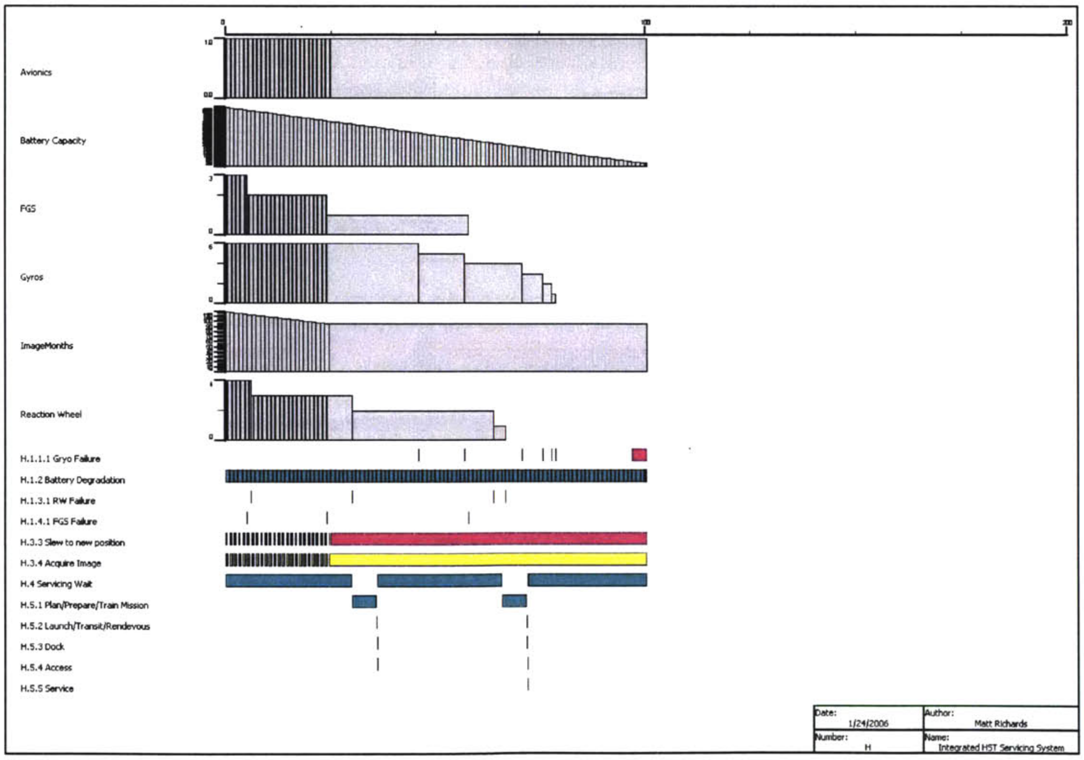
Using CORE's discrete event simulator, the dynamic performance and functional behavior of Hubble was analyzed. The simulator outputs a timeline of functional activation, execution, and duration. Wait states, resource inventory history, and queuing triggers (items waiting to be processed by functions) are all depicted. Colored duration bars are used to represent different types of events. Grey specifies the amount of resources available, teal indicates the execution of a function, yellow indicates that a function is enabled but waiting for a trigger, and magenta indicates that a function is enabled but waiting for resources. Given the probabilistic outcomes of any given simulation, a monte carlo analysis was performed with 25 simulation runs to characterize robotic vehicle performance.



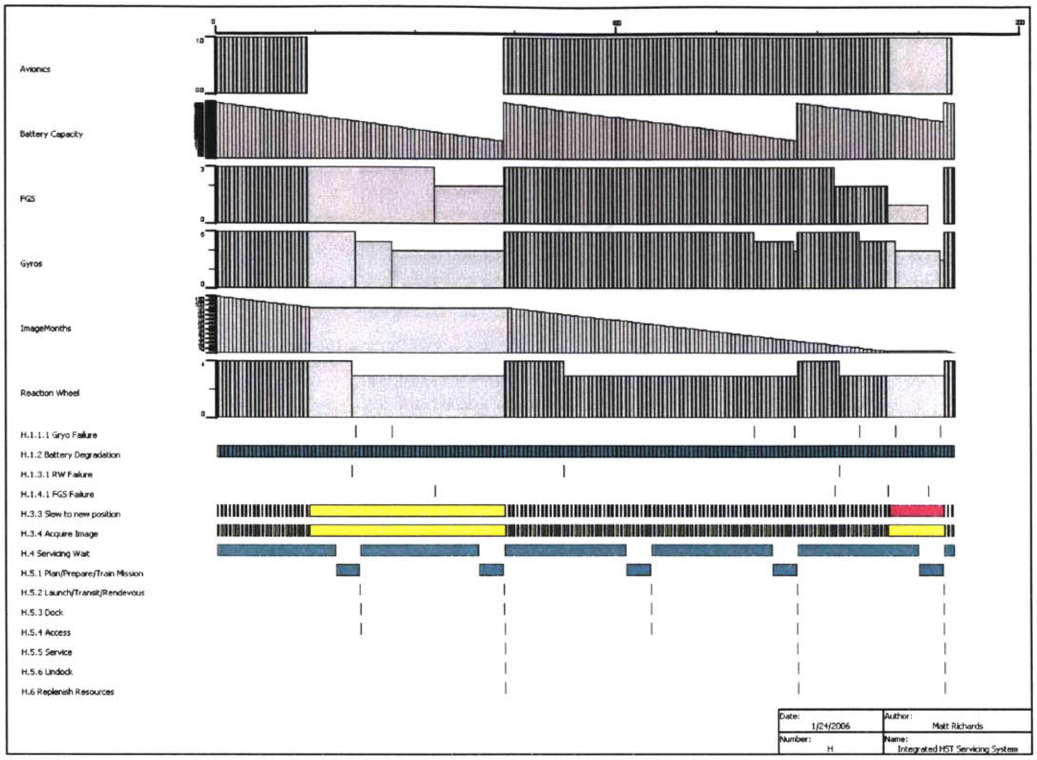
Hubble Servicing Simulation – Robotic Vehicle Run #1



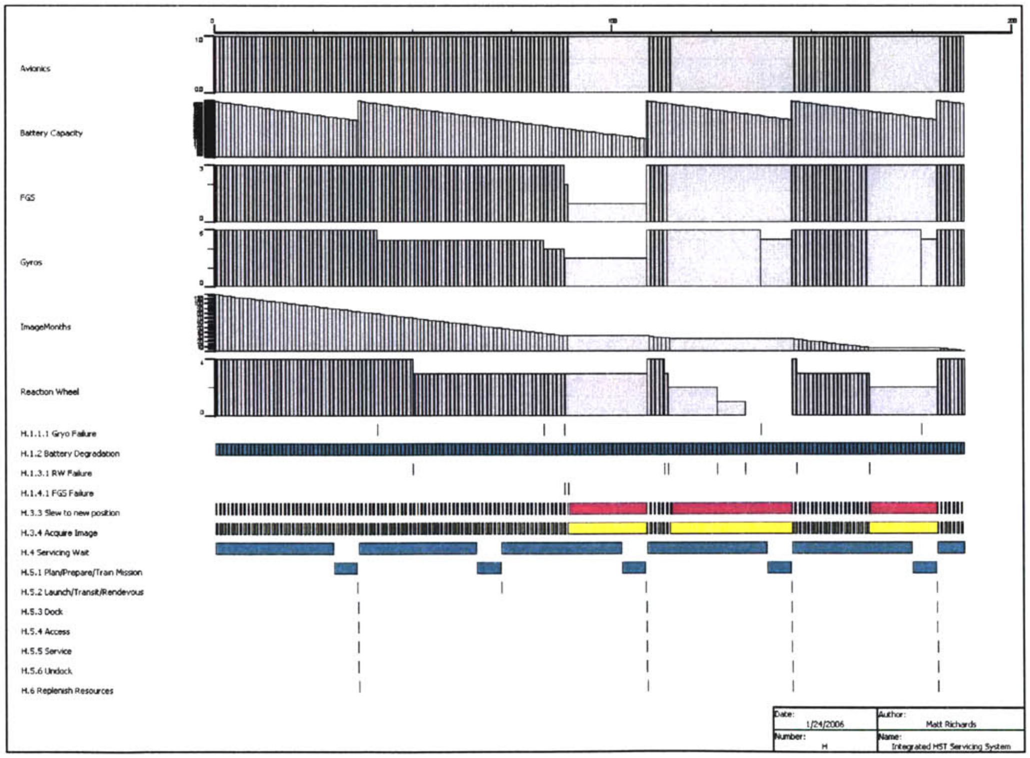
Hubble Servicing Simulation – Robotic Vehicle Run #2



