ECE 406
Senior Capstone Project Report
Integration of Wireless Technology for Automated Pump Testing

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Abstract

As the internet has become more and more ingrained in society, there has been a clamoring for more and more control over everyday objects wirelessly and through the cloud. The desire for more functionality and more control has never been greater than it is today. With the relative ubiquity of cellular networks throughout the world, control from remote locations has also never been easier to achieve. This desire for control through the internet is the impetus for the project “Integration of Wireless Technology for Variable Frequency Drives (VFDs)”.

The project aims to automate a process for assessing the functionality and performance of the solar-powered variable frequency drive, connected to a surface or submersible motor coupled with either a water pumping centrifugal pump or a positive displacement (PD) pump. The performance is judged based upon flow rate and power at a specified pressure. The pressures are representative of a specific “head”, which is the distance the Pump and Motor Assembly (PMA) can lift water. The process of determining the pump characteristic is currently achieved through the use of an “auto loop”, which is a PMA attached to a series of pipes with a pressure transducer, flow sensor, and pneumatic actuator to control pressure. In order to define the pump characteristic data must be taken for input power, water flow, and water pressure. Existing technologies currently being used by Franklin Electric will be used to take the measurements. However, these measurements need to be sent to the cloud, so existing communication schemes will be utilized, along with the improvement of such schemes and through developing new external circuitry, in order to achieve this end.

The circuitry will need to be capable of reading the output of a pressure sensor and a flow sensor in order to characterize the performance, along with communicating with the VFD. Communication will be achieved either serial and wireless means. An internet dashboard will be used to process and display the data, and it must be capable of two-way communication, so that the pressure can be regulated to a setpoint during data acquisition. Sending the data to the cloud will be accomplished either through a second microprocessor to manage and manipulate the data or through a simple Analog to Digital Converter (ADC) operation and process the data on the server side. There are many considerations to take into account when deciding how to implement these design goals, and every single one of those decisions will be made with the functional requirements of the project in mind.
Section I: Problem Statement
Functional Requirements & Specifications

- **Primary Objective** - Develop a system to characterize pump performance automatically as defined by the following parameters:
  - Collect water flow data
  - Collect water pressure data
  - Collect input voltage to the system
  - Collect input current to the system

- **Data Storage** - Store records of collected data in such a way so that it can be retrieved at a later data and processed to produce desired outputs.

- **Graphical Display of Data** - Plot performance curves as a function of speed and flow, for different pressure levels (or equivalent head measurements) as shown in Figure 1.

- **Data transmission** - Collected data needs to be communicated to cloud server by means of a cellular modem.

- **User Interface** - Develop widgets and polish interface for Internet of Things (IoT) dashboard.

- **Test Automation** - Two-way communication between cloud and VFD is necessary for test automation and delivering test setup specifications.

![Figure 1: Pump Performance Curve](image)

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These functional requirements were used as the basis for constructing the functional requirement decomposition, shown in the Appendix. This decomposition assisted in the development of the designs by structuring the dependencies of physical solution to functional requirements. If a solution affects more than one functional requirement, a red arrow was drawn to indicate any process or full coupling. This process eliminates any full coupling to ensure that the physical solutions are as independent as possible.

**Given Parameters**

As there currently exists a system through which data are collected through the various sensors, certain design variables are fixed. Also, the data acquisition system that must be designed cannot change the physical hardware of the drive and the firmware controlling the drive.

- **Pressure Sensor** - Use the given 4 to 20 mA pressure sensor.
- **Flow Sensor** - Use the given pulse based 4 to 20 mA flow sensor.
- **Motor Drive** - Use current Fhoton Drive without any modification to the existing hardware.
- **Firmware** - Current drive firmware must be used without any modification
- **Cellular modem** - the current cellular communication option is a Digi Cellular Modem.
Design Variables

In the design of the pump characteristic data collection system, there exist both hardware and software variables that must be selected in order to optimize the performance of the system and to meet the functional requirements in the best possible way. Methods of transferring the data also must be selected so as to facilitate the most reliable and efficient means of collecting the data. Once the data is received it most also be stored and displayed in an aesthetically pleasing and user friendly way.

- **IoT Dashboard** - A method for a dashboard proposed is Freeboard for its user interactivity and control, but other online dashboards may be used that are capable of importing data sources, such as a custom built website.

- **Data storage** - The proposed data storage method for this project is the Representational State Transfer (REST) Application Programming Interface (API) dweet.io to store data. However, if other, more functional options are found, they could be used in the implementation for the communication efforts. Along with that, the data that is imported to the Freeboard can also be stored to a database, such as one constructed with Structured Query Language (SQL), so it can be retrieved later.

- **Actuator** - The current autoloop uses a pneumatic actuator, which is rather large, so for the prototyping, an electric actuator may need to be used. It must be capable of varying the valve position from open to close in an analog manner.

- **Interface between drive and sensors** - The analog data that is collected must be processed before being sent to the data server. It also must collect the input data from the drive (input current and input voltage), and send it to the data server. The means through which data is received from the drive can either be done serially or wirelessly.
Limitations and Constraints

There do exist some constraints set out by Franklin Electric which will limit the scope of the project. These constraints are as follows:

- **Cost** - The budget is limited (less than $10,000).
- **Size** - This is an initial prototype so it will be a smaller version of an existing setup. As such, it must fit on small workbench, which can be worked on at IPFW.
- **Time** - The design scope of the project is limited specifically to allow for completion in a two-semester time frame. However, if time allows, more features may be added to the minimal design to enhance the final product.

Additional Considerations

- **Safety** – While there are no defined safety standards involved in the project, there are some considerations to take into account while working on the project. High voltages and pressures will be used, so appropriate caution must be taken while working on the project to keep the design team safe. All people working around the projects should be wearing safety gear, such as safety glasses. If working with the high voltage directly cannot be prevented, although that action is strongly not recommended and should be avoided if at all possible, employ the one hand rule to reduce the risk of severe, fatal electric shock. Also needed is a method to prevent others from accessing the project while not in use. Pinch points from mechanical components or being too close to another team member while working should also be kept in mind at all times to keep each team member as safe as possible. Also, all design decisions should be made with the safety of the end user in mind.

- **Philosophy of Design and Ethical Considerations** - The design will be achieved through a collaborative effort. Each team member will be open to voice his opinion, and those opinions will always be taken into consideration. If there is dissent about a particular design decision, there will be democratic style process in which the team decides together how to settle the issue and which design path to continue down. This is achievable as the team consists only of three people, so these types of disputes should be resolved readily. Along with this, ethical
standards must also be kept in mind when making all design decisions. There should be no aspect of the design which exposes an end user to undue danger or hardship. The health, safety, and welfare of the customer is absolutely paramount, so no other design choice shall circumvent that notion. Lying, subterfuge, and inappropriate behavior will categorically not be tolerated and shall be dealt with swiftly. Ethical and moral standards towards each team member, collaborator, and the public will be resolutely upheld throughout the entire process of this project.

- **Test setup variability** - This includes the variability of pumps and motors that can be tested, and, possibly as an extra feature, it could accommodate different motor drive systems. Although the design will be inherently pump and motor agnostic, we still must keep in mind that this must be a universally applicable data acquisition system, regardless of what is pumping water through the system. The pump and motor combination is an important input to the system, as that specific pairing is the characteristic that is being analyzed. Thus, when running prior to executing the test, the user should be able to input which pump and motor is being tested.

- **Board Design** - If the initial prototype functions as desired and expected, then a Printed Circuit Board (PCB) will be designed with an enclosure to house the design. This is of course, pending on the appropriate allotment of time once the initial testing of the design is complete.
Section II: Detailed Design
The different components of the project can be broken down into the following subsystems:

- Section II.1 - Plumbing Loop
- Section II.2 - Sensor Hardware and Circuitry
- Section II.3 - Communications
- Section II.4 - User Interface

**Plumbing Loop**

The main role of the plumbing loop is to provide the infrastructure for circulating the water and providing a mount for the various gauges and sensors needed to collect the requisite data. The typical plumbing loop is comprised of a set of pipes that connect the PMA to an outlet for the water source. In the application for this project, a surface PMA will be used, so the plumbing loop will connect the PMA to the water source, and then recirculate the pumped water to the source. Along the set of piping, there will reside a pressure transducer, a flow transducer, and an actuator controlled valve.

**Pressure Transducer** - The selected pressure transducer is a Dwyer 628-10-GH-P9-E1-S1, which provides a 1.5% accuracy and a range of 0 to 100 Psi. The supply voltage for the transducer ranges from 9 Vdc to 30 Vdc, and the output is 4 mA to 20 mA, with built in short circuit and reverse voltage protection. The application will utilize pumping systems that develop less than 100 psi, so this transducer will suffice and has the necessary accuracy to ensure quality and reliable data.

**Flow Sensor** - The flow sensor picked for the project was the Signet 515 Rotor-X Flow Sensor. This flow meter features an easily replace rotor, which is equipped with a paddle wheel to detect flow. The paddlewheel is equipped with a magnet which with every revolution passes by another magnetic which produces a sinusoidal output voltage with a frequency and amplitude proportional to the speed of the water. This design means that the device is self-powered by the act of measuring the water. This meter can accurately measure a flow rate range from 1 to 20 ft/s. The amplitude changes as 1V peak to peak per ft/s, and the frequency changes as 6 Hz per ft/s. This means the sensor will accurately produce an output frequency from 6 Hz up to 120 Hz.
For the project, a flow rate in gallons per minute must be measured in order to create the graphs in the way the customer desires. The flow rate by volume depends upon the cross-sectional area of the pipe being used and the speed of the water. In the final design build, 3/4" pipe was used. Thus, the flow rate can be calculated by:

\[
flowrate_1 = A \times v \quad (1)
\]

where \( A \) is the cross sectional area of the pipe in \( ft^2 \) and \( v \) is the speed of the water in ft/s. Equation 1 gives a flow rate result in cubic feet per second, so then the that value can be converted to gallons per minute by:

\[
flowrate_2 = flowrate_1 \times \frac{1gal}{0.13368ft^3} \times \frac{60s}{1min} \quad (2)
\]

Equation 2 then produces a flow rate in gallons per minute with a range for the setup that is used for the project as 1.4 gpm to 27.54 gpm.

**Actuator** - The chosen actuator is a three phase NEMA23 Hybrid Servo Motor with a 1000-line encoder. The actuator is paired with a Hybrid Servo Driver KL-5080H which will be used to drive the motor, a 36V/9.7A Switching CNC Power Supply to supply power to the motor, and a NEMA23 10:1 Planetary Gearbox to increase the torque output of the motor.

The Servo Motor has input range from 20 to 50 Vdc with an 8.0 A peak, thus requiring the power supply with a nominal output of 36V and 9.7A. The 1000-line encoder allows the motor to become a closed loop system. An encoder measures the position of the rotor shaft. This position information allows the motor and valve system to maintain stability.

