Development of a Product Architecture for a LED Based Detector for Liquid Chromatography

by

Saksham Saxena

Bachelor of Engineering in Mechanical Engineering
Delhi College of Engineering, Delhi University, 2010

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

MASTER OF ENGINEERING IN MANUFACTURING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2015

Signature redacted

Author . . . .

Saksham Saxena
Department of Mechanical Engineering
August 10, 2015

Signature redacted

Certified by . . . .

Jung-Hoon Chun
Professor of Mechanical Engineering
Thesis Advisor

Signature redacted

Accepted by . . . .

David E. Hardt
Professor of Mechanical Engineering
Chairman, Committee for Graduate Students

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ABSTRACT

This thesis develops and describes the product architecture for a LED based detector for liquid chromatography systems. The product architecture development is discussed using a customized methodology, incorporating elements from different views on product architecture development. The market scope and segmentation for such a device was studied and the effect of technologies for such a device on the product architecture was reviewed. The architecture of the product is described at 2 different levels. The first level is the concept design phase which links functional elements to physical components. The second level contains the grouping of components into sub-systems of the product. Design Structure Matrices for the key interactions at the sub-system level were created. These serve to elucidate the key interactions between the chunks for the detailed designers. Finally, the implications of the developed architecture are discussed. One configuration of the developed architecture was selected for detailed design. The optical and mechanical design for this configuration was carried out by separate MIT students.

Thesis Supervisor: Jung-Hoon Chun

Title: Professor of Mechanical Engineering

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ACKNOWLEDGEMENTS

I would like to take the opportunity to thank all the people involved in this project. I would like to thank Professor Jung-Hoon Chun, for his guidance and encouragement to strive for higher goals, both for this project and in life. He listened to our thoughts on the project and helped us pick out the right way to proceed with the project. A thanks to Professor David Hardt and Mr. Jose J. Pacheco for their support over the entire course of the M. Eng. in Manufacturing program at MIT.

I would especially like to thank Mr. Jim McPherson, Mr. Gabriel Kelly and Mr. Greg Puszko of Waters Corporation for giving us the valuable opportunity to gain industry experience by working with a firm of such high repute. A special thanks to them for their efforts in organizing the resources required for the success of this project and also for introducing us to the other managers in the organization. I would also like to give a word of thanks to Mr. Ernie Hillier and Mr. Viet Pham of Waters Corporation for their insights in to the market of detectors for liquid chromatography and for helping us gather data related to it. I would be remiss not to thank Mr. Mike Tice of Strategic Directions International for allowing me to use data from their market report on analytical instruments.

I would like to thank Mr. Daniel Gillund and Mr. Aditya Shankar Prasad, my teammates in this project. I will always look back on our discussions and their fruits with fondness. I would like to take the opportunity to thank all the friends that I made in my one year at MIT and my M. Eng. M. cohort.

Finally I would like to thank my parents and my fiancé – for their love, support and motivation without which this would not have been possible.

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Chapter 1: Introduction

This thesis envisages an absorbance detector for liquid chromatography which utilizes LEDS instead of the traditional deuterium lamps. These lamps use considerable power, generate excessive heat and are large compared to LEDs. The UV spectrum is an essential requirement for these types of detectors and till recent times LEDs emitting this type of light were not available. With recent research in the development and commercialization of deep UV emitting LEDs, it was decided to consider the possibility of designing a detector that uses these LEDs. It is hoped that such a device would address the current needs of the industry and raise the level of the state of the art so as to be prepared to meet the future needs of customers.

1.1 Objectives & Task Division

This thesis is part of a three pronged effort to describe the design of a UV detector platform for liquid chromatography which uses UV LEDs as its light source instead of the common deuterium lamps. Deep UV LEDs are an emerging technology and their development is motivated by their possible use in a number of technologies like sterilization, curing in lithography, fluorescence-based biochemical sensing, communication, etc. Furthermore they offer a number of benefits over the UV lamps currently in use making them the ideal choice for the next iteration of liquid chromatography detectors. Their only limiting factor is the fact that a single UV LED emits light in a narrow wavelength spectrum (about 20nm) as compared to UV lamps which have a considerably wider spectrum range (approximately 180 – 700nm).

The study was split into three sections – the development of the product architecture of such a device on the basis of the market and technology was done by Saksham Saxena, the optical design for a particular variant of the device was developed by Daniel Gillund[1] and the mechanical design for the casing of the optical system for that variant was done by Aditya Shankar Prasad[2]. These three documents taken together will provide the foundation for building the consumer version of such a device.

1.2 Product Architecture

At the very basic level, product architecture refers to the organization of the functional elements of a product or device with the actual physical components that make it up. The aim of creating a product architecture is to describe the basic physical 'chunks' of the product with regards to what they actually do and how they interact with each other for the product to function as required. A product architecture allows for easier detailed design of individual components and also permits these design tasks to be easily split among teams for simultaneous development of the product[3].

The functional elements of a product can be considered the various tasks it has to carry out to demonstrate required performance. The physical elements are the objects which actually implement the functional elements known as 'chunks'.

The creation of a product architecture is normally started during the concept development phase of the design process. As a general rule, the maturity of the basic product technology is the deciding factor as to whether the product architecture will be fully defined in the concept development phase or during the system level design phase[4].

In the concept development phase, product architecture links the functional elements to physical components while at the system level, product architecture groups physical components into sub-systems of the product.

At the system design level, chunks refer to the sub-systems containing groups of components.

1.3 A Topology of Product Architecture

Broadly speaking, product architecture can be differentiated as integral and modular.

Integral architecture is one where there is a one-to-many, many-to-one, or many-to-many relationship between the functional elements and the physical elements[3]. Integral architecture products often show the phenomenon of function sharing[5], where a single component is responsible for several functional elements.

Modular product architecture is one where there is a direct one-to-one mapping between the functional elements and the physical elements of the product.

Modular Architecture can be further broken down into sub-type as mentioned below[4]:

1. Slot-Modular Architecture – characterized with each chunk having different interface couplings between themselves. As a result the chunks are not interchangeable.

2. Bus-Modular Architecture – characterized by a common 'bus' chunk to which the various other chunks attach through the same type of interface. For this bus chunk, the other chunks are interchangeable.
3. Sectional-Modular Architecture – characterized by all chunks having the same kind of interface. However, unlike the bus architecture there is no common chunk.

In practical applications however, it is rare to find products that are purely modular or wholly integral. More often than not, the product as a whole has a mixed architecture, with certain sub-systems being modular or integral. Furthermore, this taxonomy provides a means to describe various modules and their layouts.

Defining the product architecture in the early stages of the design process also allows for effective task division within the various groups of the firm.

The defined product architecture for a product will end up affecting a number of key issues for the firm making the product[3]. These include:

1. Change in the product which includes replacement due to wear, upgrades and add-ons
2. Variety in the product which refers to change in the functionality of the product in a meaningful way to the customer
3. Standardization of parts which aims at using the same components in different varieties of the product
4. Product Development and Management, which deals with planning design and development of the product's individual components of the product

These implications should be kept in mind and evaluated while developing the product architecture.

1.4 Liquid Chromatography

Liquid chromatography is a technique which is used to separate out a mixture into its constituents parts. This is possible due to the different interactions of the mixture with a mobile and a stationary phase. In liquid chromatography the mobile phase is generally a liquid solvent while the stationary phase is some type of solid adsorbent material which separates out the mixtures. In its simplest representation, a liquid chromatography system consists of four components - a solvent pump, a sample injector, a stationary phase or 'column', allowing the separation, and a detector to analyze the separating components. The solvent is pumped at the required pressure and the sample is injected into this stream of solvent. This mixture is then passed through the column, which separates out the constituents of the sample and the detector is used to measure the quantity of constituent. This process and setup is represented in Figure 1.

Figure 1: Basic Liquid Chromatography Equipment

Many variations exist on this basic liquid chromatography process, especially in relation to the pressure with which the solvent is pumped through the system: low pressure liquid chromatography (around 3 bar), high pressure liquid chromatography (around 400 bar) and more recently ultra-high pressure liquid chromatography (around 1000 bar).

1.5 Detectors used in Liquid Chromatography

Existing detectors for liquid chromatography can be classified in to two categories[6]:

1. Bulk Property Detectors – which measure some bulk physical property of the column discharge.
2. Specific/Solute Property Detectors – which measure a physical or chemical property of the solute only.

The variety of detector types that exists within these categories is shown in Table 1.

Table 1: Different types of Liquid Chromatographic Detectors

Bulk Property Detectors	**Specific/Solute Property Detectors**
Refractive Index Detector	UV-Visible Light (absorbance) Detector
Electrochemical Detector	Fluorescence Detector
Light Scattering Detectors	Mass Spectroscopic Detector

1.6 UV-Vis Detectors

These are specific/solute property detectors which operate in the UV and visible light spectrum by either using filters to get a specific wavelength or by splitting the incident light (using a prism or diffraction grating) from the light source before or after it has passed the sample and measuring the intensity after it has gone through the sample to calculate absorbance of the sample. These are also known as absorbance detectors.

These type of detectors can be further subdivided into two categories:

1. Fixed Wavelength Detectors – these use a narrow band pass optical filter to get near monochromatic light for detection from the source and hence don't need to split the light.

2. Variable Wavelength Detectors – their split light into its constituent spectrum using a prism/diffraction grating. There are two variants of these types of detectors:
    2.1. Scan Detectors – either the photodetector or the prism/diffraction grating is moved via motors to allow for potentially monitoring the sample at each separate wavelength.
    2.2. Photodiode Array Detectors – light after passing through the sample is split into the constituent wavelengths and these are made incident on an array of photodiodes to allow monitoring of the sample absorbance at many different wavelengths simultaneously.

Chapter 2: Product Architecture Methodology

This chapter details the methodology followed to develop the product architecture for the proposed product. It describes the procedure followed in a step-wise manner, mentioning the sources from where the different elements are drawn from.