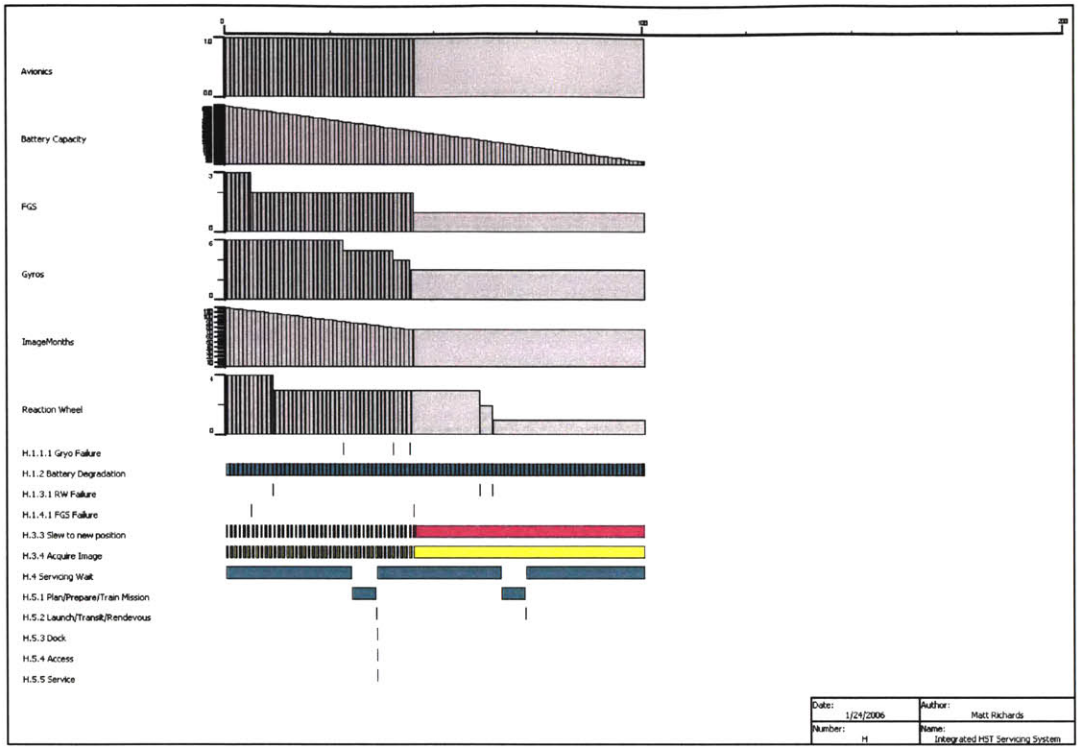
Hubble Servicing Simulation – Robotic Vehicle Run #3



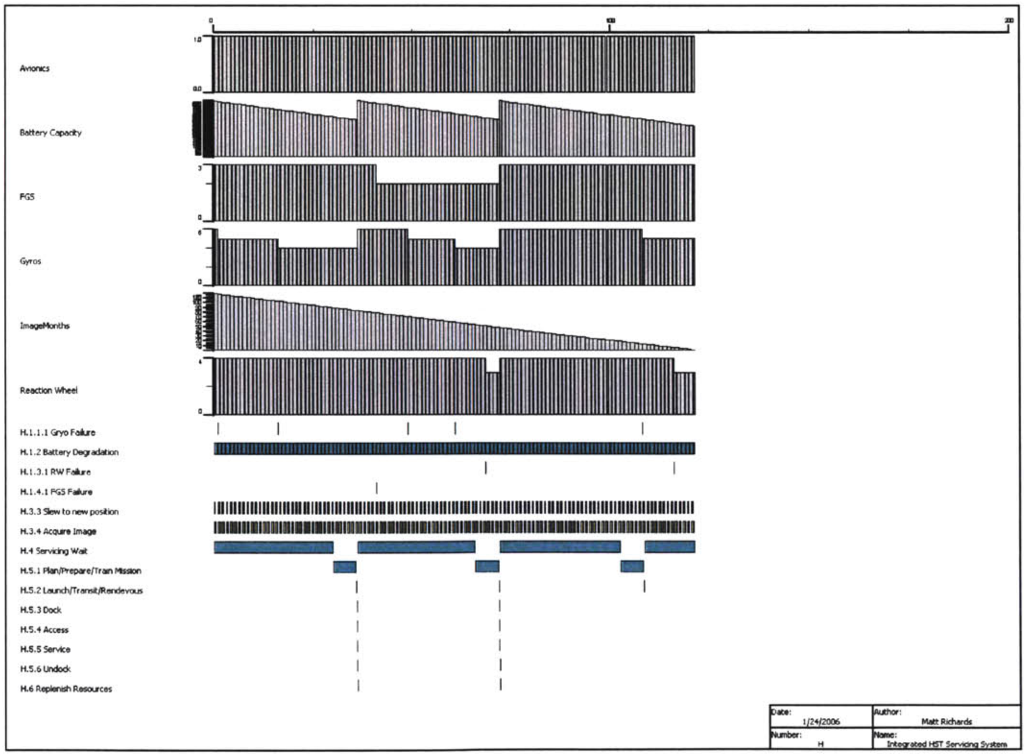
Hubble Servicing Simulation – Robotic Vehicle Run #4



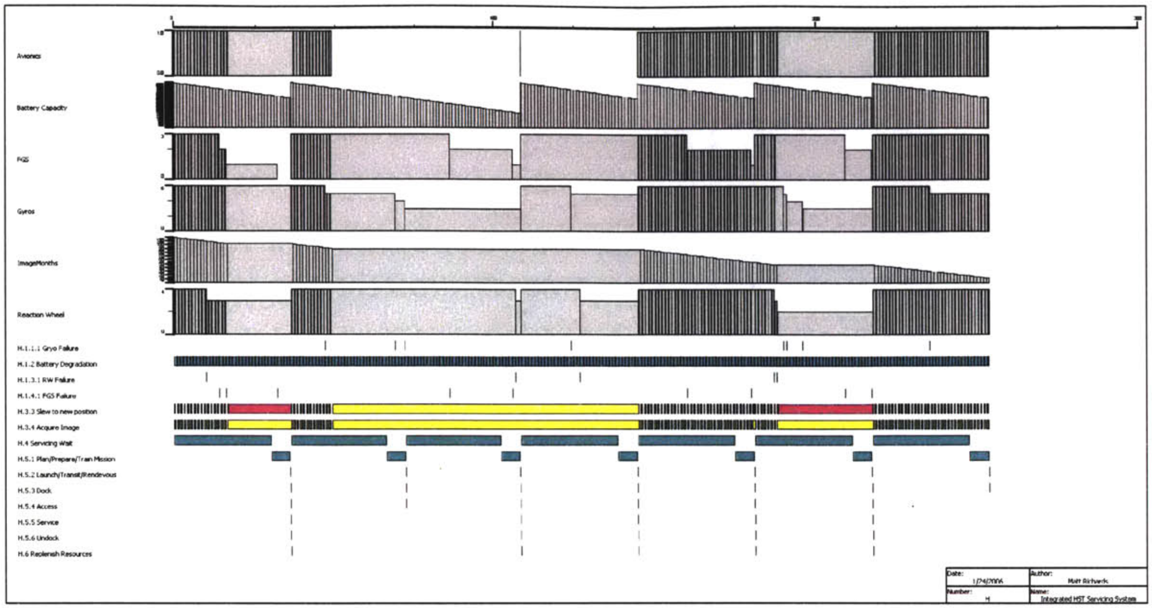
Hubble Servicing Simulation – Robotic Vehicle Run #5



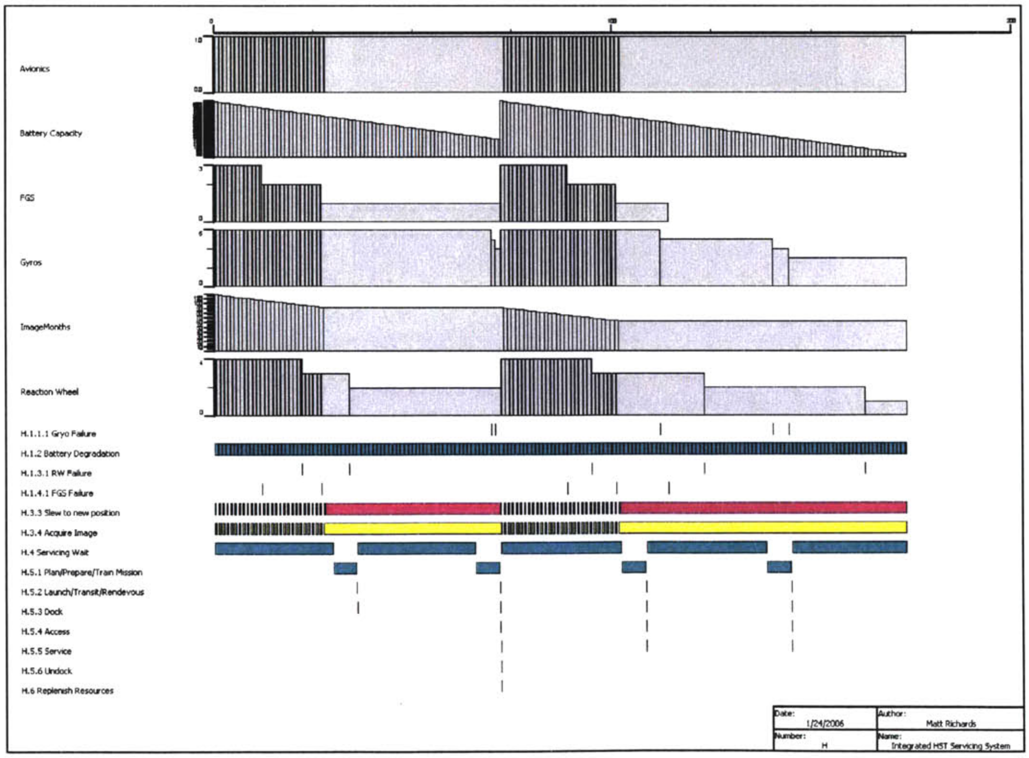
Hubble Servicing Simulation – Robotic Vehicle Run #6



