Capstone Senior Design Project
Report #2

Project Title: Force Sensor for Grippers

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Finally, the team would like to express thanks to all who attended the presentations. The feedback from these helped not only shape the presentations, but the overall project.
Abstract

This document details the design and build process used to generate a final design solution to the problem set forth by PHD, Inc. The problem detailed by PHD, Inc. consists of being able to measure the force of their grippers. The solution to this problem will be achieved using a force sensor that will be compatible with PHD’s current line of grippers. The overall purpose of the design will be to provide both a user and a PLC with a force related measurement. With this information, a user will be able to prevent damaging a part by gripping it with too much force. As for the information being available for a PLC application, this would allow for increased accuracy during an automated process. The design presented in this report has met all of PHD’s specifications and requirements.
Section I: Problem Statement
1.1 Introduction

PHD, Inc. strives to provide solutions to optimize industrial manufacturing processes. Included in these is a product known as a force gripper. This device uses either an electric motor or pneumatic piston to move synchronous mechanical jaws. The grippers are just a base design that are further adapted to meet a customer's needs by adding a specialized tooling which will be used for direct contact with the item the gripper is working with. This tooling is provided by the customer and is constructed according to their needs. The gripper can be configured to hold an object in two different ways. First, an object can be held by contraction of the two mounting plates to which the customer tooling is attached thus applying pressure on the exterior surface of an object. Second, the gripper may grab an object by moving the customer tooling apart and applying pressure to interior surfaces of an object. It is desired that the customer be able to directly measure the force applied by the grippers in real time. The gathering and communication of this information remains the focus of this project. A brief overview of the basic system, its boundaries, and its interfaces is given in figure 1.1.1 below.

![System Boundary diagram](image)

**Figure 1.1.1:** System Boundary describing interaction and interfaces
For this design project, the system engineering V model will be used to define the process by which this system will be designed. The V model defines the process from feasibility to detailed design to verification and testing. This model is shown in figure 1.1.2 below.

![Figure 1.1.2: System Engineering Process V-Model](image)

### 1.2 Requirements and Specifications

This system must meet certain requirements to prove useful to the end customer. These basic requirements are given below:

- Provide a system to measure compressive/tensile grip force applied in real time.
- The system shall be designed to interface between existing gripper hardware and customer tooling.
- Design shall be scalable to accommodate the GRH, GRK, and GRR families of PHD grippers.
- The system shall provide an analog interface that is able to communicate to the customer’s standard PLC.
- The system shall provide an analog interface to communicate with standard PLC hardware.
- The sensor shall be mounted between the gripper and customer tooling.
- Selected components and designs should be rated for 10 million cycles, or be easily serviceable.
- The measured force must remain accurate to +/- 5% over gripper lifetime.
- System shall provide an interface for customer to be able to set zero and span of the system.
1.3 Given Parameters

A given parameter represents specifications that are presented to the design team, but the team has no control over them. The following given parameters are to be recognized during the design of the force sensor and display unit. Given below are the desired specifications provided by PHD, Inc for the GRH, GRK and GRR families of grippers. These parameters are for the physical size and durability of the force sensor as well as the voltage and current specifications for signal output.

- Each gripper family has a given bolt and dowel pattern that cannot be altered. The system must interface to these patterns.
- Maximum grip force for the families is given below:
  - 12-75 lbs for the GRH series.
  - 86-805 lbs for the GRK series, and
  - Up to 805 lbs for the GRR series.
- Maximum moment for the families are given below.
  - 405 in-lbs for the GRH series,
  - 3280 in-lbs for the GRK series, and
  - 9000 in-lbs for the GRR series.
- Current PHD products all meet the IP67 environmental standard.
- All grippers have a rated lifespan of 10 million cycles.
- Standard PLCs can read analog inputs that vary from either 4-20 mA, or from 0-10 Vdc.

1.4 Design Variables

A design variable represents specifications that the design team is required to determine. The design variables are limited to the sensor hardware and controller. These are given in detail below.

- **Selection/type of Sensing Element**: The sensing unit must accurately measure within 5% of the maximum gripping force over its lifecycle. Should be scalable product for different size grippers.
- **Enclosure Material and Construction**: The sensor enclosure must be able to withstand the forces exerted and provide proper force translation to the sensing element.
- **Processor**: The processor must be able to translate the output from the sensing unit to a customer’s PLC. This processor must be able to be calibrated for customer’s specialized tooling and work over the operating range of the sensor with a linear output.
- **Sensor Mount Interface**: The sensor must interface between the gripper jaws and customer tooling. Ideally this should remain the existing mounting interface.
1.5 Limitations & Constraints
The constraints presented below represent the minimum capability that the force sensor must meet or be able to withstand.

- Must be able to measure the maximum gripping forces for each family of gripper.
- Cost per force sensing elements used at production should be under ten dollars.
- Cost for design and development of the prototype of this system must not exceed $1500.

1.6 Other Considerations
The design parameters listed below represent functions that are deemed necessary to improve the capabilities of the force sensor:

- **Programmable User Interface**: User programmed calibration to increase output accuracy; set alarms in terms of applied force
- **Sensor Package Height**: Force sensor should keep gripper jaw and customers specialized tooling as close as possible, preferably less than 0.5”
Section II: Revised Detailed Design
After choosing the concepts for the two subsystems the team worked on making the individual components for the final design. For the mechanical system to work correctly, each family of gripper needs a different design variant. This is due to varying bolt and dowel patterns on the various grippers. The concept of making an intermediate gripper jaw that directs all the strain into two locations allowing measurement from a strain gage is applied to each design and altered for differing loads and attachment bolting patterns. The detailed design is broken down into two subsystems, a mechanical system that is placed in between the gripper and tooling, and the electrical system that senses the strain and produced and output for the force placed on the gripper.

2.1 Mechanical Sub-System

The purpose of the mechanical subsystem is to transfer the force of the gripper to the customer's tooling, while allowing enough deflection that a measurable strain can be sensed by means of an attached strain gage. The strain gage is to be protected from environmental hazards, as outcome of a functional requirement, and the mechanical subsystem will be employed for this task as well. To complete both tasks an intermediate jaw was designed to bolt to the existing gripper jaw pattern on the bottom while having a similar bolt pattern on the top for the attachment of customer tooling. To keep the height of the intermediate jaw as small as possible, the top plate with the tooling bolt pattern was designed to bolt on to the bottom part of the intermediate jaw. The removability of the top of the intermediate jaw allows for a cavity to be made that encapsulates the strain gage, protecting it from environmental hazards. The critical part of this design is the thickness, the distance from the neutral axis in the x direction, and the cavity walls. These components must be designed to allow enough room for fasteners inside the intermediate jaw, and provide a strain that is within the limits of the strain gage. To prevent dust and moisture from entering the enclosed cavity a 1.5mm thick O-ring will be placed in the groove on the top plate. An 11mm hole in the face of the wall parallel with the gripper force will allow the strain gage wires to pass through the cavity wall. This hole will be sealed with a rubber grommet and a dollop of silicone to prevent the impregnation of dust and moisture. Figure 2.1.1 shows the parameters used in configuring the strain gage cavity with the dashed green line being the neutral axis, C is the distance from the neutral axis, base is the plane parallel with the gripping force, height is the plane perpendicular to the gripping force, length comes out of the page, T1 is the thickness of the walls in the z direction, and T2 is the thickness of the walls in the x direction. Each gripper family was evaluated separately due to the difference in the jaw sizes and moment capacities, however the process for designing the cavity were the same. The initial size of the cavity was designed so that the cavity walls provided enough clearance for attaching to the
gripper jaw. Once the outside dimensions were established the wall thickness of the cavity was
determined to allow for the maximum strain output. Deflection was determined with
superposition method #5 and is shown in Equation M1 to find the deflection. The second
moment of area was found using Equation M2. The strain at the inner wall of the cavity was
found using Equation M3. Tolerances for the cavity were determined by considering how precise
machining can be completed and to keep the difference in parts as low as possible. The 0.01mm
tolerance is acceptable for CNC machining without significantly adding more cost to the part,
and at the most has a difference of 0.5% in strain on the strain gage surface. The results for all of
the aforementioned design considerations are presented by gripper family in the subsequent
sections for the mechanical subsystem. The preceding sections give the results by gripper family.

Figure 2.1.1: This diagram shows how the dimensions were used for the design of the strain
gage cavity. x in the direction of the gripping force,  z is the direction perpendicular to the
gripping force, and y is the moment about the part looking from the top.
The GRR gripper family has the highest moment capacity of the three gripper families the force sensor was to be designed for and subsequently is the most robust of the three designs. Figure 2.1.2 shows the final design with the proposed strain gage location in yellow on the long wall of the cavity. The bolt pattern is the same as the pattern found on the GRR grippers, on the bottom to bolt to the gripper and on the top is a pattern mirrored of the gripper jaw itself. The dimensions of the cavity are 40 mm at the base and 84 mm for the height and a wall thickness of 10 mm for all the sides. Four M5 x 0.7 countersunk screws will attach the top plate shown in Figure 4.1.3 to the bottom. The top plate will use a 52 mm diameter O-ring that is 1.5 mm diameter thickness. A blank intermediate jaw was made for the opposing gripper jaw that is the same height as the sensing intermediate jaw. The detailed drawings for both designs can be seen in Appendix B Figures B1-B6.
Figure 2.1.2: The bottom of the GRR intermediate jaw for the larger grippers showing the cavity, wire exit and proposed location of the strain gage (yellow).
GRH Gripper Family Design

The GRH gripper family has the lowest rated moment capacity that added a different element of complexity to the design process as a large enough cavity was needed to place the strain gage in yet small enough to allow a measurable amount of strain. Figure 2.1.4 shows the design of the bottom part for the intermediate jaw with the proposed location of the strain gage shown in yellow. The mounting bolt pattern for each GRH gripper size compliments the gripper jaw and tooling without modification. There are two different cavity dimensions, a small version, for the GRH8 and GRH12 grippers and a large version for the GRH16 and GRH20 grippers. The small version has a base of 29mm and a height of 25mm with a wall thickness of 3mm z direction and 2mm x direction while the large version has cavity dimensions are 46mm base and 34mm height with wall thickness of 5.5mm z direction and 2mm x direction. Four countersunk screws are used to attach the top of the intermediate jaw shown in Figure 2.1.5 to the bottom using M2 X 0.4 for the smaller intermediate jaw and M3 X 0.5 for larger intermediate jaw. A blank intermediate jaw was made for the opposing gripper jaw that is the same height as the sensing intermediate jaw. The detailed drawings for both designs can be seen in Appendix B Figures B7-B19.
Figure 2.1.4: The bottom of the GRH intermediate jaw small design showing the cavity, wire exit and proposed location of the strain gage (yellow).
Figure 2.1.5: The top of the GRH intermediate jaw small design with a cutaway showing the o’ring groove and the tooling bolt on pattern.