2.1 Method to Develop Product Architecture

A very basic and broad way to develop the product architecture for a device has been described by Eppinger and Ulrich [4], where the following steps are prescribed:

1. Creation of a schematic of the product
2. Clustering the elements of the schematic
3. Creation of a rough geometric layout
4. Identifying key interactions

Derived from this basic approach, a number of schemes are described in literature for deciding the product architecture of a device. The key features from select few of these methodologies were adopted to augment the basic strategy described above and develop a possible product architecture for the envisioned LED detector. Because of the niche market and the relative immaturity of the technology being employed, a more qualitative approach was preferred. Furthermore, as the device in consideration is an optical one, the rough geometric layout was not pursued as its value is realized more in mechanical mechanisms and devices, instead more emphasis was laid on the clustered schematic of the product. The key interactions were detailed in the schematic of the product.

The methodology that was followed in developing the product architecture is described in the following sections before demonstrating its application to the proposed device design itself in the succeeding chapters.

2.1.1 Market Considerations

The first step was to consider the market conditions and to evaluate the potential for the product and its variants. As mentioned by Schuh, Rudolf and Vogels [7], the first stage for developing a product architecture, particularly a modular one, is to identify the platform potentials in terms of the market for the product.

They prescribe a four step method to do this which was followed here:

1. Defining the initial field of operation - the broad market scope of the product platform was identified by talking to experts for that product in development, production, marketing and logistics fields.
2. Identifying the various market segments - defined the relevant market segments on the basis of a segmentation criteria.
3. Analyzing the identified market segments - after identification of the segments, it was necessary to consider the requirements for each.
4. Define the sales scenario and required configurations - this should have been more of a quantitative step, where sales figures for each segment and the required product configurations should have been identified. However, due to unavailability of well-defined sales data, the possible configurations were identified and the market percentage for each were broadly estimated.

Market analysis is aimed at discovering the customer base and identifying their needs and demands. The analysis done for this project was quantitative and derived through secondary sources of data.

2.1.2 Technological Considerations and Constraints

The various technological constraints were considered and the existing technologies and the possibility for newer replacements was studied. The constraints of the new technologies especially the UV LEDs were key considerations affecting how to decide the architecture for the device as the entire device is based around the light source itself.

The key technology was also analyzed from the point of view of modularity. As mentioned by Kamrad, Schmidt and Ulku [8], an analysis on the value of modular product architecture versus an integral product architecture made the following conclusions about when a company will benefit most from a modular product.

1. A modular product is beneficial when the market scale for the product is low. It will be cheaper for a firm to incur the cost of integrating components if the number of customers is high, as the cost of integration can be easily distributed over a high volume of customers.
2. When, the cost for redesigning and producing an integral product is high, modularity will be a better option. Similarly, if the company's pricing power in the market is limited, the margins will be less which, in turn, will slow the rate of introduction for new products. This can, however, be offset by the use of modular upgrades.

3. It has been found that modularity in a market with technically unsophisticated customers, has a possibility of slowing down the acceptance of innovation. Even if the firm introduces frequent new upgraded modules, consumers may not replace the modules due to time and cost requirements. So modular architecture is more suitable in scenarios where high technical expertise is required.
4. The highest value of a modular architecture comes into play when the rate of innovation in different components shows a large discrepancy.

These points were considered when analyzing the new technology. Apart from this the existing technology and its limitations were noted.

2.1.3 Functional Requirement Decomposition & Functional Scheme

Taking cue from axiomatic system design principles, the broad functional requirement for the product platform was established and decomposed into the very basic functional elements for the device.

However, unlike axiomatic design, no design parameters were attached to the current functional elements. The physical elements were decided in the next step of the process after various considerations have been taken into account. This decision was made as the goal here is not the design of a single device but to develop the architecture of a product.

Using the identified functional elements, a scheme was created mapping out their key interactions. This schematic shows how the device will work in conjunction with the functional elements.

This decomposition process is carried out by the product architect based on his/her preference, knowledge of the functionality of the device and after consulting the designers.

2.1.4 Concept Level Product Architecture

Once the functional scheme had been created, the functional elements were associated with actual physical elements. These decisions were made for the identified product configurations and keeping in mind the technology constrains and considerations and the markets needs as identified in the preceding chapters. Inputs from the optical[1] and mechanical[2] designers were also considered.

2.1.5 Clustering Through Interaction Matrices for System Level Product Architecture

The functional scheme, now with physical components was represented in the form of interaction matrices or design structure matrices (DSM), one each for each key type of interaction that takes place in the device. DSM is a technique for studying interactions in complex systems which was

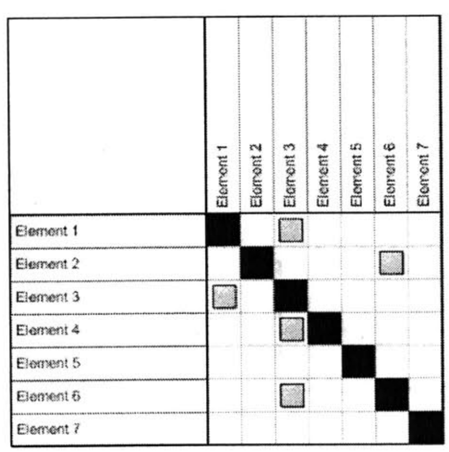

Figure 2: Example of a DSM

mentioned by Steward[9]. The DSM is a square matrix which shows the interaction of each element with other elements. An example of a DSM is given in Figure 2.

The DSM is read row-wise, in Figure 2 it is possible to see that element 1 has an interaction with element 3 but not with element 2, element 2 has an interaction with element 6, element 3 has an interaction with element 1.

Element 1 & 2 have no interaction between them. Element 2 has a single direction interaction with Element 6. Element 1 and 3 have a two directional interaction between them.

Figure 3 shows the matrix from Figure 2 after it has been clustered. With the two clusters, all interactions except one have been internalized.

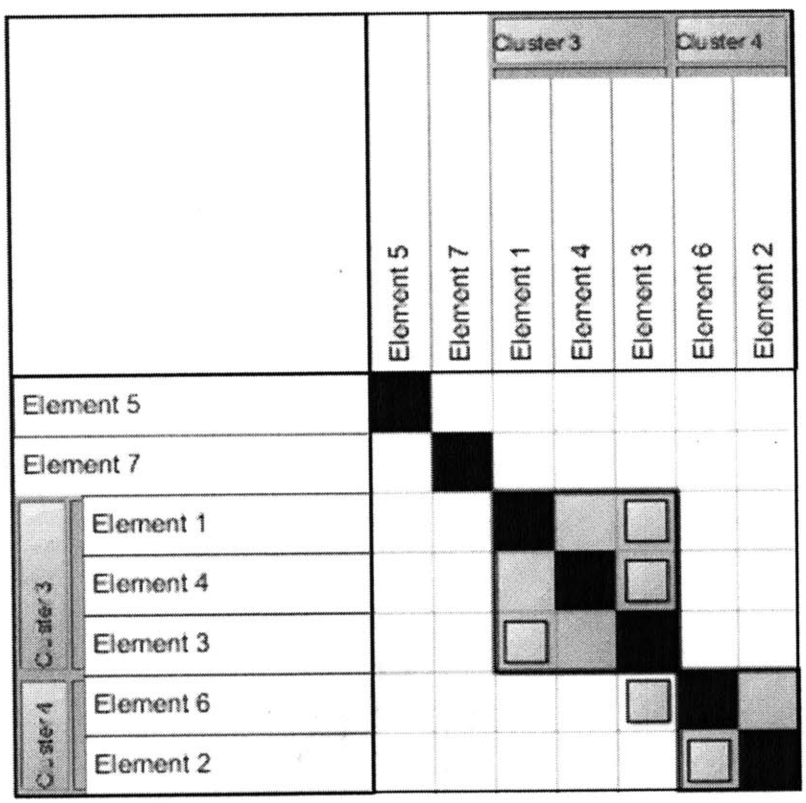

Figure 3: Example of a clustered DSM

The interaction matrix or the DSM technique to look at architecture clusters has been described by Pimmler and Eppinger[10] through the following three step methodology:

1. Decompose system into elements
2. Document the interactions in form of the DSM technique
3. Cluster elements into chunks on the basis of the different interactions

The last step aims at internalizing as much of the interactions inside the chunks while minimizing chunk to chunk interactions. Pimmler and Eppinger also caution that for a more effective application of this methodology, more strategic and architectural issues should be considered in the clustering processes. They mention the possibility of a number of out-of-chunk interactions that may remain even after clustering and these interactions should be noted for the detailed design phase.

For the specific case explored in this document, the key interaction types were identified and as suggested by Pimmler and Eppinger[10], separate DSMs for each key interaction type was created and clustered to gain perspective for possible architectural decisions. This system level architecture clustering is done from the point of view of product development and management to allow for easy allotment of different sub-systems to different teams for detailed design and development.

2.1.6 Product Architecture Description

Finally, taking into account the market, technology and the interactions in the device, a product architecture scheme was suggested for the proposed device. Each architecture chunk was described, the interactions were mapped out and the impact of the developed product architecture was discussed.

In conclusion, a brief description of how the scheme was used to design the optical system and its mechanical structure by Gillund[1] and Prasad[2] for a particular variant of the product was given.

Chapter 3: Market Considerations for Proposed Device

The key industries where liquid chromatography is used are as follows:

1. Pharmaceutical & Biotechnology
2. Chemical & Petrochemical
3. Environmental Testing
4. Food Testing

3.1 The Initial Field of Market Operation

UV Detectors for liquid chromatography equipment make up a very specialized, niche market. Most liquid chromatography equipment manufacturing companies sell their own devices, which are compatible with their own systems only. There are third-party devices in the market which can be incorporated with any liquid chromatography system but there are fewer of these as most companies recommend using their own detectors with their systems.

Due to the coupled nature of the UV detectors with the liquid chromatography system, it is possible to infer about the liquid chromatography detector market by analyzing the liquid chromatography market itself.

In 2013, the analytical high pressure liquid chromatography(HPLC) market was valued at nearly 4 billion US dollars[11]. Only the analytical HPLC chromatography market was considered as a reference since the preparative liquid chromatography market and other specialized liquid chromatography markets are considerably smaller in comparison. Hence, the initial field of market operation was chosen as the analytical HPLC chromatography market to look at market segments.

3.2 Identifying & Analyzing the Market Segments

The breakup of the demand of this market in terms of the function for which they are used is shown in Figure 4.