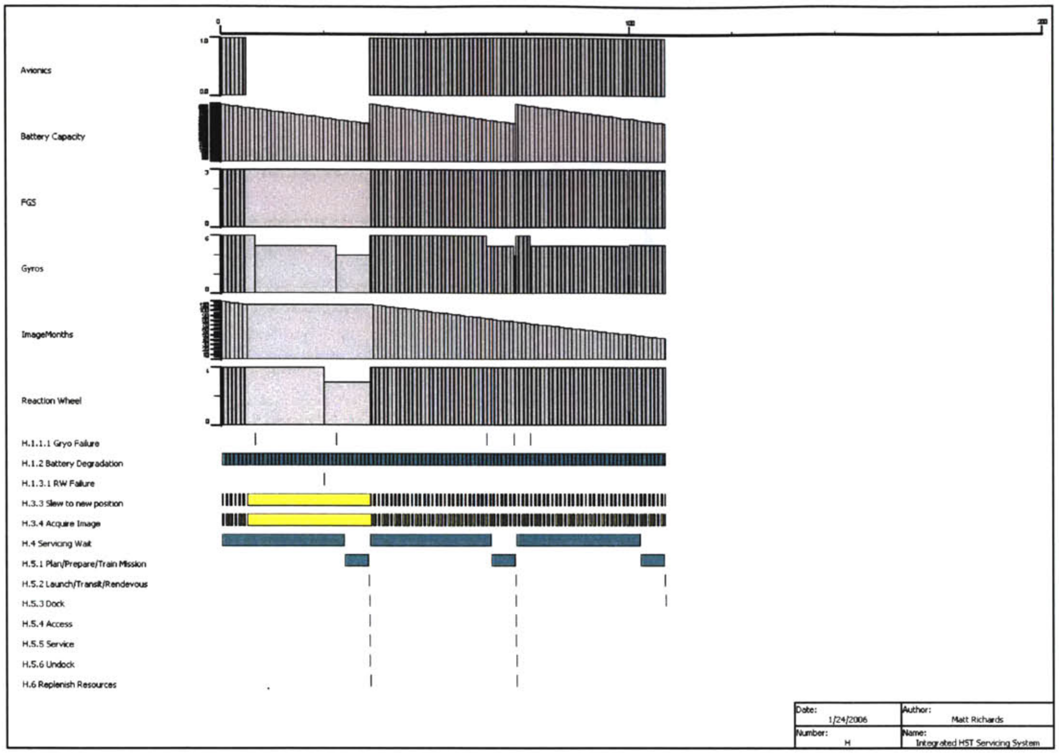
Hubble Servicing Simulation – Robotic Vehicle Run #7



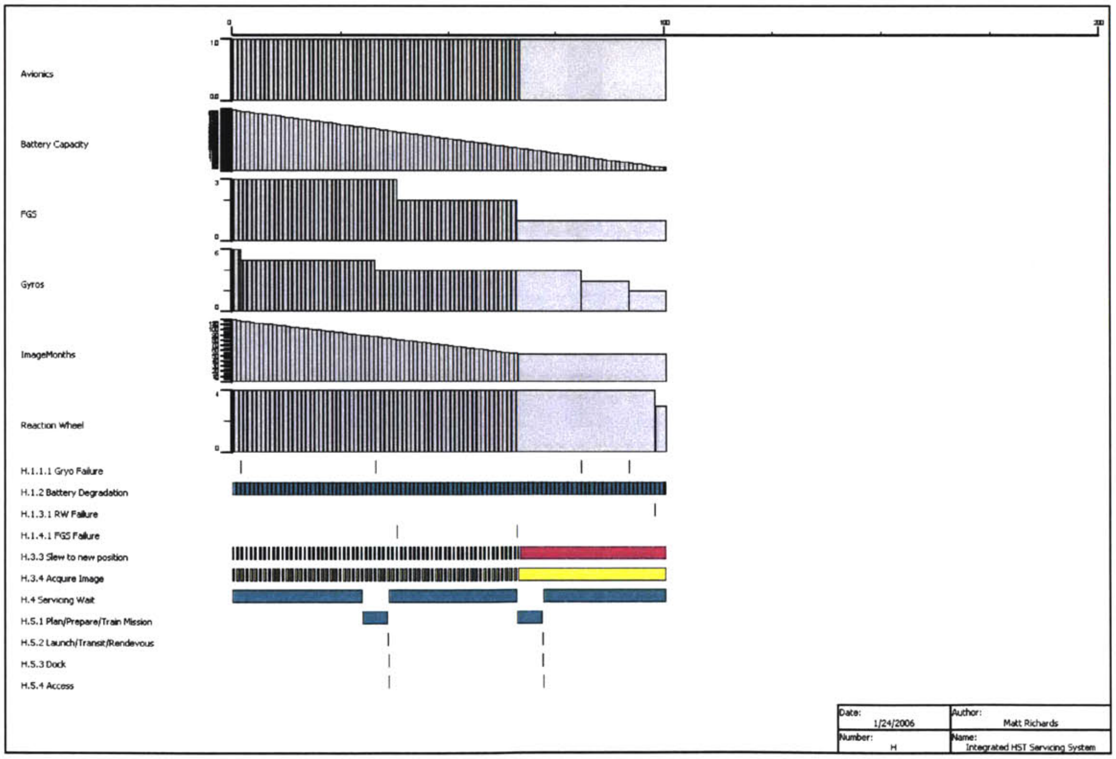
Hubble Servicing Simulation – Robotic Vehicle Run #8



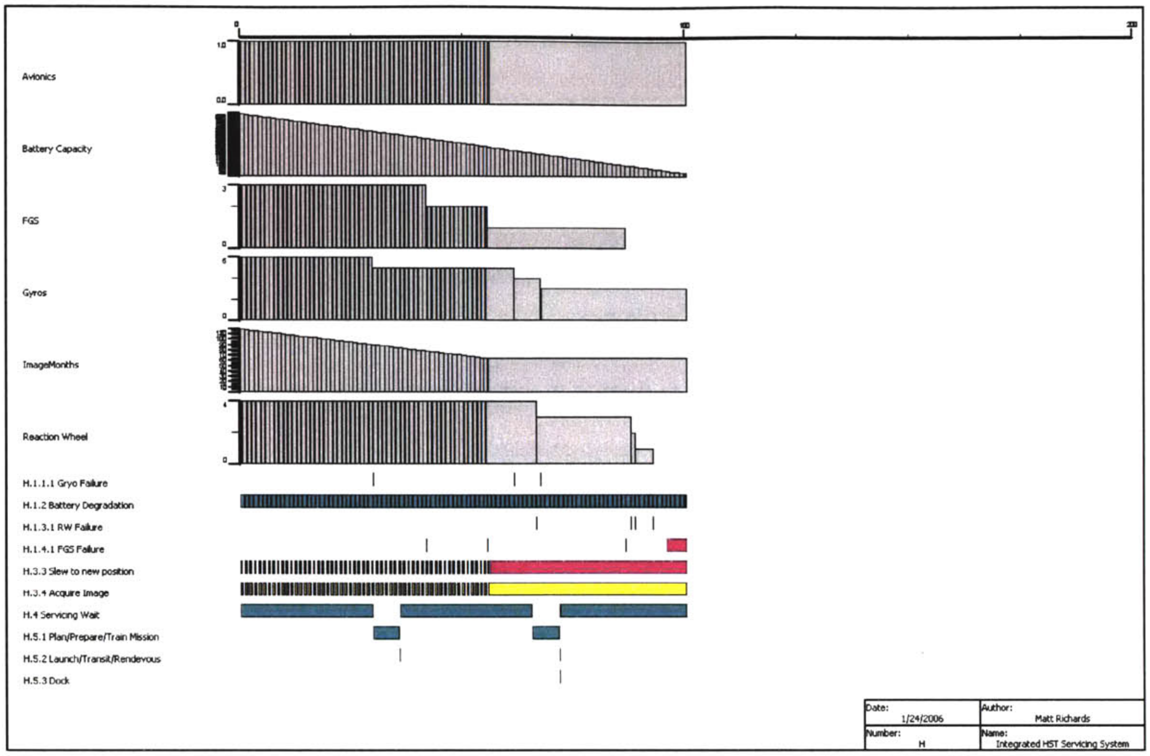
Hubble Servicing Simulation – Robotic Vehicle Run #9



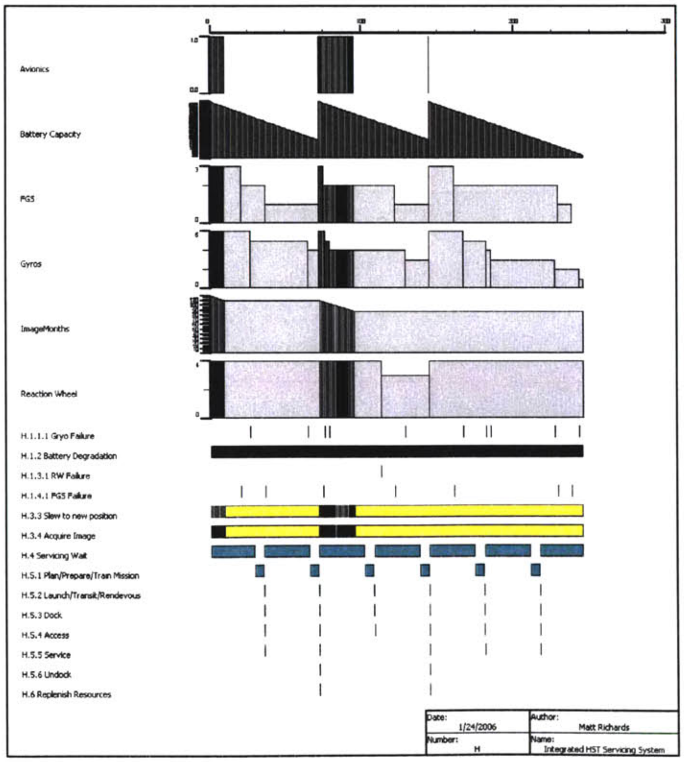
Hubble Servicing Simulation – Robotic Vehicle Run #10



