Design of a Measurement Device for Bread Dough Proofing

by
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A.B. Economics
Harvard University, 2010

Submitted to the
Integrated Design and Management Program and the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements of the Degrees of

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ABSTRACT

The structure of yeasted breads is created during the multiple stages of bread-making: mixing, proofing, and shaping. These stages serve to develop a network of gluten and air bubbles which leaven the dough and allow it to rise and achieve its final form during baking. One of the most time-sensitive and critical stages is the final period before baking, also known as the final proof. During this stage, starches in the flour break down into sugars, which are consumed by the yeast. The yeast then produces bubbles of carbon dioxide that are suspended in the dough's gluten structure. The goal of the final proof is to create the optimal dough structure for the highest bread rise during baking. However, there is a narrow window of time in which the dough is optimally proofed. If the dough is left to proof for too long, also known as overproofing, the air bubbles will grow so large that they pop and tunnel, resulting in the bread collapsing in the oven. An underproofed dough may never achieve the correct rise in baking. The boundary between the proper proofing and an over- or under-proofed dough can be as little as fifteen minutes. This optimal window is dependent on the type of dough, ambient temperature, and humidity. Without controlling each of these factors, non-industrial bakers must rely on experience or the imprecise "poke test" to ascertain whether the dough is properly proofed. This research work seeks to design a device that quantitatively measures the dough's level of proofing and identifies when the dough is optimally proofed and ready for baking. By using a precise measurement for dough structure, the non-industrial baker can then adapt to any variable that affects the final proof.

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I would also like to thank the IDM family for the warmth and joy they have brought to my life. I came to MIT feeling like the reluctantly admitted step-child, but the moment I stepped on campus I knew this is where I was meant to be.

This work is dedicated to my family, who show their love and care in ways more meaningful than words. At this time in my life and the world, I see just how blessed I am to have your support.

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CHAPTER 1. INTRODUCTION

Most breads consist essentially of only four ingredients: flour, water, salt, and yeast. However, the process of making bread is complex, with many opportunities for error and non-optimal outcomes. Each step in the process is carefully orchestrated and timed for the goal of producing an airy, voluminous loaf of bread. In commercial baking, manufacturing equipment controls these variables to reliably produce consistent bread loaves. However, this thesis focuses on home or small-batch baking of what is commonly called artisan bread. Many of the recipes for these breads give precise measurements, temperatures, and times that must be followed exactly. Failing to follow these instructions may result in a deflated, doughy ball of bread with insipid flavor development.

Prior to baking, the final step in the bread making process is the final proof. This period of resting the dough seems simple--the baker leaves the dough untouched. However, this step is crucial to the bread's success or failure: if baked too soon, the bread loaf will be too tight and undeveloped. If baked too late, the loaf will deflate, collapsing and losing volume ("How to Know", 2020). It is at this important step of final proofing that the precision and careful instructions in many bread recipes seem most lacking. For the non-industrial baker, there is no way to determine the optimal length of the final proof outside of experience and guesswork. This thesis seeks to use a human-centered design approach to understand the needs of the home baker during the final proof and design a device that solves this problem.

CHAPTER 2. BREAD BAKING PROCESS

Bread dough is essentially a collection of air bubbles contained within a network of gluten. As yeast consumes sugars in the flour, carbon dioxide and ethyl alcohol are produced. This causes the bubbles to expand and loaf to grow in volume. As long as the yeast is actively fermenting sugars, the bubbles expand, but as the sugars available to the yeast become depleted, the production of gases starts to slow down. When production stops, the bubbles lose pressure, and the dough is ready for baking (Forkish, 2012). Besides airiness, which is established in this process, the flavor of the final product is also influenced by this stage.

At this point, the moment of optimal gas production and proofing, the commonly recommended assessment method is "the finger-dent test," also called "the poke test." "To do the test, the baker pokes the rising dough with a floured finger, making an indentation about ½ inch deep. If it springs back immediately, the loaf needs more proofing time. If the indentation springs back slowly and incompletely, the loaf is fully proofed and ready to bake. If the indentation doesn't spring back at all, the loaf is overproofed" (Forkish, 2012). This window for optimal proofing can be as short as fifteen minutes. Given the difficulty of ascertaining whether the dough is ready to bake, a device that provides an accurate and repeatable test of proofing level would help the home or small-scale baker know when the dough is optimally proofed.

CHAPTER 3. FINAL PROOFING

The final proofing process aims to produce an aerated dough with optimum shape and volume when baked. There are three important factors that affect the final proof:

1. Temperature - In industrial applications, a range of 95-100°F (35-37°C) is recommended.
2. Humidity - Relative humidity of 85-95%. If humidity is too high, moisture condensation could form on the dough, resulting in a tough crust and creation of surface blisters in the finished bread. If humidity is too low, a dry skin will form on the dough, restricting expansion and causing crust discoloration.
3. Time - As mentioned above, overproofing results in bread with poor texture and flavor with acid overtones. Underproofing results in a collapsed loaf with volume bursting from the sides (Pyler and Gorton, 2008). Figure 1 illustrates the expected volume development of fermenting dough.

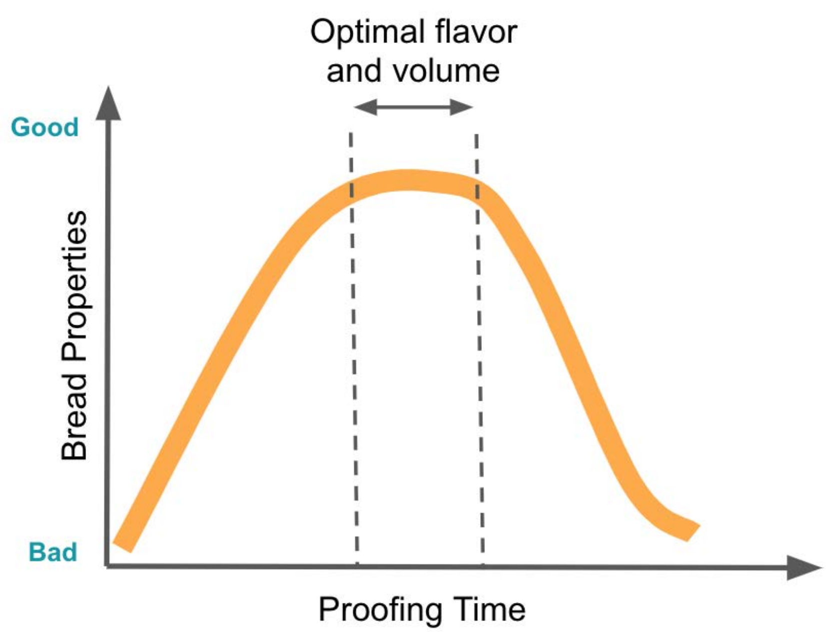

Figure 1. *Volume development during proofing (based on diagram from Giefer et al, 2019).*

In an industrial baking operation, these factors are tightly controlled so that optimal proofing is highly predictable and repeatable. Large dough proofers act as warming chambers to encourage proofing by controlling the temperature and humidity in the box. These settings have been tuned to increase the activity of the yeast, resulting in increased carbon dioxide production and a higher, faster rise (Yousefi, 2019).