The Servo Driver accepts the position information from the encoder. The drive accepts a position signal in the form of a pulse with a specific frequency, and uses this information to regulate the current in order to maintain the commanded position. It also provides motor alarm protections such as overvoltage, overcurrent, and short circuit.

The optional planetary gearbox that can be used if there are issues maintaining the valve position has
a 10:1 torque ratio and a maximum backlash specification of 8-10 arcmin. The backlash value dictates how much angular movement there is in the rotor position in a static position. One arc-min is equal to \( \frac{1}{60} \) of a degree, so an arc-min specification of 10 arc-min is equivalent to 

\[ 10 \text{ arc-min} * \frac{1}{60} \text{ degrees} = \frac{1}{6} \text{ degrees} \].

The advantage of this backlash value is that there will be minimal movement of the valve once a position is set, so the pressure should stay relatively constant as long as the water flow stays constant. However, for the project with the lower power PMA, this planetary gearbox will most likely not need to be utilized.

**Figure 2:** Design for plumbing loop for collecting data.
Sensor Hardware and Circuitry

Pressure Transducer Circuitry:
The pressure transducer used to measure water pressure in the system is a 4 mA to 20 mA and has a maximum pressure rating of 100 psi. It must be externally supplied within a range of 9V to 30V, so a 12V supply was picked to energize the circuit. Since the pressure sensor scales its outputs based on 4 to 20mA current flowing through the device, the circuit shown in Figure 9 was designed to provide an appropriately scaled voltage drop in order for an A/D to read the value of the sensor. The A/D that will be utilized in this project accepts inputs from 0 to 2.5V. The upper bound of the resistor was thus dictated by equation 3. However, in case the maximum output of 20mA is exceeded momentarily, some margin was built into the design, so a resistor value of 100Ω was chosen. Equations 4 and 5 show the upper and lower bounds for the voltage applied to the A/D with the selected 100Ω resistor in place.

\[
R_{max} = \frac{V_{AD,MAX}}{I_{MAX}} = \frac{2.5V}{0.02A} = 125Ω \quad (3)
\]

\[
V_{AD,\_min} = 0.004mA * 100Ω = 0.4V \quad (4)
\]

\[
V_{AD,\_min} = 0.020mA * 100Ω = 2V \quad (5)
\]

A low pass filter will also be applied to the measured signal in order to reduce any coupled high frequency noise on the line as shown in Figure 3. The cutoff frequency of this filter is calculated by equation 6. The filter circuit was simulated in LTSpice\textsuperscript{12} (a circuit simulation program), and the resulting frequency response is shown in Figure 4. The simulation agrees with the calculation suggesting that the filter will function as desired. The transducers are steady state output devices that rely on a DC value for measurement, so the actual value of the output will not be attenuated as a result of the filter.

\[
f_c = \frac{1}{2\pi R_C} = \frac{1}{2\pi \times 100Ω \times 0.1μF} = 15,916 \text{ Hz} \quad (6)
\]
Figure 3: Circuit to translate sensor output to scaled A/D voltage.

Figure 4: Frequency Response of simulated low pass filter.
Flow Sensor Circuitry:

In order to accurately measure the output of this sensor, it was decided to convert the frequency of the signal into an analog voltage to be read by an A/D converter. The LM2907 frequency to analog converter chip from TI\textsuperscript{10} was implemented to achieve this. It uses a charge pump with a constant current source to charge a small capacitance up to $V_{cc}/2$ during the positive half cycle of the input, and then discharges it during the negative half cycle. This process is based upon the frequency of the input signal. It uses a comparator to ground to determine when the signal is at the positive or negative half cycle, so the amplitude of the signal does not matter as long as it is below the 28V threshold of the maximum pin voltage. $V_{cc}$ in this case is the same 12V supply used for the pressure transducer circuit. Both the charging current and discharging current are mirrored as positive pulses into the output resistor. Thus, the average output voltage is directly proportional to the frequency of the input signal until a maximum readable frequency has been reached. A capacitor is then added in parallel with this output resistance in order to smooth out the signal. The design equations are given in the datasheet\textsuperscript{4} and the first step is selecting the value for $C_1$ using equation 7, refer to the Figure 5 for the reference designators.

$$C_1 = \frac{V_{fullscale}}{R_1 \times V_{CC} \times f_{max}} = \frac{1.5V}{100k\Omega \times 12V \times 120Hz} = 10.4nF \quad (7)$$

This value for $C_1$ is not a standard value, so pick $C_1 = 10nF$.

This results in full scale voltage as shown in equation 8.

$$V_3 = 12V \times 120Hz \times 10nF \times 100k\Omega = 1.44V \quad (8)$$

Also, the ripple voltage produced at the output mainly due to the filtering introduced by time constant between $R_1$ and $C_2$, with $C_2$ chosen to be 1 µF, can be calculated with in equation 9.

$$V_{ripple} = \frac{V_{CC}}{2} \times \frac{C_1}{C_2} \left(1 - \frac{V_3}{R_1 \times C_2 \times f_2}\right) = \frac{12V}{2} \times \frac{22nF}{22\mu F} \left(1 - \frac{1.9V}{60\Omega \times 12V \times 180\mu A}\right) \quad (9)$$

This results in an output voltage ripple of 55.7 mV.

The maximum readable frequency of the LM2907 is given by equation 10.
\[ f_{\text{max}} = \frac{I^2}{C_{\text{max}} V_{\text{cc}}} = \frac{180 \mu A}{10 \mu F \times 12 V} = 1500 \text{ Hz} \quad (10) \]

The maximum frequency for the flow sensor used is 120 Hz, which corresponds to \( 20 \pi \), so there is significant margin from the maximum readable frequency of 1500 Hz.

**Figure 5**: Schematic for Flow Sensor Circuit.

**Position Sensor Circuitry:**

Usage of the actuator required a method for sensing the position of the valve in relation to the fully open and fully closed positions. The design used involved implementing a voltage divider circuit along with a potentiometer that turns in conjunction with the actuator. In order to record across the entire 3.75 turn range of the valve, a 5 turn, 10kohm potentiometer\(^\text{13}\) was chosen to turn alongside the actuator. This multi-turn potentiometer can be seen below in Figure 6.
Figure 6: Potentiometer used for position sensing.

The incoming voltage used is 5V but the input on the modem is from 0-2.5 volts so a voltage divider was built by adding R17 to cut the voltage in half. The remainder of the voltage goes through the potentiometer which, depending on the position, gives a specific voltage value returned to AD0. These readings can be used as upper and lower limits of the valve and not allow the actuator to overturn the valve. The resistor R18 and capacitor C7 are used to reduce noise and act as a low pass filter to improve the repeatability of the measurements. The circuit used to send the position readings back to the drive can be seen below in Figure 7.

Figure 7: Schematic for Position Sensor Circuit.
Calculations for frequency cutoff based upon chosen values for C7 and R18 are done in equation 11.

\[ f_c = \frac{1}{2\pi R C} = \frac{1}{2\pi \times 100 \Omega \times 0.1 \mu F} = 15,916 \, Hz \]  

(11)

Below in Figure 8 are interlocking nylon gears that relay the valve position to a potentiometer. The potentiometer then reports a voltage value back to the modem to be interpreted as a position. Figure 9 shows the backside of the holding bracket and how the potentiometer is mounted into the position sensing setup.

![Figure 8: Gears connecting actuator to potentiometer.](image1)

![Figure 9: Actuator adjacent to potentiometer.](image2)
Interface To Actuator Drive

The actuator that was picked out is a NEMA 23 servo stepper motor actuator, and the drive that controls the motor, the KL-5080H\textsuperscript{1}, steps the motor based on a rising edge pulse. These drive and motor are shown in Figure 10. The KL-5080H has three inputs, a pulse, a direction, and an enable. The pulse input is how the actuator determines when to step the actuator, the direction input tells the drive which way to spin the actuator, and the enable input allows the drive to energize the actuator or deenergize it. The stepper motor actuator allows for precise movement in 0.09° steps\textsuperscript{3}. Since the movement of the actuator is based on rising edges of a pulse, it was decided to use the PWM output of the Digi Modem to actuate the motor. However, the PWM frequency of the Digi Modem was found to be fixed at around 24 kHz, as seen in Figure 11. Based on the data taken for the actuator drive the resulting rotor speed can be predicted. This resulted in an effective motor rotor speed of 360 rpm, which was deemed too fast for the level of control desired for the project, as it would fully close the 3.75 turn valve from open to close in approximately 0.625 milliseconds.

**Figure 10:** Actuator drive, KL-5080H (left). NEMA 23 Servo Stepper Motor (right).
As a result of this high PWM frequency, circuitry had to be designed to divide it down to a lower frequency. The resulting scheme for frequency division is shown in Figure 12. A simple CMOS 4018 Divide-By-N chip from Texas Instrument, the CD4018B, was implemented in the divide by eight configuration in order to obtain an effective PWM frequency of 3 kHz, which allows for a fully open to close time eight times longer than that of the original 24kHz PWM frequency, or about 5 seconds. The clock input is the signal that is divided down, but the pin only accepts input voltages above 3.5V as the ‘high’ level. The Digi Modem outputs 3.3V as a high, so the signal had to be amplified in order to comply with the specifications of the CD4018B chip. Thus, the simple amplifier seen going into the CLOCK pin takes the clock signal from a max of 3.3V and amplifies it to 5V. The Q4 input is tied back to the DATA pin in order to set the division level given by the Q number multiplied by two. The output of the CD4018B is incapable of sourcing enough current to drive the actuator drive pulse input, so an amplifier needed to be designed for this signal as well.

**Figure 11:** PWM Frequency for Digi Module
The Fairchild 2N3904 is an NPN transistor for amplification applications. It was selected for its high bandwidth of operation, low on state voltage of 0.2V, high gain, and ease of access.

The circuit was designed under the assumption that the DC current gain was 20, which is an underestimate based upon the circuit parameters; however, it provides margin for the variances in the parts and variance in circuit conditions while operating under this assumption. In order to select the resistance needed at the base in order to drive the 2N3904 into saturation, the collector current which makes the collector to emitter, \( V_{CE} \), zero volts. Then, assuming a low current gain, a minimum base current can be found by dividing the calculated collector current by the current gain. Any value above this will drive the transistor to saturation. Table 1 shows the calculated base resistances needed for the different amplifiers needed. For all but one of the signal amplifiers for toggling the enable and direction pins of the actuator drive, shown in Figures 13 and 14, the maximum possible current driven by the BJT is 5mA since there are 1kΩ resistors to limit the current and the switching voltage is 5V. The other amplifier drives the pulse input to the actuator drive, and it is a lower impedance input, so the equivalent collector resistance is 100Ω, as seen in Figure 15. This results in a maximum current of 50mA. However, this amplifier is driven by a signal that is at a duty cycle of 50%, so the total power dissipation is cut in half. Average power dissipated is \( \frac{1}{2} \left( V_{CE} * I_C + V_{BE} * I_B \right) * D = 9.25 mW \), based upon a \( V_{CE} \) of 0.3V and a \( V_{BE} \) of 0.85V, values which were taken from the datasheet. The
transistor maximum continuous current is 200mA, and the power dissipated is small, so there should be no thermal issues at this level. These resistance values limit the current through the transistor while still allowing the actuator drive logic pins change states.