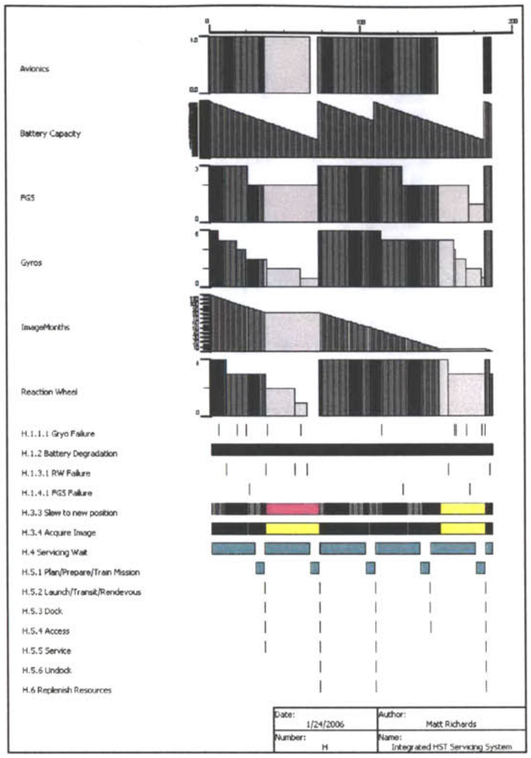
Hubble Servicing Simulation – Robotic Vehicle Run #11



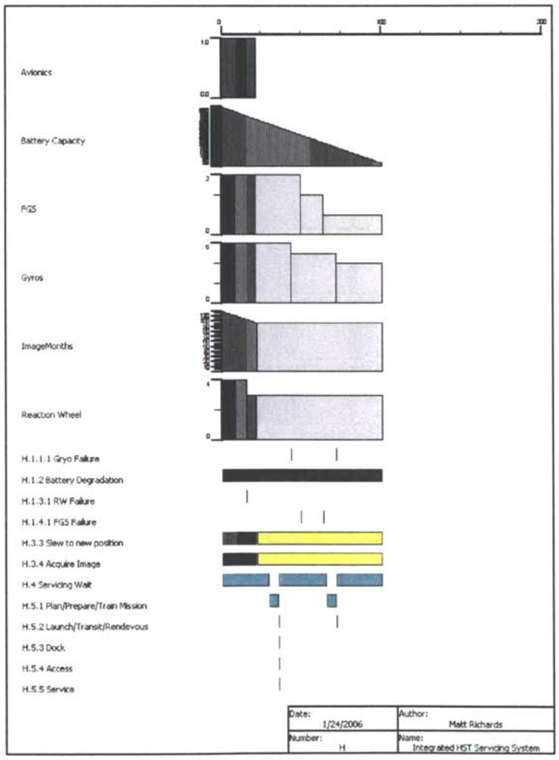
Hubble Servicing Simulation – Robotic Vehicle Run #12



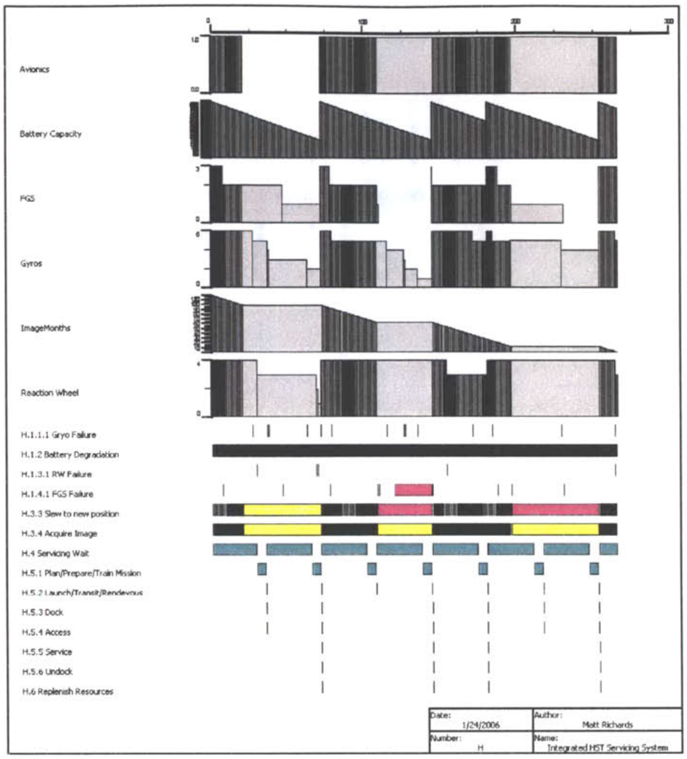
Hubble Servicing Simulation – Robotic Vehicle Run #13



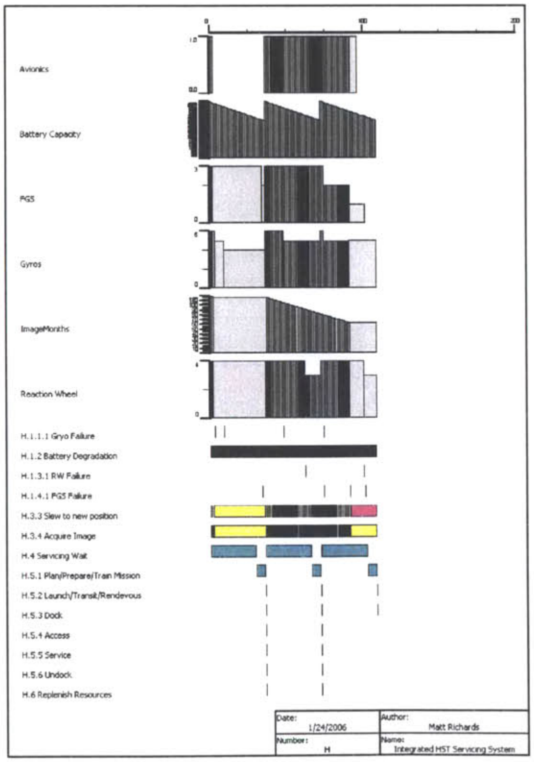
Hubble Servicing Simulation – Robotic Vehicle Run #14



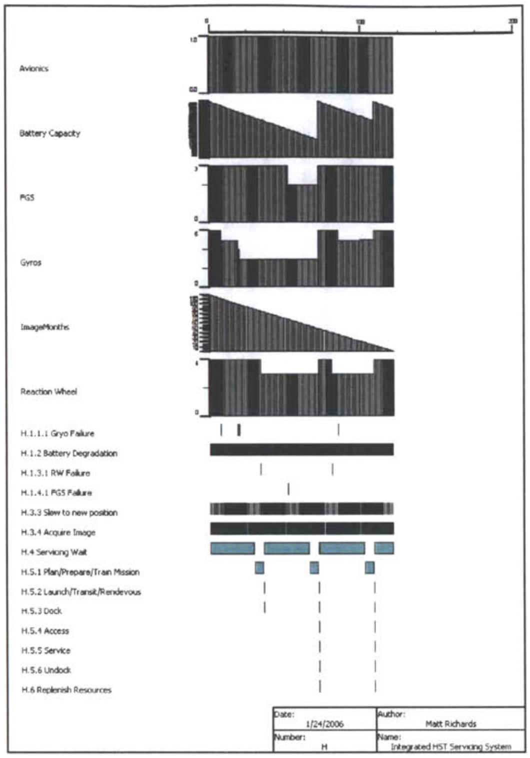
Hubble Servicing Simulation – Robotic Vehicle Run #15



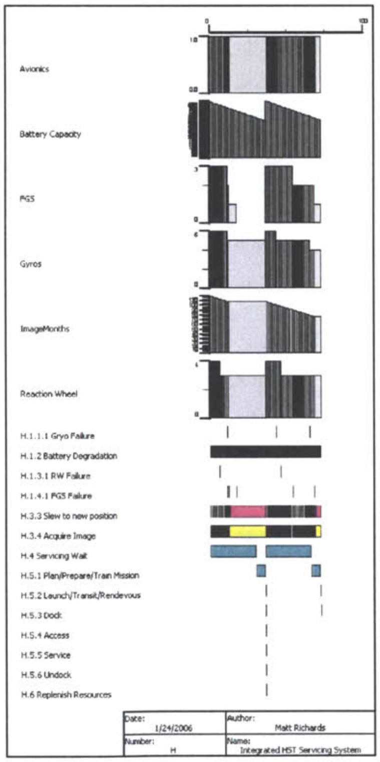
Hubble Servicing Simulation – Robotic Vehicle Run #16



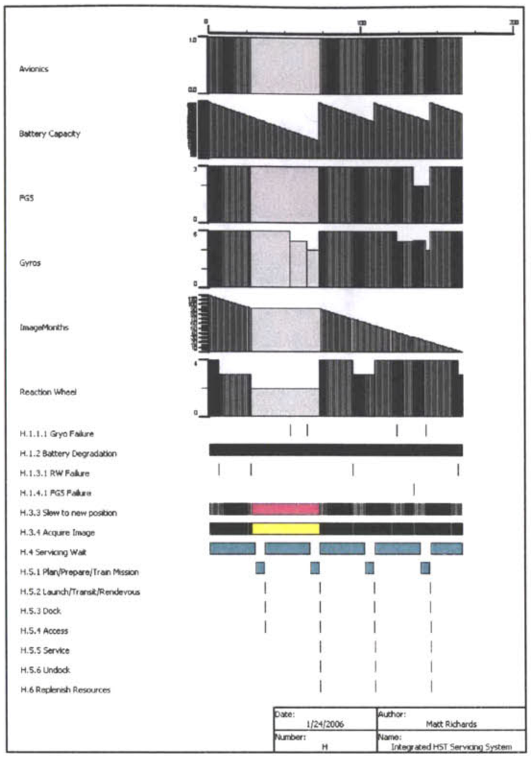
Hubble Servicing Simulation – Robotic Vehicle Run #17