In the non-industrial setting, the first two factors--temperature and humidity--are not usually as easily controlled. Home bakers might increase humidity and temperatures by placing a bowl of water in an oven with the pilot light on or by purchasing a countertop proofer designed for home use. However, with the exception of the countertop proofer, which are quite costly, these methods remain difficult to control. Even with the faster proofing induced by increased warmth and humidity, the baker must continue to check whether the dough is ready.

Studies have shown that desirable bread qualities such as gas retention in the dough and loaf volume are closely related to the physical properties of dough. These properties include instantaneous elasticity, regularity coefficient of viscosity, and relaxation time (Matsushita et al., 2018). Various researchers (Janssen et al., 1996; Yamauchi et al., 2000) have theorized that the expansion behavior of dough during fermentation (also known as proofing) is related to rheological properties. In their study, Matsushita et al. measured the physical properties of various doughs using the Maxwell model. The Maxwell model is represented by a purely viscous damper and a purely elastic spring connected in series. Figure 2 illustrates the Maxwell model system of spring and damper. E_0 is instantaneous elasticity, η_N is the regularity coefficient of viscosity, γ_0 is the strain of instantaneous elasticity region, and γ_N is the strain of regularity viscosity region.

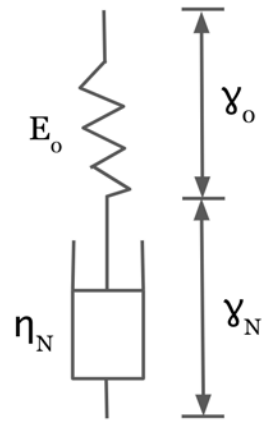

Figure 2. *The Maxwell model consists of a spring and damper.*

The researchers then used a creep meter to measure the physical properties of the dough. The creep test involves loading the dough at constant stress and measuring the response. In some ways this is a highly controlled and accurate form of the poke test that is recommended for assessing proofing. While such a device would be impractical outside of the factory or laboratory, a novel device applying the same principles could be designed for the small-scale baker.

CHAPTER 4. NEEDS OF THE SMALL-SCALE BAKER

In order to create a product that solves the problem of proofing in the home environment, the needs of the user must be understood first. Human-Centered Design (HCD) is a process and set of techniques that examines the needs and behaviors of the people who will be affected by the solution (*Human Centered Design*, 2011). In this process, qualitative research enables the designer or researcher to develop empathy for the people they are designing for, to question assumptions, and to inspire new solutions.

This thesis used HCD to design the proofing device by first identifying customer needs. This involves interviewing and gathering data from customers, interpreting these needs, and organizing them into a hierarchy, and incorporating them into the design process (Ulrich, 2019). Although a broader phase of surveying and interviewing will be necessary as a next step, Table 1 gives an example of potential customer needs. They are listed and grouped into a hierarchy of needs that will be addressed by the proofing measurement device.

Table 1. *Customer Needs Hierarchy. (In the format of Ulrich et al., 2019.) Importance ratings for the critical needs are indicated by the number of *'s.*

***The device is easy to use. The device lets the user know when the dough is ready to bake. The device does not have too many buttons or settings. The device interaction with the dough is easy to understand. The device notifies the user in an attention-catching way. The device is easily to attach and remove when desired. The device works immediately without need for setting up. The device automatically adjusts to the bread being baked. The device can be stored and accessed readily. The purpose of the device is readily apparent.	**The device is suitable for its environment. The device is small enough to fit in a kitchen drawer. The device can be wiped clean. The device is easy to handle and maneuver with a single hand. The device stands out visually in a cluttered space. The device is multi-functional. **The device is safe. The device is food-safe and cleanable. The device is durable under normal kitchen circumstances: splashes, drops, and burns. The device is not dangerous to the user, especially while in motion.

***The device is reliable.** The device gives accurate, consistent readings. The device performs well for a variety of doughs. The device is capable of “set it and forget it”. The device requires minimal maintenance. The device is unobtrusive and not demanding. The device will inform the user if it cannot work in a certain situation. The device informs the user if it does need maintenance. ***The device inspires confidence.** The device gives new bakers knowledge when they need it. The device enables professional and experienced bakers to do more of what they care about.	***The device is a lifetime investment.** The device is extremely durable. The device is adaptable to a wide range of bread baking. The device can be repaired if damaged. The device inspires confidence that it will not be damaged if used incorrectly. ***The device is attractive.** The device is more than just a tool to its users. The device feels good to use. The device connects people to baking and to each other. The device is a symbol of home baking. The device is visually appealing.

While this thesis focuses on the mechanical device design, these customer needs will be incorporated into the design of the device. The priorities, as marked by the asterisks, are just as important to the customer as a functional proofing measurement device.

CHAPTER 5. MECHANISM DESIGN

The primary need of the home baker in the final proof of artisan bread baking is to identify the moment at which the optimal level of gluten and gas has developed within the bread dough. Using the recommended technique of the poke test, optimal proofing is determined by a manual depression of the dough followed by visual estimation of the partial spring back of the depression (Forkish, 2012; “How to Know,” 2020).

The initial design for a mechanism to measure proofing imitated the poke test. A piston simulated a finger pushing into the surface of the dough while a visual sensor or accelerometer sensed the spring back of the dough. However, in analyzing the mechanical construction and complexity of this design, a simpler approach was required in order to test the core functionality: a mechanical simulation of the poke test should first be evaluated before the design evolved into a more complex device.

The resulting design pared down the device to the simplest expression of the poke test. A single motor with an attached arm would rotate a fixed angle into the dough. As the elasticity of the dough structure caused it to spring back, an encoder attached to the motor would capture the movement of the arm as it was forced back. The level of proofing would be measured by the angular position of the arm as it depressed the dough surface and then sprang back, similar to the functionality of the poke test. As the optimal measurement of this movement is not a known quantity, the device would need to be calibrated through experimentation.

The device prototype uses a Pololu brushed DC motor with a 18.75:1 metal gearbox and an integrated quadrature encoder that provides a resolution of 64 counts per revolution of the motor shaft, which corresponds to 1200 counts per revolution of the gearbox’s output shaft (“Pololu,” 2020). This motor was chosen for its integrated encoder and availability. The motor is driven by the Flagship FRDM-K64F board, which runs an mbed compiler. This board was selected due to its ease for prototyping applications, Ethernet interface, and compatibility with the Pololu motor.