**Table 1:** Parameters of amplifier circuits, used to put transistors into saturation.

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Vin (V)</th>
<th>Vcc (V)</th>
<th>Collector Resistance (kΩ)</th>
<th>Minimum Base current (mA)</th>
<th>Maximum base resistance (kΩ)</th>
<th>Base resistance used (kΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>3.3</td>
<td>5</td>
<td>1</td>
<td>0.25 mA</td>
<td>9.8</td>
<td>1</td>
</tr>
<tr>
<td>Type 2</td>
<td>5</td>
<td>5</td>
<td>0.1</td>
<td>2.5 mA</td>
<td>1.66</td>
<td>1</td>
</tr>
</tbody>
</table>

**Figure 13:** Output amplifier for the direction pins of the actuator drive.
Figure 14: Output amplifier for the enable pins of the actuator drive.

Figure 15: Output amplifier for the pulse pins of the actuator drive.
Communications

Cellular Modem - For the chosen design, the method of cellular communication is the Digi Modem, which is capable of mounting directly to Franklin Electric's VFD. This convenience allows plug and play accessibility, so no additional circuitry is needed to get the modem to work. The software resident to the VFD also supports the features of the Digi Modem, so functionality already exists. The modem also has digital inputs and outputs, A/D inputs, and a single pulse width modulation (PWM) output. The A/Ds resident on the modem are utilized to read the values from the pressure and flow transducers, and the PWM output is used to control the actuator, since its position is controlled through pulses.

Data Storage – The storage platform used for this project is dweet.io. This web utility allows a “dweet” to be created that essentially just stores a set of information based on the name of the dweet. dweet.io allows for the collected data to be quickly and easily stored in an accessible way. Data that is published to dweet.io is open source, but with the purchase of keys, the data can be locked so that only those who know the code can access the information. This is a vital feature for the storage platform to include, as the data collected should be private for security reasons. Another important feature is the storage of information. A locked dweet will store data for up to 30 days, so any test information within that time span can be accessed.6

In addition to the dweet.io as the means to store any incoming data on the cloud, a complete set of test data can be stored locally. Once a test has been fully completed, a table of data is created that can be downloaded as an Excel readable file. This allows for complete manipulation of the raw data by the user. This feature is vital for the long-term storage of test information, so no pump curve data is ever lost.
User Interface

The user interface consists of a custom web application operating in tandem with the dweet.io data storage system. The website contains code for presenting all necessary controls to the user, such as starting and stopping data collection, in addition to housing the procedures for actually running the tests. Other controls may include options to show collected data in tabular form and export it to a downloadable file. A live-updating chart is shown prominently to display test performance along with progress. Optionally, additional pages such as an FAQ and User's Guide may be included to instruct potential users on how to perform tests using the web page. To ensure compatibility with all device form factors, a reactive framework like Bootstrap provides the foundation upon which to build the site. An prototype for how this user interface would look is shown in Figure 16.

Figure 16: Example of Graphing Utility on a website made from scratch.
Section III: Building Process
Building the Plumbing Loop

Testing a water pumping system requires a setup to facilitate water movement, this is where the plumbing comes into place. The motor chosen for this project is the WEG 3/4HP, 100V, 3 phase motor and the pump is a Schneider Motobombas 3/4HP, 11.9 GPM centrifugal pump. This size of motor and pump combination provides a good platform for data acquisition because it has a wide range of pressure and flow performance points but does not have the danger of overpressurizing like a larger system would. This motor and pump should produce about 40 psi when running with the valve fully closed and the motor at full speed of 60Hz, this low pressure allows for safe working and testing conditions before vetted safety features and shutoffs have been implemented.

The next step is to choose the appropriate size plumbing for the application. The table below has equations for sizing pipes based upon known values such as flow or velocity of liquid. The table 2 entry boxed in red is the appropriate equation because we are moving less than 100 gallons per minutes and the water is a non-viscous flow.

**Table 2: Determination of range and limitations for flow given nominal pipe size**

<table>
<thead>
<tr>
<th>EXPLANATION</th>
<th>EQUATION</th>
<th>RANGE &amp; LIMITATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressurized Flow of Liquids</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Darcy-Weisbach frictional head loss</td>
<td>( d = 12 \left( \frac{0.0311 f L Q^2}{h_f} \right)^{0.2} )</td>
<td></td>
</tr>
<tr>
<td>Liquid general flow equation</td>
<td>( d = 0.64 \sqrt[3]{\frac{Q}{V}} )</td>
<td>( Q \text{ in gal/min.} )</td>
</tr>
<tr>
<td>Nominal pipe size for non-viscous flow</td>
<td>( d = \left( \frac{Q}{12} \right)^{1/3} - 2 )</td>
<td>( Q &gt; 100 \text{ gal/min} )</td>
</tr>
<tr>
<td>Nominal pipe size for non-viscous flow</td>
<td>( d = 0.25 \sqrt{Q} )</td>
<td>( Q \leq 100 \text{ gal/min} )</td>
</tr>
<tr>
<td>Pump suction size to limit frictional head loss</td>
<td>( d = \sqrt[3]{0.0744 Q} )</td>
<td>( Q \text{ in gal/min} )</td>
</tr>
</tbody>
</table>

The maximum expected flow rate based upon the current limit of the Fhoton drive is approximately 9 GPM at a speed of 50Hz. Using this value in the equation above, the diameter is calculated as

\[
D = 0.25 \times \sqrt{9} \quad (12)
\]

\[
D = 0.75 \text{ inches} \quad (13)
\]

Based on the findings above, the pipe diameter of 3/4inch was chosen for this project and the
material for this pipe is 316 stainless steel due to its standard use in plumbing applications.

Once the motor, pump, and plumbing size were determined, the next step was choosing the plumbing fixtures that would satisfy the given requirements. The plumbing must gather pressure and flow data in a safe manner. The safety aspect can be achieved with the implementation of a pressure relief valve (PRV). The PRV allows pressure to build in the system until a predetermine limit is met and then the valve opens and allows water to bypass safely while reducing the pressure. The PRV implemented in the system can be seen below in Figure 17.

![Pressure relief valve](image)

**Figure 17**: Pressure relief valve to keep pressure at safe levels

Next, the chosen measurement instruments must be implemented in the plumbing loop. The measurement devices are the flow meter and the pressure transducer which will gather the performance data and transfer it back to the drive. The flow meter is attached to a PVC MPV8T007F which holds the meter in the appropriate position for the vane to spin freely in the water flow. The Signet 515 Rotor-X flow meter used in the setup can be seen below in Figure 18.
The other measurement required is the pressure reading which is gathered by the Dwyer 628-10-GH-P9-E1-S1 pressure transducer. This pressure transducer has ¼" NPT threading which allows for easy application in the plumbing loop with a simple ¾" to ¼" coupler. The transducer used can be seen below in Figure 19.

Controlling the pressure and flow must occur with a change in the cross sectional area of the pipe, this is done by adjusting a gate valve with an actuator. The gate valve chosen provides no discernable friction loss when fully open and has 3.75 turns from fully open to fully closed. The valve used can be seen below in Figure 20.
The handle of the valve was removed to allow the actuator to attach via the coupler. The coupler was provided with the actuator and the attached system can be seen below in Figure 21.

The final non-pipe element in the plumbing loop is the foot valve to keep water from draining backwards through the pump when it is not running. The centrifugal pump must maintain a certain water level inside to move water. Running out of water will cause the pump to lose prime and require it to try to pull water up the pipe by producing a vacuum. The foot valve prevents this by maintaining
prime at all times. The foot valve used is shown in Figure 22.

Figure 22: Foot valve that maintains prime in the pump

The completed plumbing loop can be seen below in Figure 23 and Figure 24 as a functional setup with which performance and efficiency data can be collected.

Figure 23: Top down view of plumbing loop
Figure 24: Isometric view of plumbing loop
Building the Circuitry

In order to interface with the actuator drive, the amplifier circuitry along with the divide-by-N counter had to be constructed. Shown in Figure 25, the circuitry for this use was prototyped on a breadboard. It was then attached to the actuator drive, and tested to ensure that all of the functionality of the drive could be utilized. The board consisted of all amplifiers necessary to drive the pulse, direction, and enable inputs to the actuator. It also contained the amplifier for the clock input to the divide-by-N input to the CD4018B chip that was necessary to reduce the PWM frequency of the digi modem down from 24 kHz to 3 kHz.

Figure 25: Prototype of interface circuitry for control of actuator drive system.
PCB Design and Building Process

After implementing the circuit on a breadboard, a more permanent solution was required to make the system sustainable. The options for circuitry were soldering parts onto a prototyping board or design a printed circuit board using Altium. The decision to design a printed circuit board was an easy one because it allowed for compact repeatable setups to be produced. The first step was to lay out the designed circuit using Altium, the initial schematic can be seen below in Figure 26.

Figure 26: Initial schematic for instrument measurement and actuator control
The next step was to lay out the individual components onto the prospective printed circuit board in Altium. When the first iteration of board layout and trace running was complete the board looked like Figure 27 below.

![Initial PCB layout for instrument measurement and actuator control](image)

**Figure 27**: Initial PCB layout for instrument measurement and actuator control

The oversized blue ground plane was implemented to equalize the amount of copper on the top and bottom layers. This was done because an imbalance can cause larger boards to flex during temperature changes and even though this would not be an issue for a board this size, it is good industry practice to be mindful of the manufacturing process. The yellow markings are for the placement of a silk screen which gives the end user instruction on how to hook up the instruments. A 3D model was produced to give a representation of the part in space, this can be seen below in Figure 28.
Figure 28: Initial 3D model of printed circuit board

Changes were made to the actuator control pin by swapping out the 12 pin connector for a 6 pin connector because the output could not be easily interfaced with the actuator driver. Other changes included adding circuitry on the PCB for a potentiometer to read in the actuator position, adding capacitors to the incoming flow measurements, and adding two LEDs to indicate when the 5V line is powered and the 12V line is powered. The updated board is shown in Figure 29 with all the necessary changes before sending out the files for production. The corresponding 3D model for the new layout is shown below in Figure 30.

Figure 29: Updated PCB layout for instrument measurement and actuator control
The backside of the board contains the project logo and the names of the team members. The 3D model of the rear of the board can be seen below in Figure 31.