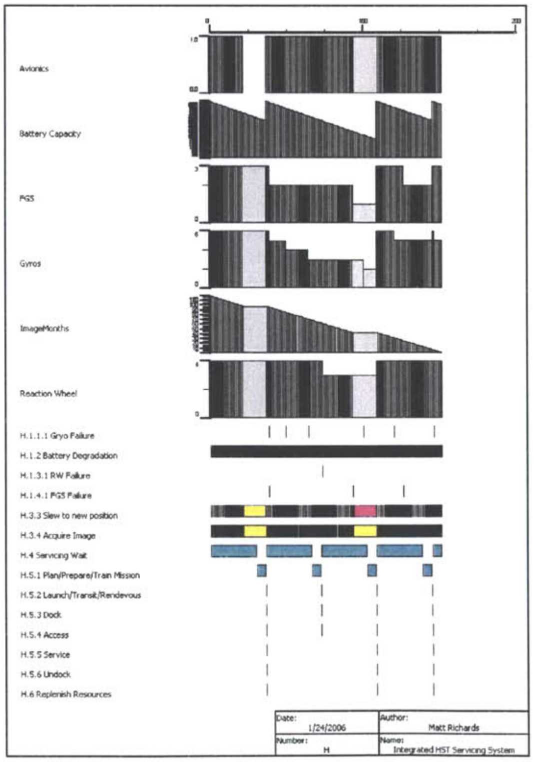
Hubble Servicing Simulation – Robotic Vehicle Run #18



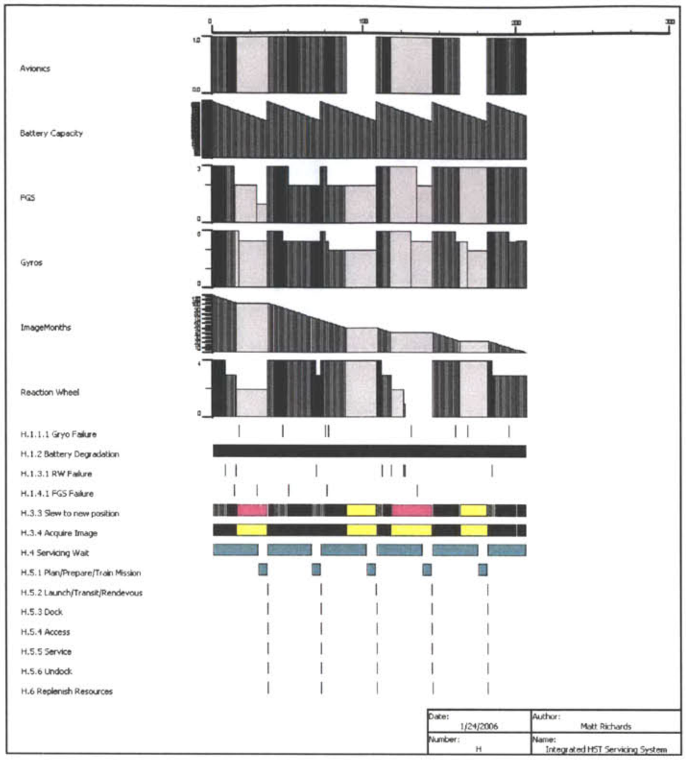
Hubble Servicing Simulation – Robotic Vehicle Run #19



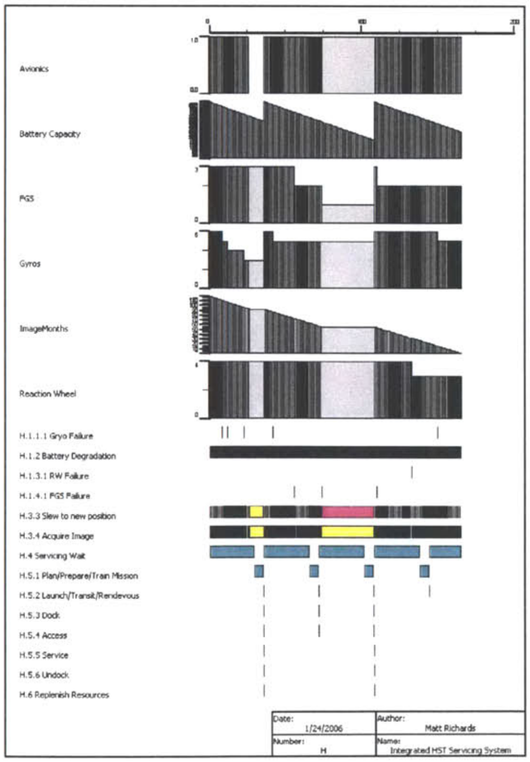
Hubble Servicing Simulation – Robotic Vehicle Run #20



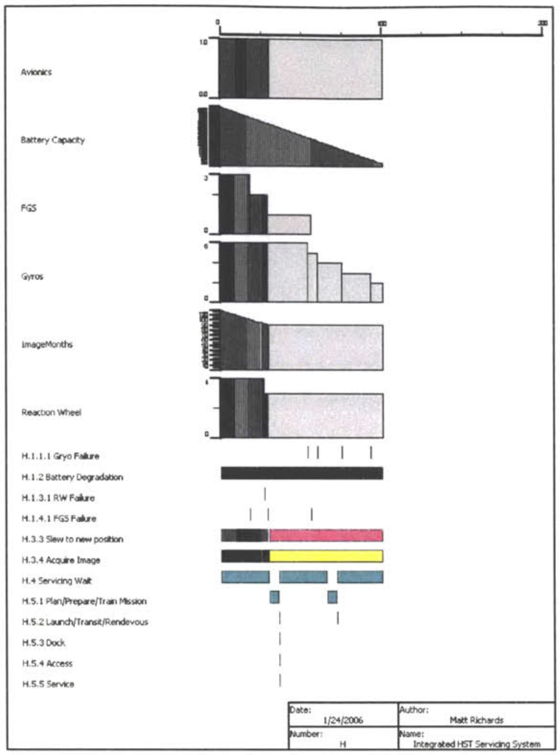
Hubble Servicing Simulation – Robotic Vehicle Run #21



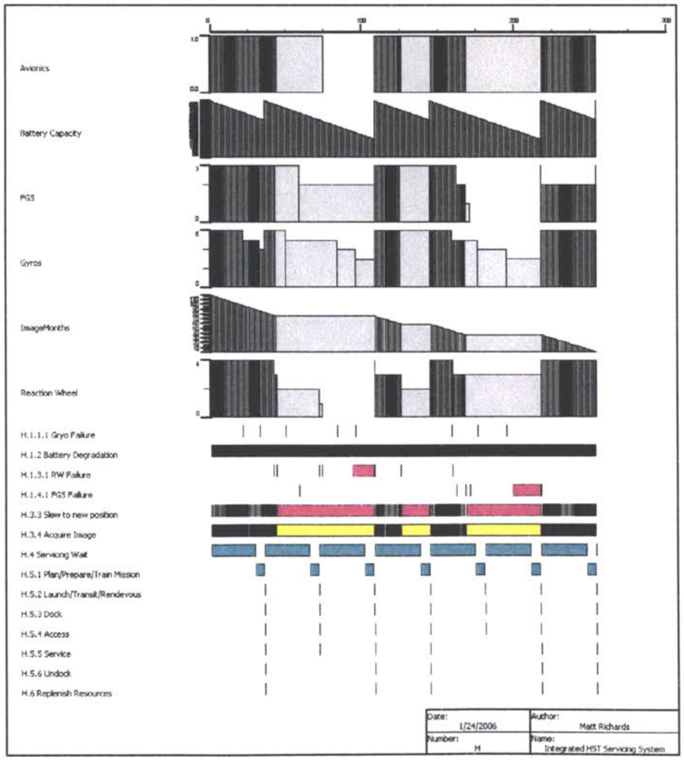
Hubble Servicing Simulation – Robotic Vehicle Run #22