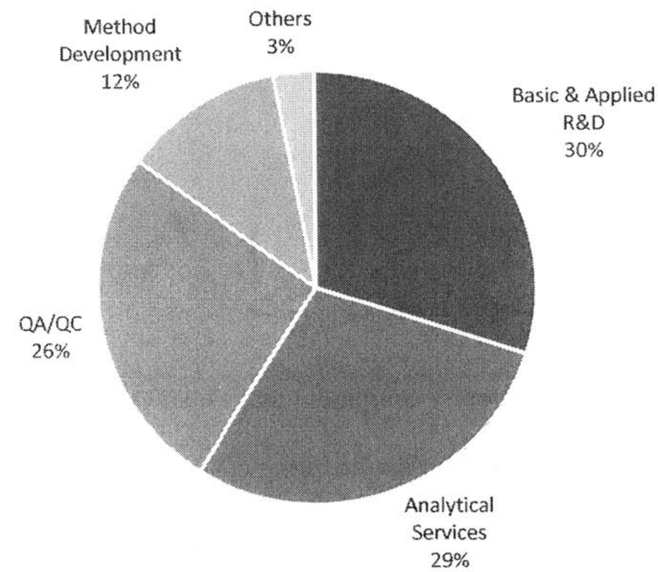

Figure 4: Demand of Analytical HPLC by function in 2013[11]

For the proposed LED detector design, the focus was on customer segmentation by considering their interest in different wavelengths of light.

The quality assurance/quality control segment is interested in the testing of a specific known substance using the suitable wavelength. Similarly, the analytical services segment, which is oriented towards water analysis applications and environmental testing, will have the need for specific wavelengths only. These customers are more oriented towards a single wavelength type detector or possibly a scanning type detector if they require more automation in terms of switching wavelengths.

This is supported by some partial data that was acquired from the U.S. Pharmacopeial Convention (USP) via the marketing division of a leading liquid chromatography equipment manufacturer[12]. The USP is a scientific non-profit organization that sets the standards for the identity, strength, quality and purity of medicine, food ingredients, dietary supplements, etc., to be manufactured, distributed and consumed worldwide[13].

One of the tasks that the USP undertakes is to develop and maintain monographs for various medications, food ingredients, dietary supplements, etc. A monograph is a standard which details a substance – provides its name; its definition; packaging, storage and labeling requirements; and all the information on tests required to ensure that the substance is of appropriate strength, quality and purity[14].

The key information in these monographs is the specific wavelength that is recommended to detect these substance.

As shown in Figure 5, the data from USP shows that there are a number of testing methods that use specific wavelengths, e.g. nearly 30% of the registered LC methods are using 254 nm wavelength light. Discussion with marketing executives of a leading liquid chromatography system manufacturer revealed that a number of such preferred wavelengths exist and their use is established in standard tests for various substances.

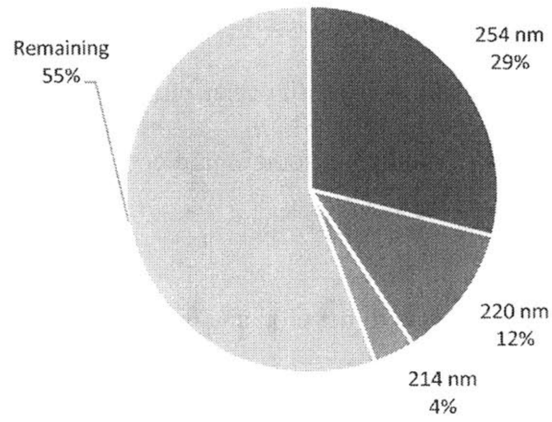

Figure 5: Percentage of Monographs with liquid chromatography broken down by different wavelengths

On the other hand, the method development, basic and applied research, and development customers are more interested in the response of new and unknown substances to the whole spectrum of light (UV-visible). In essence, this sector demands more flexibility in wavelength selection and therefore prefers the photodiode array or the scanning type detector with their liquid chromatography equipment.

Furthermore, interviews with the marketing division of a leading liquid manufacturing company revealed that approximately 70-80% of their customers were interested in the 200nm to 320nm UV range[12]. This is further supported by the fact that UV absorption detectors are generally designed for the wavelength range of 180nm to 350nm and many substances are known to absorb light in this range[6].

On the basis of this gathered information, three customer segments were identified for the proposed device, as seen in Table 2.

Table 2: Customer segmentation for the proposed device

S. No.	Customer Segment Requirement
1	Single Wavelength Requirement
2	Wavelength varying capability requirement in the UV range
3	Wavelength varying capability requirement in the UV - Visible range

3.3 Sales Scenarios and Configurations

Considering the customer segments, three possible configurations for the device were decided upon and their market share was estimated as seen in Table 3.

Table 3: Identified configurations for the device

S. No.	Configuration	Estimated Market share
1	Single wavelength configuration, with ability to change wavelengths if needed.	50%
2	UV range scanning capability.	40%
3	UV-visible range light scanning capability.	10%

For estimating the market share, we theorize that 90% of the QC/QA and the analytical service segment will be interested in the single wavelength configuration.

Of the remaining customers, we surmise that 80% will have their demand met by the UV range scanning capability device and the rest will want the UV-visible range scanning capability.

The estimated market share gives some indication of the possible sales scenario for the detectors.

Chapter 4: Technological Considerations for Product Architecture

This chapter briefly talks about the existing UV detectors that are used in liquid chromatography equipment and the key technologies in them. Then it discusses the technologies that are being used in the new design and their impact on the product architecture. A more detailed discussion of the optical components mentioned here can be found in Gillund[1].

4.1 Existing UV Light Detectors

The construction of the various type of UV detectors mentioned in Section 1.7 are considered.

The fixed wavelength type detectors are simple in design and construction, and the schematic for the light path in such a device is given in Figure 6.

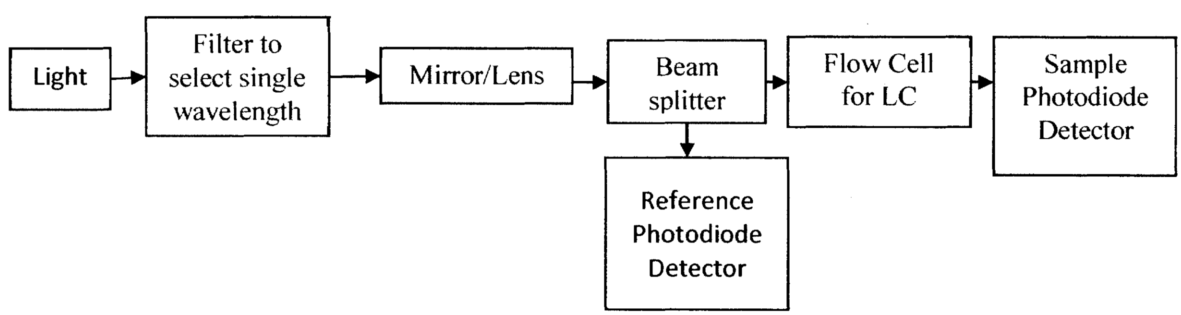

Figure 6: Schematic of a fixed wavelength detector

For the scanning type detector, a basic schematic depicting its working is shown in Figure 7.

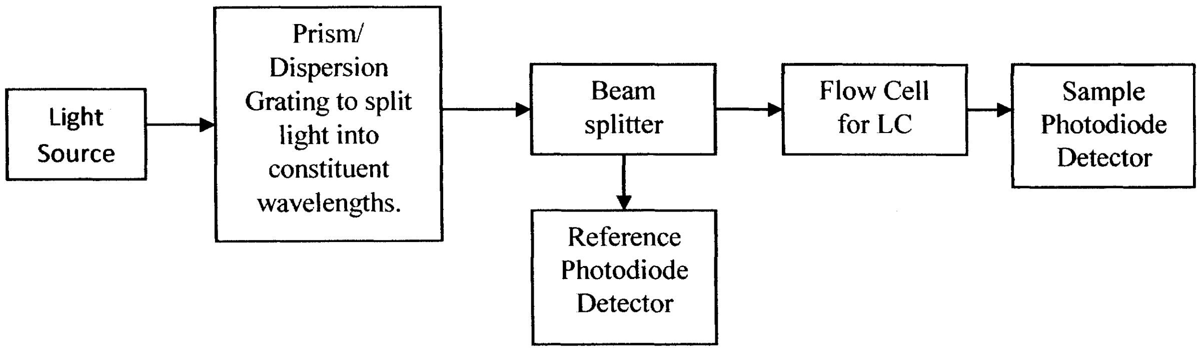

Figure 7: Schematic of a scanning type detector

In this type of detector, the prism/dispersion grating is moved via a motorized mechanism for the purpose of selecting different wavelengths. However because of the inertia of the prism/grating and motorized mechanism, it is impossible to switch between wavelengths at very high speeds,

For the photodiode array detector, the basic schematic is shown in Figure 8.

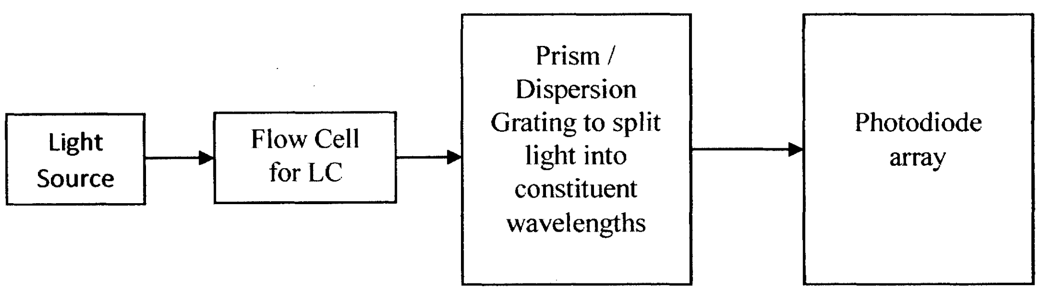

Figure 8: Schematic of a photodiode array detector

This is the most expensive type of UV absorption detector available in the market, with the key cost coming from the photodiode array.