GRK Gripper Family Design
The GRK family of gripper has a similar grip force as the GRR but has far less moment capacity. Figure 2.1.6 shows the final design with the proposed strain gage location in yellow on the long wall of the cavity. The mounting pattern shown is the same as the jaw mounting pattern on the GRK to make assembly easier. This pattern is mirrored to the cap shown in Figure 2.1.7 with the exception of threads being added to the fastener holes so the customer can bolt their existing tooling to the sensor housing. Four different size housings had to be created, one for each size of GRK. This is because the GRK has top mounting holes and the distance between the mounting holes changes with each bore size. The sensor housing can not interfere with these mounting
holes, so the geometry had to change for every size. The geometry and dimensions for the housings can be seen in Appendix B Figures B13-B20. The cavity is sealed from the top with a 1.5mm O-ring to help comply with the IP67 standard and the placement and groove for the O-ring can be seen in Figure 2.1.7. The cap is attached to the base of the housing using M5 X 0.7 FSHCS fasteners for the GRK75 and GRK58, while the GRK46 and GRK35 use M4 X 0.7 FSHCS. A blank intermediate jaw was made for the opposing gripper jaw that is the same height as the sensing intermediate jaw. The detailed drawings for both designs can be seen in Appendix B Figures B20-B26.

Figure 2.1.6: The bottom of the GRK intermediate jaw showing the cavity, wire exit and proposed location of the strain gage (yellow).
Figure 2.1.7: The top of the GRK intermediate jaw small design with a cutaway showing the o’ring groove and the tooling bolt on pattern.

Mechanical Sub System Design Changes

After reviewing the final design drawings with the model shop manager some changes were recommended to reduce manufacturing time. The first change was to increase the base for each model by 12mm to allow the tight tolerance required for the cavity to only pertain to the geometry of the cavity. The o’ring groove was found to be incorrectly designed and did not allow enough room for O-ring compression. The groove geometry was changed from the original round design to a larger square design. The GRR grommet hole was thicker than allowable for the chosen grommet and a counterbore was added to reduce the wall thickness to 3mm. To reduce the amount of deflection on the GRR gripper, the cap thickness was increased from the original 12mm to 18mm. The GRH and GRK dowel pin holes in the cap were through holes and were changed to blind holes to prevent moisture impregnation.

2.2 Electrical Sub System
The electrical sub system will use a microprocessor, along with some amplifier circuitry, to convert the detected signal from the strain gauges to a usable format for a PLC. The design revolves around the chosen microprocessor and strain gauge setup.

The design will utilize a half bridge strain gauge configuration, using gauges which are temperature compensated for our chosen housing material that is aluminum. The microprocessor we will use will be a simple PIC 8-bit, designed for basic signal conditioning applications. It will have at least a 12 bit A/D converter built in, and will drive a high precision D/A converter for the output signal. A block diagram overview of the system is given in figure 2.2.1 below.

![Block diagram of processor circuit. These are the major components of the physical processor board.](image)

**Figure 2.2.1:** Block diagram of processor circuit. These are the major components of the physical processor board.

**Functions of the Processor**

The processor circuit shown above is responsible for the following tasks. Details of the above design are given in the following sections.

- Change mode of operation in response to user inputs which include a reset button and buttons to increase or decrease the span of the output.
- Drive a display to communicate with the user. The display will primarily indicate the output voltage, but also indicate the mode of operation (i.e. span adjustment, zeroing/reset, and force output.)
- Adjust input to represent the span the user has chosen and display the corresponding force measurement.
- Provide an output signal to a Digital to Analog converter. The resulting analog signal will be adjusted with an Operational Amplifier to provide the correct output for the customer’s PLC.
• Control a feedback loop to an offset amplifier in order to condition the signal coming into the microprocessor.

Microcontroller Selection
The center of the processor design is the selection of microprocessor. The microprocessor must meet some minimum requirements to perform adequately. The minimum requirements are as follows.

• Processor must include at least a 12-bit ADC to measure strain gauge.
• Processor must include I²C and SPI communication protocols for peripheral communication.
• Processor must be inexpensive (< $5 per chip at production volume).
• Processor must include non-volatile read-write memory for storing zero and span values.
• Processor must include approx. 20 IO pins to accommodate all circuit needs.

After some research, it is quickly found that an 8 bit PIC microprocessor, designed by Microchip, will provide the needed functionality without excessive features or cost. Using Microchip’s online search tool, called MAPS, a suitable chip is found. A sample image of the MAPS software is shown below.

![Figure 2.2.2: MAPS Search Software Interface.](image)
It is selected to utilize a PIC16F1786 processor. These are available in both through hole and smt packages. They contain 8k words flash program space and 256 bytes of EEPROM non-volatile memory. The internal oscillator allows the processor to run at 32 MHz, or 8 MIPS. This should be sufficient for performing multiple ADC samples, linear scaling operations, and DAC writes every second, meeting the soft real time requirement. This chip also includes an internal 8-bit DAC, which will be used for the zero feedback circuitry.

The PIC16F1786 has 25 IO pins available for use. Should this be found to be insufficient, a PIC16F1784 will be substituted, which has the same characteristics, but with over 40 IO pins.

**Strain Gauge Selection**

Strain gauges must be sourced and chosen to work with the gripper designs given in section 2.2. The criteria for the strain gauge are as follows:

- Gauge body length must be within ½” long.
- Gauge must be able to compensate for steel or aluminum.
- Gauge must be available for under $10 at production quantity.
- Gauge must include mounting adhesive and terminal leads.
- Gauge must be able to read the maximum applied strain, which is \( \epsilon = 350 \times 10^6 \)
- Gauge must meet the lifetime fatigue of 10 million cycles within operating strain.

From these requirements, we select a gauge from the wide variety offered by Omega. Two general purpose gauges are selected from a family with a nominal resistance of 120 ohms and a gauge factor of 2. Gauge factor is defined as follows.

\[
GF = \frac{\Delta R}{R} \frac{\Delta L}{L} = \frac{\Delta R}{R} \frac{1}{\epsilon}
\]

This relation allows for conversion for a mechanical strain into a known change in resistance. The strain gauge with aluminum compensation is Omega part # SGD-6/120-LY13. For steel compensation, part # SGD-6/120-LY11 will be used. Omega also sells terminal pads and single part bonding adhesive to match their gauges. These are included in the BOM.

Two individual strain gauges are to be used and connected in a half bridge configuration. The bridge will be excited by a 5v dc source, which is also the supply voltage to the microprocessor. The strain connections within the mechanical housing are shown in figure 2.2.3 below.
Input and Offset Amplifiers

To analyze this circuit, we first find an equation for the change in voltage by the gauge for maximum strain. This is calculated as follows.

$$ V_{gauge} = V_{dd} * \frac{R_{lower}}{R_{lower} + R_{upper}} = V_{dd} * \frac{R + \Delta R}{R + \Delta R + R + \Delta R} = V_{dd} * \frac{R + \Delta R}{2R} = V_{dd} * \left(\frac{1}{2} \pm \frac{\Delta R}{2R}\right) $$

Plugging in the known relationship for strain and change of resistance and since Vdd is known to be 5 volts, we find Vgauge as follows.

$$ V_{gauge} = 5 * \left(\frac{1}{2} \pm 350 \times 10^{-6}\right) = 2.5 \pm 0.00175 \, \text{v} $$

The gain of instrumentation amplifier is calculated to amplify the small signal from the gauge to use the entire 5v span of the ADC converter on the microcontroller. Therefore, the gain of the amplifier is calculated as follows.

$$ Gain = \frac{V_{out}}{V_{strain}} = \frac{2.5}{0.00175} = 1428.5 = \frac{R_{feedback}}{R_{in}} $$

The gauges have a tolerance of 0.5%. We can calculate the maximum error as follows:

$$ R_{lower} = R_{nominal} * (1 + U) = 120 * (1 + 0.5\%) = 120.6 \, V $$
$$ R_{upper} = R_{nominal} * (1 - U) = 120 * (1 - 0.5\%) = 119.4 \, V $$

$$ V_{gauge} = V_{dd} * \left(\frac{R_{lower}}{R_{upper} + R_{lower}}\right) = 5.0 * \left(\frac{120}{240}\right) = 2.5125 \, V $$

$$ V_{error} = \pm (V_{gauge} - V_{nom}) = \pm (2.5125 - 2.5) = \pm 0.0125V $$

Since this is the error that must be accounted for, we can calculate the necessary gain of the amplifier to reduce the 0 to 5v signal to this level.

$$ G = \frac{V_{error}^2}{V_{out}} = \frac{0.0125^2 * 2}{5.0} = \frac{1}{200} = 0.005 $$
In figure 2.2.4, there are three different amplifiers presented. The first amplifier incorporates an instrumentation amplifier and has a gain of 100. The second amplifier incorporates a differential amplifier and has a gain of 15. Thus, this provides an input gain of 1500. The final circuit in the figure is the zeroing circuit. This allows for the input signal to be calibrated to 0. The gain of this circuit is 1/200 allowing it to compensate for the nominal resistance variance of the gauges.
Figure 2.2.4: Circuit Schematic for Input and Offset Amplifier
Output Digital-to-Analog Converter

To produce an output signal which can provide feedback to a PLC. This ADC should be controllable over I2C and should provide at least 12 bits of resolution. A Texas Instruments surface mount chip is chosen with part number MCP4725. This device operates on the 5v logic level of the processor and has a settling time of 6 μs.

Output Amplifier

The circuit in figure 2.2.5 is the output amplifier. U9 on the left is the 12-bit DAC which converts the output from the PIC to an analog signal to be output to the 7-segment display and the customer PLC. In order to meet the voltage requirement required for a PLC input, a gain of 4 is applied to the signal before it is used. An output feedback circuit is included to allow the system to self-compensate its output logic.

![Figure 2.2.5: Circuit Schematic for Output Amplifier](image)

User Interface

The users will input information into the system using simple momentary tactile buttons. Three will be used, and each will provide a digital input to the processor. The buttons will be labeled as up, down, and zero. The simple user interface shall provide the user the ability to fully configure the device processor.
Uncertainty Analysis on Strain Measurement

To verify the performance of the system, we shall perform an uncertainty analysis on the electrical subsystem as a whole. Starting with the strain gauge, the strain gauges have a standard deviation in their gauge factor of about 0.5%. Also, the resistors selected for the feedback circuitry are to be 0.1% tolerance. The op-amp was selected due to its low input offset of 3 uV. Finally, the microprocessor has both 12-bit D/A and A/D converters. Knowing this, we can determine the total uncertainty of the system.