The files were sent to Imagineering Inc for production and the final product was returned in one week. Printed board are displayed below in Figure 32.
The next step was to populate the PCB with the correct components and to implement the board into the measurement setup. Soldering the 0603 size components took some getting used to but became easier with time. The completely populated, wired, and mounted PCB can be seen below in Figure 33. In Figure 34, the PCB mounted in the box is shown energized, with both the 5V and 12V LEDs emitting light.
Light pipes were used to allow the LED light to be viewed when the protective cover was in place. They act similarly to fiber optics and efficiently transfer the light to the outside of the case. Figure 35 shows the light pipes shunting the light through the cover of the box.
Lastly, the completed PCB, case, and wiring were mounted onto the cart and connected to the sensors for data acquisition. This setup proved to be very helpful in keeping our components protected from physical damage such as impact or water intrusion and made setup very simple because no wiring had to be done. The only step required to start up the system is to plug it in. The completed PCB and case can be seen mounted onto the cart in Figure 36 below.

**Figure 36:** PCB case mounted and wired into sensors, actuator driver, and modem
User Interface and Website Design

In order to implement a user interface to interact with the project, to create the required plots of data, and as a method of saving the collected data, a website was developed. The interface is seen in Figure 37 while in the dashboard view. The main graph shown on the dashboard gives the flow versus power information for a given pressure. The buttons floating along the bottom give the user the ability to interact with the website, allowing for starting and stopping the test, clearing the collected data, and downloading the collected data to a local .csv copy of the data, which can be opened in Excel or similar spreadsheet programs. This bar can be expanded to allow the pressure target to be set, and a data source to be added according to which drive is setup to run the test.

When a data source is to be added, it opens up a window with forms to fill out for Name of the datasource, and this Name can be anything the user desires. Next is the Thing Name, which is the serial number of the drive, and this serial number is the component unique to each drive that composes the dweet name. Finally there is a form to add the key, which is the security seed that is generated for each drive. Figure 38 shows what this window looks like when the add data source button is clicked.

The ‘Dweet Tester’ tab, seen in Figure 39, gives access to manual adjustments for setting the speed, the security key, enabling test mode, actuator movement, and auto sequencing the dweet number. This Dweet Tester also allows for system parameters to be viewed about the drive, such as the speed of the motor running and the power drawn by the drive. The speed command tells the drive what speed to run the motor. The key allows the drive to accept the commands issued by the dweet, enabling test mode tells the drive to move the actuator and change the speed when commanded. The auto sequencing ensures that a new command must be sent in order to be read by the drive, so that it does not act upon the same information if unintentionally sent more than once. Finally, the user manual tab is for a future implementation to include a user manual for running the test.
Figure 37: Main dashboard for autoloop testing.

Figure 38: Method to add a new data source.
Since the website needed to be an interactive application, the obvious, if not only, choice of programming language was JavaScript. To reduce unnecessary boilerplate code and ensure a responsive look and feel, the jQuery JavaScript library and Bootstrap CSS framework were also employed. The website uses a Model-View-Controller (MVC) architecture to organize its data and functionality into separate entities. Figure 40 displays a high-level overview of this design.

This design has several benefits, such as separation of concerns. Perhaps the most important benefit, however, is its expandability. For example, since model objects can notify subscribers of changes without any knowledge of their subscribers, any number of views can listen for changes to the model and update themselves accordingly without changing the implementation of the model.
Figure 40: Flow chart for software setup

While the code for the UI is more reactive and event-based, the code that operates the hardware is much more procedural. To simplify the interactions with dweet and to ensure that the UI does not lock up, this code executes in a separate thread, using the web worker API. A graphical overview of the procedure used is shown in Figure 41 below. The DatasourceController object spawns the worker that performs executes the control loop, and the worker passes results back to the main UI thread when it is ready to display.
Figure 41: Flow chart for control algorithm of software
Section IV: Design Changes
Overview of Design Changes

Through the course of the project, several issues were discovered that needed to be resolved to more adequately meet the functional requirements of the project. A brief overview of the change description and the reason for the change are summarized in Table 3.

**Table 3:** Summary of design changes from the detailed design made throughout the project

<table>
<thead>
<tr>
<th>Number</th>
<th>Change Description</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Switched to Digi Wifi Modem</td>
<td>The cellular modem was not available at the time of project commencement.</td>
</tr>
<tr>
<td>2</td>
<td>Adjusted Flow Measurement Circuit Component Values</td>
<td>The full scale voltage was too low for adequate measurement resolution.</td>
</tr>
<tr>
<td>3</td>
<td>Decreased cutoff frequency of pressure transducer measurement filter</td>
<td>The pressure measurement still had the occasional outlier in static hydraulic conditions, so the signal needed to be filtered more heavily.</td>
</tr>
<tr>
<td>4</td>
<td>LEDs resistor values increased</td>
<td>LEDs were too bright with initial resistor values.</td>
</tr>
<tr>
<td>5</td>
<td>Earth ground reference instead of floating ground</td>
<td>Noise was potentially introducing measurement error, so earth ground reference was used.</td>
</tr>
<tr>
<td>6</td>
<td>Decreased cutoff frequency of position sensor measurement filter</td>
<td>The position measurement fluctuated more than expected so the capacitor size was increased to filter the signal more heavily</td>
</tr>
<tr>
<td>7</td>
<td>Add ground connection to LM2907</td>
<td>Initially, the negative lead of the flow sensor was hooked up to a pin that was not referenced to ground, but instead was floating.</td>
</tr>
</tbody>
</table>
Detailed Design Changes

**Design Change 1:**
In the detailed design, it was desired to use the digi cellular modem, so that the data could be sent directly to dweet.io through a cellular tower without first having to go through a gateway, such as a router. However, this Digi cellular modem was not available at the time of the project development and building process, so it was decided to use the Digi wifi modem instead. The advantage to this change lies in the similarity between the two modems. The pinouts are exactly the same, so in terms of interfacing with the circuitry, the Sponsor could switch between the two if so desired. The only required change would be internal the Photon drive’s communication between the controller and modem, so that provisions for cellular versus wifi communication could be distinguished. The downside to this switch to the Digi WiFi Modem is that a wireless hotspot, the Verizon Jetpack MiFi cellular hotspot, had to be used so that connectivity to the internet was always ensured. This essentially added in another step between the modem and the cellular connectivity, which slightly increases latency.

**Design Change 2:**
After initially testing the flow sensor, the full range of the measurement circuit output initially set up turned out to not provide enough resolution, so the component values were changed, aiming at a 2V full scale voltage, instead of the previous 1.5V, as shown in equation 14.

\[
C1 = \frac{V_{fullscale}}{R1 * V_{CC} * f_{fullscale}} = \frac{2V}{60k\Omega * 12V * 120Hz} = 23.1nF
\]  

(14)

This value for \( C1 \) is not a standard value, so pick \( C1 = 22nF \)

This results in full scale voltage to be 1.90V as seen in equation 15.

\[
V3 = 12V * 120Hz * 15nF * 60k\Omega = 1.90V
\]  

(15)

The ripple voltage on the output can also be calculated using equation 16.

\[
V_{ripple} = \frac{V_{CC}}{2} * \frac{C1}{C2} \left(1 - \frac{V3}{R1 * V_{CC} * f2}\right) = \frac{12V}{2} * \frac{22nF}{22\mu F} \left(1 - \frac{1.9V}{60\Omega * 12V * 180\mu A}\right)
\]  

(16)

This results in a ripple voltage on the output of 4.97mV.
Each count from the A/D converter corresponds to $V_{\text{per\_count}} = \frac{2.5\, V}{1024} = 2.4\, mV$, so this ripple, which is peak to peak ripple, corresponds to approximately $\pm 1$ A/D count, which is an acceptable error for the measurement that is needed. The maximum readable frequency is given by equation 17.

$$f_{\text{max}} = \frac{12}{C_{1}+V_{cc}} = \frac{180\, \mu F}{42\, \mu F + 22\, \Omega} = 682\, Hz$$  \hspace{1cm} (17)

The final schematic for the flow sensor frequency to analog conversion circuit is shown in Figure 42.

\textbf{Figure 42}: Flow sensor measurement through frequency to analog conversion.
Design Change 3:

In running tests on the data collection, it was found that the pressure measurement was oscillating quite a bit, with the occasional outlier. The cutoff frequency of the filter on the pressure measurement circuit was increased by changing the $0.1 \mu F$ capacitor to a $22 \mu F$, which stabilizes the measurement almost fully. The cutoff frequency of the filter added to the pressure transducer measurement circuitry moved from 15,916 Hz down to 72 Hz. Although, the effective filter cutoff frequency, including the measurement resistor of $100\Omega$, results in a 36 Hz pole with respect to the source. In order to take the requisite data points, the pressure measurement needs to be very stable. Thus, the DC component of the pressure measurement is the desirable, and considering the data points are taken in a stable system wherein the signal has a large DC offset, the low filter pole will not result in real signal attenuation, while also eliminating most of the higher frequency signal components, induced either from noise or brief system transients. Figure 43 shows the revised schematic for that measurement circuit.

![Finalized Pressure Transducer measurement circuitry.](image)

**Figure 43:** Finalized Pressure Transducer measurement circuitry.
Design Change 4:
The current limiting resistors in line with the LEDs were sized to provide the max current of 20mA to the LEDs. This current was deemed to be too high and the LEDs were too bright for normal viewing in this application. The solution was to recalculate the resistor values to provide a lower current to the LEDs. The calculated values were 565 ohms for R15 and 215 ohms for R16 as seen in green in Figure 44.

![Figure 44: Current limiting resistors boxed in green.](image)

The calculations for current can be seen below.

\[ R_{16} = \frac{(V_{source} - V_{diode})}{I} \] (18)

\[ 215 \text{ ohms} = \frac{(5V - 0.7V)}{0.020A} \] (19)

\[ R_{15} = \frac{(V_{source} - V_{diode})}{I} \] (20)

\[ 565 \text{ ohms} = \frac{(12V - 0.7V)}{0.020A} \] (21)

The actual resistors chosen were 604 ohms for R15 and 255 ohms for R16. These values resulted in the LEDs being too bright so the values were changed to 7.5 kohms for R15 and 2 kohms for R16 with the resulting calculations seen below.

\[ R_{16} = \frac{(V_{source} - V_{diode})}{I} \] (22)

\[ 2000 \text{ ohms} = \frac{(5V - 0.7V)}{0.00215A} \] (23)

\[ R_{15} = \frac{(V_{source} - V_{diode})}{I} \] (24)

\[ 7500 \text{ ohms} = \frac{(5V - 0.7V)}{0.00573A} \] (25)
Design Change 5:
The ground reference used throughout the interfacing circuitry on the PCB was originally floating with respect to earth ground. It was found that switching the ground reference to earth allowed for more stability of the measurements. This is most likely due to noise present on the floating ground that was eliminated by switching the reference.