In the software, the board is programmed through the mbed compiler. This program controls the motor through a proportional-integral-derivative (PID) controller (see Appendix A). A PID controller is a closed feedback loop that can be tuned for a responsive and accurate correction to the motor output despite external disturbances. This is useful in this experiment because the corrective measures of the PID controller can be tracked as the device encounters different doughs. In this program, the PID controller continuously calculates an error value based on a control loop rate of 1 KHz. Given a shaft angle $\theta[k]$ at time step k, and a desired angle θ_d, the error $e[k] = \theta_d - \theta[k]$ is related to the commanded voltage through:

$$V[k] = K_p e[k] + K_d \dot{e}[k] + K_i \sum_{j=0}^{k} e[j]$$

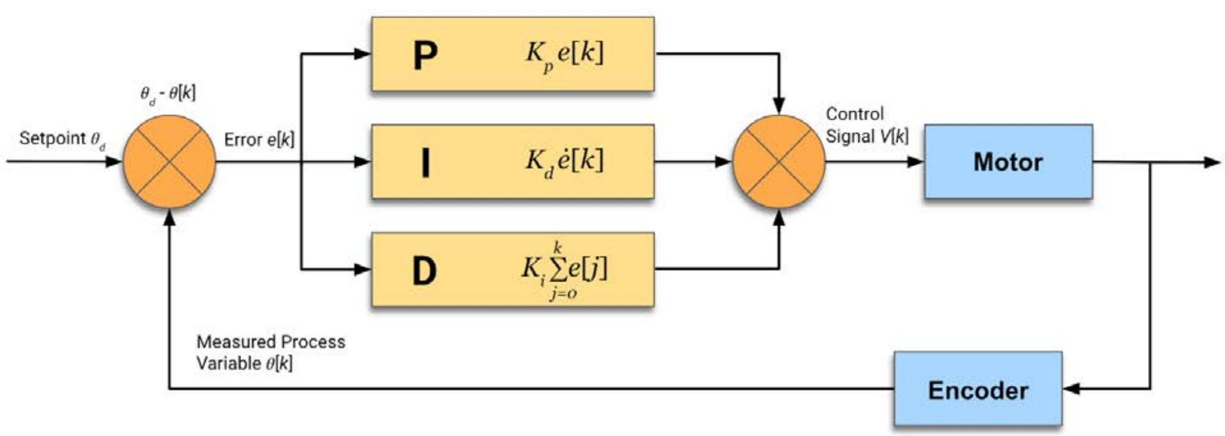

Figure 3. *A block diagram of the PID controller in the motor feedback loop.*

In the program, θ_d, K_p, K_d, and K_i are inputs to the FRDM board; $t[k]$, $\theta[k]$, $\dot{\theta}[k]$, $V[k]$ are outputs from the FRDM board. A MATLAB interface is connected to the board through Ethernet, allowing for quick adjustments to the inputs as well as capturing and processing the outputs (see Appendix B).

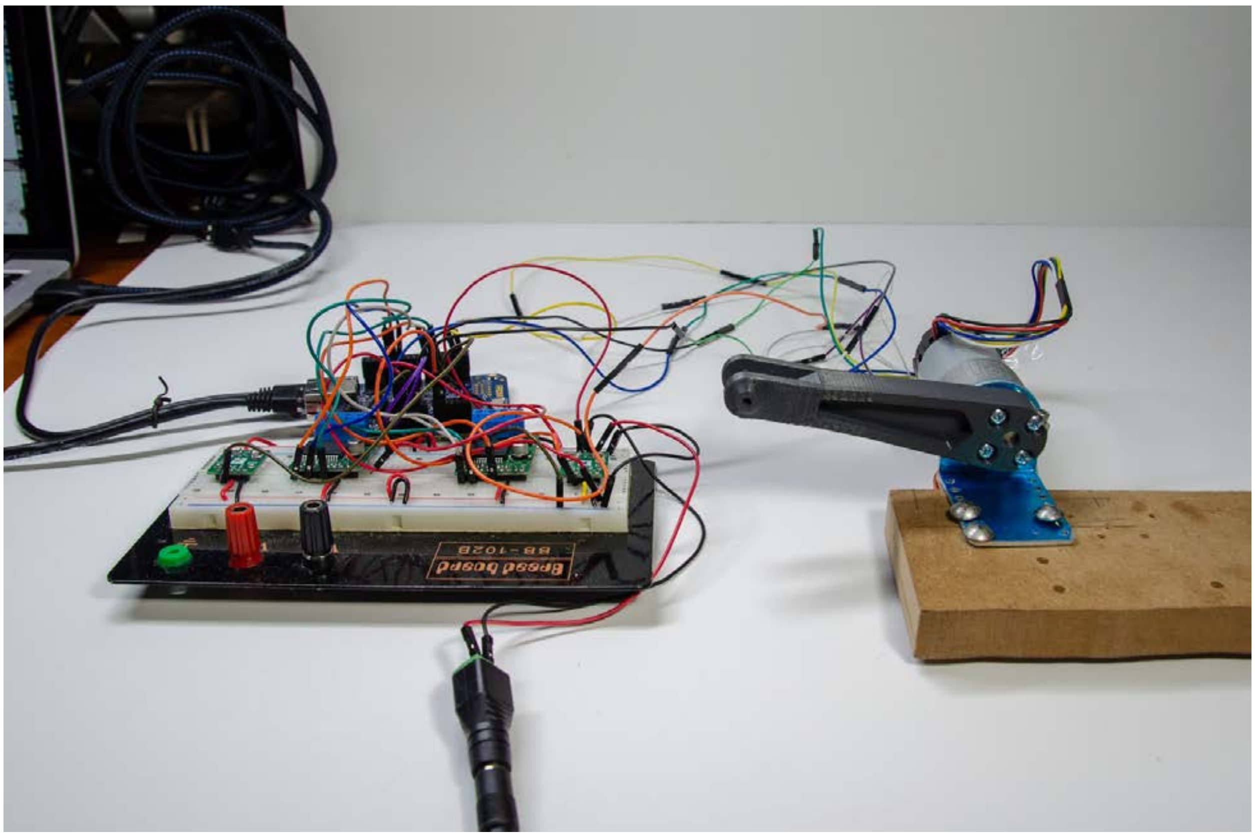

Figure 4. *The testing prototype consists of the FRDM-K64F board connected to a breadboard with amplifier and current sensor and the Pololu 2822 DC motor with integrated encoder. The single arm and motor assembly is mounted on MDF for stability.*

While this prototype is capable of testing the hypothesis, it is not designed to meet the other customer requirements. In order to meet the need of ease of use, such a device would need a stable mount, preferably attachable to the proofing basket or container. It would need to be adjustable so that the depressing arm could reach the surface of the dough from wherever the motor is mounted. Finally, in a home or even small-batch bakery environment, the device would need to be self contained and portable. This could look like the proofing equivalent of a large thermometer. All of these design requirements and user needs have been made secondary to the priority of testing the mechanical functionality of the measuring device.