4.2 Current Light Sources used in UV detectors

Quite a few light sources have evolved over time for use with UV-Visible Light detectors for liquid chromatography. The earliest sources were metal-vapor discharge lamps, which produced a discrete spectrum. The most common among them was the mercury-vapor lamp, which produces a peak wavelength at 253 nm. This is considered a legacy wavelength as it serves as the basis for a number of current chromatographic methods. Because these lamps had a discrete spectrum, they were favored in the construction of the fixed wavelength detectors. These are now superseded by gas discharge lamps and incandescent lamps, both of which produce a continuous spectrum[15] and are used in scanning and photodiode array type detectors. A detailed discussion of the current light sources used in these detectors is present in Gillund[1].

4.3 UV LEDs and Implications for Product Architecture

The proposed device uses high powered UV LEDs as a light source. It should be noted here that high power LEDs in the visible range are a very established technology and are easily available in the market. The innovation in LEDs is in the deep UV range of the light spectrum.

High power LEDs (in the milliwatt and higher range) emitting light in the near-ultraviolet range (300 – 400nm) are an established technology and easily available. They are manufactured by depositing Gallium-Nitride or Aluminum-Gallium-Nitride on a sapphire substrate. Deep UV

LEDs with AlN-AlGaN based LEDs have already been demonstrated at wavelengths of 210nm to 360nm[16]. However these LEDs have considerably low efficiencies as compared to traditional visible light LEDs. Research is being carried out to improve the efficiency of these LEDs and has shown promising results. By using metal-organic chemical vapor deposition methods to grow high quality AlN buffers on sapphire substrates, LEDs at 261nm and 227.5nm with power 1.65mW and 0.15mW respectively were demonstrated[16].

High power deep UV LED's are a relatively new product. These deep UV LEDs are created is by using AlN as the substrate itself and have an optical output of 0.5 mW or 1 mW. Because of the similarity of the material which results in lower density of dislocations, AlGaN UV LEDs grown on low density bulk AlN exhibit distinct improvements in light output and thermal management[17]. Companies like Crystal IS have already started offering deep UV or UVC LEDS in peak wavelengths from 250nm to 280nm based on this technology[18].

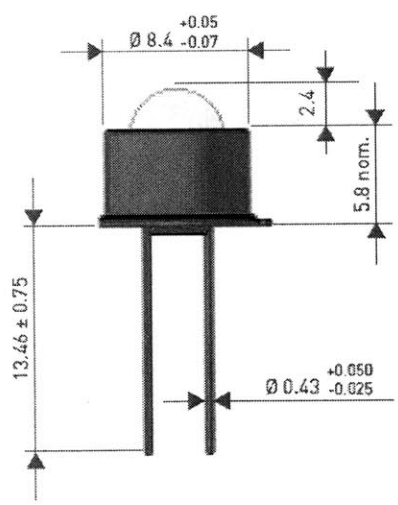

Figure 9: UV LEDs offered by Crystal IS[18]

As UV LEDs are a relatively new and developing technology, they will play a more influential role in deciding the product architecture, especially the need for modularity.

While looking at the product architecture for the detector, a key aspect in LED usage is their limited range of wavelengths as compared to the deuterium UV lamp, making this a technological constraint. The half intensity range for these LEDs is essentially +/- 6nm from the peak wavelength of the LED, so a single LED would cover an band of 12 nms[1]. Figure 10 shows the approximate spectral distribution of a UV LED whose peak wavelength is 260nm.

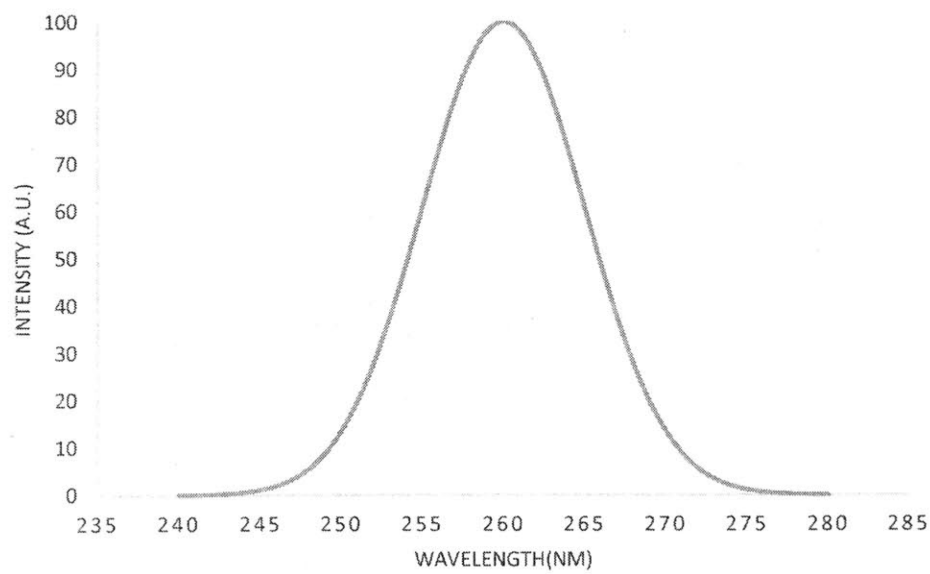

Figure 10: Spectral Distribution of a UV LED with maxima at 260nm

The UV LEDs are also considerably smaller than UV lamps. They can be approximated as a cylinder with diameter 9mm and height 6mm[18].

The deep UV LED technology is currently at a nascent stage of its lifecycle and is expected to mature for the next few years. From a cost perspective, while the current iterations of the LEDs are expensive, they are expected to become cheap as the technology is established and mass production becomes the norm.

These two aspects – the short spectrum range and the current state of the UV LED technology should be considered when deciding the product architecture for the detector. These two considerations push for a modular approach for UV LEDS as a component in the device. UV LEDS also meet all the criteria discussed in Section 2.1.2 for modularity.

4.4 Optical Fibers for UV LEDs and Implications for Product Architecture

The use of optical fibers as a light delivery mechanism allows for flexibility in the product architecture. With optical fibers, there is less need to place the light source close to the remaining optical elements, as the fiber can easily route the light to them from the source.

For UV light applications down to the wavelengths of 200nm, optical fibers made by using slica-glass as the core material and tetrafluoroethylene-hexafluoropropylene copolymer or methylpolysiloxane as the sheath material are appropriate. Such optical fiber systems are optically transparent between 200nm to 2200nm range with the only exception being at an absorption band at 1400nm. These fibers are also thermally stable upto temperatures of 250 °C and show no loss of transmission efficiency[19].

4.5 Digital Micromirror Device

A DMD is essentially a light modulator, made up of an array of micro mirrors, each of which can be moved independently. The device has a memory cell below the mirror array where data is loaded to control the tilt angle of each individual mirror electrostatically. Each mirror has the two states, either +x degrees or –x degrees where x is usually 12 degrees or 17 degrees. This mirror array in a DMD is covered by a transparent window for protection as well as to control the incident light properties. The rate at which the orientation of the individual mirrors can be changed varies from about 4 kHz for the most basic variants to 32 kHz for the advanced variants[20]. The first DMD was made by Texas Instrument in 1987 and the first patent for the technology was granted in 1991[21]. DMDs are a relatively mature technology, with Texas Instruments introducing DMD incorporating commercial products in 1996. DMDs are used in digital cameras, HD televisions, digital projectors, etc. Figure 11 shows the mirror array of a DMD.

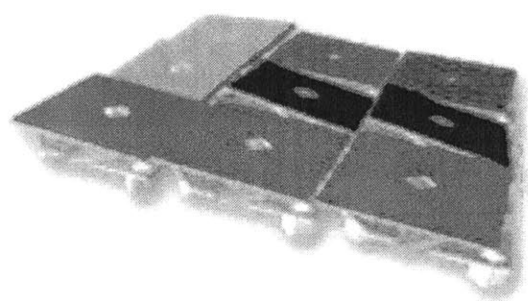

Figure 11: DMD mirror array close-up[22]

While the currently available DMDs are specified to work in the visible light to infrared light region only, research is being done on how to adapt these devices for UV applications. This research is especially driven by the use of the DMDs in maskless lithography devices. DMDs with reliable operating characteristics down to 390nm have already been demonstrated and Texas Instruments is working to develop DMD's capable of working down to the 200nm ranges[22]. Research in this area has also demonstrated viable operation of DMDs with specialized windows of sapphire or quartz down to 265nm wavelength light [23]. So it is reasonable to expect development of viable DMD's capable of operating in the deep UV region within the next few years.

It should also be noted, that while the DMD's themselves are an established device, their use in the UV spectrum is still in developmental phase.

The design being considered for the new device includes using a diffraction grating to shine the spectrum of light from a UV LED array on to a DMD, then selecting the required bandwidth of light by switching on the required micromirror rows and using the rest of the micromirror array in the off-position to direct the remaining light elsewhere. Because of the extremely small size of the micromirrors compared to a motor mounted diffraction grating, it will now be possible to switch wavelengths at extremely high speeds. This capability is not present in current detectors.

4.6 Other Components

The other components in the device, especially optical components like mirrors, diffraction gratings, beam splitters, etc. are technologically mature standard components which are and have well understood applications. The electrical and electronic components are also well established technologies. Hence the components can be easily made more integral from the product architecture standpoint.

Different types of flowcells exist for any given liquid chromatography equipment depending on the sample tube diameter and path length. Furthermore the construction of these flowcell varies from manufacturer to manufacturer. This fact pushes for a modular approach regarding the flowcell.

Chapter 4: Functional Elements and Functional Scheme of the Product

This chapter describes the top level functional requirement for the device and shows how this was decomposed into its basic functional elements.

4.1 Top Level Functional Requirement

A top level functional requirement was formulated in order to encapsulate the product's purpose. This top level functional requirement is a general description and is not configuration specific, see Table 4.

Table 4: Top Level Functional Requirement for the device – FR1

FR1	Product with possible configurations for different customer segments to detect liquid chromatography sample constituents using various wavelengths.

4.2 Decomposition of Top Level Functional Requirement into Functional Elements

This top level functional requirement was decomposed into broad sub-level functional requirements. These are depicted in Table 5.

Note that FR1.1 is related to the optical function of the device. FR1.2 deals with the control, operation and communication of the device within as well as external to itself. FR1.3 is a functional specification that ensures that the device can work in a range of temperatures. FR1.4 is related to the optical system again and has been kept separate as it will come into play when the system has to deal with multiple wavelengths and needs a referencing method. FR1.5 is a broad requirement to keep the inner components of the device covered.