Design Change 6:
The initial position measurements being gathered were unstable and moved about 10% of full scale when no changes should have been registered. It was determined that the low pass filter was allowing too many high frequencies to pass through because the cutoff frequency was not low enough. The solution was to lower the cut-off frequency by either increasing the resistor value in R18, increasing capacitance of C7, or increasing the values of both. The chosen route was to replace the existing 0.10µF capacitor with a 2.2µF capacitor. This change effectively brought the cut-off frequency down from 15,916Hz to 723Hz as seen in the equation 26.

\[
f_c = \frac{1}{2\pi R C} = \frac{1}{2\pi \times 100\Omega \times 2.2\mu F} = 723.42 \text{ Hz} \quad (26)
\]

The capacitor change greatly improved the stability of the position value and allowed for accurate readings. Below in Figure 45 is the updated schematic of the position sensing circuit. Capacitor C7 can be seen with the new value of 2.2µF.

![Figure 45: Finalized position sensor measurement circuitry.](image)
Design Change 7:
In the initial schematic, there was an oversight in the connections from the flow sensor. The negative lead from the flow sensor was connected to the right pin on the LM2907, but that pin was supposed to be ground referenced to the same reference as the 12V supply that powered the chip. This error resulted in a floating input, which caused the output of the chip to not function correctly. Once the jumper was added as shown in Figure 46, the sensor worked as desired.

Figure 46: Voltage to analog converter with jumper to circuit ground.
Section V: Testing and Evaluation
Test Plan

Once the chosen design was complete and functioning, tests were performed in order to verify that each functional requirement of the project had been met. Thus, a test plan was developed for all foreseeable functional requirement (FR) that would need to be tested to verify it meets the specifications. All of these functional requirements were taken from the Functional Requirement Decomposition, which can be found in the Appendix. Some functional requirements do not require testing, such as a user-friendly interface, so those functional requirements have been excluded from the plan. The verification test plan was broken up further by category. In each table of the test plan, the importance column details the priority of the test to be completed, where a ‘1’ is a must be done test and a ‘3’ is an optional test. The marginal value details the minimum acceptable outcome of the test, whereas the ideal value specifies the desired outcome. Table 4 explains the test plans for verifying the data collection category of functional requirements. Table 5 gives the test plans for the verification process of the data storage method and the graphical user interface. Finally, Table 6 details the plan for verifying the robustness and capability of the hardware.

List of Planned Test Procedures

The following list outlines the various tests that are further detailed in Tables 4, 5, and 6. Each item is associated with specific category of tests, with the associated functional requirements as determined by the Functional Requirements Decomposition as shown in the Appendix.

1. Data collection
   FR3-7: Use calibrated pressure gauge to test pressure transducer measurements – compare values.
   FR3-6: Use a known method to test flow transducer measurements – compare values

2. Actuator Control
   FR3-8: Vary input frequency to actuator drive to determine input pulse frequency to rotor speed
   FR3-9: Feedback System test – keeps pressure stable within ±0.5 psi

3. Speed Control
   FR2-12: Speed command to variable frequency drive results in speed change of drive/motor.
4. Cloud Storage
FR3-4: Verify data sets are sent together – compare received data values with present data values so synchronicity is achieved.
FR3-5: Test ability to retrieve past data sets, either through downloadable file or by accessing data stored to a database.

5. User Interface
FR3-2: Vary input to Test Parameter Fields and run autoloop test to ensure parameters have indeed been changed, such as max pressure, minimum pressure, number of data points per curve, etc.
FR2-2: Graphs are displayed, axes are labeled, and individual curves are labeled by pressure. All graphs should appear as they do in a traditional solar pump curve.
FR2-3: Exported file’s filename can be changed manually, or through automatic identification of test # or a test ID.
FR2-4: Data can be posted and read from dweet.io storage website.

6. Hardware
FR1-5: The 4-20mA sense circuit outputs linear voltage. Need to characterize for pressure to get accurate readings.
FR1-4: Test flow transducer measurement circuit. Flow transducer outputs sinusoid with amplitude and frequency proportional to water speed. Implement a frequency to analog voltage and ensure linear characteristic.
FR2-11: Test to ensure that the Divide-by-N circuitry functions as designed, dividing the input frequency by eight.
Table 4: Test plan for verification of data collection method.

<table>
<thead>
<tr>
<th>Functional Req.</th>
<th>Importance</th>
<th>Specification (description)</th>
<th>Unit of measure</th>
<th>Marginal Value</th>
<th>Ideal Value</th>
<th>Test Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR3-7</td>
<td>1</td>
<td>Pressure transducer accuracy</td>
<td>Pounds per square inch (Psi)</td>
<td>±1 Psi</td>
<td>±0.5 Psi</td>
<td>Use a calibrated pressure gauge to test pressure transducer and compare values to received data.</td>
</tr>
<tr>
<td>FR3-6</td>
<td>1</td>
<td>Flow transducer accuracy</td>
<td>Gallons per minute (GPM)</td>
<td>±0.5 GPM</td>
<td>±0.2 GPM</td>
<td>Use a known method to test flow transducer and compare values to received data.</td>
</tr>
<tr>
<td>FR3-8</td>
<td>1</td>
<td>Speed characteristic of actuator</td>
<td>Control signal moves actuator</td>
<td>Proportional movement</td>
<td>Linear movement</td>
<td>Vary input to actuator to obtain speed characteristic if needed</td>
</tr>
<tr>
<td>FR3-9</td>
<td>1</td>
<td>Feedback Control</td>
<td>Psi</td>
<td>±1 Psi</td>
<td>±0.5 Psi</td>
<td>Test to verify that the actuator is able to reach the correct pressure value and maintains the pressure within the specification.</td>
</tr>
<tr>
<td>FR2-12</td>
<td>1</td>
<td>Speed Control</td>
<td>RPM</td>
<td>±30 rpm</td>
<td>±20 rpm</td>
<td>Speed command to variable frequency drive results in speed change of drive/motor</td>
</tr>
</tbody>
</table>


Table 5: Test plan for verification of data storage and graphical user interface.

<table>
<thead>
<tr>
<th>Functional Req.</th>
<th>Importance</th>
<th>Specification (description)</th>
<th>Unit of measure</th>
<th>Marginal Value</th>
<th>Ideal Value</th>
<th>Test Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR3-4</td>
<td>1</td>
<td>Data synchronicity</td>
<td>Percentage</td>
<td>99%</td>
<td>100%</td>
<td>Verify data sets are sent together – compare received data values with present data values so synchronicity is achieved. Possibly need to attach some order identifier to each data point (i.e. a counter that begins when powered on/implement an RTC system) so all received data is from one sampling period.</td>
</tr>
<tr>
<td>FR3-5</td>
<td>1</td>
<td>Data retrievability</td>
<td>Percentage</td>
<td>95%</td>
<td>100%</td>
<td>Test ability to retrieve past data sets, either through downloadable file or regenerate graph, preferably both.</td>
</tr>
<tr>
<td>FR3-2</td>
<td>1</td>
<td>User ability to change test parameters</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Vary input to Test Parameter Fields and run autoloop test to ensure parameters have indeed been changed.</td>
</tr>
<tr>
<td>FR2-2</td>
<td>1</td>
<td>Display test results graphically</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>The axis and title of the graph are labeled and all curves are labeled by their respective pressure. All graphs should appear as they do in traditional pump curve.</td>
</tr>
<tr>
<td>FR2-3</td>
<td>1</td>
<td>Unique file identifiers</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Exported file’s filename can be changed manually, or through automatic identification of test number or a test id.</td>
</tr>
</tbody>
</table>
Table 6: Test plan for verification of hardware reliability and accuracy.

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Functional Reqs</th>
<th>Importance</th>
<th>Specification (description)</th>
<th>Unit of measure</th>
<th>Marginal Value</th>
<th>Ideal Value</th>
<th>Test Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FR1-4</td>
<td>1</td>
<td>Flow transducer frequency to analog voltage converter</td>
<td>Offset and linearization</td>
<td>Some offset and mostly linear</td>
<td>No offset and linear through the range</td>
<td>Test flow transducer measurement circuit. Flow transducer outputs sinusoid with amplitude and frequency proportional to water speed. Implement a frequency to analog voltage and ensure linear characteristic.</td>
</tr>
<tr>
<td></td>
<td>FR2-11</td>
<td>1</td>
<td>Division by N circuitry</td>
<td>Frequency</td>
<td>Division frequency with 5% error</td>
<td>Division frequency with 1% error</td>
<td>Test to ensure that the divide by N circuit functions as designed.</td>
</tr>
<tr>
<td></td>
<td>FR3-2</td>
<td>1</td>
<td>Sensor Circuitry Test</td>
<td>Volts</td>
<td>Linearized with error &lt;5%</td>
<td>Linearized with error &lt;1%</td>
<td>Test that the 4-20mA sensor circuitry outputs linear voltage. Use this test to characterize both flow and pressure in order to get accurate readings. If the voltage linearly increases, then just take a few points to verify. However, need to verify that the sensors themselves also function linearly corresponding to their present state.</td>
</tr>
</tbody>
</table>

Of course, even if the whole design is verified, the project is for naught if the design cannot be validated. Validation is a process to determine how well the design meets the customer needs. Thus, during the process of construction and verifying the design, there was constant feedback to ensure that the design was built to both specifications and the needs of the customer. By doing so, progress towards validation was monitored and evaluated in real time, which allowed for adjustment if an aspect of the design was determined to be inadequate during construction.
Testing the Pressure Transducer Circuitry (FR 1-5 and FR3-7)

**Test Setup:** The pressure transducer circuitry was tested for its ability to regulate the appropriate current for the given pressure. A calibrated DPG4000 Pressure Gauge was used as the reference pressure measurement for the data shown in Figure 47. The current through the pressure transducer was measured with a calibrated Fluke 179 Digital Multimeter. A motor and pump combination was ran in conjunction with a valve in order to create pressure. The valve position was varied in order to develop different levels of pressure, and the resulting current through the pressure transducer was measured in order to relate the pressure to the current.

**Results:** From the linearization of the measured data, the current at zero psi is 4.0069 mA, which gives a 0.1725% error from the desired zero psi value of 4 mA. The slope, which ideally is 0.16 mA/psi, was measured to be 0.1592 mA/psi, which produces a -0.5% error. This error level is acceptable within the margins of the test that needs to be performed in order to create the constant pressure curves.

![Figure 47: The current-pressure characteristic of the pressure transducer circuitry.](image)
Ultimately though, the pressure measured that will be used comes from the voltage measurement at the A/D input from the Digi Wifi Modem. Thus, the relationship between the voltage and its associated pressure was measured, and the results are shown in Figure 48.