CHAPTER 6. EXPERIMENT DESIGN

In order to determine whether the prototype could measure a level of proofing, it needed to be calibrated through experimentation. The experiment compared bread dough at different ranges of proofing time by using the device's arm depressor and capturing the resulting dough spring back. The various samples of dough were then baked and measured. The bread with the largest, most voluminous form after baking is considered the most optimally proofed (Forkish, 2012). The device can be evaluated and calibrated as a proofing measurement tool by comparing its readings to the size of the baked bread samples.

Not all breads would be appropriate for proofing calibration. There are many types of bread involving different types of flours, leavening agents, additives, and dough processing techniques, all of which affect proofing. The Saturday White Bread recipe was chosen from Ken Forkish's award-winning bread baking book *Flour Water Salt Yeast* because it is a physically delicate and proofing time-sensitive recipe. As an "artisan" bread recipe, it relies on hand mixing as opposed to improved or intensive mixing, which shortens time required at the expense of gluten development ("Artisan Breads," 2020). For the goal of achieving a high resolution on optimal proofing times, the bread rise needed to be clearly affected by proofing time. According to Forkish (2012), "with this bread, 15 minutes can make the difference between being perfectly proofed and collapsing a bit" (p. 83).

This recipe is a multi-step process that relies on each step to develop the gluten and gases produced by the yeast in order to create the volume and crumb structure of the final baked bread (see Appendix C). The first step is to autolyse the flour and water. The goal of this step is to allow complete hydration of the flour before mixing the final dough. The next step is mixing in the salt and yeast, thoroughly incorporating all of the ingredients throughout the mix.

As the yeast is mixed in, fermentation begins. The yeast consume the sugars in the flour, releasing carbon dioxide and alcohol. In the first hour of fermentation, the recipe calls for two folds of the dough, which help develop the gluten that gives the dough its structure and contributes to the overall volume of the final baked bread. After over five hours of fermentation, gases expelled by the yeast are trapped in the web of gluten, resulting in the dough tripling in volume.

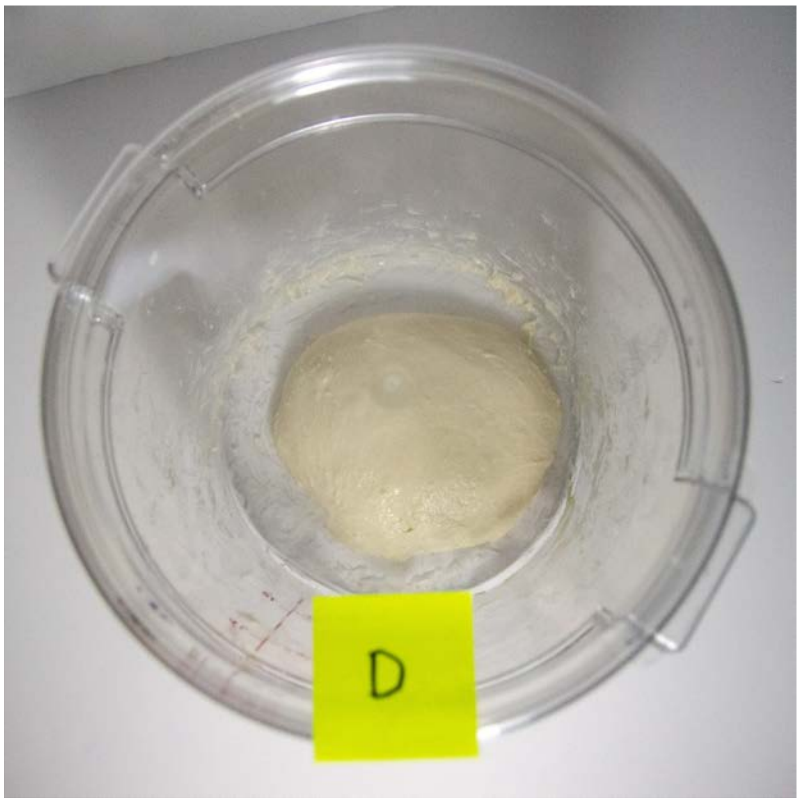

Figure 5. *Batch D dough after the second fold and at the start of fermentation.*

Finally, the dough is divided into loaves and shaped for the final proof. It is at this critical juncture that the full potential of the bread loaf is achieved. The dough must reach its physical limit for containing the gases before the gluten network begins to break down as the proteins degrade over time. If the bread is baked too soon, the loaves will be too tight and not fully develop. If the bread is baked too late, the loaves will start to deflate, collapsing and losing volume (Forkish, 2012). This recipe estimates a final proof time of 75 minutes at room temperature.

Given this estimated optimal proof time, the experiment tested twelve samples of dough ranging from zero minutes proofing time to two hours 45 minutes proofing time in increments of fifteen minutes. As the process of mixing, fermenting, and baking the dough lasts over seven hours from beginning to end, the dough samples were made in four staggered batches (see Table 2 and Figure 6) with each batch divided into three dough samples as seen in Figure 7. By baking all of the experimental loaves in the same session, external variables such as temperature and humidity are held constant. The only variable left is time. After the dough is formed into round loaves, they are proofed for the allotted amount of time before baking. The baking groups were timed in such a way that groups of four loaves finished proofing at the same time, the number of loaves that could safely fit in the Dutch oven at one time (see Table 3).

Table 2. *Dough Processing Steps in Minutes after Start of Batch D.*

	Batch A	**Batch B**	**Batch C**	**Batch D**
Start Autolyse	45	30	15	0
Mix in Salt & Yeast	70	55	40	25
Fold 1	85	70	55	40
Fold 2	135	120	105	90
Divide & Shape	375	360	345	330
Proof Start Time (example)	9:45 AM	9:30 AM	9:15 AM	9:00 AM

Figure 6. *Four batches of dough started at staggered increments of 15 minutes.*

Figure 7. *Each batch of dough is divided and shaped into three loaves. These loaves are then proofed for an allotted amount of time before measuring and baking.*

Table 3. *Proofing times for each baking group.*

Label	Proofing Time	Mixing Batch	Baking Group	Bake start (example)
A1	0 min	A	1	9:45 AM
B1	15 min	B	1	9:45 AM
C1	30 min	C	1	9:45 AM
D1	45 min	D	1	9:45 AM
A2	1 hour	A	2	10:45 AM
B2	1 hour 15 min	B	2	10:45 AM
C2	1 hour 30 min	C	2	10:45 AM
D2	1 hour 45 min	D	2	10:45 AM
A3	2 hours	A	3	11:45 AM
B3	2 hours 15 min	B	3	11:45 AM
C3	2 hours 30 min	C	3	11:45 AM
D3	2 hours 45 min	D	3	11:45 AM

Prior to baking and after proofing, the loaves are measured using the device prototype. The motor is aligned with the lip of the proofing container. The controller program then depresses the arm into the dough surface and captures the angular position feedback in MATLAB (see Figure 8).