The uncertainty will be calculated in volts at the output to the PLC. Maximum error occurs when the gauge factors are both off by 0.5% in opposite directions. The maximum deviation will therefore occur at the maximum strain of $350 \times 10^{-6}$. We can calculate the resistances for this error, shown below. $V_{a}$ represents the error in the output voltage of the output amplifier circuit.

\[
V_{\text{strain error}} = V_{dd} \times \text{Tolerance} \times \text{Strain} = 5.0 \times 0.5\% \times 350 \times 10^{-6} = 8.75 \times 10^{-6} V
\]
\[
V_{a1} = V_{\text{strain error}} \times \text{Input Gain} \times \text{Output Gain} = 8.75 \times 10^{-6} \times 1500 \times 4 = 0.05 V
\]

Next, we determine the maximum error introduced by the first differential amplifier. It is known to have at most a 3 uV offset voltage.

\[
V_{a2} = 3 \mu \times \text{Input Gain} \times \text{Output Gain} = 3 \times 10^{-6} \times 1500 \times 4 = 0.018 V
\]
Then the maximum possible gain error introduced by the first gain stage, U1-B. All resistors are 0.1% tolerance, and to calculate this error, we will set the smaller resistor to its upper limit and the larger one to its lower limit.

\[
G_{\text{error}} = \left( \frac{R_{\text{upper}}}{R_{\text{lower}}} \right) - G = \frac{15000 \times (1+0.1\%)}{10000 \times (1-0.1\%)} - 15 = 0.03003
\]

\[
V_{a3} = V_{dd} \times \text{Strain} \times G_{\text{error}} \times \text{Output Gain} = 5.0 \times 350 \times 10^{-6} \times 0.03003 \times 4 = 0.00021 \text{ V}
\]

Also include the offset error in this amplifier.

\[
V_{a4} = 3\mu \times \text{Input Gain} \times \text{Output Gain} = 3 \times 10^{-6} \times 15 \times 4 = 0.0018 \text{ V}
\]

The processor utilized a 12 bit A/D and D/A converter. There is therefore sampling and reconstruction error on the signal as well

\[
V_{a5} = \frac{V_{dd}}{2^b} \times \text{Output Gain} = \frac{5.0}{2^5} \times 4 = 0.00488 \text{ V}
\]

\[
V_{a6} = \frac{V_{dd}}{2^6} \times \text{Output Gain} = \frac{5.0}{2^6} \times 4 = 0.00488 \text{ V}
\]

Lastly, there is some error induced by the output amplifiers. The resistors on these amplifiers will only be 1% tolerance. There are three resistor pairs to consider: the 1.25v reference, the inverter, and the amplifier. They are calculated as follows.

\[
V_{a7} = \frac{V_{dd}}{4} \times \text{Tolerance} \times 2 \times \text{Output Gain} = 1.25 \times \frac{0.1\%}{2} \times 2 \times 4 = 0.005 \text{ V}
\]

\[
V_{a8} = \frac{V_{dd}}{2} \times \text{Tolerance} \times 2 \times \text{Output Gain} = 2.5 \times \frac{0.1\%}{2} \times 2 \times 4 = 0.010 \text{ V}
\]

\[
V_{a9} = \frac{V_{dd}}{4} \times \text{Tolerance} \times \text{Output Gain} = 5 \times \frac{0.1\%}{2} \times 4 = 0.010 \text{ V}
\]

The uncertainty budget is shown in table 2.2.1 below.
Table 2.2.1: Uncertainty Budget

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
<th>Unit</th>
<th>Distribution</th>
<th>Divisor</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge Factor</td>
<td>0.049</td>
<td>V</td>
<td>Normal (k=1)</td>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
<td>Input Buffer Offset</td>
<td>0.0168</td>
<td>V</td>
<td>Normal (k=1)</td>
<td>1</td>
<td>0.018</td>
</tr>
<tr>
<td>Input Amplifier</td>
<td>0.0196</td>
<td>V</td>
<td>Normal (k=1)</td>
<td>1</td>
<td>0.00021</td>
</tr>
<tr>
<td>Input Amp Offset</td>
<td>0.0168</td>
<td>V</td>
<td>Normal (k=1)</td>
<td>1</td>
<td>0.0018</td>
</tr>
<tr>
<td>A/D Sampling</td>
<td>0.00488</td>
<td>V</td>
<td>Rectangular</td>
<td>$\sqrt{3}$</td>
<td>0.00281</td>
</tr>
<tr>
<td>D/A Reconstruction</td>
<td>0.00488</td>
<td>V</td>
<td>Rectangular</td>
<td>$\sqrt{3}$</td>
<td>0.00281</td>
</tr>
<tr>
<td>1.25v Reference</td>
<td>0.005</td>
<td>V</td>
<td>Normal (k=1)</td>
<td>1</td>
<td>0.005</td>
</tr>
<tr>
<td>Inverter</td>
<td>0.010</td>
<td>V</td>
<td>Normal (k=1)</td>
<td>1</td>
<td>0.010</td>
</tr>
<tr>
<td>Output Amplifier</td>
<td>0.010</td>
<td>V</td>
<td>Normal (k=1)</td>
<td>1</td>
<td>0.010</td>
</tr>
</tbody>
</table>

**Combined Standard Uncertainty** 0.0553

**Expanded Uncertainty (2 std. deviations, 95% confidence)** 0.1108

From this analysis, we can clearly see that the total expanded uncertainty is 0.1108 volts on the output. The system provides a total output swing voltage of 20V. Therefore, our percent error is as follows.

\[
\%\text{Error} = \frac{\text{Uncertainty}}{\text{Range}} = \frac{0.1108}{20} = 0.6\%
\]

This percent error is much less than our minimum of 5% and within our optimum target of 1%. Therefore the processor as a whole can achieve the target accuracy required. Note there is no uncertainty in the zeroing feedback circuit, as this system is self-calibrating and will correct itself at runtime.

**Top-Level Schematic**

Below in figures 2.2.7 and 2.2.8 is the top-level circuit schematic for the processor unit. This includes all of the components described above, as well as their interconnections.
Figure 2.2.7: Top-Level Schematic part 1. This shows the voltage regulators, microcontroller, display, and switch inputs to the system.
Figure 2.2.8: Top-Level Schematic page 2. This shows the input amplifiers, zeroing amplifier, and output amplifier
Software Design

A software program must be written for the PIC16F1786 chip on the processor board. This software is rather simple, and implements all of the needed features of the system. This includes writing to the I2C devices, reading the analog inputs and storing settings in internal eeprom memory. The program flow is shown by the diagram in figure 2.2.9.

![Software Logical Flowchart](image)

Figure 2.2.9: Software Logical Flowchart. The ADC interrupt process is driven by an internal timer in the system.

Electrical Sub System Design Changes

Upon constructing the first prototype of the original design, it was observed that the MAX4425X amplifier did not have enough open-loop gain or CMRR to properly amplify the input signal. Therefore, an instrumentation amplifier was employed to provide a base gain of 100 to the system and reduce the load on the MAX4425X chip. The gain is adjustable by changing the feedback resistor on the second amplification stage.
Also, the LED display was dropped in favor of an LCD display which uses less energy and is lower in cost. This allows the design to work with only linear regulators, keeping the noise on the board low.
Section III: Assembly
3.1 Mechanical System Assembly

The intermediate jaw drawings were sent to PHD’s model shop and machined using a horizontal cnc mill and the finished bottom and cap were ready for assembly. The first step in assembly was to install the strain gages at the center of the cavity. The machining process was to place a alignment mark in the bottom of the cavity, however due to the tool diameter the alignment mark was not close enough to the wall of the cavity to be of any use. The center of the cavity was found (shown with the green arrow in Figure 3.1.1) and two lines were etched in the wall of the cavity to align the edges of the strain gage (shown with the orange arrows in Figure 3.1.1). The example figures are from the GRR installation.

To install the strain gage Loctite 401 instant adhesive was applied evenly to the surface that the strain gage would be in contact with. The strain gage was then placed on the surface of the cavity the result of this procedure can be seen in Figure 3.1.2. A solder connection pad is used to connect the strain gages to the connection wire and is placed in the bottom of the cavity shown in Figure 3.1.2. Two of the strain gage wires are twisted together and connected to the signal wire one of the strain gage wires is connected to the power wire and the remaining strain gage wire is attached to the ground wire as shown in Figure 3.1.2.

The rubber grommet was then placed in the exit hole and wire run through the grommet as shown in Figure 3.1.3. The O-ring material was cut to length and the ends were glued together with Turbo Fuse instant bonding adhesive after the glue dried the O-ring was placed in the O-ring groove in the cap. The intermediate jaw was then placed on the gripper jaw with mounting bolts and torqued to specification. The cap is then placed over the cavity and installed with flat head screws and torqued to specification. The gripper tooling is then placed on the top of the intermediated jaw and fastened with mounting bolts torqued to specification.
**Figure 3.1.1:** Showing the inside of the intermediate jaw cavity where the strain gage alignment marks were located. The center line is shown with the green arrow and the edge lines are shown in orange.
GRR Assembly

- The GRR family of grippers have the same intermediate jaw assembly as the only difference for each member is the bolt pattern. The intermediate jaw bottom is attached to the gripper jaw with 4-M12 bolts torqued to 300 in-lbs and 2-12mm dowel pins.
- The O-ring is to be cut to 158 mm and placed in the cap. The GRR intermediate jaw cap is attached to the bottom with 8-M5 flat head cap screws torqued to 40 in-lb torqued in a cross pattern shown in Figure 3.1.3.
- The customer tooling is attached to the top of the intermediate jaw with 4-M12 bolts torqued to 300 in-lbs and 2-12mm dowel pins. The installed intermediate jaw can be seen in Figure 3.1.4 and Table 3.1.1 shows the torque specification for each of the bolts used in assembly. Figure 3.1.5 shows an exploded view of the GRR intermediate jaw and how it is to be assembled.

Figure 3.1.2: Showing the installed strain gages in the GRR housing.
Figure 3.1.3: The torquing pattern for the GRR intermediate jaw cap.

Figure 3.1.4: Showing the intermediate jaw (orange) installed on the gripper jaw (yellow) and the Customer tooling installed on the intermediate jaw (blue).
Table 3.1.1: The torque specifications for bolts used on installation of GRR gripper prototype.

<table>
<thead>
<tr>
<th>Bolt</th>
<th>Torque (in-lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M12</td>
<td>300</td>
</tr>
<tr>
<td>M5</td>
<td>40</td>
</tr>
</tbody>
</table>

Figure 3.1.5: Exploded view of the GRR Prototype
GRK Assembly

The GRK family of grippers have two intermediate jaw assemblies one for GRK 75 & 58 and one for GRK 46 & 35.