Hubble Servicing Simulation – Robotic Vehicle Run #23



Hubble Servicing Simulation – Robotic Vehicle Run #24



Hubble Servicing Simulation – Robotic Vehicle Run #25

Appendix E. Space Tug Tradespace

This appendix includes MATLAB code used to perform a Multi-Attribute Tradespace Analysis for the design of a space tug servicing vehicle. Utility functions are based on assumptions discussed in "Understanding the Orbital Transfer Vehicle Tradespace," (McManus and Schuman, 2003).

```
% Name: SpaceTug_Main
% Description: This function calls all the files in the correct order
% Author : Matt Richards
% Date: 5/14/05
% Inputs: none
% Outputs: cost-utility tradespace
% ------------------------------------------------------------------

function [SpaceTug_DV] = SpaceTug_Main

clear all
close all

% call Space Tug functions
[Constants] = OOS_Constants;
[SpaceTug_DV] = SpaceTug_Enumerate_DV(Constants);
[SpaceTug_DV] = SpaceTug_Payload_Mass(SpaceTug_DV);
[SpaceTug_DV] = SpaceTug_Response_Time(SpaceTug_DV);
[SpaceTug_DV] = Calc_Delta_V(SpaceTug_DV, Constants);
[SpaceTug_DV] = Calc_Weighted_Utility(SpaceTug_DV);
[SpaceTug_DV] = Calc_Cost(SpaceTug_DV, Constants);

figure
for i=1:size(SpaceTug_DV,2);
    plot(SpaceTug_DV(i).Cost, SpaceTug_DV(i).Utility,'o')
    axis([0, 4000, 0, 1])
    title('Space Tug Tradespace')
    xlabel('Cost ($M)')
    ylabel('Utility (dimensionless)')
    hold on
end
```

```
% Name: SpaceTug_Enumerate_DV
% Description: This function enumerates the design vector (DV) for the space
tug
% Author : Matt Richards
% Date: 5/14/05
% Inputs: none
% Outputs: space tug design vector
%-----------------------------------------------------------------------

function [SpaceTug_DV] = SpaceTug_Enumerate_DV(Constants)

clear SpaceTug_DV
```

```
i=1;

for Capability = {'Low' 'Medium' 'High' 'Extreme'};
    for Propulsion_Type = {'storable_bi' 'cryogenic' 'nuclear' 'electric'};
        for Propellant_Mass = [30 100 300 600 1200 3000 10000 30000];

            % input design parameters
            SpaceTug_DV(i).Capability = Capability;
            SpaceTug_DV(i).Propulsion_Type = Propulsion_Type;
            SpaceTug_DV(i).Propellant_Mass = Propellant_Mass;
            i=i+1;

        end
    end
end

SpaceTug_DV = SpaceTug_Payload_Mass(SpaceTug_DV)
SpaceTug_DV = SpaceTug_Response_Time(SpaceTug_DV)
SpaceTug_DV = Calc_Delta_V(SpaceTug_DV, Constants)
SpaceTug_DV = Calc_Weighted_Utility(SpaceTug_DV)
SpaceTug_DV = Calc_Cost(SpaceTug_DV, Constants)
```

```
% Name: SpaceTug_Payload_Mass
% Description: This function assigns payload mass values
% Author : Matt Richards
% Date: 5/15/05
% Inputs: Capability
% Outputs: Payload_Mass
%-------------------------------------------------------------------------

function[SpaceTug_DV] = SpaceTug_Payload_Mass(SpaceTug_DV)

for i=1:size(SpaceTug_DV,2);

    if strcmp(SpaceTug_DV(i).Capability, 'Low');
    SpaceTug_DV(i).Payload_Mass = 300;  %kg;
    end

    if strcmp(SpaceTug_DV(i).Capability, 'Medium');
    SpaceTug_DV(i).Payload_Mass = 1000;  %kg;
    end

    if strcmp(SpaceTug_DV(i).Capability, 'High');
    SpaceTug_DV(i).Payload_Mass = 3000;  %kg;
    end

    if strcmp(SpaceTug_DV(i).Capability, 'Extreme');
    SpaceTug_DV(i).Payload_Mass = 5000;  %kg;
    end

end
```

```
% Name: SpaceTug_Response_Time
% Description: This function assigns response time
% Author : Matt Richards
% Date: 5/15/05
% Inputs: Propulsion_Type
% Outputs: Response_Time
%--------------------------------------------------------------------------

function[SpaceTug_DV] = SpaceTug_Response_Time(SpaceTug_DV)

for i=1:size(SpaceTug_DV,2);

    if strcmp(SpaceTug_DV(i).Propulsion_Type, 'storable_bi');
    SpaceTug_DV(i).Response_Time = 'fast';
    end

    if strcmp(SpaceTug_DV(i).Propulsion_Type, 'cryogenic');
    SpaceTug_DV(i).Response_Time = 'fast';
    end

    if strcmp(SpaceTug_DV(i).Propulsion_Type, 'nuclear');
    SpaceTug_DV(i).Response_Time = 'fast';
    end

    if strcmp(SpaceTug_DV(i).Propulsion_Type, 'electric');
    SpaceTug_DV(i).Response_Time = 'slow';
    end

end
```

```
% Name: Calc_Delta_V
% Description: This function calculates change in velocity
% Author : Matt Richards
% Date: 5/15/05
% Inputs: SpaceTug_DV, Constants
% Outputs: Delta_V
%--------------------------------------------------------------------------

function [SpaceTug_DV] = Calc_Delta_V(SpaceTug_DV, Constants)

for i=1:size(SpaceTug_DV,2);

    if strcmp(SpaceTug_DV(i).Propulsion_Type, 'storable_bi');
    SpaceTug_DV(i).Mass_Propsys_Base = Constants.Base_storable_bi;
    SpaceTug_DV(i).Mass_Propsys_Fraction = Constants.Fraction_storable_bi;
    SpaceTug_DV(i).Isp = Constants.Isp_storable_bi;
    end

    if strcmp(SpaceTug_DV(i).Propulsion_Type, 'cryogenic');
    SpaceTug_DV(i).Mass_Propsys_Base = Constants.Base_cryogenic;
```

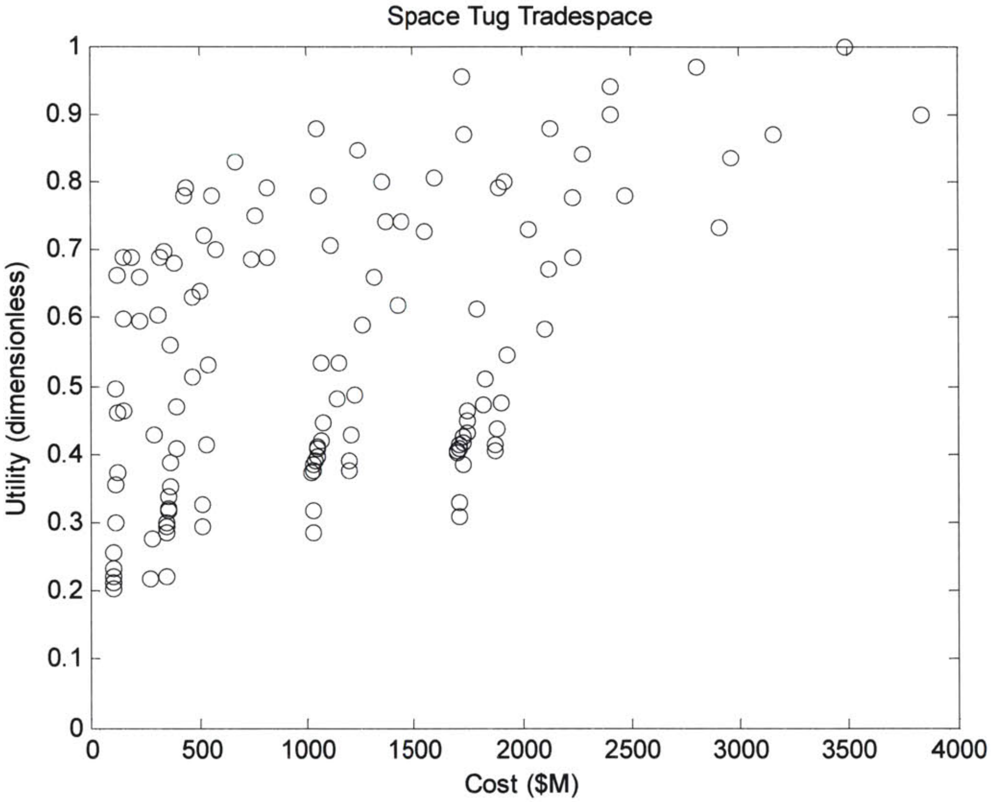
```
    SpaceTug_DV(i).Mass_Propsys_Fraction = Constants.Fraction_cryogenic;
    SpaceTug_DV(i).Isp = Constants.Isp_cryogenic;
    end

    if strcmp(SpaceTug_DV(i).Propulsion_Type, 'nuclear');
    SpaceTug_DV(i).Mass_Propsys_Base = Constants.Base_nuclear;
    SpaceTug_DV(i).Mass_Propsys_Fraction = Constants.Fraction_nuclear;
    SpaceTug_DV(i).Isp = Constants.Isp_nuclear;
    end

    if strcmp(SpaceTug_DV(i).Propulsion_Type, 'electric');
    SpaceTug_DV(i).Mass_Propsys_Base = Constants.Base_electric;
    SpaceTug_DV(i).Mass_Propsys_Fraction = Constants.Fraction_electric;
    SpaceTug_DV(i).Isp = Constants.Isp_electric;
    end

SpaceTug_DV(i).Mass_Propsys = SpaceTug_DV(i).Mass_Propsys_Base +
SpaceTug_DV(i).Mass_Propsys_Fraction * SpaceTug_DV(i).Propellant_Mass;

SpaceTug_DV(i).Mass_Bus = SpaceTug_DV(i).Mass_Propsys +
Constants.Fraction_payload * SpaceTug_DV(i).Payload_Mass;

SpaceTug_DV(i).Mass_Dry = SpaceTug_DV(i).Mass_Bus +
SpaceTug_DV(i).Payload_Mass;

SpaceTug_DV(i).Mass_Wet = SpaceTug_DV(i).Mass_Dry +
SpaceTug_DV(i).Propellant_Mass;

SpaceTug_DV(i).Delta_V = Constants.g * SpaceTug_DV(i).Isp *
log(SpaceTug_DV(i).Mass_Wet / SpaceTug_DV(i).Mass_Dry);

end
```

```
% Name: Calc_Weighted_Utility
% Description: This function calculates utility for the space tug
% Author : Matt Richards
% Date: 5/18/05
% Inputs: space tug design vector
% Outputs: space tug design vector
%--------------------------------------------------------------------------

function [SpaceTug_DV] = Calc_Weighted_Utility(SpaceTug_DV)

for i=1:size(SpaceTug_DV,2);

    % calculate utility for delta v
    if SpaceTug_DV(i).Delta_V < 12000;
    Delta_V = [0,4200,8400,12000];
    Utility_DeltaV = [0,.68,.9,1];
    SpaceTug_DV(i).Utility_Delta_V = interp1(Delta_V, Utility_DeltaV,
SpaceTug_DV(i).Delta_V, 'linear');
    end
```

```
    if SpaceTug_DV(i).Delta_V >= 12000;
    SpaceTug_DV(i).Utility_Delta_V = 1;
    end

    % calculate utility for capability
    if strcmp(SpaceTug_DV(i).Capability, 'Low');
    SpaceTug_DV(i).Utility_Capability = .3;
    end

    if strcmp(SpaceTug_DV(i).Capability, 'Medium');
    SpaceTug_DV(i).Utility_Capability = .6;
    end

    if strcmp(SpaceTug_DV(i).Capability, 'High');
    SpaceTug_DV(i).Utility_Capability = .9;
    end

    if strcmp(SpaceTug_DV(i).Capability, 'Extreme');
    SpaceTug_DV(i).Utility_Capability = 1;
    end

    % calculate utility for response time
    if strcmp(SpaceTug_DV(i).Propulsion_Type, 'storable_bi');
    SpaceTug_DV(i).Utility_Response_Time = 1;
    end

    if strcmp(SpaceTug_DV(i).Propulsion_Type, 'cryogenic');
    SpaceTug_DV(i).Utility_Response_Time = 1;
    end

    if strcmp(SpaceTug_DV(i).Propulsion_Type, 'nuclear');
    SpaceTug_DV(i).Utility_Response_Time = 1;
    end

    if strcmp(SpaceTug_DV(i).Propulsion_Type, 'electric');
    SpaceTug_DV(i).Utility_Response_Time = 0;
    end

    % aggregate utility
    Weighted_Delta_V(i) = .6 .* SpaceTug_DV(i).Utility_Delta_V;
    Weighted_Capability(i) = .3 .* SpaceTug_DV(i).Utility_Capability;
    Weighted_Response_Time(i) = .1 .* SpaceTug_DV(i).Utility_Response_Time;
    SpaceTug_DV(i).Utility = Weighted_Delta_V(i) + Weighted_Capability(i) +
Weighted_Response_Time(i);

end
```

```
% Name: Calc_Cost
% Description: This function calculates cost of the space tug in $M
% Author : Matt Richards
% Date: 5/19/05
% Inputs: space tug design vector, constants
% Outputs: space tug design vector
```

```
%-------------------------------------------------------------------------

function [SpaceTug_DV] = Calc_Cost(SpaceTug_DV, Constants)

for i=1:size(SpaceTug_DV,2);

    SpaceTug_DV(i).Cost = (SpaceTug_DV(i).Mass_Dry * Constants.Cost_Dry + 
SpaceTug_DV(i).Mass_Wet * Constants.Cost_Wet)/1000000;

end
```