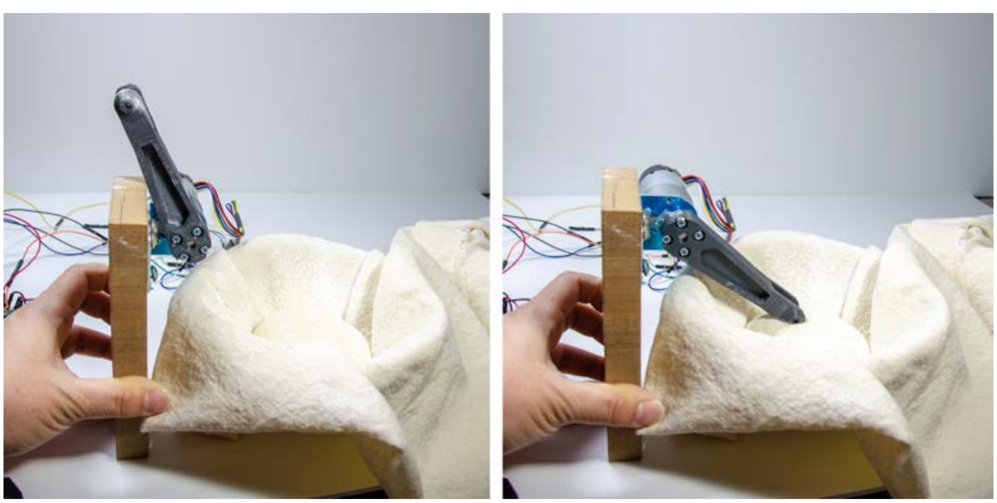

Figure 8. *Left) Start/Reset position of the device arm. Right) After running the program, the arm depresses into the dough surface.*

CHAPTER 7. RESULTS

The experiment resulted in two sets of data: the loaves of bread baked at different proofing times, and the device measurements. As described in existing research on bread proofing (Pyler, 2008; Matsushita, 2019), the physical characteristics of the bread are directly affected by the proofing time. As shown in Figure 9, the different proofing times did affect the overall shape and height of the loaves in the experiment. In general, loaf size from the top does increase the longer the proof time.

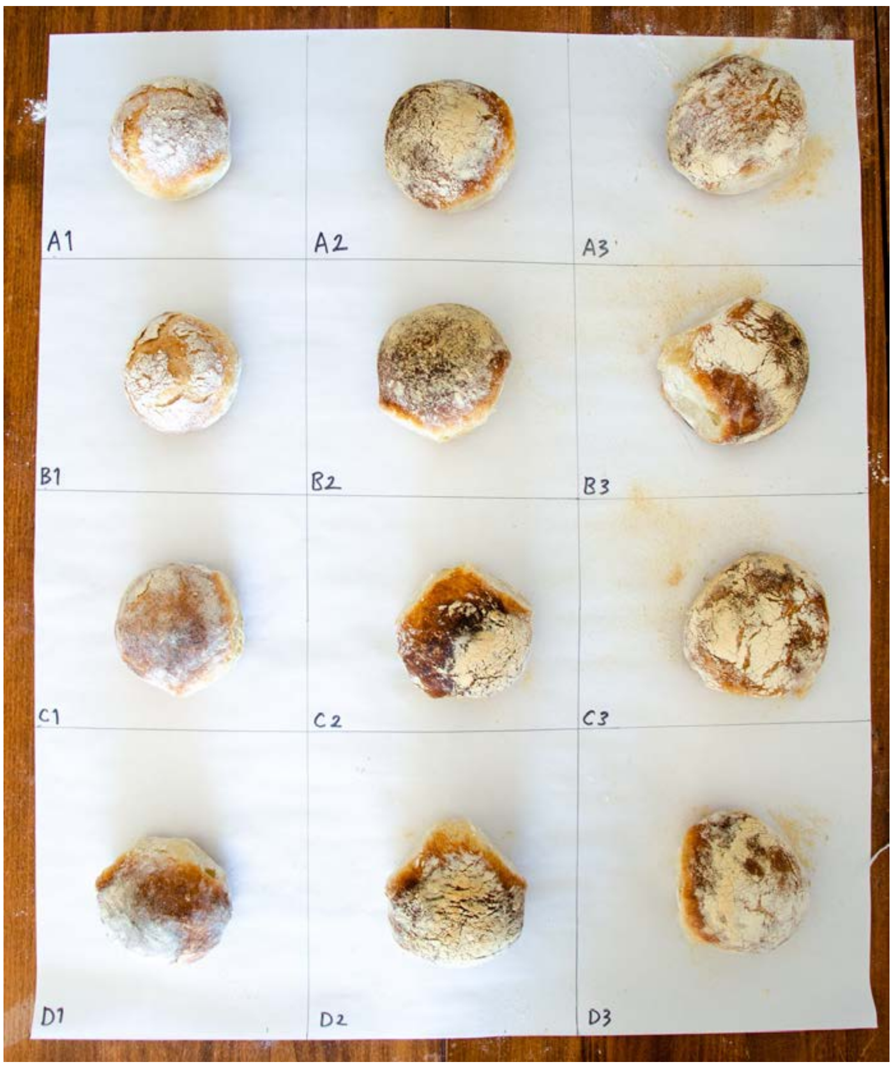

Figure 9. *Going from top to bottom, left to right, the baked loaves are lined up from lowest proofing time of 0 minutes (A1) to highest proofing time of 2 hours 45 minutes (D3).*

According to the original recipe, the loaf with the optimal proofing time should be B2, at one hour and fifteen minutes. Based on the height of each cross-section, the experimental loaves reached maximum height at one hour 45 minutes of proofing. Despite the discrepancy, there does seem to be an optimal proofing time window of about an hour, as seen in loaves A2, B2, C2, and D2 (see Figure 9). From a proofing time of one to two hours, loaf height pleateaus at 6.8 cm (see Figure 10). Because proofing results are dependent on the specific conditions of temperature and humidity during the proofing process, these results can only be compared to each other and to the measurements of the device during the experiment.