- The GRK 75 intermediate jaw bottom is attached to the gripper jaw with 2-M8 bolts torqued to 200 in-lbs and 2-5mm dowel pins. The O-ring is to be cut to 145.6 mm and placed in the cap. The GRK 75 intermediate jaw cap is attached to the bottom with 4-M5 flat head cap screws torqued to 40 in-lb. The customer tooling is attached to the top of the intermediate jaw with 2-M8 bolts torqued to 200 in-lbs and 2-5 mm dowel pins.
- The GRK 58 intermediate jaw bottom is attached to the gripper jaw with 2-M6 bolts torqued to 80 in-lbs and 2-4mm dowel pins. The O-ring is to be cut to 145.6 mm and placed in the cap. The GRK 58 intermediate jaw cap is attached to the bottom with 2-M5 flat head cap screws torqued to 40 in-lb. The customer tooling is attached to the top of the intermediate jaw with 2-M6 bolts torqued to 80 in-lbs and 2-4mm dowel pins.
- The GRK 46 intermediate jaw bottom is attached to the gripper jaw with 2-M5 bolts torqued to 40 in-lbs and 2-4mm dowel pins. The O-ring is to be cut to 135 mm and placed in the cap. The GRK 46 intermediate jaw cap is attached to the bottom with 2-M4 flat head cap screws torqued to 30 in-lb. The customer tooling is attached to the top of the intermediate jaw with 2-M5 bolts torqued to 40 in-lbs and 2-4mm dowel pins.
- The GRK 35 intermediate jaw bottom is attached to the gripper jaw with 2-M4 bolts torqued to 30 in-lbs and 2-3mm dowel pins. The O-ring is to be cut to 135 mm and placed in the cap. The GRK 35 intermediate jaw cap is attached to the bottom with 2-M4 flat head cap screws torqued to 30 in-lb. The customer tooling is attached to the top of the intermediate jaw with 2-M4 bolts torqued to 30 in-lbs and 2-3 mm dowel pins.

Table 3.1.2 shows the torque specification for each of the bolts used in assembly. Figure 3.1.6 shows the proper torquing sequence for the intermediate jaw cap bolts. Figure 3.1.7 shows an exploded view of the GRK 75 intermediate jaw and how it is to be assembled.

Figure 3.1.6: The torquing pattern for the GRK intermediate jaw cap.
Table 3.1.2: The torque specifications for bolts used on installation of GRK gripper intermediate jaw.

<table>
<thead>
<tr>
<th>Bolt</th>
<th>Torque (in-lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M8</td>
<td>200</td>
</tr>
<tr>
<td>M6</td>
<td>80</td>
</tr>
<tr>
<td>M5</td>
<td>40</td>
</tr>
<tr>
<td>M4</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 3.1.7: Exploded view of the GRK 75 prototype
GRH Assembly

The GRH family of grippers have two intermediate jaw assemblies one for GRH 20 & 16 and one for GRH 12 & 8.

- The GRH 20 intermediate jaw bottom is attached to the gripper jaw with 2-M6 bolts torqued to 80 in-lbs and 2-5mm dowel pins. The O-ring is to be cut to 118.6 mm and placed in the cap. The GRH 20 intermediate jaw cap is attached to the bottom with 4-M3 flat head cap screws torqued to 5 in-lb. The customer tooling is attached to the top of the intermediate jaw with 2-M6 bolts torqued to 80 in-lbs and 2-5 mm dowel pins.
- The GRH 16 intermediate jaw bottom is attached to the gripper jaw with 2-M5 bolts torqued to 40 in-lbs and 2-4mm dowel pins. The O-ring is to be cut to 118.6 mm and placed in the cap. The GRH 16 intermediate jaw cap is attached to the bottom with 2-M3 flat head cap screws torqued to 5 in-lb. The customer tooling is attached to the top of the intermediate jaw with 2-M5 bolts torqued to 40 in-lbs and 2-4mm dowel pins.
- The GRH 12 intermediate jaw bottom is attached to the gripper jaw with 2-M4 bolts torqued to 30 in-lbs and 2-3mm dowel pins. The O-ring is to be cut to 105 mm and placed in the cap. The GRH 12 intermediate jaw cap is attached to the bottom with 2-M2 flat head cap screws torqued to 2 in-lb. The customer tooling is attached to the top of the intermediate jaw with 2-M4 bolts torqued to 30 in-lbs and 2-3mm dowel pins.
- The GRH 8 intermediate jaw bottom is attached to the gripper jaw with 2-M3 bolts torqued to 30 in-lbs and 2-2.5mm dowel pins. The O-ring is to be cut to 105 mm and placed in the cap. The GRH 8 intermediate jaw cap is attached to the bottom with 2-M2 flat head cap screws torqued to 2 in-lb. The customer tooling is attached to the top of the intermediate jaw with 2-M3 bolts torqued to 30 in-lbs and 2-2.5 mm dowel pins.

Table 3.1.2 shows the torque specification for each of the bolts used in assembly. Figure 3.1.8 shows the proper torquing sequence for the intermediate jaw cap bolts. Figure 3.1.9 shows an exploded view of the GRH 20 intermediate jaw and how it is to be assembled.

![Figure 3.1.8: The torquing pattern for the GRH intermediate jaw cap.](image)
Table 3.1.3: The torque specifications for bolts used on installation of GRH 20 gripper prototype.

<table>
<thead>
<tr>
<th>Bolt</th>
<th>Torque (in-lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M6</td>
<td>80</td>
</tr>
<tr>
<td>M5</td>
<td>40</td>
</tr>
<tr>
<td>M4</td>
<td>30</td>
</tr>
<tr>
<td>M3</td>
<td>5</td>
</tr>
<tr>
<td>M2</td>
<td>2</td>
</tr>
</tbody>
</table>
Figure 3.1.9: Exploded view of the GRH Prototype
3.2 Electrical System Assembly

The electrical subsystem is responsible for translating the change in resistance from the half bridge strain gauge configuration into a usable signal for a PLC. The schematic from Section 2 is translated into a two layer PCB layout. This board is designed to implement the schematic, as well as provide some additional prototyping area, if needed. Figure 3.2.1 below shows the PCB layout in EagleCAD.

![PCB Layout for Force Sensor, generated in EAGLE](image)

This board includes the display and switches mounted on the secondary side of the board, and all SMT components on the primary side. This allows for more space for the SMT components and allows the board to be reduced to a two-layer PCB, reducing assembly cost. This board is mounted into a clear case with clearance holes drilled for the switches.

Assembly of the board is documented in Figures 3.2.2 - 3.2.4 below.
**Figure 3.2.2:** Unpopulated PCB Primary Side. This is the PCB as ordered.

**Figure 3.2.3:** Unpopulated PCB Secondary Side. This is the PCB as ordered.
The board was hand assembled at the contract electronics manufacturing facility JPD Controls, Inc. The SMD components were soldered using leaded water soluble solder. The board was then washed with deionized water. Through hole components were then placed using leaded no-clean solder.

This board contains all of the power regulators on the top-right side, the processor in the top-middle, the input and offset amplifiers on the top-left side, and the display driver in the middle. This board is then mounted and installed into the machined case. This is shown in figures 3.2.5 - 3.2.6 below.
Figure 3.2.5: Assembly mounted into case, showing the user interface. No face label is present here, but one is recommended.

Figure 3.2.6: PCB installed inside view. Note, the connectors are not installed in the case in this image. 22 AWG wire is used to connect the board to the connectors.
This system is then connected to the mechanical system and PCB using the IP67 rated connectors and shielded cable. A complete assembled unit, powered up, is shown in figure 3.2.7.

![Fully Assembled Unit](image)

**Figure 3.2.7: Fully Assembled Unit**

The finished product is shown in figure 3.2.7 above. The system is connected to the housing and to the PLC via IP68 rated connectors. A length of 3 conductor shielded cable connects to the gripper housing. A length of 4 conductor cable connects to the PLC. These wire outputs are Ground (blk), Power (15-30v) (red), Remote Zero input (wht), Force output (grn). The implemented software for the controller can be found in Appendix E.
Section IV: Testing
4.1 Test Procedures

Provide A System to Measure Compressive/Tensile Grip Force Applied in Real Time

- Test for real time measurement
  1. Program test mode into processor
  2. Simulate application of full grip force using the zeroing feedback loop.
  3. Ensure the rise time of the output signal is less than 50 ms. (Rise time is defined as the time delay between the start of signal rise to 95% of full signal output, as measured by an oscilloscope)

The System Shall Be Designed to Interface Between Existing Gripper Hardware and Customer Tooling

- Install the force sensor onto gripper jaw, pass fail test either it fits or does not fit.
  1. Look at the intermediate jaw after installation and determine that it is indeed between the gripper jaw and customer tooling.

Design Shall Be Scalable to Accommodate the GRH, GRK, and GRR Families of PHD Grippers

- Install force sensor on each family of gripper to ensure each family has a sensor.
  1. Check that each gripper family has a sensor that correctly measures the force of the gripper.

The System Shall Provide an Analog Interface that is Able to Communicate to the Customer’s Standard PLC.

- Power the system over the working voltage range to confirm its operation.
  1. Power the board with a 15v supply and confirm its operation. Check that all voltage regulators operate within range.
  2. Power the board with a 30v supply and reconfirm all results.
- Check the full scale output of the board.
  1. Subject the board to full scale force inputs and check that the output also registers full scale.
- Plug interface into a PLC or a voltmeter to check system output.
  1. Connect board to sample PLC and ensure the value measured by the PLC agrees with the intended output on the display.

Selected Components and Designs Should be Rated for 10 million Cycles, or be Easily Serviceable

- Check component data sheets to assure component has a life rating of at least 10 million cycles.

System Shall Provide an Interface for Customer to Be Able to Set Zero and Span of the
System
  o Check zero span button that it works and the customer can use it.

The Measured Force Must Remain Accurate to +/- 5%
  o Take various measurements of grip force with the unit at different pressures and tooling lengths.
  o Plot the system output with respect to the gripper pressure at a given tooling length.
  o Find the best linear fit of each dataset for a given tooling length.
  o Find the maximum deviation from the linear regression in the dataset
  o Divide this difference by the full scale output from the largest force output provided to determine maximum percent error.

Meet IP67 Environmental Rating
  o Submerge in 1 meter of water for .5 hour, dry exterior then check the interior components for water.

  1. Place intermediate jaw and interface in water tank at a depth of 1m
  2. Wait 0.5 hour
  3. Remove intermediate jaw
  4. Install intermediate jaw in gripper
  5. Place load cell in gripper jaw
  6. Connect user interface
  7. Adjust gripper air pressure to manufacturer specifications
  8. Close gripper on load cell, record load cell reading and interface reading
  9. Repeat previous step for 30 cycles
 10. Compare load cell values and interface values. Must be within 5%
 11. Disassemble intermediate jaw and user interface
 12. Check for moisture pass if sensor works, and no moisture present.