Table 5: Decomposition of FR1

FR1.1	Generate & manipulate light of required wavelength to pass through sample and measure it and a reference portion prior to it interacting with the sample.
FR1.2	Control the various components, supply them power when needed and interpret the light measurements and coordinate with external systems.
FR1.3	Be functional in a range of temperature conditions.
FR1.4	Have auto referencing capabilities in terms of the optical system.
FR1.5	Protect device from unintended physical interactions from outside.

These sub-level functional requirements are now further decomposed into the constituent functional elements of the device. FR1.1 was decomposed into twelve functional elements as shown in Table 6. These functional elements essentially make up the entire optical system of the device.

Table 6: Decomposition of FR1.1

FE1.1.1	Generate light of different wavelengths.
FE1.1.2	Identify light source to system.
FE1.1.3	Collect light from source.
FE1.1.4	Imitate a point source of light.
FE1.1.5	Split light into different wavelengths.

FE1.1.6	Select required band of wavelength at high speed.
FE1.1.7	Focus light.
FE1.1.8	Split light into reference and sample beams.
FE1.1.9	Detect light for reference.
FE1.1.10	Detect light after it has gone through the sample.
FE1.1.11	Give structural support and hold optical elements in place.
FE1.1.12	Allow passage of liquid chromatography sample and expose it to light in different optical path lengths as required.

FR1.2 was decomposed into five functional elements shown in Table 7. These functional elements deal with distributing power in the device and controlling the various components that make up the device.

Table 7: Decomposition of FR1.2

FE1.2.1	Supply power to the device.
FE1.2.2	Convert incoming power to the required voltages.
FE1.2.3	Control the various components.
FE1.2.4	Interpret signals from the detector.
FE1.2.5	Communicate with the rest of the liquid chromatography system and the control software.

FR1.3 was decomposed into two functional elements shown in Table 8. These two functional elements are responsible to monitoring and maintaining a steady temperature in the device.

Table 8: Decomposition of FR1.3

FE1.3.1	Measure temperature inside device.
FE1.3.2	Maintain steady temperature conditions in device.

FR1.4 and FR1.5 could not be decomposed any further and hence were directly converted to functional elements as shown in Table 9 & Table 10.

Table 9: Decomposition of FR1.4

FE1.4.1	Generate reference wavelength light.

Table 10: Decomposition of FR1.5

FE1.5.1	Enclose device in a body.

4.3 Functional Schematic

After this decomposition process, the 21 identified functional elements are arranged in a functional schematic to show how the device is supposed to work. This schematic is shown in Figure 12.

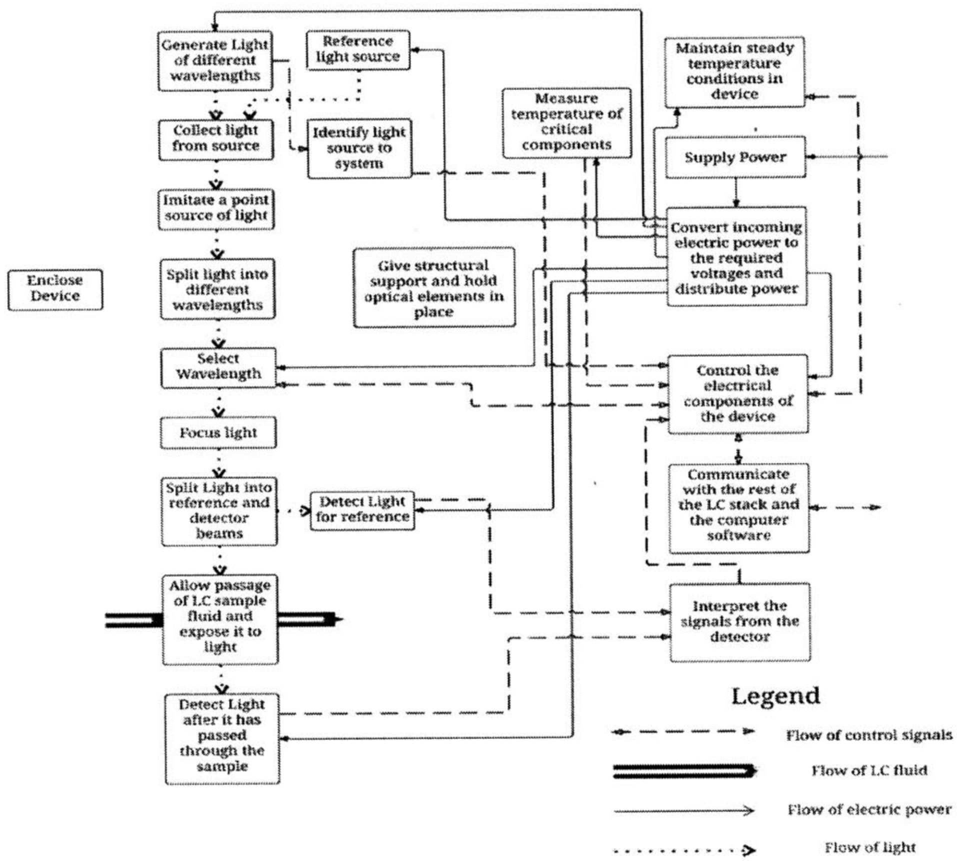

Figure 12: Functional Schematic of Proposed Device

The schematic depicts the different type of interactions that are occurring in the device. There is a light source to generate light of different wavelengths along with a reference wavelength light source. Light from these two sources is collected and sent through the system by imitating a point source. This is necessary for achieving good optical resolution as discussed by Gillund[1]. The light is then split into its constituent wavelengths and the required wavelengths are selected and focused. This focused light is split into a sample beam and a reference beam which is recorded for comparison to the sample beam after it has gone through the liquid chromatography sample. An element is required to introduce the liquid chromatography sample to the light. There has to be an element to hold all these optical elements in position relative to each other and give them structural support.

To run the device, power has to be supplied to it. The incoming power has to be converted to the required voltages for the different components to be distributed to them, and then the various components, especially the electrical ones have to be controlled. The light measurements have to be interpreted and this data has to be communicated to the control software as well as input from the rest of the liquid chromatography system.

Finally, an element should enclose the entire device to allow protection from outside elements.

It should be noted that for the purpose of deciding the product architecture, only the key functional elements were considered.

Chapter 5: Concept Level Product Architecture

At this stage, the functional elements are assigned to physical components. Keeping in mind the technological constraints and considerations, two different schemes were recommended for the three product configurations identified in Chapter 3.

5.1 Architecture Scheme for Configuration 1

As mentioned in Chapter 3, configuration 1 of the device is a single wavelength type detector which should have the capability to switch wavelengths if required. This is aimed at the QC/QA and analytical customer who will be using a single wavelength most of the time and would prefer the capability to change the wave length if needed.

The suggested linking of the functional components to physical elements is given in Figure 13 and the resulting device schematic from these choices is given in Figure 14.

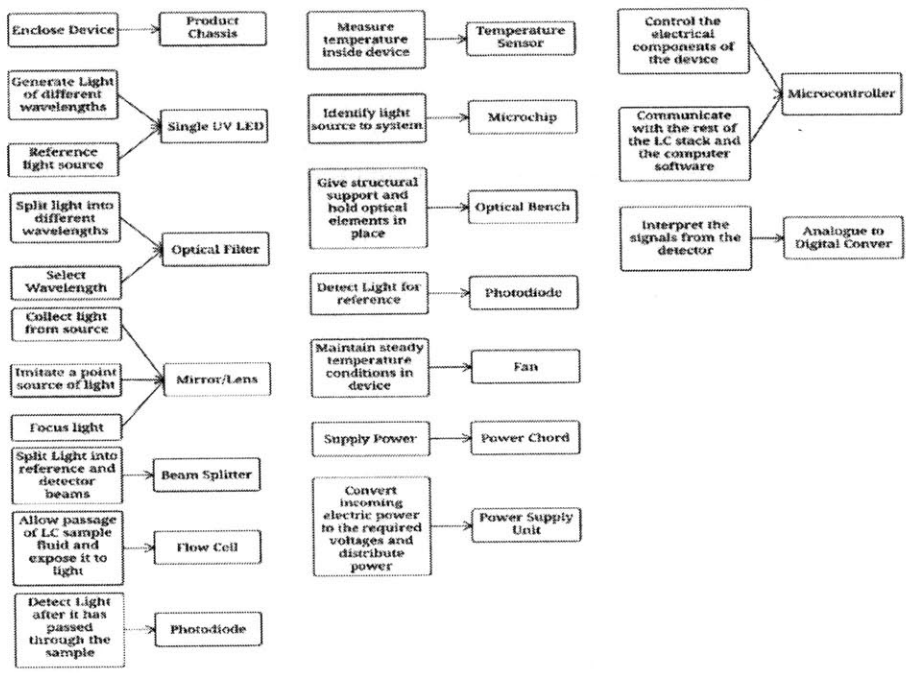

Figure 13: Linking Functional Elements to Physical Components - Configuration 1

This linking of functional elements to physical components for Configuration 1 is based on the design of existing fixed wavelength detectors. With a single LED, this architecture represents a more efficient method of manipulating the light. In the optical system, only a single UV LED is considered, which will have a half height wavelength range of about 12nm. This range will be further narrowed to the required wavelength by the using narrow pass optical filters which can narrow the half height bandwidth up to 2nms. The LED will have a microchip to identify it to the system. Also, as this configuration is working with a single wavelength, there is no need for a reference light source as this functional element is redundant and is linked with the LED itself. Then a mirror or a lens can be used to focus the light on a beam splitter, which would split the light into a reference beam for the reference photodiode and a sample beam which would go through the flowcell and be recorded by the sample photodiode. An optical bench would support and hold the optical elements in place. Temperature sensors would measure the device's internal temperature and appropriately placed fan(s) would regulate the temperature inside. Power would be supplied to the device through a power cord and would be converted to the required voltages using a power supply unit, which could be an off-the-shelf component or a customized build. For the electronic control, circuitry incorporating a microcontroller with the requisite analogue to digital converters for the photodiodes will be used. The circuitry would also communicate with the rest of the liquid chromatography system and the control software. Finally, a product chassis would enclose the device to protect it from outside conditions.