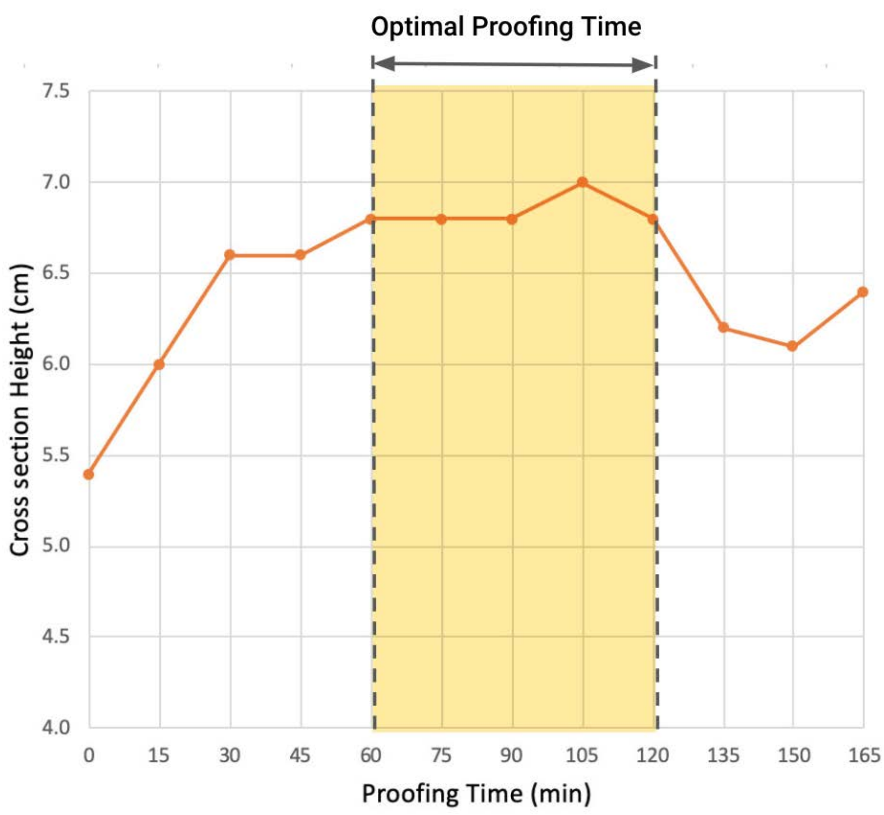

Figure 10. *The height of the cross section of each loaf based on proofing time.*

Lining up the loaves from mixing batch A, with proofing times of zero, one hour, and two hours, the effect of proofing time can be more clearly seen. In Figure 11, the left loaf (A1) had zero proofing time, which has resulted in a shorter loaf and denser interior structure. The middle loaf (A2) proofed for one hour, which is close to the described optimal proofing time. It has risen much higher than A1 and has a more desirable, open interior structure. Lastly the right loaf (A3), which was proofed for two hours, did not lose much height despite being considered "overproofed". However, the cross section reveals that the loaf is beginning to collapse: the interior structure is dense, with pockets of gas starting to flatten, pushing the side walls of the loaf outward and causing the loaf to slump. A similar trend can be seen in the other batches (see Appendix D).

Figure 11. *From left to right, A1: zero proofing time, A2: one hour, A3: two hours.*

While the bread loaves rose as expected, the device measurements were less conclusive. The tracking of the motor encoder of the angular position of the arm, which was supposed to measure the spring back of the dough surface, did not seem sensitive enough to detect differences in dough elasticity (Figure 12).

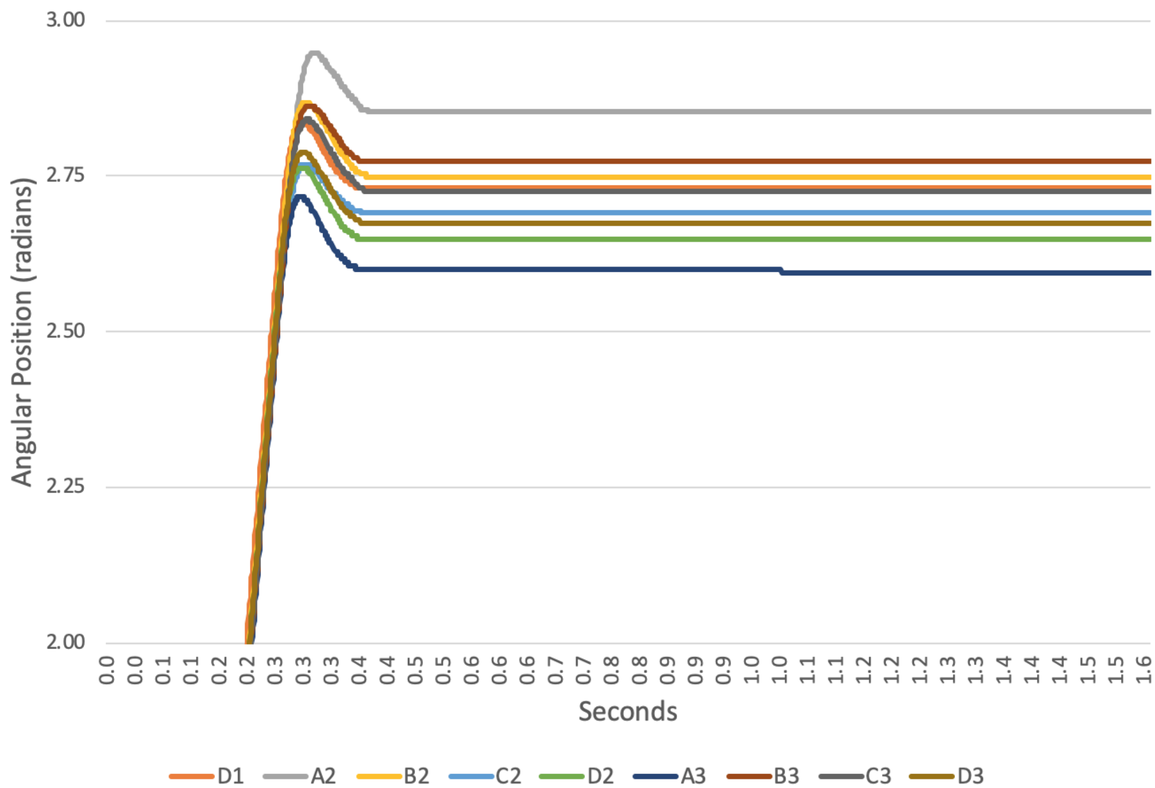

Figure 12. *Angular position of the motor arm over time.*

While the spring back as detected by the motor encoder did not seem to provide a discernable pattern, the speed at which the arm went from the deepest point of depression in the dough to motionless showed possibly interesting data points. Figure 13 plots the tenths of a second it took for the arm to swing back after pushing into the dough. One interpretation is that the gluten and gas development of an optimally proofed dough slows the spring back. The graph shows that the arm is indeed moving slower in that proofing window of one to two hours. However, the numbers are so miniscule and the data points so few that it is difficult to draw any meaningful conclusions from this data.

A second iteration of this prototype would need to address the sensitivity of the encoder and the internal resistance to change of direction in the motor. While these results do not immediately invalidate the angular approach, it did not successfully demonstrate a clear measurement of proofing. It would also be worth exploring in the future a prototype that incorporates a mechanism that more closely matches the actions of the poke test with a piston or other linear actuator. More testing will need to be done to address these hypotheses.