No More Than 0.030” Deflection
  o To measure the maximum tooling deflection the intermediate jaw is to be installed with tooling that allows maximum length. The following steps were used to determine the maximum deflection.
  o GRR Test
    1. Install intermediate jaw onto gripper jaw as shown in Figure 4.1.1.
    2. Install intermediate jaw cap and tighten bolts to specified torque for bolt size.
    3. Install tooling on intermediate jaw as shown in Figure 4.1.1.
    4. Place spacer in between tooling to allow contact at maximum tooling length as shown in Figure 4.1.1.
    5. Measure the length of the intermediate jaw on the gripping side.
6. Without air pressure applied to gripper jaw manually push gripper jaws until spacer is in contact with tooling connected to jaws.
7. Connect air supply to control valve.
8. Increase air pressure supplied to jaw until maximum pressure is supplied to jaw.
9. Measure the distance of the intermediate jaw on the gripping side (L in Figure 4.1.2) with load applied.
10. Find the change in length of the intermediate jaw (ΔL in Figure 4.1.2) by subtracting second measurement from first.
11. Determine the angle the intermediate jaw moved from horizontal (θ for ΔL in Figure 4.1.2)
12. Use the angle of from the horizontal with the tooling maximum tooling length to determine the tooling deflection with equation ΔX = (Tooling Length * sin(θ))/sin(90-θ).

o GRK and GRH Test
  1. Bring the jaws together and touching without air pressure.
  2. Place distance gage behind gripper jaw and zero.
  3. Add pressure to full rating of gripper.
  4. Record measurement on distance gage.
  5. Release air pressure.
Figure 4.1.1: Setup for testing the maximum tooling deflection GRR.
Figure 4.1.2: How the maximum tooling deflection was calculated on GRR.
4.2 Mechanical Subtest Results

The System Shall Be Designed to Interface Between Existing Gripper Hardware and Customer Tooling

The intermediate jaw for each gripper installed between the gripper jaw and the tooling using the original hardware and bolting pattern. The GRR can be seen in Figure 4.2.1, the GRK can be seen in Figure 4.2.2, and the GRH can be seen in Figure 4.2.3.

Figure 4.2.1: Showing the GRR intermediate jaw installs between the gripper jaw and tooling.
Figure 4.2.2: Showing the GRH intermediate jaw installs between the gripper jaw and tooling.
Figure 4.2.3: Showing the GRK intermediate jaw installs between the gripper jaw and tooling.
Design Shall Be Scalable to Accommodate the GRH, GRK, and GRR Families of PHD Grippers

Each of the gripper families have an intermediate jaw that is scaled for the gripper bolt pattern and the load that is to be carried by the gripper as shown in Figure 4.2.1, 4.2.2, and 4.2.3.

Meet IP67 Environmental Rating

The GRH and GRK intermediate jaws were not able to be tested due to the requirement that they need to be mounted to the gripper to be tested. The GRR intermediate jaw had water impregnation after 30 minutes through the O-ring seal, thereby failing the test.

No More Than 0.030” Deflection

GRR
To test the GRR an internal gage was used along with micrometer to determine the length of the intermediate jaw before and after loading as shown in Figure 4.2.1. The initial testing showed a tooling deflection of 0.046”. Analysis of the design showed that if the cap thickness were increased from 0.4724” to 0.7087” that the flex in the cap would reduce enough to be below the target deflection. The new cap was made and the maximum tooling deflection for this prototype was recorded as 0.031”. While this does not meet the requirement, it does show it is achievable with another minor design revision.
Figure 4.2.1: Measuring the length of the GRR intermediate jaw with a telescoping gage and micrometer.

GRK & GRH
The GRK and GRH tooling deflection was able to be tested with the extension gage as planned. Both passed with the GRK having a deflection of 0.009” at max pressure and tooling length and the GRH having a deflection of 0.025” at max pressure and tooling length. These deflections also account for any skew in the jaw movement and the tooling deflection concluding that intermediate jaw contributes less than the measured amount of deflection.

4.3 Electrical Subtest Results
The System Shall Provide an Analog Interface that is Able to Communicate to the Customer’s Standard PLC.

For the system to be useful, it must be able to interface with any standard PLC. These PLC’s can run on 15-30 volts and accept analog inputs from -10 volts to +10 volts. To test this the unit is powered with both 15 volts and 30 volts to ensure it functions correctly. The linear regulator on the board does generate a bit of heat at the higher voltages, but it is within reason. Also, the unit must output the analog voltage shown on the display. This is shown in figure 4.3.1 and 4.3.2 below.
Figure 4.3.1: Amplifier unit powered by a 15v and a 30v supply

Figure 4.3.2: Amplifier unit shows same voltage on output and display, within the margin of error.

Provide A System to Measure Compressive/Tensile Grip Force Applied in Real Time

In determining the risetime of the system, we take the approach of individually measuring the hardware risetime of the input amplifier, of the output amplifier, and of the software ADC/DAC. Figures 4.3.3 and 4.3.4 below shows the risetime of the software
From these figures, we see that the risetime of the input amplifier is 3.8 ms and the output amplifier is 1.46 ms. Note these rise times are defined as the time it takes to reach 95% peak value. With the addition of the 14ms maximum software delay*, we can calculate the total system latency.

\[ \text{Risetime} = \text{Input} + \text{Software} + \text{Output} = 3.8 \text{ ms} + 14 \text{ ms} + 1.46 \text{ ms} = 19.3 \text{ ms} \]

* Guaranteed by design

This is much less than our target of 50 ms, and therefore satisfies the realtime requirement. In addition, figure 4.3.5 below shows the amplified input to the system on channel 1 and the output to the PLC on channel two during a zeroing operation.
Figure 4.3.5: System input (amplified) and output during a zeroing operation

From this figure, it is seen that the output channel is set to 1.25 volts during the operation, and that the input amplifier is adjusted incrementally toward the target value of zero. The response of the system is tuned to be slightly underdamped, to ensure it converges within a timely manner. The total zeroing time in this demo is 412 ms. The system is zeroing from a completely incorrect point. This operation can be as short as 50 ms, if the system is already near zero to start with. This also satisfies the “real-time” ability of the system.

System Shall Provide an Interface for Customer to Be Able to Set Zero and Span of the System

The software on the board provides two menu options. These are accessed by pressing up and down simultaneously on the device. The first option (shows an ‘r’ on the display) allows the user to select the working range of the unit. There are four options available:

1. -10V to 10V span
2. 0V to 10V span
3. -5V to 5V span
4. 0V to 5V span

The user presses the zero button to move onto the next menu options. This then allows the user to specify a software gain in the system (shown a ‘G’ on the display). The user can then specify a software gain between 1.0 and 4.0 in increments of 0.2. The user can then press zero to return to measurements.

When the device is performing a zeroing operation, it will set its analog output equal to 1.25 volts. This is so the connected PLC has feedback to know when the device is still zeroing and when the operation is complete.
4.4 Full system test

Selected Components and Designs Should be Rated for 10 million Cycles, or be Easily Serviceable
The design of all three grippers make them easily serviceable should replacement parts be necessary. The lifetime fatigue testing from the design report shows a large safety factor on all of these housings. Therefore, on paper, the design is capable of 10 million cycles, both electrically and mechanically. However, more detail to the manufacturing process of these units is necessary to ensure a capable product. This is beyond the scope of this project.

Gripper must remain accurate within 5% of actual grip force.
To test the accuracy of the system for all three gripper designs, we devise a method to compare the deviations in the grip force measured with itself. Since this device is a relative force measurement tool and not an absolute one (like a load cell), its output primarily depends upon two factors: Gripper force and tooling length. We take readings at multiple different pressures and tooling lengths to generate our data.

This data is then processed by finding the best fit linear regression of sensor output to pressure at a given tooling length. Note that this method approximates a constant force applied as a given pressure. This is a fairly good estimate, as confirmed by earlier load cell testing, but is not perfect. We then take the datapoint that deviates from this dataset the most and find the percent error of this point over the full scale of the system. This is detailed in the equation below.

\[
\% \text{ Error} = \frac{MAX(\text{datapoint}_y - (\text{slope}\times \text{datapoint}_x + \text{offset}))}{MAX(\text{datapoint}_y)}
\]

Where:
- Datapoint\_y is the output voltage of the system and the given datapoint
- Datapoint\_x is the input pressure of the system at the given datapoint
- Slope and offset are the coefficients of the linear regression

This is calculated for all datapoints in the dataset. The datapoints which maximize the output are the final result. This data is then plotted to show a representation.
Table 4.4.1: GRR Grip Force Data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0</td>
<td>0.13</td>
<td>0.2</td>
<td>0.3</td>
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<td>20</td>
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<td>0.92</td>
<td>1.17</td>
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<td>40</td>
<td>-0.04</td>
<td>0.57</td>
<td>0.88</td>
<td>1.31</td>
<td>1.66</td>
</tr>
<tr>
<td>50</td>
<td>-0.04</td>
<td>0.75</td>
<td>1.13</td>
<td>1.73</td>
<td>2.16</td>
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<tr>
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<td>0.96</td>
<td>1.44</td>
<td>2.13</td>
<td>2.57</td>
</tr>
<tr>
<td>70</td>
<td>-0.05</td>
<td>1.15</td>
<td>1.7</td>
<td>2.43</td>
<td>2.88</td>
</tr>
<tr>
<td>80</td>
<td>-0.06</td>
<td>1.35</td>
<td>1.97</td>
<td>2.7</td>
<td>3.14</td>
</tr>
</tbody>
</table>

| Linear Slope  | -0.00090 | 0.01774 | 0.02608 | 0.03571 | 0.04183 |
| Offset        | 0.00821  | -0.10321 | -0.14000 | -0.09214 | -0.05500 |
| Largest Error | 20.0397%  | 4.1358%  | 4.0186%  | 2.9365%  | 4.8301%  |

Figure 4.4.1: Plot of GRR grip force data
The GRR gripper showed adequate test results. The output provided is clearly linear, and the maximum error from the system was 4.8%. However, it is important to note the test results for 2.715” tooling length. This dataset has a very weak negative correlation, whereas all other test points show strong positive correlation. This dataset show that the gripper is working outside its specified range. Therefore, this system does not work with such short tooling lengths. However, it is impractical for a customer to be using this gripper model with a tooling length this short. So, this still meets the use case requirement.

Table 4.4.2: GRH Grip Force Data

<table>
<thead>
<tr>
<th>Pressure (PSI)</th>
<th>Tooling Length (in)</th>
<th>GRH Grip Force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.117</td>
<td>2.609</td>
</tr>
<tr>
<td>10</td>
<td>-0.14</td>
<td>-0.07</td>
</tr>
<tr>
<td>20</td>
<td>-0.24</td>
<td>-0.14</td>
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<tr>
<td>30</td>
<td>-0.32</td>
<td>-0.28</td>
</tr>
<tr>
<td>40</td>
<td>-0.43</td>
<td>-0.34</td>
</tr>
<tr>
<td>50</td>
<td>-0.52</td>
<td>-0.55</td>
</tr>
<tr>
<td>60</td>
<td>-0.64</td>
<td>-0.59</td>
</tr>
<tr>
<td>70</td>
<td>-0.74</td>
<td>-0.64</td>
</tr>
<tr>
<td>80</td>
<td>-0.83</td>
<td>-0.77</td>
</tr>
</tbody>
</table>

| Linear Slope  | -0.00998            | -0.01017       | -0.00723       | -0.00612       |
| Offset        | -0.03357            | 0.03500        | -0.01357       | -0.01214       |
| Largest Error | 1.5491%             | 9.9567%        | 8.0991%        | 4.9048%        |
The GRH gripper does not have the same ideal characteristics as the GRR gripper. The figures above show that the data is not very linear for two of the dataset plots. These plots show a variation of up to 10%. This could be attributed to a variety of factors, ranging from gripper wear to strain gauge placement and attachment.