**Figure 48**: The pressure-voltage characteristic for the pressure transducer measurement circuitry.

Since a 100Ω resistor is used to translate the regulated pressure transducer current into a voltage of the appropriate level, the resulting slope should be 16 mV/psi, and the measured slope from the linearization is 15.9mV/psi. Based on the previously measured data shown in Figure 48 with a slope of 0.1592 mA/psi, the resistance value of the resistor used to measure the pressure is approximately $R = \frac{15.9 \text{ mV}}{0.1592 \text{ mA/psi}} = 99.8\Omega$. This leads to the error introduced by the external circuitry components. The selected resistor has a 1% tolerance, so $R = 100\pm1\Omega$. The calculated value of 99.8Ω means that the resistor used in this circuit falls within the tolerance of the type of resistor. This test satisfied FR1-5, for the linearity of the sensor measurement, and FR3-7, for the accuracy to a calibrated pressure meter reading.
Testing the Flow Transducer Circuitry (FR 1-4)

Test Setup: The flow transducer was powered externally by a 12V source, and the Tektronix AFG1022 was used to generate sine wave of varying frequencies. The voltage from the output of the LM2907 was measured as the frequency was changed. The frequency will be changed from 6 Hz up to 120 Hz, since that is the full range of the flow meter being used to measure the flow rate.

Results: After running the test, the data collected resulted in the graph shown in Figure 49. The results show a very linear relationship between the input frequency and the corresponding output voltage. However, this relationship does not tell the full picture, because it is desired to relate this output voltage to a given flow rate in GPM. Based upon the conversion factor for our given pipe size, the frequency can be related to GPM of water by 0.2295 GPM/Hz. This allows a graph to be created to show the relationship between the flow in GPM to output voltage, as seen in Figure 50. The slope of this graph gives the voltage per GPM scaling factor necessary to convert the collected A/D values to their respective flow rates in GPM. The scale factor used going forward is 0.0664 V/GPM based upon this measure data. The results of this test satisfy the FR1-4, for the linearity of the measurement.

![Graph](image)

Figure 49: Shows the relationship between the input frequency and the corresponding output voltage for the flow transducer measurement circuit.
Figure 50: Shows the relationship between the flow rate in GPM to the output voltage for the flow transducer measurement circuit.

Flow Rate Measurement Accuracy (FR3-6)

The measurements from the flow meter in the previous section were implemented in converting the A/D values into a flow measurement of GPM. In order to verify these flow meter readings, calibration testing was needed. The 7 universal calibration standards are second, meter, Ampere, kilogram, Kelvin, mole, and candela and all other measurements are comprised of these universal standards. Each of the 7 standards has a master standard somewhere in the world that all other standards are referenced. The flow meter calibration requires a measurements of gallons per minute which can be broken down into individual universal calibration standards. A cubic centimeter of water has a known mass of 1 gram which can be converted to a gallon of water weighing 3.785412 Kg. The mass can be further converted into 1 gallon weighing 8.345404 pounds. The other side of the measurement is very simple when the universal measurement of 1 second can be converted to 1 minute by multiplying by 60. These converted units can be used to find the actual flow rate of the system and used as a comparison for the reported readings.
The test was conducted by reaching steady state water flow through the system and collecting water over a recorded amount of time. Once the water started to reach the top of the container, the test was stopped and the mass of the water was weighed using a calibrated scale. The result was a mass vs time comparison which can be converted using the values above. Figure 51 below depicts the water gathering process and how the system was modified to prevent recirculation of the water and allow for separate collection.

Figure 51: Water gathering to use for mass vs time

The test was run several times to ensure the data points are repeatable and linear throughout a range of flow rates. The collected data can be seen below in Figure 52. The final offset was 0.260 GPM which was used to calibrate our flow meter with the appropriate zero offset.
Testing the Actuator (FR3-8)

Test Setup: The KL-5080H drive that controls the selected stepper motor actuator based on the rising edges that it sees at the pulse logic inputs. This means that an equivalent speed can be obtained based upon the frequency of the pulses into the drive’s pulse input. In order to determine the relationship, the pulse frequency into the actuator drive was varied in order to measure the resulting shaft speed of the actuator. Measurements were taken for both clockwise (CW) and counterclockwise (CCW) rotation of the shaft.

Results: Figure 54 below shows the relationship between the shaft speed of the actuator when turning CW and the input pulse frequency. The linearization taken of the data shows that the relationships is an extremely linear one, with almost no single data point deviating from the
linearization. Based on the assumption that this linear trend continues, the time per revolution can be predicted for a given input pulse frequency. The data taken for the CCW direction also indicates that the relationship is linear. Although the slope is slightly higher, 0.0151 rpm/Hz compared to 0.0149 rpm/Hz, the deviation is small enough that the result is most likely due to measurement error. Knowing that at a frequency of 0 Hz the actuator will not rotate at all, and taking the average of these two slopes which results in 0.015 rpm/Hz, a final closed form equation for the relationship between the actuator shaft speed and the input pulse frequency can be defined as shown in equation 27.

\[ f_{\text{actuator}} = 0.15 * f_{\text{pulse}} \quad (27) \]

This equation gives a way to predict how fast the shaft of the actuator will spin when a given frequency pulse is applied to the pulse input of the actuator drive. This test was not specifically part of the test plan, but its results helped to achieve FR3-8 and FR3-9.

![Figure 54: Relationship between the shaft speed (CW) of the actuator and the input pulse frequency.](image)
Figure 55: Relationship between the shaft speed (CCW) of the actuator and the input pulse frequency.
Amplifier Test and Divide-by-N Test:

Amplifier Test Setup: In order to ensure that the amplifiers were fully saturating while switching, the switching waveform was examined on a Tektronix THS3024 oscilloscope to look at the on-state voltage of the switch. According to the datasheet for the 2N3904 transistor, the on-state voltage for \( V_{ce} \) when collector current is 10mA and the base current is 1mA is approximately 0.2V. In order to simultaneously test both the amplifier and the Divide-by-N circuitry, a 24 kHz square wave was put into the clock input of the CD4018B chip, which was produced by the Tektronix AFG1022, as seen in Figure 56. The 24 kHz square wave is approximately the frequency generated by the Digi Wifi Modem, which is used in the project to control the movement of the actuator. Also, the square wave generated has an amplitude of 3.3V, and a minimum of 0v, just like the output of the Digi Wifi Modem. The arbitrary function generator and the wiring of the circuit board used to measure is shown in Figure 57. To measure the on-state voltage of the 2N3904 transistor, a probe was attached to the collector and emitter of a transistor. This was done for both types of amplifiers, Type 1 and Type 2.

Divide-by-N Test Setup: Since the 24 kHz signal simulates the PWM signal from the Digi Wifi Modem, the output of the CD4018B can be examined to ensure that it divides the signal by eight as prescribed. If it is capable, and accurate, at achieving the divide function, then when the Digi Wifi Modem is attached it will perform the same function. The same circuit configuration used in the Amplifier Test Setup is used to examine the Divide-By-N circuitry.
Figure 56: Tektronix AFG1022 arbitrary function generator generating a 24kHz square wave.

Figure 57: Circuit board used to connect electrical components of the system for measurement.
Amplifier Test Results (FR2-11):

As with the actuator testing, this test was not specifically required by the testing plan, but since the amplifiers had to be implemented, verification of functionality wanted to be assured. As the 24 kHz square wave oscillates, it turns on and off the transistor, which allows the on state voltage to be measured for both types of circuits. The input amplifier to the clock signal of the CD4018b will directly see this type of signal. Thus, figure 58 shows the on-state voltage for the type 1 amplifier as described in Table 1. The on-state voltage from collector to emitter measured at this point is around 70 mV, which is less than the required 0.5V or lower to be seen as a low signal from the input to the CD4018b.

![Oscilloscope trace for on state of amplifier circuitry of Type 2 amplifier (channel1: yellow trace).](image)

**Figure 58**: Oscilloscope trace for on state of amplifier circuitry of Type 2 amplifier (channel1: yellow trace).

The output of the CD4018b has a type 2 amplifier as specified by Table 1. When examining the on state of the type 2 amplifier, the collector to emitter voltage settled to around 160 mV, which is seen in Figure 59. According to the KL5080-H, the required voltage to be read as low is 0.5V, so this value of 160 mV is more than enough low enough. This is below the 0.2V target. Compared to the Type 1 amplifier, though, the one state voltage is much higher and this is due to the higher collector and base current as a result of both the lower collector resistance and the higher base voltage applied to the circuit. The type 2 amplifier is the circuit that drives the pulse input of the actuator drive, and in the
configuration presented, it is able to successfully drive the input so that the actuator spins as the amplifier switches on and off, thus satisfying FR2-11. The type 1 amplifiers were also able to drive both the enable and the direction inputs of the actuator drive as well.

![Oscilloscope trace](image)

**Figure 59:** Oscilloscope trace for on state of amplifier circuitry of Type 2 amplifier (channel1: yellow trace).

**Divide-By-N Test Results (FR2-11):**

This test was relatively straightforward. The 24.0 kHz signal, as measured by the oscilloscope, that is equivalent to the PWM signal was placed on the input to the clock amplifier for the CD4018b. The resulting waveform seen on the output was measured by the oscilloscope to be at 3.00 kHz. This strongly suggests that the Divide-By-N, which was set to divide by eight, circuitry works as designed, since the frequency of the signal was taken from 24.0 kHz down to 3.00 kHz, which comes out to a ratio of exactly 8.00. The Divide-By-N circuit overcomes the problem initially presented by the high frequency of the PWM output of the Digi Modem by slowing down the signal, which results in a slower actuator movement. The slower actuation allows for more precise control, and for the autoloop project to achieve tighter pressure regulation during test. FR2-11 was met through this test since the division of the PWM frequency achieved tolerance within 1% of the desired division from the input frequency.
**Figure 60:** Equivalent 24 kHz PWM input signal (channel 3: purple trace). Output signal from CD4018b at 3 kHz (channel 1: yellow trace).

**Speed Control of Drive (FR2-12):**

By sending a dweet to the drive with a speed command in Hertz, the drive was able to read the dweet, and change the motor speed accordingly. This was verified by changing the speed and then looking at the reported motor speed from the drive in order to see the command speed matched the actual speed. This was done with several different speeds over the operating range of the motor to ensure there would be no issues while running the autoloop test. Thus, FR2-12 was successfully met by verifying the speed changes.
Data Exchange (FR2-4)

Dweet offers a REST API for interacting with its services, and there are a multitude of ways to consume it. In the case of JavaScript, the method of interaction is the XmlHttpRequest (XHR). Using XHR functions, the website can perform HTTP POST and GET requests, which write to and read from specified dweet endpoints, respectively. It currently handles the analysis of this data in a semi-autonomous manner with the user needing only to enter testing parameters and initiate the testing sequence. The ability for the website to post information to dweet and to get information from satisfies FR2-4.