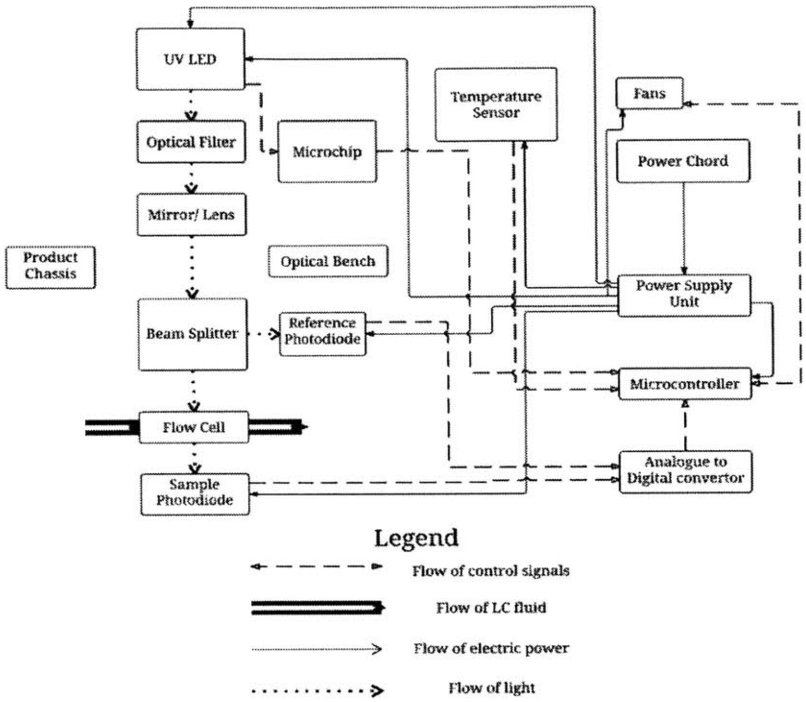

Figure 14: Schematic for Configuration 1

This particular scheme was decided upon as it is the most efficient when considering light from a single LED only. Similar devices are already on the market however they do not offer modular LED capability but are rather set to one or two wavelengths with no options to change them[24]. The key innovation suggested here is to make the LEDs modular so as to allow the customer to change the wavelength if and when required.

5.2 Architecture Scheme for Configuration 2 and 3

For Configurations 2 and 3, the linking of functional elements to physical components was done as shown in Figure 15 and the resulting schematic from this set of choices is shown in Figure 16.

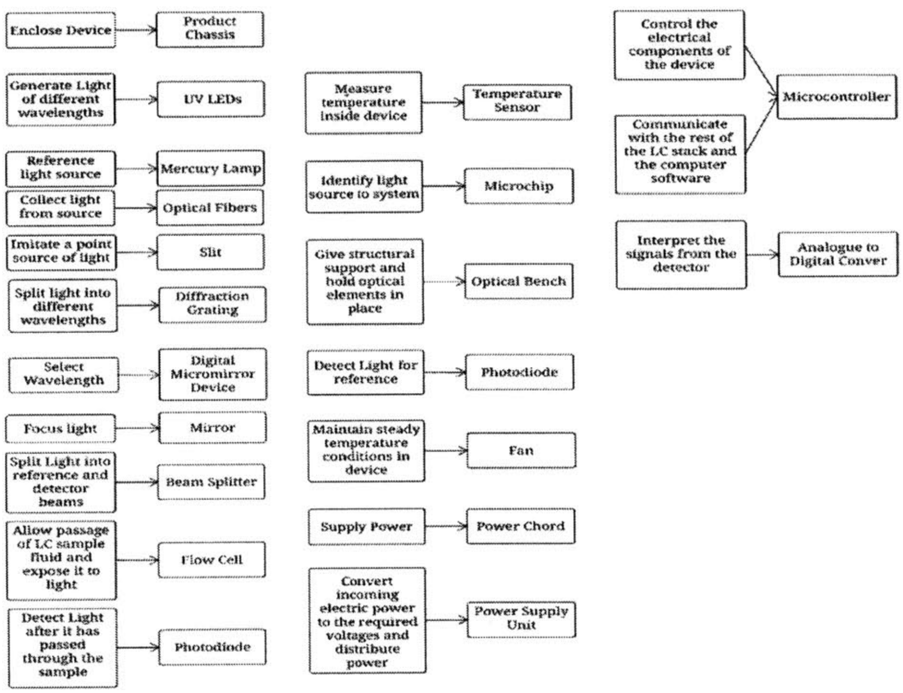

Figure 15: Linking Functional Elements to Physical Components - Configurations 2 and 3

These configurations are aimed at customers who want to scan through a range of wavelengths and simultaneously measure the response of the liquid chromatography sample to various wavelengths. As discussed in Section 4.1, the current methods to do so employ either a turnable prism/grating or split the light on to a photodiode array after it has passed through the sample. After discussion with the optical designer[1], it was decided to use a digital micromirror device in combination with a diffraction grating to switch wavelengths at high speeds. As the range of wavelengths required for such a device would be more than what is provided by a single UV LED, an array of such LEDs would be needed. In this array, the LEDs would be modular and each would have a microchip to identify itself to the system. For Configuration 2, the array would cover the UV light range while for Configuration 3, the array would cover the UV and visible light range both. To collect and combine the light from these LEDs, optical fibers would be used. These optical fibers would end on a slit, which would act as a point source and determine the lower limit on the resolution of the system. The light would then be split into its constituent wavelengths and made incident across the digital micromirror device. By controlling the mirror array, it would be possible to select specific wavelengths as well as the bandwidth of wavelengths at very high speed. The selected light would then be incident on a beam splitter and split into the reference beam and the sample beam. The reference beam would be recorded by the reference photodiode and the sample beam would pass through the flowcell carrying the liquid chromatography sample. The rest of the functional elements are linked to similar physical elements as in Configuration 1.

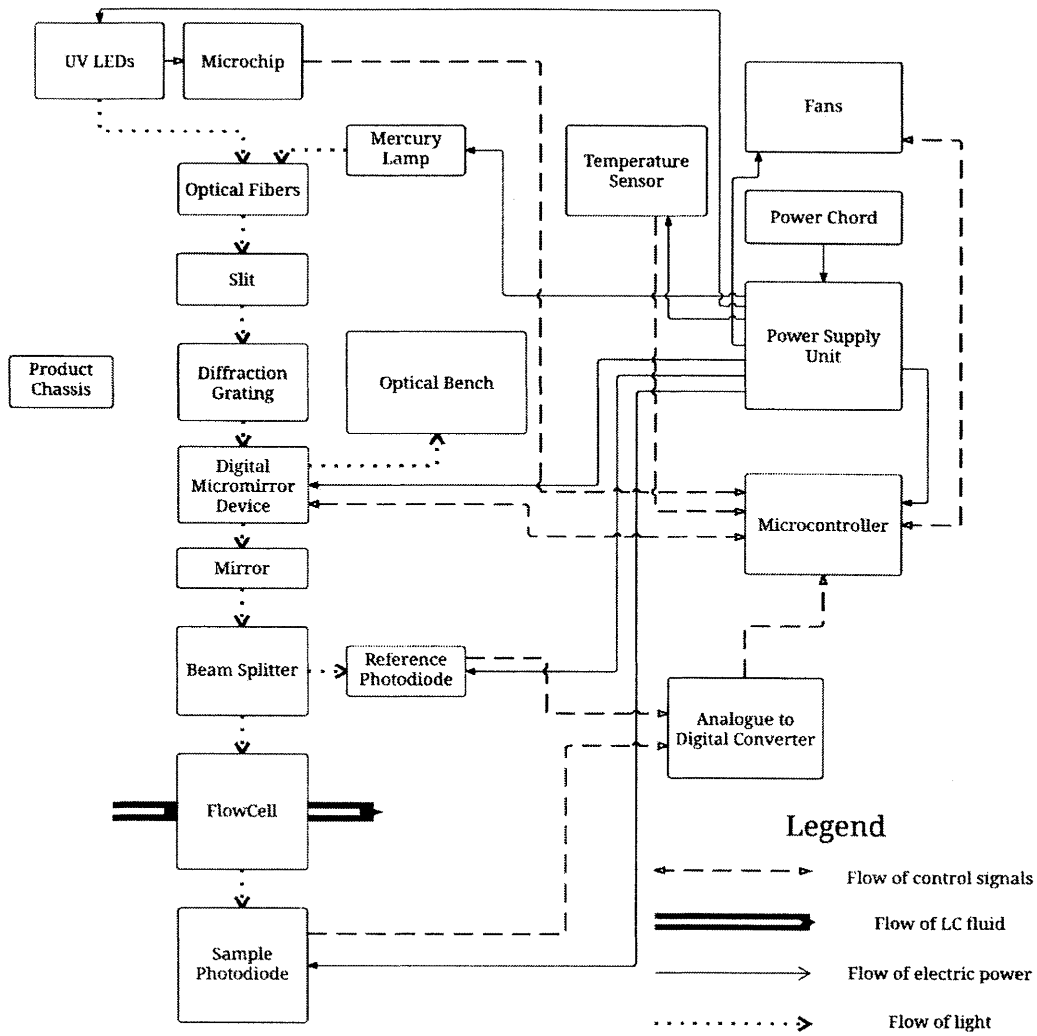

Figure 16: Schematic for Configurations 2 and 3.

This schematic was mapped out on a DSM for studying the key interactions to define product architecture at system level.

Chapter 6: Clustering Through DSM for System Level Architecture

The key interactions in the device for the scheme selected for Configurations 2 and 3 are the light interaction and the spatial interactions. Configuration 1 was not considered for DSM analysis as it is a relatively simple design. As electric power and information can be easily transmitted through flexible wires, these interactions were not considered for system level grouping. It should be noted, that these clustering are not final but are a method to look at the effect of the proposed clustering on interactions between various sub-systems. The clustered DSM shown in this chapter are one of many possible and have been selected by the product architect. They also serve as a technique to communicate system level design information to detailed designers.