Appendix F. Space Tug Concept-of-Operations

How might the social constructs identified in Chapter 7 (*i.e.*, policy, law, economics) drive the design of a concept of operations for a servicing vehicle? This section addresses this question with the development of a concept of operations for a space tug in geosynchronous orbit, including parking orbit selection and approach strategies, with emphasis placed on safety and reliability.[1] Given that one of the most likely OOS provider architectures is that of a GEO space tug (due to the large number of potential targets and favorable orbital dynamics in that orbit), a GEO space tug concept guides the discussion in this appendix and is used as an illustration of the challenges facing OOS implementation.

This section addresses issues associated with the operation of a GEO space tug with a focus on parking orbit selection and target spacecraft rendezvous strategies. Assumptions implicit in the GEO space tug concept are briefly discussed as well. The most important considerations throughout all phases of space tug operation—or any OOS operation—are safety and reliability. It is imperative that tug operations not damage or otherwise interfere with the function of the target spacecraft or any other nearby spacecraft. This follows, for one, from the issue of liability discussed in Chapter 7. Additionally, program managers for major military space programs have identified reliability as the primary operational concern for space tugs. Other considerations in space tug operations include fuel efficiency and timeliness. These are secondary to safety and reliability. Typically, timeliness will be a low priority, so fuel efficiency will be the primary driver of tug operations after safety. It is conceivable, however, that an urgent mission might utilize a faster rendezvous strategy, albeit with a higher fuel consumption than would otherwise be necessary.

Assumptions

The concept contains two assumptions. First, the tug will execute multiple missions over its design lifetime. That is, from a parking orbit near the geostationary belt, it will rendezvous and dock with a target satellite, carry out the required maneuvers, and return to its parking orbit until it is needed again. Second, it is assumed that the tug will have the capability to dock with an arbitrary target spacecraft.

Parking Orbit

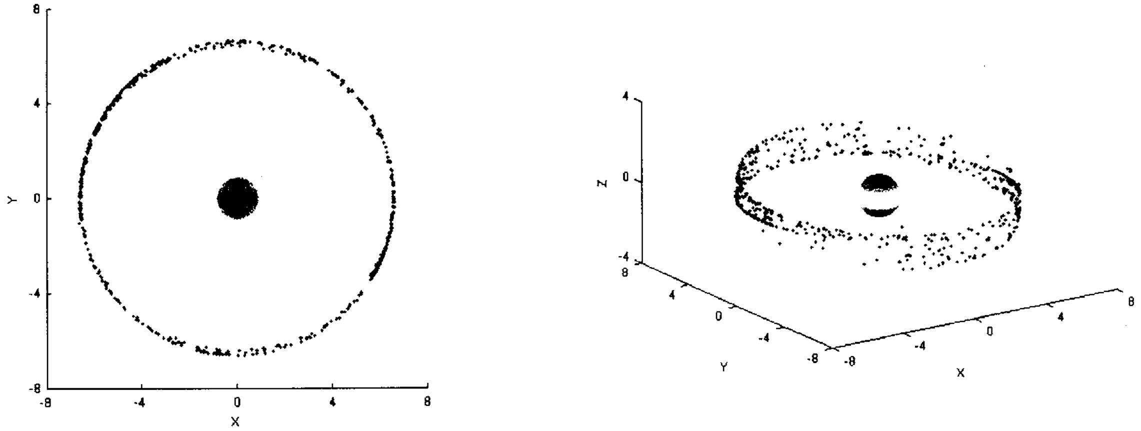
The figure on the next page shows all unclassified space objects in geosynchronous or near-geosynchronous orbits as of January 10, 2005, according to element sets available from Air Force Space Command. Parking a space tug in a geostationary slot seems out of the question given the high commercial and military value of these slots. However, as the figure indicates, unused regions of the geostationary belt do exist where a space tug "parking space" could be located.[2] A slightly inclined geosynchronous orbit can be ruled out as a parking orbit by the expensive maneuvers that would be required to reach target spacecraft in the geostationary belt.

---

[1] This appendix is based on a paper entitled "Assessing the Challenges to a Geosynchronous Space Tug System" (Richards, Springmann, and McVey, 2005).

[2] While there is space in GEO to accommodate many satellites with little risk of collision, radio frequency interference and its bandwidth limit parking spot spacing to two degrees (Wertz and Larson, *et al.*, 1999). Furthermore, space tugs would communicate little compared to direct broadcast satellites.

A better option for space tug parking orbits might be equatorial orbits near geosynchronous altitude.

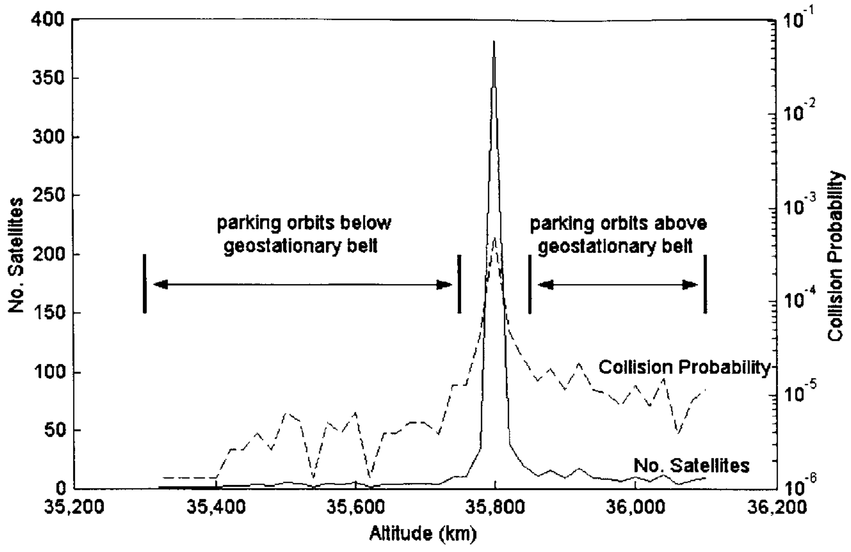


(a) **(b)**

The view in (a) is from above the north pole. The positive y-axis points toward 0° longitude and the positive z-axis in points toward the north pole. The axes have units of Earth radii.