**Table 4.4.3: GRK Grip Force Data**

<table>
<thead>
<tr>
<th>Pressure (PSI)</th>
<th>3.812</th>
<th>4.993</th>
<th>6.174</th>
<th>6.962</th>
<th>7.749</th>
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<tbody>
<tr>
<td>40</td>
<td>-1.52</td>
<td>-1.75</td>
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<td>-2.9</td>
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<tr>
<td>50</td>
<td>-1.88</td>
<td>-2.35</td>
<td>-3</td>
<td>-3.35</td>
<td>-3.9</td>
</tr>
<tr>
<td>60</td>
<td>-2.47</td>
<td>-3.15</td>
<td>-3.8</td>
<td>-4.25</td>
<td>-4.75</td>
</tr>
<tr>
<td>70</td>
<td>-3.21</td>
<td>-3.9</td>
<td>-4.6</td>
<td>-5</td>
<td>-5.55</td>
</tr>
<tr>
<td>80</td>
<td>-3.67</td>
<td>-4.6</td>
<td>-5.4</td>
<td>-5.8</td>
<td>-6.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Linear Slope</th>
<th>Offset</th>
<th>Largest Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.05630</td>
<td>0.82800</td>
<td>2.9155%</td>
</tr>
<tr>
<td></td>
<td>-0.07250</td>
<td>1.20000</td>
<td>1.6304%</td>
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<tr>
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<td>-0.07900</td>
<td>0.93000</td>
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</tr>
<tr>
<td></td>
<td>-0.08250</td>
<td>0.70000</td>
<td>1.2069%</td>
</tr>
<tr>
<td></td>
<td>-0.08850</td>
<td>0.59000</td>
<td>1.0000%</td>
</tr>
</tbody>
</table>
The GRK gripper showed the best results of all three designs. This gripper had a variation of 1.6% in the overall system output. The data has a negative correlation, which just related to the direction in which grip force was applied. This design had to be modified to work, as there was an error in the print. This change concentrated the strain provided to the gauges, increasing the working range of the unit and providing better test data.

**Summary of Test Results**

Table 4.4.4 below shows a summary of all tests and the results gathered from them.

<table>
<thead>
<tr>
<th>Test For</th>
<th>Result</th>
</tr>
</thead>
</table>
| The System Shall Be Designed to Interface Between Existing Gripper Hardware and Customer Tooling | GRR - Passed  
GRH - Passed  
GRK - Passed |
| Design Shall Be Scalable to Accommodate the GRH, GRK, and GRR Families of PHD Grippers | GRR - Passed  
GRH - Passed |
| Requirement                                                                 | GRK - Passed                                                                 | GRR - Failed  
|                                                                            |                                                                            | GRH - Not Tested  
|                                                                            |                                                                            | GRK - Not Tested  
| Meet IP67 Environmental Rating                                              |                                                                            |  
| No More Than 0.030” Deflection                                             |                                                                            |  
| The Measured Force Must Remain Accurate to +/- 5%                          |                                                                            |  
| Selected Components and Designs Should be Rated for 10 million Cycles, or be Easily Serviceable | All - Passed                                                               |  
| Provide A System to Measure Compressive/Tensile Grip Force Applied in Real Time | All - Passed                                                               |  
| System Shall Provide an Interface for Customer to Be Able to Set Zero and Span of the System | All - Passed                                                               |  
| The System Shall Provide an Analog Interface that is Able to Communicate to the Customer’s Standard PLC. | All - Passed                                                               |
Section V: Final Evaluation and Recommendations
5.1 Mechanical System Final Evaluation

The GRR prototype mechanical subsystem held up to maximum gripper force. The cap had to be redesigned to reduce deflection in the cap and reduce the tooling deflection. The modification of adding 6mm to the thickness brought the deflection from 0.046” down to 0.031”. This deflection was over the specified functional requirement by 0.001”.

The GRH and GRK also withstood the maximum gripper force without having excessive deflection or other signs of fatigue. A design mistake on the GRK means that it may not withstand the lifetime testing, but the error in the busing placement is easily correctable.

Overall, the mechanical system worked well. All designs past almost all of the tests. Only a few issues were found during the testing, such as excessive deflection on the GRR model, and insufficient Ingress Protection against water submersion. A complete mechanical bill of materials can be found in Appendix A.

5.2 Electrical System Final Evaluation

The electrical processor is perfectly adept at measuring and amplifying strain gauge input. The board layout and schematic included use of a very precise instrumentation amplifier to perform the initial amplification of the signal. Along with various other tricks, like bypass capacitors, low-pass filters with cutoff frequencies around 100Hz, and a digital moving average filter, the system performed well in all working environments. It passed all of the individual tests presented to it.

5.3 Final Prototype Evaluation

The prototypes as a whole worked effectively when tested at PHD, Inc. on April 20th, 2017. These units did provide accurate relative force readings and are based linearly on force applied as well as tooling length. The GRH gripper did not perform as well as the GRR and GRK models, having nearly 10% variance in measurement. This could be due to an issue with the mechanical design or the strain gauge placement and mounting itself. However, the other two units worked flawlessly and provided good, reliable, repeatable output.

5.4 Mechanical System Recommendations

Anodize

In order to protect the aluminum housing from corrosive environments, it is recommended that the base and cover should be treated with an anodizing process. Since both the cover and base of
each prototype will not encounter heavy wear, a thin layer of anodize, commonly called “clear anodize”, will suffice. The variant of anodize the components should receive should be Type II anodize per military specification MIL-A-8265. This specifies that the aluminum components should be treated with an electrolytic bath containing sulfuric acid to produce a uniform anodic coating on the surface of the metal. This is superior to paints or other coatings applied to surfaces because the anodic coating will not chip or peel and provides superior protection against corrosion. The coating is essential aluminum oxide that grows on the surface and penetrates the surface of the aluminum. Since the coating grows from the surface, part drawings will need to be adjusting accordingly to achieve the intended dimensions after anodizing.

**Gasket**

A gasket should result in a more reliable seal than the existing O-ring design and will yield a much smaller footprint. A gasket can be designed to fit in a shallow groove on either the cover or base of the prototypes and can have through holes so that the fasteners do not have to be relocated. The compression ratio of the gasket will be chosen so that the base and cover still make contact with the base in order to keep the deflections within the required .030”. The gasket, in combination with the grommet, will then seal the cavity to protect the strain gauge. This idea was formulated early in the detailed design process but custom gaskets in a small quantity would have been prohibitively expensive. In order to preserve budget, the very inexpensive O-ring design was chosen instead. The design variation for the gasket concept can be seen in Figure 5.4.1
Threaded Steel Inserts
The GRR gripper uses threaded steel inserts in the jaws to extend the life of the threads. Since the cover of the intermediate jaw is designed to mimic the mounting pattern of the jaw, adding the threaded steel inserts to the design would add the same element of durability as the threaded holes on the jaw. This design was not incorporated in the the GRR intermediate jaw to decrease the cost and because the threads on this prototype would not endure the amount of cycles that the jaws on a GRR would endure. Therefore the durability of the aluminum threads were sufficient. In a final production version of this design, these inserts should be added.

Strain Gauge Alignment in Production
The placement of the strain gauge is critical to obtain accurate measurements. However, it can be difficult to maintain precision in assembly. To maintain consistent placement of strain gauges, marks can be made in the intermediate jaw base. These marks would be made during the machining process in the form of very shallow grooves on a surface where the strain gauge is not
placed. In combination with assembly prints, these marks will ensure proper placement, alignment, and application of the strain gauge.

**GRR Steel Cap**

The GRR prototype was designed for the shortest stroke GRR and therefore has a shorter mounting pattern. In order to make the design fit GRR’s of longer strokes and the longer mounting pattern, the cap would have need to be wider. This would increase the deflection since this is essentially extending a cantilever beam. This means the cap would have to become even thicker than its already increased thickness. A recommended solution to this is using steel for the cap to reduce the thickness and the deflection. This would require the anodize recommendation so the difference in metals do not corrode.

**5.5 Electrical Recommendations**

**Enclosure and PCB**

To improve upon the design, it is recommended to layout a more compact four-layer board and utilize a smaller enclosure for the PCB. This was not practical in this stage of the project, as designing and ordering smaller boards is more expensive to prototype. A custom molded enclosure is desired to provide the best form factor for this product.

**Display**

The display was difficult to implement and a bit pricier than necessary. It was desired to locate a segmented display with an integrated driver that was cheaper, but one was not found.

**Strain Gauge Connections**

It is desired to provide better or simpler strain gauge connections within the gripper housing themselves. The aluminum strain gauge wire leads are not coated, and could therefore short out if they contact the aluminum housing. This design must be improved to increase robustness and manufacturability of the system.
Section VI: Conclusion
In conclusion, the design team was able to produce a product that met many of the project requirements as listed in table 4.4.4. Fortunately we were able to meet what the design team decided were the most pertinent criteria.

Furthermore, we believe that if the design changes in sections 5.4 and 5.5 are implemented, the testing results could be further improved, and more requirements could be met. We are particularly confident in the GRR and GRK models, whose larger size and higher grip force will, we believe, be especially effective because they allow shear forces to be relatively small compared to the moment applied to the customer tooling. This larger ratio between moment applied and shear force, is a potential explanation for their better performance in accuracy testing as the shear force can essentially be mathematically ignored.

There is always room for improvement upon the design. However, our original goal to develop and prototype a functional test sensor was successfully achieved.
## Appendix A: BOM and Cost

### GRR Housing Bill of Materials (priced through model shop, not in production quantity)

<table>
<thead>
<tr>
<th>Part Name</th>
<th>Qty</th>
<th>Vendor</th>
<th>Part Number</th>
<th>Part Material</th>
<th>Extended Part Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cap</td>
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<td>PHD, Inc.</td>
<td>011817JAB-01</td>
<td>6061 T6 Aluminum</td>
<td>$94.73</td>
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<tr>
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</tr>
<tr>
<td>O-ring</td>
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<td>O-ring Store, LLC</td>
<td>04-130-TF</td>
<td>Rubber</td>
<td>$1.00</td>
</tr>
<tr>
<td>Screw</td>
<td>8</td>
<td>PHD, Inc.</td>
<td>14308-589</td>
<td>Steel</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Total</strong></td>
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</tbody>
</table>

### GRH Housing Bill of Materials (priced through model shop, not in production quantity)

<table>
<thead>
<tr>
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<th>Part Number</th>
<th>Part Material</th>
<th>Extended Part Cost</th>
</tr>
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<tr>
<td>O-ring</td>
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<td><strong>Total</strong></td>
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Electrical Processor BOM (Pricing for one unit, including one set of strain gauges)

<table>
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<th>Vendor</th>
<th>Part Number</th>
<th>Each</th>
<th>Ext Cost</th>
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<td>Digikei</td>
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<tr>
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<tr>
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Total: $130.74
Appendix B: Mechanical Drawings

Figure B1: Drawing for the small GRR gripper sensor base.
Figure B2: Drawing for the small GRR gripper sensor top.
Figure B3: Drawing for the small GRR gripper sensor blank.
Figure B4: Drawing for the larger GRR grippers sensor base.
Figure A5: Drawing for the larger GRR grippers sensor top.
Figure B6: Drawing for the large GRR gripper sensor blank.
Figure B7: Drawing for GRH8 sensor base.