6.1 Suggested Clustering on the Basis of Light Interactions

The clustered DSM for light interactions in the device is shown in Figure 17. The clustering has been done manually minding the various considerations discussed so far and since the UV LEDs have to be kept modular for technological considerations, they are not included in any cluster. Cluster 1 consists of the optical fibers and the reference light source, a small mercury lamp generating light at 254mn. It will link with the UV LEDs. Cluster 2 consists of all the remaining optical elements and the optical bench holding the optical elements together. Such a grouping allows for internalization of a number of interactions and the design teams for each cluster will have to take special consideration of only 2 optical interactions – the LED to optical fiber interactions and the optical fibers to the slit in the optical bench.

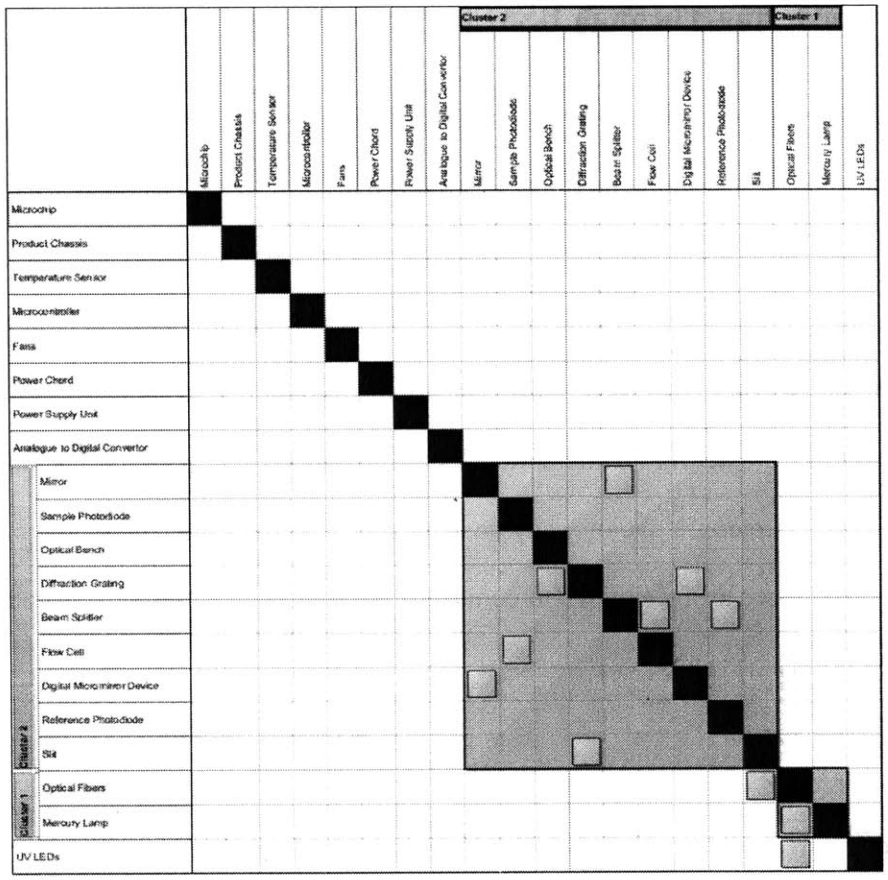

Figure 17: Clustered DSM for light interactions

The DSM not only provides perspective on how to cluster the various components together but also acts as documentation to allow communication of the architectural information to managers and designers. This is a reference to see what sub-systems would be affected by any proposed change later on.

6.2 Suggested Clustering on the Basis of Spatial Interactions

The spatial interactions for the various components in the device was mapped out on a DSM and the clustering was done as shown in Figure 18. These interactions refer to the adjacency between the various components.

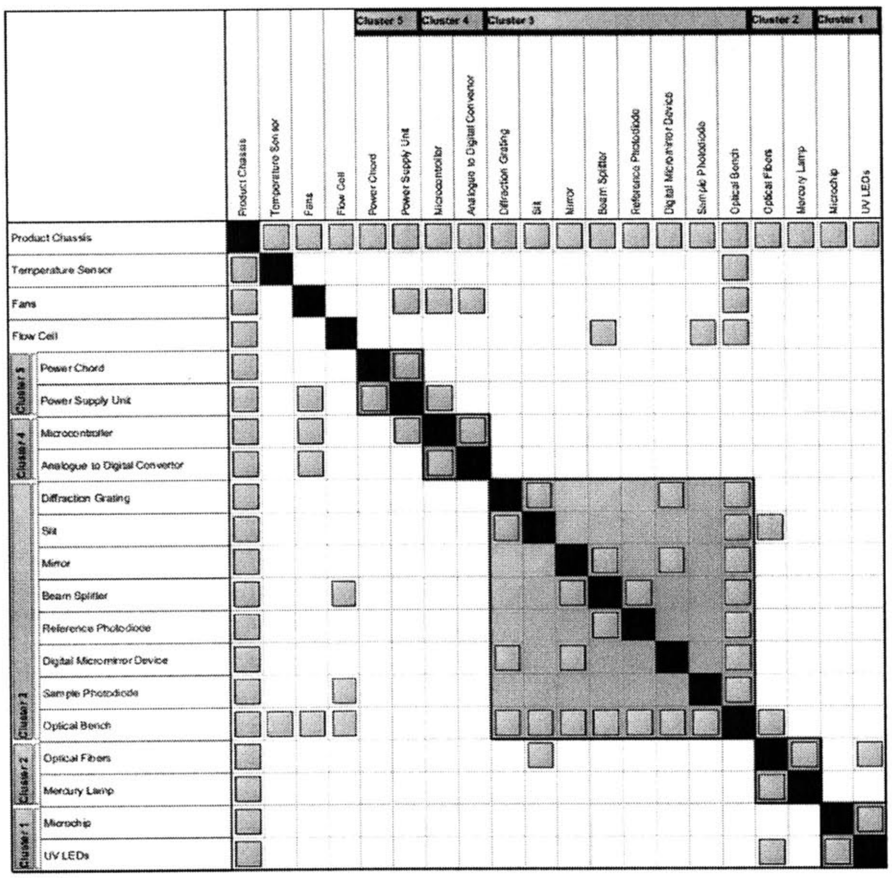

Figure 18: Clustered DSM for spatial interactions

The clustered DSM for spatial interactions shows that even with the suggested clustering, there are still numerous out-of-chunk interactions. The design teams for the device will have to take special note of these interactions when carrying out its detailed design.

Chapter 7: Developed Product Architecture

Taking into account the market, technology and the key interactions, the final architecture for each of the three configurations was developed.

7.1 Product Architecture for Configuration 1

The product architecture for Configuration 1 with the selected components and subsystems is shown in Figure 19. This grouping was done keeping in mind the technological considerations and discussions with the optical[1] and mechanical[2] designers for such a device as discussed in Chapter 4.

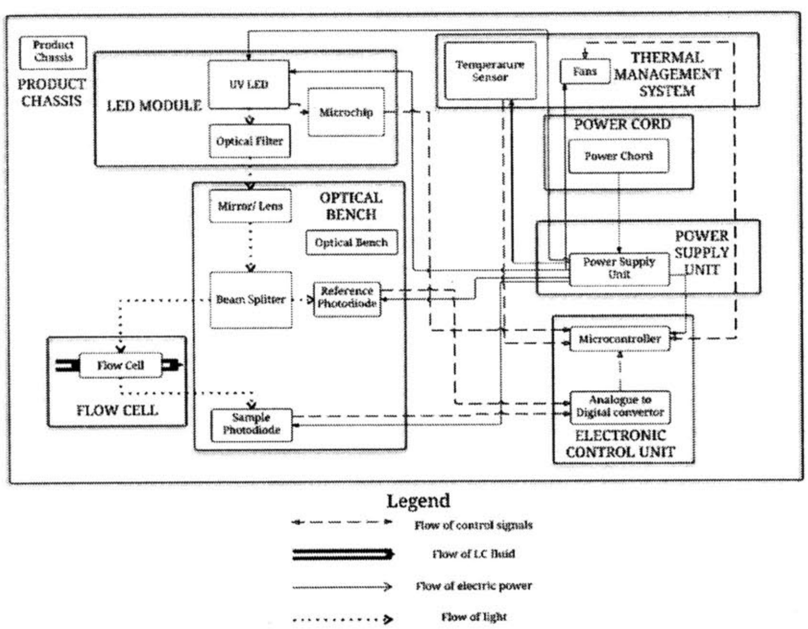

Figure 19: Suggested Architecture Scheme for Configuration 1

7.1.1 Led Module

For Configuration 1, the LED module will consist of the LED, a narrow pass optical filter to select a single wavelength and a microchip to identify the wavelength of the LED module to the system. This enables the customers to buy the LED module of the wavelength they are interested in.

7.1.2 Optical Bench

The optical bench will consist of the casing to hold the remaining optical elements – the mirror/ lens, the beam splitter, the reference photodiode & the sample photodiode. The optical casing will also have interfaces for the LED module and the flowcell module. The casing should be designed in such a manner to allow for easy replacement of the optical elements in case of wear.

7.1.3 Flow Cell

As mentioned in Section 4.8, each liquid chromatography system manufacturer has its own variety of flowcells, varying in optical pathlength and the volume of the sample exposed to the light. The flowcell chunk should be able to accommodate these various flowcells as well as provide a standard interface for them to the optical bench.

7.1.4 Thermal Management System

The thermal management system will consist of temperature sensors and fan(s) to maintain a steady temperature inside the device. It will have to be setup to be able to take into account heat from all sources.

7.1.5 Power Cord

The power cord has been kept as a separate module as its design will vary from country to country.

7.1.6 Power Supply Unit

The power supply unit can be a standard off-the-shelf component or a custom built unit which will convert the wall electrical power input to the various voltages required by the other components.

7.1.7 Electronic Control System

The electronic control system will comprise of the circuitry including the microcontroller, the analogue to digital converters and the various ancillary electronics to control the device, and to communicate with the control software and the rest of the liquid chromatography system.

7.1.8 Product Chassis

The product chassis will enclose the entire device and protect it from outside elements and should have an appropriate receptacle for the LED module in conjunction with optics bench.

7.2 Product Architecture for Configurations 2 and 3

For Configurations 2 and 3 of the device, the developed product architecture is shown in Figure 20.