Data Synchronization (FR3-4)

FR3-4 was met because the structure in which the data storage service, dweet.io, is set up means that the data must be posted as a set. Each new data point is collected by the drive, which are collected in rapid succession by A/D’s, so that they points are essentially synchronous. Then, each time the drive posts a new dweet containing the test information, the whole data set is posted to dweet.io in key-value pairs onto the SUMM dweet.

Data Retrievability (FR3-5 and FR2-3)

In order to satisfy FR3-5, an option was added to the website to download any collected data to a .csv file. This type of file is able to be opened in excel, so the data is viewable both offline and at any time the use desires so long as the data for a particular test is saved from the website. Access to a server to host the website could allow for the data to be stored on said server, however, this option was never explored in the scope of the project. For now, the .csv file allows for long term storage, so FR3-5 was met, and the user can rename the file when downloading through the browser native downloader, so FR2-3 was met.

User Ability to Change Test Parameters (FR3-2)

In order for the user to varying test parameters, boxes were added to adjust the pressure setpoint for the curve that is desired. The website steps through the speed range in 2 Hz increments based upon these parameters. With these features, the website successfully met FR3-2 for the user interface.
Automation Testing (FR2-2)

An example of the results after running a test are shown in Figure 61. The red curve shows how the flow varies with power into the Fhoton drive, while the blue curve shows that the pressure in the system is kept constant within a tolerance of ±0.3 psi around 12 psi. The horizontal axis shows power in units of Watts, and the legend contains the units for each curve. The title of the chart is “collected data”, and the user knows the pressure the curve is set to based upon the Target Pressure that was selected. Thus, FR2-2 is met as a graph of the collected data is displayed, it is appropriately labeled, and the curve displayed is constant pressure, just as displayed in the solar catalog. The entirety of the test was run in an automatic fashion, with a pressure setpoint tracked by the controller resident on the website. The test starts by running the motor at 35 Hz, then after a data point is collected, increments by 2 Hz all the way up to 50 Hz. At each speed, after reaching the pressure target, five samples are taken and averaged to ensure data precision. Notice that at the end of the curve, there are several overlapping data points. This is due to the motor’s speed being limited by the current limit of the motor. The actual speed achieved by the motor in this case is only around 46 Hz, which limits the number of data points able to be taken.

Figure 61: Example of collected data and displayed graph for a 12 psi setpoint.
A collection of three different constant pressure curves were plotted on the same graph to display the effect of the pressure on the characteristic of the flow measurement. All of these data points were taken automatically by controlling the valve position to regulate a pressure within the tolerance ±0.3 psi. As shown from the graph in Figure 62, there is a consistent trend that as the pressure goes up, the flow rate goes down for a given power level.

![Constant pressure curves collected automatically.](image)

**Figure 62:** Constant pressure curves collected automatically.

There are a few points that are inconsistent with the general trend of a given constant pressure curve. Based upon observation of the system under test, and the consistency of the data collected, these are most likely due to the tolerances applied to an acceptable pressure measurement. It is possible one data point could be taken at the high end of the pressure tolerance, which would result in a lower flow rate, and then the next data point could be taken at the low end of the tolerance, resulting in a high flow rate. This would create the fluctuation in the path of the curve. Even after several attempts at the same pressure curve, it displayed the same overall trend. Seen in Figure 63 is the first data set collected at a constant pressure of 10 psi, and the second set is shown in Figure 64. These two sets
of data are almost identical in their behavior, even having the inconsistent point at the same place in the curve. This indicates that the outlier from the curve arises from the behavior of the system and the inherent constraints set by the control method and regulation of the pressure.

Figure 63: First run for a 10 psi constant pressure curve.

Figure 64: Second run for a 10 psi constant pressure curve.
Uncertainty Budget

All measurements taken over the course of a test have an associated uncertainty. This uncertainty provides information on the accuracy of the data or inaccuracy for that matter. The overall uncertainty takes the uncertainties of the individual components that have an influence on the measurement and computes them using a standardized equation. The equation is provided by the National Institute of Standards and Technology (NIST) and allows for easy entry of component tolerances.

The first measurement uncertainty is the water pressure. Aspects such as transducer tolerance, A/D converter tolerance, and 12V power supply tolerance were taken into account when calculating the uncertainty. The table in Figure 65 below shows the individual uncertainties and their relative contribution to the overall uncertainty. The overall pressure uncertainty is calculated to 1.42 psi which means without calibration or implementing known offsets, the most certain one can be about the reading is that it is within 1.42 psi of the displayed value.

<table>
<thead>
<tr>
<th>Measurement Result Units:</th>
<th>PSI</th>
<th>Measurement Parameter: Pressure Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty Component Description</td>
<td>Symbol</td>
<td>Estimated Uncertainty</td>
</tr>
<tr>
<td>Transducer</td>
<td>T</td>
<td>0.2500%</td>
</tr>
<tr>
<td>A/D converter</td>
<td>A/D</td>
<td>0.1800%</td>
</tr>
<tr>
<td>12V Power Supply</td>
<td>12V</td>
<td>0.5000%</td>
</tr>
<tr>
<td>Min Degrees of Freedom</td>
<td>ν</td>
<td>2</td>
</tr>
<tr>
<td>Effective Degrees of Freedom</td>
<td>νₑ</td>
<td>2</td>
</tr>
</tbody>
</table>

Combined Uncertainty, $u$, 0.314

Coverage factor, k, times effective degrees of freedom 4.53

Expanded Uncertainty, $U$, 1.4224

| Expanded Uncertainty, $U$, Rounded | 1.42 | PSI |

Figure 65: Pressure uncertainty

The next measurement is the flow in gallons per minute. The uncertainty comes from the flow meter itself, the A/D converter, 12V power supply, and frequency divider. The total uncertainty for this measurement is 0.84 GPM which, similar to above, the most certain one can be about the flow reading is that it is within 0.84 GPM. The flow uncertainty can be seen below in Figure 66.
Next is the power uncertainty calculation which consists of current, voltage, and A/D uncertainty. The largest relative contributor to power uncertainty is the current measurement with 55.38% of the uncertainty. This is due to the instantaneous current measurements that occur within the firmware of the drive. The power uncertainty can be seen below in Figure 67.

Lastly, the position uncertainty was calculated with several contributing factors. These factors included, Potentiometer resolution, tolerance, linearity, the 5V supply, and the voltage divider resistor’s tolerance. The bulk of the uncertainty for position comes from the potentiometer tolerance of 5%. The tolerance may seem too large to use for this application but it is completely removed when the high and low voltage values of the position are calibrated. Calibration will assign a specific value to when the valve is fully closed and fully open and then the tolerance is negligible because the main contributing factor at that point would be the linearity. This allows for precise measurements due to the small linearity of the potentiometer. The position uncertainty can be seen below in Figure
Schedule of Project Completion

Figure 69 below shows the Gantt Chart currently being used to track the team’s progress through the project.

The Gantt Chart is a useful tool for determining whether incremental goals for the project are being achieved. The goals are given due dates based upon priority. If one task is an integral part to proceed in the development of the project, it needs to be finished before any of the following objectives are attempted. There do exist goals that can be completed in parallel, which will help expedite the progress of the project. While the due dates presented here are not strictly defined, they are there to
encourage the team to focus on the objective that either has the closest due date or is passed due. Some due dates are dictated by the schedule of the Senior Design course, and are therefore inflexible. The remaining due dates were suggested by Franklin Electric to coincide with their schedule and goals.

The longest-term goal that exists is completing the verification and validation stage of the project by March 21st, 2017. By pushing toward finishing the project more than a month ahead of the hard deadline of May 2nd, 2016, there will be more time to fix any unforeseen issues that arise during the course of the development.
Risk Management

Risks are future uncertainties that could delay the project or potentially prevent its completion. Good practice is to foresee potential problems to mitigate delays and subsequent costs. Risks can be categorized by their likelihood of occurrence and impact on the project. The method for ascertaining risk and developing strategies for mitigating that risk is presented by the Department of Defense. The rankings of consequences can be seen below in Table 7. The likelihood of occurrence can be seen in Table 8. At the beginning of the project development, the team determined four possible risks that had to be managed going forward with design choices. The four main risks can be seen below listed as risks 1 through 4. Finally, the risks are put into a grid in Figure 70 to display their impact on the project.

Potential Risks

- Risk 1 - Inability to update pressure control quickly enough to complete timely tests.
- Risk 2 - Freeboard Pro does not allow adaptability to designer.
- Risk 3 - Lack of long term storage ability with dweet.io.
- Risk 4 - Digi Modem 1st quarter of 2017 release may not be soon enough for our needs.

The first risk to be covered is the inability of update the pressure control quickly enough. The usage of a cellular modem for all of our data transmission, input control, and output control has the potential to slow down the operation of the system due to unknown of using a cellular tower. It was determined that likelihood of occurrence is a two out of five while the consequence is a three out of five. The consequence value was given a three because it would require the implementation of a coprocessor to handle the actuator feedback loop.

The second risk is if Freeboard Pro does not give the designer enough control over the user interface. While the utility has a vast feature set, the flexibility we need for this niche project may not be there. The likelihood of its occurrence is very high based on the information thus far in the project but luckily the consequence is low because the alternative solution is already fairly functional.
Risk three is the potential lack of long term storage ability with dweet.io. Dweet.io is going to be used to transfer data packets through the cloud in the hopes that data storage could be implemented. There is a chance that the free version of dweet.io does not support a long enough storage time or that it does not support data storage at all. The consequence is low because the data would just need to be stored locally.

Risk four is the Digi modem not updating to a 3G or 4G model in time for project completion. The current model available is the 2G option which may become obsolete in the near future. The hopes are that the newer model will be available for purchase and that the project will not have to adapt to a necessary change. It is very unlikely for this problem to occur but the consequences would be fairly high considering the design would have to change to a different modem or potentially a coprocessor that uses the on-board modem of the Fhoton drive.
Risk Management Plan

If any of the described risks do occur, there needs to be a way to mitigate the consequence of the risk. The functional requirement alternatives take on this role. If Risk 1 occurs, speed control will be implemented as the data collection since it is not dependent upon the response time of pressure feedback like pressure control. If Freeboard is used to implement the graphical user interface, and it does not allow for the needed flexibility (Risk 2), then a website will be created from scratch. In order to manage Risk 3, an alternative storage system will be used that has more flexibility and control, such as a private server with a database. Finally, Risk 4 will be mitigated by either using the Digi Wi-Fi module that has the same I/O pinout as the Digi Cellular Modem or by using an existing cellular modem with the Serial Connection design that uses a co-processor.