Geosynchronous Space Objects, 10 January 2005

The altitude bounds on potential equatorial parking orbits (shown on the next page) are established by the United States Government Orbital Debris Mitigation Standard Practices. The upper limit on disposal orbit apogee between MEO and GEO is an altitude of 35,300 km, and the lower limit on disposal orbit perigee above GEO is 36,100 km. Furthermore, it may be prudent to exclude orbital altitudes between approximately 50 km below and 50 km above the geostationary altitude because the probability of collision, while still low, is significantly higher at these altitudes due to variance in the actual orbital altitudes of geosynchronous satellites. Estimates of collision probabilities according to altitude were calculated using the Poisson distribution and principles of the kinetic theory of gases based on research conducted by the Federal Aviation Administration's Office of Commercial Space Transportation Licensing and Safety Division (FAA Office of Commercial Space Transportation Licensing and Safety Division, 1992). A ten year tug lifetime was assumed.



Possible Geosynchronous Space Tug Parking Orbit Altitudes

Velocity change (ΔV) requirements for stationkeeping are approximately constant over the range of parking orbit altitudes. However, the ΔV and time requirements to reach geosynchronous altitude do vary over this range. The ΔV requirement varies between 1.8 m/s and 16.6 m/s depending on the altitude change necessary. Propulsion choice (*i.e.*, chemical vs. electric) affects the time requirements for transfer from parking to geosynchronous orbit, although the ΔV's between chemical and electric propulsion are nearly equal since the kinetic inefficiency of a continuous thrust transfer is low for small changes in altitude near geosynchronous orbits. The time required for transfer via electric propulsion can range to as high as 180 days, depending on the acceleration produced by the engine, while the transfer time via chemical propulsion is approximately 12 hours over the range of possible parking orbit altitudes.

The advantage of low thrust electric propulsion systems with specific impulses exceeding 1,000 seconds is a combination of reduced tug mass and increased ΔV capability. On the other hand, because of the slow, spiraling trajectory followed when changing altitude, the tug would orbit repeatedly at altitudes where the probability of collision is heightened slightly. In addition, the power requirement for electric propulsion systems, ranging from 0.5 kW up to 4.5 kW, is much higher than for chemical propulsion (Wertz and Larson, *et al.*, 1999). It should be noted that even if a space tug were equipped with electric propulsion for all or part of the transfer between its parking orbit and the target orbit, chemical thrusters would still be required for maneuvers in close proximity to the target spacecraft. The use of electric propulsion to reach the vicinity of the target spacecraft would also restrict the responsiveness of a space tug. Although rendezvous times in geosynchronous orbit are on the order of days, not hours, it may be desirable to assure a shorter response time than is achievable using electric propulsion.

A final issue relevant to the tug parking orbit is the potential for interference with other geosynchronous spacecraft. Two types of interference could result from space tug operations. The first is communications interference. The Federal Communications Commission and

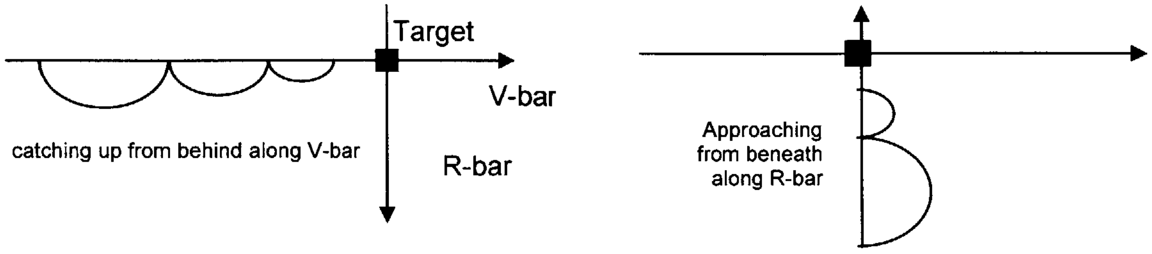
International Telecommunication Union licensing processes are intended to mitigate communications interference between communications satellites in geostationary orbits, but it is unclear how these processes would apply to a spacecraft constantly moving near the geostationary belt. However, given the number communications satellites already operating in the geostationary belt and the relatively low communications requirements of a space tug, it is unlikely that communications interference would be a major issue. The second type of interference is electromagnetic interference (EMI). The potential for electromagnetic incompatibility between a tug and target has not been fully explored.

Approaching Target Spacecraft

The position of a satellite at geosynchronous altitude can be determined from the ground to within 24 km in the along-track direction, 17 km in the cross-track direction, and 2.6 km in range (Settelmeyer, 1997). Therefore, a tug could conceivably navigate to within a few kilometers of the target satellite on its own. Realistically, this distance will be larger, for example due to the propagation of small thrusting errors. Performing the transfer from parking orbit to target orbit under ground supervision should help reduce such errors and assure that the tug can be brought reliably to within radar range of its targets as well as ease autonomous navigation requirements. Once the target is acquired by on-board radar or other long-range sensors, rendezvous maneuvers can commence.

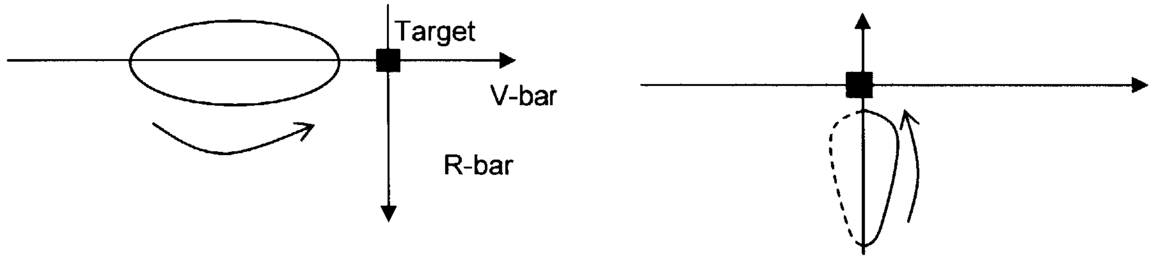
Space rendezvous is a complex but well understood procedure. Fehse (2003) provides one introduction to automated rendezvous in space and discusses the major drivers of approach strategy (Fehse, 2003). It is impossible to devise a detailed rendezvous sequence here since target- and time-specific information would be required. Given the necessary emphasis on the safety of the target spacecraft, passive trajectory safety should heavily influence planning. A longer-term look at trajectory safety must take into account disturbance forces. The most prominent trajectory disturbances at geosynchronous altitude are due to solar radiation pressure and, at close range, thruster plume impingement. Thruster plume impingement is also a concern in terms of direct damage to the target spacecraft. Solar radiation pressure is relatively easy to model. To analyze fully the effects of thruster plume impingement, much more detailed modeling reflecting the geometry of both the tug and target as well as the nature of thruster plumes is needed. This is beyond the scope of this section.

A method of final approach that is advantageous in terms of safety and fuel consumption, based on Zero Closing Speed (ZCS) guidance, has been developed by Bell (2003). This type of approach consists of a series of small "hops" toward the target, either along V-bar (aligned with the velocity of the target spacecraft) or R-bar (aligned with the nadir from the target spacecraft) (see figure on the next page). Simulations performed on hardware at the Naval Research Laboratory (NRL) Spacecraft Robotics Engineering and Controls Lab have validated this method of final approach (Bell, 2003). The direction of final approach (*e.g.*, +/- V-bar, +/- R-bar) depends on the state of the target satellite. For an attitude-stable but non-operational target satellite, the direction of final approach can simply be chosen according to the location of the most convenient docking area on the target spacecraft. Operational targets could require that the tug dock from a specific direction to maintain a certain attitude. For instance, if the target were a communications satellite, it may require an approach from above in order to maintain a nadir-pointing orientation. In the case of uncooperative or tumbling targets, approach and docking could prove exceedingly difficult. Proximity operations for two close orbiting satellites are further addressed by the Clohessy-Wiltshire or Hill's equations (see Section 4.1.5).



(a) elliptical V-bar hops

(b) tear-drop shaped R-bar hops



(c) resulting trajectory for failed V-bar braking, repeats forever under Keplerian motion (*i.e.*, no pertubations)

(d) resulting trajectory for failed R-bar braking, does not repeat forever (less passively safe than V-bar)

Zero Closing Speed Guidance

Automated rendezvous and docking has already been demonstrated in LEO by the Japanese ETS-VII mission (Kawano, 2001). Another demonstration is planned later this year with DARPA's Orbital Express (see Section 2.3 for other U.S. technology demonstrations). The state of the art in relative navigation lies in relative GPS and sensors such as the Advanced Video Guidance Sensor (Polites, 1999; and Wertz and Bell, 2003). However, these technologies are not entirely suitable for use by a space tug as it is conceived in this section. At geosynchronous altitude, the use of relative GPS is not possible. Additionally, the space tug cannot assume that the target satellite is cooperative. The advances in autonomous navigation technology that will enable a space tug to rendezvous and dock with an arbitrary target in geosynchronous orbit are under development but not yet flight-proven. A flight demonstration of the ability to reliably deal with uncooperative targets will be a critical milestone on the way to an operational space tug.

Future Servicing Architectures

There are implicit assumptions in this section that a space tug system would consist of a single spacecraft and that its targets would be single spacecraft such as Intelsat or Milstar satellites. These assumptions permit this analysis to concentrate on issues associated with the tug parking orbit and rendezvous with the target spacecraft. Other potential space tug architectures, such as those involving multiple tugs or on-orbit fueling stations, are not considered. Looking forward, technological advances could radically alter the architecture of target spacecraft, which would in turn affect tug operations. For instance, future concepts for geostationary communications satellites include tethered or formation flying satellite clusters and even swarms of up to 100,000 pico-satellites (Pelton, 2003). In the case of tethered or formation flying spacecraft, the problem of tugging would be compounded by the dynamics of tethers and the need to move multiple modules. For clusters of very small satellites, orbit determination at geosynchronous altitudes could become a problem.

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