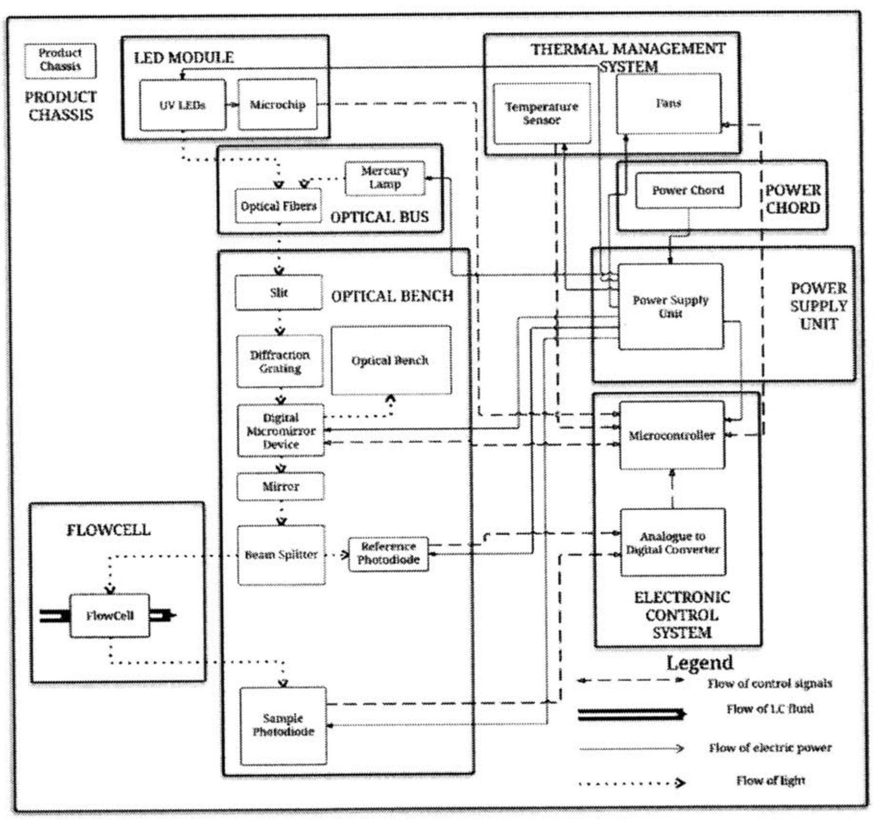

Figure 20: Suggested Architecture Scheme for Configurations 2 and 3

7.2.1 Led Module

The LED module for Configuration 2 and 3 will consist of the LED and the microchip identifying the specific LED to the system. The LED modules should have electrical and information interfaces for taking power and allowing the microchips to be read by the system.

7.2.2 Optical Bus

The optical bus will essentially be the LED array holder with receptacles where the LED modules will fit. The optical bus will also have a small mercury lamp to act as a reference source for the system. Optical fibers from the receptacles and the mercury lamp will take the light to the entrance of the optical bench. It should be noted here that the receptacles in the optical bus have to be designed such that they can supply power to the LED modules as well as read the microchips in them to identify which wavelengths are they emitting. The optical bus will be the common bus chunk and the LED modules will have a bus-modular architecture with the optical bus. Configuration 2 will have about 11 LED receptacles to cover the UV range[1] while Configuration 3 will have a greater number of receptacles to extend this range to the visible spectrum.

7.2.2 Optical Bench

The optical bench for Configurations 2 and 3 will be larger to accommodate more optical elements. The casing of the optical bench will hold the slit of the required width to determine the resolution of the system[1], the optical fibers from the optical bus will interface with this slit. It will also hold the remaining optical elements in place as required by the optical design, these being the diffraction grating, the DMD, the focusing mirror, the beam splitter, the reference and sample photodiode. It should be noted that in these two configurations, the optical bench also has to absorb the light that the DMD shunts away for the unselected wavelengths. Furthermore the optical bench needs to have the appropriate interface for the flowcell module. The casing should be designed to keep in mind the issues of assembly as well as serviceability. It would be beneficial if a slot-modular architecture was followed in its design, with each optical element fitting into its own specific slot and being easily accessible for replacement.

7.2.3 Flow Cell

As mentioned in Section 4.8, each liquid chromatography system manufacturer has its own variety of flowcells, varying in optical pathlength and the volume of the sample exposed to the light. The flowcell chunk should be able to accommodate these various flowcells as well as provide a standard interface for them to the optical bench.

7.2.4 Thermal Management System

The thermal management system will consist of temperature sensors and fan(s) to maintain a steady temperature inside the device. It will have to be setup in such a manner to account for all heat sources. This system will be more critical for Configurations 2 and 3 as the DMD will also generate heat in these.

7.2.5 Power Cord

The power cord will be a separate module as its design will vary from country to country.

7.2.6 Power Supply Unit

The power supply unit can be a standard off-the-shelf component or a custom built unit which will convert the wall electrical power input to the various voltages required by the other components.

7.2.7 Electronic Control System

The electronic control system will comprise of the circuitry including the microcontroller, the analogue to digital converters and the various ancillary electronics to control the device, and to communicate with the control software and the rest of the liquid chromatography system.

7.2.8 Product Chassis

The product chassis will enclose the entire device and protect it from outside elements and will expose the optical bus to the customer for switching out the LED modules.

Chapter 8: Implications of the Developed Product Architecture

This chapter describes the implications of the developed product architecture with respect to the following issues[4]:

1. Product Change
2. Product Variety
3. Component Standardization
4. Product Development and Management

8.1 Product Change

There are two key elements that are likely to require upgrades in the device as their technology matures: the UV LEDs and the DMD. By making the LED chunk completely modular as shown in the architecture, it is possible for the company manufacturing such a device to offer customer upgrades as soon as they are available. The DMD on the other hand is part of the optical bench chunk and while the optical bench should be designed keeping in mind serviceability issues any change involving the size of the DMD will lead to a redesign of the optical bench. However as discussed in Section 4.7, the key feature in the DMDs that is still in the developmental phase is the window covering the micromirror array, for their use in the UV region. Henceforth it may be possible to upgrade a same size DMD with an improved window in the device.

8.2 Product Variety

As discussed in Chapter 3, there are three key customer segments that have been identified and a suitable product architecture for three product configurations developed. Table 11 shows the differentiation plan[4] for the three configurations and represents how the three products will be different for the customer and the market in terms of the various chunks. It should be noted that only the chunks which the user will interact with are considered here.

Table 11: Differentiation Plan for the three device configurations

Differentiating Attributes	**Single Wavelength**	**UV Region Scanning**	**UV-Visible Region Scanning**
LED Module	LED with optical filter: optimized for single wavelength	LED with full possible emission spectrum	LED with full possible emission spectrum
Optical Bus	Not applicable	Smaller optical bus to cover the UV range	Larger optical bus to cover the UV-visible range
Product Chassis	Smaller Chassis	Large Chassis	Large Chassis

8.3 Component Standardization

Table 12 shows the commonality plan[4] for the three device configurations. This plan considers all the chunks and shows how different chunks will be common or different across the three configurations. For each configuration, the type of the chunk that will be used in it is shown.

Table 12: Commonality Plan for the three device configurations

Chunk	Number of types	Single Wavelength	UV Region Scanning	UV-Visible Region Scanning
LED Module	2(with multiple sub-types depending on wavelength)	Type I	Type II	Type II
Optical Bus	2	NA	Type I	Type II
Optical Bench	3	Type I	Type II	Type III
Flowcell	1(with subtypes depending on the liquid chromatography system)	Type I	Type I	Type I
Electronic Control System	2	Type I	Type II	Type II
Thermal Management System	1	Type I	Type I	Type I
Power Chord	1	Type I	Type I	Type I
Power Supply Unit	2	Type I	Type II	Type II
Product Chassis	2	Type I	Type II	Type II

8.4 Product Development and Management

The various chunks identified in the product architecture scheme can be easily distributed to different design teams in the organization. Especially in terms of the optical interactions, the DSM created will allow communicating to the different teams working on the LED module, the optical bus and the optical bench the exact interactions between the modules they are designing and would ensure that this architectural knowledge is communicated down the line to the detail designers. Similarly the architectural schematic would serve a same purpose.

Chapter 9: Conclusions

After the architectural scheme was finalized, Configuration 2 was selected for detailed design by the team. This decision was made as Configuration 1 has a very simplified design while Configurations 2 and 3 have a complex design incorporating a digital micromirror device along with the UV LEDs and share similar chunks. Furthermore, it was estimated that this configuration would appeal to approximately 40% on the market as discussed in Chapter 3.

9.1 Summary

To summarize, the product architecture for a liquid chromatography detector using UV LEDs instead of traditional deuterium lamps was developed. Three possible product configurations were identified and two architectural schemes for these were developed and described. The chunks of these product architecture schemes were described to allow for the detailed designers to have access to the architectural decisions.

Considering the various modules, the optical bench was identified as the key innovative feature in the entire device. Its optical design was carried out by Gillund[1] and based on that the casing for the optical bench was designed by Prasad[2]. A 3D printed prototype of the optical bench was also created to see the fitting of the various components with the designed casing.

This thesis provides documentation of the architectural design and decisions and allows transfer of this knowledge to the detailed designers. The architectural schematics and DSM allow the detailed designers to see how their parts will interact with the rest of the system. Furthermore detailing the product architecture in advance and in parallel with the detailed design phase allows for minimizing risk.

9.2 Future Work

More detailed market analysis should be carried out before considering designing the commercialized version of the device proposed in this document. Despite extensive searching, more robust data on the value of different wavelengths to liquid chromatography users could not be found. This will be especially helpful in identifying more finely the key wavelengths that are of interest to customers. This data will be of particular value for Configuration 1, where each LED module is tuned to a particular wavelength. Any liquid chromatography system manufacturing firm looking at adopting this design should consider surveying its customers to get first hand data on the wavelengths that are of interest. This will allow for a more accurate and finer market segmentation.

The architecture developed in this thesis can be extended further as the detailed design for the different modules proceeds. The described architecture puts emphasis on the optical design and the detail design of the optical system was done simultaneously by Gillund[1]. When all modules are being developed simultaneously and the product architect has inputs with all the detail designers, more nuances in the product architecture will come to light.

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