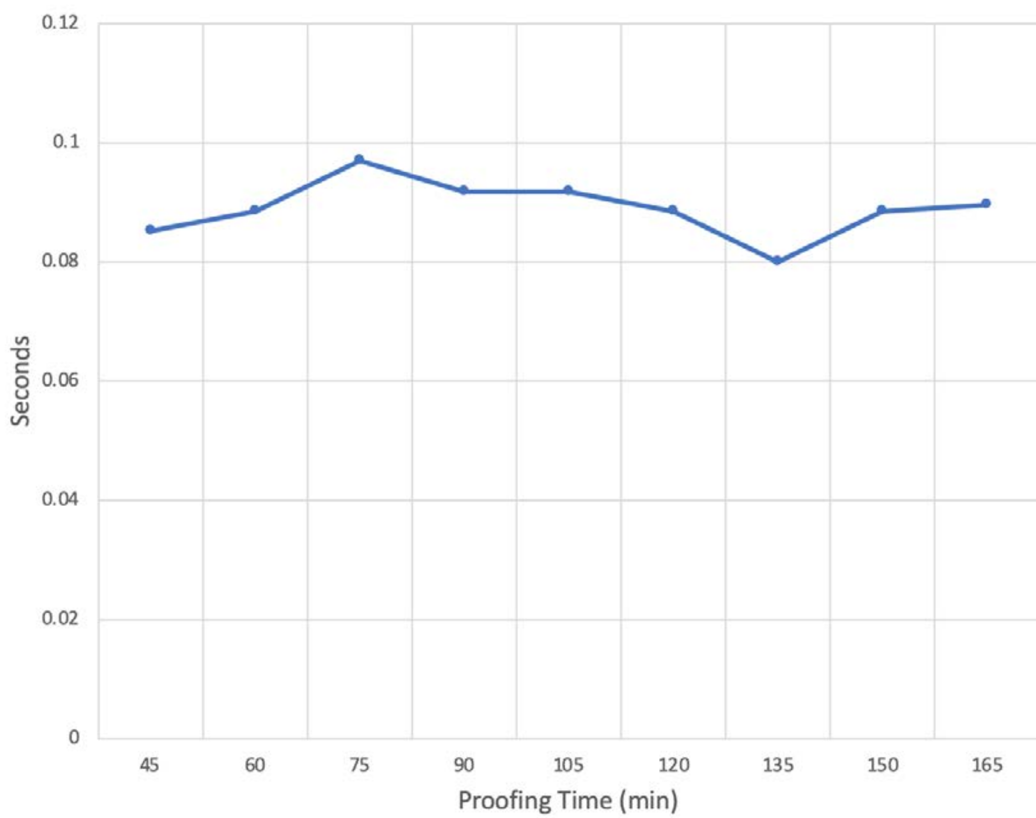

Figure 13. *The time between the arm fully depressing into the dough and springing back to a steady state.*

CHAPTER 8. DISCUSSION AND CONCLUSION

Breadmaking is a complex chemical, physical, and structural transformation. In particular, the final proof transforms carbohydrates and amino acids induced by the metabolism of yeast into carbon dioxide and ethyl alcohol (Giefer et al., 2019). In this process, the dough structure begins to exhibit viscoelastic properties, which are closely linked to the gas retention of the dough and the volume of the baked bread (Matsushita et al., 2018). The complexity of the physical properties of dough and the way in which they rapidly change in a relatively short amount of time make it difficult to be measured outside of the laboratory.

This experiment tests the use of a PID controlled motor as a potential measurement device for dough proofing. The results demonstrate that such a device would need to have much greater sensitivity to the elasticity of the dough than the current motor and encoder feedback loop provides. Figure 13 gives a clue to how minute the movement of the dough's surface could be. The physical properties of dough are not easily captured by a DC motor encoder. Despite the difficulty in measuring the proofing level of dough, the experiment confirmed the importance of identifying the optimal proof time in baking bread. While the window for optimal bread proofing was not found to be as narrow as fifteen minutes, there were observable differences between correctly proofed bread and the overproofed and underproofed examples. In non-industrial environments, determining whether the dough is in that window is entirely reliant on human experience, which for amateurs or even professionals can be highly error prone. It is, therefore, a worthwhile endeavor to make the proofing process less reliant on guesswork and more measurable and therefore repeatable and accessible.

Without a repeatable and reliable method of testing proof-ness, the breadmaking market misses an opportunity to serve home bakers and small-scale bakeries. There is still a need for a device that is compact, easily operated, and accurately gives bakers the information they need for a successful bake. The challenge remains in developing a method that is sensitive and tuned enough to quantify and identify optimal proofing in a way that integrates with existing bread-making processes.

CHAPTER 9. FUTURE WORK

Research has been done on new methods for controlling the dough proofing process, albeit generally for industrial-scale applications. Experiments have been conducted using low-intensity ultrasonic waves to monitor the fermenting state of dough (Elmehdi et al., 2003). Others have proposed using magnetic resonance microscopy for continuous control of dough fermentation (Bajd et al., 2011). One promising method has been Giefer et al.'s use of lidar and other optical sensors, deep learning, and neural networks to optically monitor the dough as it ferments (2019). Optical image processing appears to be one way to integrate sensor feedback into a closed loop control system for dough fermentation. As interesting and effective as some of these methods are, most of them are out of reach for the average consumer due to the complexity of processing the output from these different techniques and the technical challenge of operating what is essentially laboratory equipment.

Several alternative possibilities for an individual device remain to be explored. A variety of force sensors and accelerometers may have greater sensitivity to the viscoelasticity of the dough. Additionally, as used by Matsushita et al. the Maxwell model creep test could be adapted to a smaller scale for individual bread loaves (2018; Tanaka et al., 2019). While such tests do deform the dough severely, there may be ways to conduct similar tests that allow the bread to remain intact and bakeable.

Another possible exploration is the use of impedance control on the motor as a way to compensate for the changing environment and materials with which this device will need to interact. Impedance control, which is a dynamic approach to controlling the manipulator within an environment and the forces imposed on it, could serve to increase the device's ability to manipulate the dough (Hogan, 2005). While the question of sensitivity to delicate changes in dough structure would still exist, impedance control could be more nimble than the current PID controller.

Finally, the prototype should develop the mechanism for sensing and measuring the proofing level of dough simultaneously with incorporating other user needs into the design. As a product aimed at consumers and small-scale professionals, the device needs to take a minimal amount of space and function with enough precision to provide accurate guidance to the baker. Further work needs to be done on establishing use cases and interactions with the device without overcomplicating the already challenging process of making bread. It needs to be accessible by those who are completely new to baking and those who are professional bakers. While much more remains to be explored in the design of this device, this work helps open the door to potential solutions and establish an experimental procedure that can be repeated for testing of future prototypes.