Drawing Notes:

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SECTION A-A

SCALE 2:1

M3 X 0.5 Threaded / 8mm Depth X 2

2.5 mm Dowel Holes 2.5mm Depth X 2

M2 X 0.4 Threaded 3 mm Depth X 4

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DRAWN: [JLK] 11/16

GRH 8 Sensor Bottom

A GRH8BO

SIZE:DWG. NO. REV

SCALE: 1:1 WEIGHT:

SHEET 1 OF 1
Figure B8: Drawing for GRH8 sensor top.
Figure B9: Drawing for GRH8 sensor blank.
Figure B10: Drawing for GRH12 sensor base.
Figure B11: Drawing for GRH12 sensor top.
Figure B12: Drawing for GRH12 sensor blank.
Figure B13: Drawing for GRH116 sensor base.
Figure B14: Drawing for GRH16 sensor top.
Figure B15: Drawing for GRH16 sensor blank.
Figure B16: Drawing for GRH20 sensor base.
Figure A17: Drawing for GRH20 sensor top.
Figure B18: Drawing for GRH20 sensor blank.
Figure B19: Drawing for the GRK35 gripper sensor base.
Figure B21: Drawing for the GRK46 gripper sensor base.
Figure B22: Drawing for the GRK46 gripper sensor top.

GRK46 sensor cover

Scale: 1:1

Weight:

Sheet 1 of 1
Figure B23: Drawing for the GRK58 gripper sensor base.
Figure B24: Drawing for the GRK58 gripper sensor top.
Figure B25: Drawing for the GRK75 gripper sensor base.
Figure B26: Drawing for the GRK75 gripper sensor top.
Appendix C: Updated Mechanical Drawings

**Figure C1:** Final Drawing and specifications for the GRR prototype base.
Figure C2: Final Drawing and specifications for the GRR prototype cover.
Figure C3: Final Drawing and specifications for the GRK prototype base.
Figure C4: Final Drawing and specifications for the GRK prototype cover.
Figure C5: Final Drawing and specifications for the GRH prototype base.
Figure C6: Final Drawing and specifications for the GRH prototype cover.
Appendix D: Electrical Drawings

Figure D1: PCB Top Copper and Slikscreen
Figure D2: PCB Bottom Copper and Silkscreen

Figure D3: Enclosure Machining locations for switch holes
Appendix E: PIC16F1786 Software

Included below are implementation files for the software on the microcontroller. Only included are the implementation files for the project. Header files are omitted.

main.c:
/**
* @file main.c
* @author Andrew Whiteman
* @date 15 Mar 2017
* @brief main implementation for force sensor program
* This is the main file for the Force Sensor for Grippers Signal Processor unit. This program is written and configure for the pic16f1786 microprocessor.
*/

#include "main.h"
#include "i2c.h"
#include "adc.h"
#include "interrupt.h"
#include "menu.h"

unsigned int zero = 0x7FF; // set to middle for init
unsigned char mode = 1; // set the mode of operation
float gain = 1.0; // software gain of the system

void main(void)
{
    int adc = 0;
    int i = 0;

    OSCCONbits.IRCF = _XTAL_RATE; // set system clock setting

    I2C_Init(); // initialize MSSP for I2C
    Disp_Init(DISPLAY); // initialize the LCD Display
    ADC_Init(); // initialize ADC
    Int_Init(); // initialize and enable interrupt
    Menu_Init(); // initialize menu settings from EEPROM

    mode = Get_Mode(); // get the gain and mode from EEPROM
    gain = Get_Gain();
    zero = (eeprom_read(0x00) << 8) + eeprom_read(0x01);

    Tmr0_Enable(); // start A/D interrupt timer

    __delay_ms(100);

    while (1)
    {
        adc = Get_Strain();
        adc = (int)(adc * gain);
if (adc > 0x7FF)
    adc = 0x7FF;
if (adc < -0x800)
    adc = -0x800;

switch(mode)
{
    case 1: // -10 to +10 mode
        adc += 0x800;
        break;
    case 2: // 0 to +10 mode
        adc >>= 1;
        adc += 0xC00;
        break;
    case 3: // -5 to +5 mode
        adc >>= 1;
        adc += 0x800;
        break;
    case 4: // 0 to 5 mode
        adc >>= 2;
        adc += 0xA00;
        break;
}

if (adc > 0xFFF)
    adc = 0xFFF;
if (adc < 0)
    adc = 0;

i++;
if (i == 10)
{
    // only write to display every 10th update
    Disp_Num(DISPLAY, adc);
    i = 0;
}

adc = 0x800;
adc *= -1;
adc = 0x800;

DAC_Write(DAC1, adc);

// re-zero the device
if (PORTCbits.RC0 == 0)
    Zero();

if (PORTCbits.RC1 == 0 && PORTCbits.RC2 == 0)
{
    Tmr0_Disable(); // Stop measurements while in menu
    Run_Menu(); // run the settings menu and store results
    mode = Get_Mode(); // recover settings from previous run
    gain = Get_Gain();
    Tmr0_Enable(); // Restart measurement taking when gain and mode are set
}
__delay_ms(5);
/**
 * @brief Takes ADC samples and sets zeroing DAC to compensate
 */
void Zero(void)
{
    int error = 0;
    char i = 0;

    Tmr0_Enable(); // start A/D interrupt timer, if not already running

    Disp_Text(DISPLAY, "----");

    DAC_Write(DAC1, 1792); // set output to 1.25 volts

    DAC_Write(DAC0, zero); // set to middle

    __delay_ms(8);
    i = 0; // reset the counter i

    while (i < 6)
    {
        error = Get_Strain(); // get the current error

        if (error < 0x08) // error within tolerance
            i++;
        else
            i = 0;

        zero += (error >> 3); // set new zero to half of the error signal
        DAC_Write(DAC0, zero);
        __delay_ms(8);
    }

    eeprom_write(0x00, zero >> 8); //Saves zeroing data for use on reboot
    eeprom_write(0x01, zero & 0xFF);

    DAC_Save(DAC0, zero); // save result to DAC EEPROM
}
/**
 * @file i2c.c
 * @author Andrew Whiteman
 * @date 15 Mar 2017
 * @brief definition of I2C communication functions
 *
 * This declares all of the functions for communication to all I2C devices from
 * the pic16F1786
 */

#include "i2c.h"

/**
 * @brief Initialize I2C functionality
 */
void I2C_Init()
{
    SSPCON = 0b00101000;  // enable MSSP and set to I2C Master Mode
    SSPCON2 = 0; // clear SSPCON2 register
    SSPADD = 3;  // set baud rate
    SSPSTAT = 0; // clear status register
    TRISC3 = 1;  // Setting as input
    TRISC4 = 1;  // Setting as input
}

/**
 * @brief Waits for I2C bus to go idle
 */
void I2C_Wait()
{
    while ((SSPSTAT & 0x04) || (SSPCON2 & 0x1F));
}

/**
 * @brief Starts the I2C bus communication with a specified device and direction
 * @param device - enumerated value to select which device to communicate with
 * @param read - bit to specify read/write bit
 */
void I2C_Start(I2C_Device device, unsigned char read)
{
    I2C_Wait();
    SEN = 1;
    I2C_Write(((device & 0x7F) << 1) | (read & 0x1));
}

/**
 * @brief Restarts the I2C bus communication with a specified device and direction
 * @param device - enumerated value to select which device to communicate with
 * @param read - bit to specify read/write bit
 */
void I2C_Restart(I2C_Device device, unsigned char read)
{
    I2C_Wait();
    RSEN = 1;
    I2C_Write(((device & 0x7F) << 1) | (read & 0x1));
}
void I2C_Stop()
{
    I2C_Wait();
    PEN = 1;
}

void I2C_Write(unsigned char data)
{
    I2C_Wait();
    SSPBUF = data;
}

void I2C_Char(char c, unsigned char dec)
{
    unsigned char data = 0;
    switch (c)
    {
    case '0':
        data = 0b0111111;
        break;
    case '1':
        data = 0b0001001;
        break;
    case '2':
        data = 0b1011110;
        break;
    case '3':
        data = 0b1011011;
        break;
    case '4':
        data = 0b1101001;
        break;
    case '5':
        data = 0b1110011;
        break;
    case '6':
        data = 0b1110111;
        break;
    case '7':
        data = 0b0011001;
        break;
    }
case '8':
    data = 0b1111111;
    break;
case '9':
    data = 0b1111011;
    break;
case '-':
    data = 0b1000000;
    break;
case 'A':
    case 'a':
    data = 0b1111101;
    break;
case 'B':
    case 'b':
    data = 0b1100111;
    break;
case 'C':
    case 'c':
    data = 0b0110110;
    break;
case 'D':
    case 'd':
    data = 0b1001111;
    break;
case 'E':
    case 'e':
    data = 0b1110110;
    break;
case 'F':
    case 'f':
    data = 0b1110100;
    break;
case 'G':
    case 'g':
    data = 0b0110111;
    break;
case 'R':
    case 'r':
    data = 0b0110100;
    break;
case ' ':
    default:
    data = 0b0000000; // default to blank
    break;
}
I2C_Write((data << 1) | (dec & 0x01));

/**
 * @brief Initialize and blank the I2C display. Must be called after I2C_Init
 * @param device - enumerated value to select which device to communicate with
 */
void Disp_Init(I2C_Device device)
{
    I2C_Start(device, 0); // start write communication
/*
 * @brief Complete I2C command to write a value to the display
 * @param device - enumerated value to select which device to communicate with
 * @param output - 12 bit value to write to the display
 * 0xFFF =  9.99
 * 0x800 =  0.00
 * 0x000 = -9.99
 */
void Disp_Num(I2C_Device device, int output)
{
    unsigned char isNeg = 0;
    int disp = 0;

    output &= 0xFFF;  // trim to 12 bit value
    output -= 0x800;  // center the value in the middle of the range

    if (output < 0)  // normalize if negative and set isNeg flag
    {
        isNeg = 1;
        output = 0 - output;  // change sign of output
        if (output == 0x800)
            output = 0x7FF;
    }

    // divide to normalize number between 0 and 999
    output = (unsigned int)(output / 2.048);