<table>
<thead>
<tr>
<th>Level</th>
<th>Technical Performance</th>
<th>Schedule</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Minimal or no consequence to technical performance</td>
<td>Minimal or no impact</td>
<td>Minimal or no impact</td>
</tr>
<tr>
<td>2</td>
<td>Minor reduction in technical performance or supportability</td>
<td>Able to meet key dates</td>
<td>Budget increase or unit cost increase</td>
</tr>
<tr>
<td>3</td>
<td>Moderate reduction in technical performance or supportability with limited impact</td>
<td>Minor schedule slip. Able to meet key milestones. Slip &lt; 3 weeks</td>
<td>Budget increase or unit cost increase</td>
</tr>
<tr>
<td>4</td>
<td>Significant degradation in technical performance or major shortfall in supportability</td>
<td>Program critical path affected. Slip &lt; 1 month</td>
<td>Budget increase or unit cost increase</td>
</tr>
<tr>
<td>5</td>
<td>Severe degradation in technical performance. Unable to meet FRs</td>
<td>Cannot meet key program milestones</td>
<td>Budget increase or unit cost increase</td>
</tr>
</tbody>
</table>

Table 7: Consequence levels and subsequent project impact.
Table 8: Likelihood levels and subsequent probability

<table>
<thead>
<tr>
<th>Level</th>
<th>Likelihood</th>
<th>Probability of Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Not Likely</td>
<td>~10%</td>
</tr>
<tr>
<td>2</td>
<td>Low Likelihood</td>
<td>~30%</td>
</tr>
<tr>
<td>3</td>
<td>Likely</td>
<td>~50%</td>
</tr>
<tr>
<td>4</td>
<td>Highly Likely</td>
<td>~70%</td>
</tr>
<tr>
<td>5</td>
<td>Near Certainty</td>
<td>~90%</td>
</tr>
</tbody>
</table>

Figure 70: Four main risks on a likelihood vs consequence grid.
Final Analysis of Risks

At the beginning of the project, potential risks were assessed in an attempt to foresee potential issues with the design or scope of the project. At the end of the project, these risks can be further addressed by determining if they occurred and, if so, if they caused any issues. The first risk was the inability to update pressure control quickly enough to perform timely tests. This did not pose an issue because the final tests could be completed in less time than the standard auto loop at Franklin Electric. The second risk was that Freeboard Pro does not allow adaptability to the designer. This risk definitely caused some issues because, as expected, there was not enough customization in that software to produce the user interface required for this project. The remedy was to produce a website from scratch with all the charts being fully customizable. Producing a custom website on a server requires more effort than using Freeboard but it was a necessity to meet the function requirements of the project. Risk 3 was not having long term storage ability with dweet.io. This issue was resolved with the same solution for risk 2 because a custom website was designed with a data saving already implemented. The final risk was that the Digi Modem would not be available in the first quarter of 2017. This risk also came to light when the release date was not met by the producer. The alternative was to use a Digi wifi module and alter the method of data acquisition. Ultimately the risks were mitigated without much delay because they were anticipated ahead of time which allowed the team to foresee alternative solutions to the problems that arose.
Cost Analysis

Shown in Table 9 is a tentative list of the materials needed for the completion of the final design for the project. Included in the table is the approximate cost of each component, the quantity needed for a single design, the manufacturer of the component, its corresponding part number, and a description of the component’s function. The sum total is less than the allocated budget, while still leaving room for any unforeseen acquisitions needed to complete the project.

Table 9: Bill of Materials for Franklin Electric Project

<table>
<thead>
<tr>
<th>Item #</th>
<th>Qty</th>
<th>Description</th>
<th>Manufacturer</th>
<th>Model #</th>
<th>Function</th>
<th>Cost Per Unit</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Photon Drive</td>
<td>Franklin Electric</td>
<td>581013000864-SP075HP</td>
<td>Solar variable frequency Drive</td>
<td>Classified</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>AC Supply</td>
<td>Franklin Electric</td>
<td>None</td>
<td>AC to DC converter to power drive</td>
<td>Classified</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Motor</td>
<td>Weg</td>
<td>13183065</td>
<td>1/3 HP Motor - 100 Volts</td>
<td>Classified</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>Pump</td>
<td>Schneider Motobombas</td>
<td>None</td>
<td>1/3 HP Pump</td>
<td>Classified</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>Actuator</td>
<td>Automation Technologies</td>
<td>KL26-2N-100</td>
<td>Actuator to control water flow</td>
<td>$130.00</td>
<td>$130.00</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>Actuator Drive</td>
<td>Automation Technologies</td>
<td>KL5080-H</td>
<td>Drive to control actuator direction and speed</td>
<td>$50.00</td>
<td>$50.00</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>Power Supply</td>
<td>Keling</td>
<td>KL350-36</td>
<td>36V power supply to run actuator</td>
<td>$39.95</td>
<td>$39.95</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>Modem</td>
<td>Digikey</td>
<td>None</td>
<td>Modem to facilitate communication to the cloud</td>
<td>$80.00</td>
<td>$80.00</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>Switch/Fuse Panel</td>
<td>custom</td>
<td>Custom</td>
<td>Panel to turn on and off power to drive</td>
<td>$30.00</td>
<td>$30.00</td>
</tr>
<tr>
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<td>Proto Board</td>
<td>Sparkfun</td>
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<td>Resistor</td>
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<td>CF1/4W104JR</td>
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<td>$0.40</td>
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<td>VGD-60-D512</td>
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<td>100 PSI Pressure Transducer</td>
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<td>Powerpole Pak</td>
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<td>$25.00</td>
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<td>20</td>
<td>Wire</td>
<td>Grainger</td>
<td>02727.85.01</td>
<td>One foot of 10/4 SOOW portable cord</td>
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<td>$21.80</td>
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<td>Pipe Nipple</td>
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<td>3/4&quot; diameter NPT 1&quot; stainless steel nipple $4.33 $43.30</td>
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<td>Plumbing Size Adapter</td>
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<td>28</td>
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<td>Gearbox</td>
<td>Keling</td>
<td>KL-23GH101S</td>
<td>Gearbox to increase actuator torque $239.95 $239.95</td>
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<td>29</td>
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<td>Cart</td>
<td>Luxor</td>
<td>LP34CE-B</td>
<td>Cart to hold and store equipment $203.98 $203.98</td>
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<td>Bucket</td>
<td>Leaktite</td>
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<td>5 gallon bucket to serve as water source $3.97 $3.97</td>
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<td>Actuator Bracket</td>
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<td>33</td>
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<td>Fasteners</td>
<td>Home Depot</td>
<td>801736</td>
<td>Stainless steel fasteners to hold lumber in place $0.31 $1.24</td>
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<td>Paint</td>
<td>Krylon</td>
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<td>35</td>
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<td>Rubber Strap</td>
<td>ULINE</td>
<td>H-3602</td>
<td>Rubber strap to hold water container $1.60 $1.60</td>
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<td>36</td>
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<td>Software License</td>
<td>Freeboard/Dweet</td>
<td>None</td>
<td>Cellular transmission licenses $100.00 $100.00</td>
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<tr>
<td>37</td>
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<td>PCB Enclosure</td>
<td>PolyCase</td>
<td>WP-24F</td>
<td>Plastic enclosure to protect PCB $21.70 $21.70</td>
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<tr>
<td>38</td>
<td>2</td>
<td>Nylon Gears</td>
<td>Traxxas</td>
<td>None</td>
<td>Gears for actuator encoder $1.00 $2.00</td>
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<td><strong>Total</strong> $1877.81</td>
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</table>

## Miscellaneous

|   |   | Gearbox                | Keling       | KL-23GH101S      | Gearbox to increase actuator torque $239.95 $239.95 |
|   |   | Cart                   | Luxor        | LP34CE-B         | Cart to hold and store equipment $203.98 $203.98 |
|   |   | Lumber                 | Home Depot   | 161659           | 2"x4" board to hold water source $3.97 $3.97 |
|   |   | Bucket                 | Leaktite     | 2GL WHITE PAIL   | 5 gallon bucket to serve as water source $3.97 $3.97 |
|   |   | Actuator Bracket       | Custom       | N/A              | Bracket to hold actuator in place $10.00 $10.00 |
|   |   | Fasteners              | Home Depot   | 801736           | Stainless steel fasteners to hold lumber in place $0.31 $1.24 |
|   |   | Paint                  | Krylon       | K08970000        | Black spray paint for bucket supports $12.11 $12.11 |
|   |   | Rubber Strap           | ULINE        | H-3602           | Rubber strap to hold water container $1.60 $1.60 |
|   |   | Software License       | Freeboard/Dweet | None       | Cellular transmission licenses $100.00 $100.00 |
|   |   | PCB Enclosure          | PolyCase     | WP-24F           | Plastic enclosure to protect PCB $21.70 $21.70 |
|   |   | Nylon Gears            | Traxxas      | None             | Gears for actuator encoder $1.00 $2.00 |
|   |   |                        |              |                  | **Total** $1877.81 |
Summary

This report has shown that the final design and implementation of the performance measurement device met all of the initial requirements set forth at the beginning of the project. The main objectives were to develop a system that characterizes pump performance automatically, store records of collected data, plot performance curves as a function of speed and flow, provide interface to user, and enable two-way communication between cloud and variable frequency drive. Each of these requirements were met by producing a well-designed system and mitigating known risks to prevent setbacks or failures. Minimizing delays allowed the project to be completed in a timely manner and meet the schedule that was set early in the project.

One of the biggest hurdles to overcome in this project was the requirement to communicate the real-time measurements via a cellular or wifi connection. The added complexity of synchronizing the sending and retrieval of data without losing any packets of information in the process proved to be an engineering test. Ultimately, this hurdle was overcome by writing robust software that would handle interruptions and execute the necessary delays to prevent loss of synchronization. Providing stable and consistent data from the physical system to the user interface was also a necessity to log an accurate representation of the system response. Filtering and signal processing were key to transferring the actual values to the end user.

Even with the success experienced, however, there are still some innate limitations with the method of implementation. One such suggestion to improve the process would be to alter the method of pressure regulation. Since currently the feedback information has to be relayed to the website, which results in a very slow response time. One possible mitigation of this would be to allow the website to merely display and store the information, while the pressure regulation is done locally. A microprocessor would speed up the response time and allow for more dynamic and accurate control of the pressure level.

While the project at the time of completion is by no means perfect, it does provide a foundation upon which to build a platform that provides a robust data collection scheme while utilizing the vast collection of cloud utilities that exist today. This design will allow for quick and easy gathering of pressure curves and efficiency data from various motors and pumps.
References


Figure 71: Entire Functional Requirement Decomposition.

Figure 72: Top level functional Requirement
Figure 73: 1st branch of functional Requirement
Figure 74: 2nd branch of functional Requirement
**Figure 75:** 3rd branch of functional Requirement
Figure 76: Preliminary testing of pump and motor
Figure 77: Preliminary testing of motor drive
Figure 78: Franklin Electric Team with Mobile view of website.
Figure 79: Franklin Electric team after a hard day’s work.