10.1 APPENDIX A

PID Controller Code for Mbed Compiler

```
#include "mbed.h"
#include "rtos.h"
#include "EthernetInterface.h"
#include "ExperimentServer.h"
#include "QEI.h"
#include <stdio.h>

#define NUM_INPUTS 4
#define NUM_OUTPUTS 4

Serial pc(USBTX, USBRX);    // USB Serial Terminal
ExperimentServer server;    // Object that lets us communicate with MATLAB
PwmOut motorPWM(D5);        // Motor PWM output
DigitalOut motorFwd(D6);    // Motor forward enable
DigitalOut motorRev(D7);    // Motor backward enable
Timer t;                    // Timer to measure elapsed time of experiment
AnalogIn ain(A0);           // Current sensor

QEI encoder(D1,D2, NC, 1200 , QEI::X4_ENCODING); // Pins D1, D2, no index,
1200 counts/rev, Quadrature encoding

int main (void) {
    // Link the terminal with our server and start it up
    server.attachTerminal(pc);
    server.init();

    // PWM period should nominally be a multiple of our control loop
    motorPWM.period_us(500);

    // Continually get input from MATLAB and run experiments
    float input_params[NUM_INPUTS];
    float kp ;
    float kd;
    float ki;
    float desired_ang;
    float prev_angle =0 ;
    float curr_ang = (360.0/1200.0)*encoder.getPulses();
    float vel = (curr_ang - prev_angle) / .001; // Velocity
    float error_ang = desired_ang - curr_ang;
    float v; //output voltage to motor
    float motorvoltage; //output from motor model equation
    float integral; //sum of error angles
    float current; //current
```

```
while(1) {
    if (server.getParams(input_params,NUM_INPUTS)) {
        float desired_ang = input_params[0];
        float kp   = input_params[1];
        float kd   = input_params[2];
        float ki  = input_params[3];

        // Setup experiment
        t.reset();
        t.start();
        encoder.reset();
        motorFwd = 1;
        motorRev = 0;
        motorPWM.write(0);

        //send absolute value of voltage to pwm
        while(t.read() <4){

            curr_ang = (360.0/1200.0)*encoder.getPulses();
            vel = (360.0/1200.0)*encoder.getVelocity();
            error_ang = desired_ang - curr_ang;
            integral += error_ang;
            current = 36.7*ain - 18.3; //calculate current

      // Motor Model Equation
            motorvoltage = kp*error_ang - kd*vel + ki*integral;

      // Forward and backward voltage
            v = motorvoltage/12;
            if (t.read() >1) {
                motorPWM.write(0);
                }
            else {
            if (v<0) {
                motorFwd = 0;
                motorRev = 1;
                motorPWM.write(-v);
                }
            if (v>0) {
                motorFwd = 1;
                motorRev = 0;
                motorPWM.write(v);
                }
            }
            prev_angle = curr_ang;

            // Form output to send to MATLAB
```

```
            float output_data[NUM_OUTPUTS];
            output_data[0] = t.read();
            output_data[1] = (2*3.14/1200)*encoder.getPulses();
            output_data[2] = (2*3.14/1200)*encoder.getVelocity();
            output_data[3] = current;

            // Send data to MATLAB
            server.sendData(output_data,NUM_OUTPUTS);
            wait(.001);
        }

        // Cleanup after experiment
        server.setExperimentComplete();
        motorPWM.write(0);
    } // end if
  } // end while
} // end main
```

10.2 APPENDIX B

MATLAB Interface Code to Communicate with FRDM Board via Ethernet

```
function output_data = Experiment_Example_MATLAB()
    figure(1);  clf;
    subplot(311)
    h1 = plot([0],[0]);
    h1.XData = []; h1.YData = [];
    ylabel('Position (radians)');

    subplot(312)
    h2 = plot([0],[0]);
    h2.XData = []; h2.YData = [];
    ylabel('Velocity (radians/s)');

    subplot(313)
    h3 = plot([0],[0]);
    h3.XData = []; h3.YData = [];
    ylabel('Current');

    % This function will get called any time there is new data from
    % the FRDM board. Data comes in blocks, rather than one at a time.
    function my_callback(new_data)
        t = new_data(:,1);   % time
        pos = new_data(:,2); % position
        vel = new_data(:,3); % velocity
        cur = new_data(:,4); % current
        N = length(pos);

        h1.XData(end+1:end+N) = t;   % Update subplot 1
        h1.YData(end+1:end+N) = pos;
        h2.XData(end+1:end+N) = t;   % Update subplot 2
        h2.YData(end+1:end+N) = vel;
        h3.XData(end+1:end+N) = t;   % Update subplot 3
        h3.YData(end+1:end+N) = cur;
    end

    frdm_ip  = '192.168.1.100';     % FRDM board ip
    frdm_port= 11223;               % FRDM board port
    params.callback = @my_callback; % callback function
    params.timeout  = 2;            % end of experiment timeout

    % Four Inputs to FRDM
    desired_ang = 180.0;            % desired angle
    kp = 0.02;                  % kp
    kd = 0;                     % kd
```

```
    ki = 0;                     % ki
    input = [desired_ang kp kd ki];    % input sent to FRDM board
    output_size = 4;    % number of outputs expected

    output_data =
RunExperiment(frdm_ip,frdm_port,input,output_size,params);

end
```

10.3 APPENDIX C

"The Saturday White Bread" Recipe from *Flour Water Salt Yeast* (abbreviated for simplicity)

Ingredient	Quantity		Baker's Percentage
White flour	1,000 g	7 ¾ cups	100%
Water	720g, 90-95F	3 ⅛ cups	72%
Fine sea salt	21 g	1 tbsp + 1 scant tsp	2.1%
Instant dried yeast	4 g	1 tsp	0.4%

1. **Autolyse** Combine the 1,000 grams of flour with the 720 grams of 90-95F water. Mix by hand until incorporated. Cover and let rest for 20 to 30 minutes.

2. **Mix** Sprinkle the 21 grams of salt and the 4 grams of yeast evenly over the top of the dough. Mix by hand until the salt and yeast are fully enclosed. Let the dough rest for a few minutes, then fold for another 30 seconds or until the dough tightens up. Cover the tub and let the dough rise.

3. **Fold** This dough needs two folds. Apply the first fold about 10 minutes after mixing and the second fold during the next hour. When the dough is triple its original volume, about 5 hours after mixing, it's ready to be divided.

4. **Divide** Cut the dough into desired pieces.

5. **Shape** Dust proofing baskets with flour. Shape each piece of dough into a medium-tight ball. Place each seam side down in its proofing basket.

6. **Proof** Lightly flour the tops of the loaves. Cover with a kitchen towel and allow to proof until optimally proofed. At room temperature of 70F, the loaves will be done proofing at 1 ¼ hours.

7. **Preheat** At least 45 minutes prior to baking , preheat the oven and dutch oven to 475F.

8. **Bake** Place the loaf into the dutch oven so that the top of the loaf was the side facing down in the basket. Cover the Dutch oven and bake at 475F. Bake for 30 minutes, then remove the lid and bake for about 20 more minutes, until at least medium dark brown around the loaf. Remove and let cool.

10.4 APPENDIX D

Cross Sections of Bread Loaves Grouped by Proofing Batch

Figure 14. *From left to right: B1 (15 minutes), B2 (1 hour 15 minutes), B3 (2 hours 15 minutes).*

Figure 15. *From left to right: C1 (30 minutes), C2 (1 hour 30 minutes), C3 (2 hours 30 minutes).*

Figure 16. *From left to right: D1 (45 minutes), D2 (1 hour 45 minutes), D3 (2 hours 45 minutes).*

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