    // Double Dabble algorithm to convert decimal to BCD
    unsigned char i = 0;
    for (i = 0; i < 12; i++)
    {
        if (((disp >> 4) & 0xF) > 0x4)
            disp += 0x030;  // add 3 to 10s place
        if ((disp & 0xF) > 0x4)
            disp += 0x003;  // add 3 to 1s place
        disp = (disp << 1) | ((output >> 11) & 0x1);  // shift into display register
        output = output << 1;  // shift out of the output register
    }

    I2C_Start(device, 0);  // start I2C communication
    I2C_Write(0b00000000);  // set load data pointer

    if (isNeg)
        I2C_Char('-', 0);
    else
        I2C_Char(' ', 0);
}
I2C_Char(((disp >> 8) & 0xF) + '0', 1);
I2C_Char(((disp >> 4) & 0xF) + '0', 0);
I2C_Char((disp & 0xF) + '0', 0);
I2C_Stop(); // stop bus communication

/**
 * @brief Complete I2C command to write a string to the display
 * @param device - enumerated value to select which device to communicate with
 * @param string - constant pointer to the string to display
 */
void Disp_Text(I2C_Device device, const char* string)
{
    const char* p = string; // pointer to the string characters
    char i = 0; // index counter to prevent display overrun

    I2C_Start(device, 0); // start I2C communication
    I2C_Write(0b00000000); // set load data pointer

    while (*p != 0 && i < 4) // terminate for four characters or if string ends
    {
        if (*(p + 1) == '.') // there is a decimal point after this character
        {
            I2C_Char(*p, 1);
            p += 2;
        }
        else // no decimal point
        {
            I2C_Char(*p, 0);
            p++;
        }
        i++;
    }
    I2C_Stop(); // stop bus communication
}

/**
 * @brief Complete I2C command to just write the given value to the DAQ output
 * @param device - enumerated value to select which device to communicate with
 * @param output - 12 bit unsigned value to write to the DAQ
 */
void DAC_Write(I2C_Device device, unsigned int output)
{
    I2C_Start(device, 0); // start write communication
    I2C_Write((output >> 8) & 0xF); // write upper nibble
    I2C_Write(output & 0xFF); // write lower byte
    I2C_Stop(); // stop bus communication
}

/**
 * @brief Complete I2C command to write DAQ output and store value in memory
 * @param device - enumerated value to select which device to communicate with
 * @param output - 12 bit unsigned value to write to the DAQ
 */
void DAC_Save(I2C_Device device, unsigned int output)
{
    I2C_Start(device, 0); // start write communication
I2C_Write(0b01100000); // set to write and save mode
I2C_Write((output >> 4) & 0xFF); // write upper byte
I2C_Write((output & 0xF) << 4); // write lower nibble
I2C_Stop(); // stop bus communication

adc.c:
/**
 * @file adc.c
 * @author Andrew Whiteman
 * @date 20 Mar 2017
 * @brief implements analog to digital converter functionality inside th 1786
 *
 * This implements all of the functions for initializing and utilizing the analog
 * to digital converter within the pic16f1786 microcontroller
 */
#include "adc.h"

/**
 * @brief Initialize ADC functionality
 */
void ADC_Init()
{
    ANSELA = 0b00000011; // set ports A0 and A1 as analog inputs
    WPUA = 0b00000011; // disable their weak pull-ups

    ADRMD = 0; // set to 12 bit result mode
    ADCON0 = 0b00000000; // set to 12 bit result mode. Do not turn on ADC yet
        // reads A0 input by default
    ADCON1 = 0b10010000; // set to 2s complement mode, use FOSC/8 and
        // default +/- reference
    ADCON2 = 0b00001111; // select no trigger and single ended conversion
    ADON = 1; // turn on ADC
}

/**
 * @brief Take and return a single-ended ADC reading
 * @param input - 5-bit analog input number to read
 * @return 12 bit ADC value 2's compliment
 */
int ADC_Get(unsigned char input)
{
    return ADC_Get_Diff(input, 0b1111);
}

/**
 * @brief Take and return a differential (double-ended) ADC reading
 * @param pos_input - 5-bit positive differential analog input number to read
 * @param neg_input - 4-bit negative differential analog input number to read
 * @return 12 bit ADC value 2's compliment
 */
int ADC_Get_Diff(unsigned char pos_input, unsigned char neg_input)
{
    ADCON0bits.CHS = pos_input & 0x1F; // get input channel; limited to 5 bits
    ADCON2bits.CHSN = neg_input & 0xF; // get ground reference channel; 4 bits
}
GO_nDONE = 1; // start ADC conversion
while (GO_nDONE == 1) ; //wait for completion
return ((ADRESH << 8) | ADRESL) & 0xFFFC; // concatenate the high and low registers
}

/**
* @brief Initialize the AvgBuffer struct for use
* @param buffer - pointer to the buffer to initialize
* @param data - pointer to the array of allocated integers for the buffer
* @param size - the length of the buffer. This must equal the size of the
*   "data" parameter
*/
void AvgBuffer_Init(AvgBuffer* buffer, int* data, unsigned char size)
{
    buffer->data = data;
    buffer->next = 0;
    buffer->size = size;
    buffer->sum = 0;

    // determine the factor to shift by for the buffer
    buffer->shift_by = 0;
    while (size > 1)
    {
        buffer->shift_by++;
        size = size >> 1;
    }
}

/**
* @brief Take and return a differential (double-ended) ADC reading after a moving average
* @param pos_input - 5-bit positive differential analog input number to read
* @param neg_input - 4-bit negative differential analog input number to read
* @param buffer - pointer to the structure containing the buffer to be used in memory
* @return 12 bit ADC value after averaging
*/
int ADC_Get_Avg(unsigned char pos_input, unsigned char neg_input, AvgBuffer* buffer)
{
    // subtract old value from buffer sum
    buffer->sum -= buffer->data[buffer->next];

    // take and store a reading in the buffer
    buffer->data[buffer->next] = ADC_Get_Diff(pos_input, neg_input);

    // add new value to buffer sum
    buffer->sum += buffer->data[buffer->next];

    // increment buffer->next and reset to zero if needed (circular buffer)
    buffer->next++;
    if (buffer->next == buffer->size)
        buffer->next = 0;

    // divide by the number of elements
    return ((buffer->sum) >> (buffer->shift_by));
    // NOTE: This is the same operation as dividing by the number of elements.
}
interrupt.c:

/**
 * @file interrupt.c
 * @author Andrew Whiteman
 * @date 27 Mar 2017
 * @brief defines analog to digital converter functionality inside the 1786
 * handler within the pic16f1786 microcontroller
 */

#include "interrupt.h"
#include "adc.h"

int StrainVal; // current strain value
AvgBuffer buffer; // buffer for the StrainVal FIR filter

/**
 * @brief Initialize Interrupt functionality for timer 0
 * NOTE: Must invoice ADC_Init() before calling.
 */
void Int_Init(void)
{
    static int __buffer_data[AVGBUFFERSIZE]; // memory space for the buffer array
    AvgBuffer_Init(&buffer, __buffer_data, AVGBUFFERSIZE); // initialize the buffer for use

    TMR0 = TMR0RESETVALUE; // preset timer value
    INTCON = 0b10000000; // enable global interrupts, but leave all others disabled

    #ifdef TMR0ENABLEPRESCALAR
        OPTION_REG = (0b11000 << 3) | TMR0PRESCALEBITS; // set timer 0 to Fosc/4 and enable pre-scaler
    #else
        OPTION_REG = 0b11001000; // set timer 0 to Fosc/4 without prescale
    #endif

    TMR0IE = 1;
}

/**
 * @brief Enable the timer 0 interrupt to start A/D conversions
 * NOTE: Must invoke Int_Init() before calling;
 */
void Tmr0_Enable(void)
{
    TMR0IE = 1;
}

/**
 * @brief Disable the timer 0 interrupt to stop A/D conversions
 */
void Tmr0_Disable(void)
{
    TMR0IE = 0;
}

/**
 * @brief main interrupt callback function

void interrupt Interrupt(void)
{
    if (TMR0IE && TMR0IF) // interrupt caused by timer 0, take a reading
        TMR0IF = 0; // reset timer flag
        TMR0 = TMR0RESETVALUE; // reset timer

        StrainVal = ADC_Get_Avg(0, 1, &buffer); // take the new reading
}

int Get_Strain(void)
{
    return StrainVal;
}

menu.c:

#include "menu.h"
#include "main.h"
#include "i2c.h"

void Menu_Init()
{
    // load eeprom values
    _mode[3] = eeprom_read(0x02);
    _gain[2] = eeprom_read(0x03);
    _gain[4] = eeprom_read(0x04);
}

void Mode()
{
    Disp_Text(DISPLAY, _mode);

    while(PORTCbits.RC1 == 0 || PORTCbits.RC2 == 0);

    LOOP1:
    if(PORTCbits.RC1 == 0)
    {
        _mode[3]++;
        if(_mode[3] == '5')
            _mode[3] = '4';
    }
Disp_Text(DISPLAY, _mode);

while(PORTCbits.RC1 == 0); goto LOOP1;
else if(PORTCbits.RC2 == 0) {
    _mode[3]--;
    if(_mode[3] == '0')
        _mode[3] = '1';
    Disp_Text(DISPLAY, _mode);
    while(PORTCbits.RC2 == 0);
}
else if(PORTCbits.RC0 == 0) {
    eeprom_write(0x02, _mode[3]); // save value to eeprom
    Gain();
    return;
} else{
    goto LOOP1;
}  }

void Gain()
{
    Disp_Text(DISPLAY, _gain);
    while(PORTCbits.RC0 == 0);

    LOOP2:
    if(PORTCbits.RC1 == 0) {
        if(_gain[2] != '4') {
            _gain[4] += 2;
            if(_gain[4] == ':') {
                _gain[4] = '0';
                _gain[2] += 1;
            }
        } else goto LOOP2;
    }
    Disp_Text(DISPLAY, _gain);
    while(PORTCbits.RC1 == 0);
    goto LOOP2;
} else if(PORTCbits.RC2 == 0) {

    goto LOOP2;
else if (_gain[2] >= '1')
{
    _gain[4] -= 2;
    if (_gain[4] == '.')
    {
        _gain[4] = '8';
        _gain[2] -= 1;
    }
}
else
    goto LOOP2;
Disp_Text(DISPLAY, _gain);
while (PORTCbits.RC2 == 0);
    goto LOOP2;
} else if (PORTCbits.RC0 == 0)
{
    eeprom_write(0x03, _gain[2]); // save value to eeprom
    eeprom_write(0x04, _gain[4]); // save value to eeprom
    return;
}
else
{
    goto LOOP2;
}
}

void Run_Menu()
{
    Mode();
}
/**
 * @brief Returns the current mode
 * @return mode as a selection between 1 and 4
 */
unsigned char Get_Mode()
{
    return (_mode[3] - '0');
}
/**
 * @brief Returns the software gain
 * @return Software gain as a float between 1.0 and 4.0
 */
float Get_Gain()
{
    return (float)(_gain[2] - '0') + (float)((_gain[4] - '0') / 10.0);
}