WaterMainia Senior Design Project Report

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***Abstract*—WaterMainia is a leak detection system installed in a home to detect all ranges of leaks. WaterMainia is a multifaceted flow detection, data analysis and disaster prevention device aimed with preventing catastrophic home flooding via burst pipes, and water conservation through the detection of smaller leaks that would otherwise be undetectable. The device is composed of a magnetic flow meter, proprietary software on a single board computer and is being prototyped on a home plumbing simulation. When WaterMainia detects a water flow rate indicative of a leak it will notify the end user via an Android application and shut off water to the home if the leak is severe enough.**

I. Introduction

In the past decades we have been more conscious of water conservation and sustainability than ever before. Homeowners are threatened by water damage caused by flooding and burst pipes. 98% of basements will experience a flood in their lifetime. Repairing the damage of a flood can cost upwards of $8,000 from frozen pipe related failures. In terms of water conservation even a tiny leak can be extremely costly. [1]

Typically homeowners try to solve the issue of flooded basements by installing sump pumps, but otherwise homeowners don't have many options in the way of prevention. Typically floods from burst pipes occur due to oversights and negligence from homeowners neglecting to keep their homes properly heated during the winter. This leads to pipes bursting inflicting large damage upon the home.

Other systems similar to ours are being implemented. However, these systems are very costly (upwards of $2000) and also not market tested. The systems we found similar to ours include WaterHero and LeakDefense.

Water conservation has more or less emerged as a societal issue in the past few decades when concerns of sustainability became apparent. Recently droughts have become of major concern, especially in California, where homeowners can be fined for using too much water. 10% of homes in the United States have leaks that dump out at least 90 gallons of water a day so in drought conditions such homeowners could be heavily fined for a leak they're not even aware of.

Issues with small leaks are generally solved by the user hearing or somehow detecting the leak and getting a plumber to fix it. Fixing a small leak has of late become much easier with the advent of sharkbite fittings which allows pipes to be swapped out faster but identifying that there is a small leak and locating it is very difficult for the end user without any tools. The requirements for our project can be seen in Figure I.1.

WaterMainia also has the potential to be expanded into a leak detection network so that it can more accurately locate and isolate pipe bursts or leaks. In a networked system, flow sensors with shutoff valves would be placed at various points in the plumbing system such as at sink, or other fixture connections and would relay information back to the Raspberry Pi for further processing. Thus, the networked system would allow the user to continue using water without worrying about causing damage to the user's home.

Specification	Requirement Value
Simulate Household Plumbing	¾" Pipe
Close main during pipe burst	Within 1 Minute
Water flow metered+recorded	Tables, Line Charts, Pie Charts
Alert owner of leaks	Any Size
Power Consumption	<50W
Cost	<$500

Figure I.1: Project Specifications

II. Design

A. Overview

Our solution to these problems is to build a system that will detect and record all water flow into the end user's home. Through analysis of the water flow data, the system will detect leaks within the home and alert the owner to the issue so that they may fix it or electronically close a valve that immediately closes the user's water main, thereby stopping any and all water from flowing into the house and alerting the user.

Our system will be comprised out of three main stages, the flow meter stage, the computation stage and the power system stage. The flow meter stage consists of an electromagnetic Flow Meter which will measure the water flow passing through the water main and into the home.

B. Home-Plumbing Simulation

The Home-plumbing simulation will act to simulate a household water main. To build this block we used our physics and reasoning courses to outline and produce a system capable of simulating city pressure with minimal interference to our water sensing system. Since this design was used to test our waterflow sensor testing of the system included a U.S. Gallon/minute study. And a visual check for air bubbles and backflow.

Our system was built around a wooden box and comprised of ¾" PEX pipe. This was implemented in conjunction with a sump pump used to displace water and pressurize our system to within residential household standards. Several redesigns were in order as unforeseen factors came into play. In our final design we hope to improve on our system by making it more readily assembled and more resistant to vibrations and magnetic interference.

C. Electromagnetic Flow Sensor

WaterMania measures the user's water consumption using an electromagnetic flow sensor. This sensor is comprised of two electromagnetic coils which are placed on the top and bottom of the pipe. The coils create a uniform magnetic field within the pipe which polarize the ions in the water within the pipe which in turn creates a potential difference within the water. The two electrodes which are set into the pipe perpendicular to the electromagnetic coils, as seen in Figure II.C.1, allow WaterMania to output the potential difference to the amplification and filtration component of the sensor, as seen in Figure II.C.2, which in turn outputs a voltage to the MCP3008 [2] analog to digital converter. Lastly, the MCP3008 outputs a digital voltage reading to the Raspberry Pi 3 for further processing as described in Section II.D. The graphs for each signal are displayed after their corresponding sections: electrodes, amplification, filtering.

1) Electromagnetic Coils: The two electromagnetic coils are configured as Helmholtz Coils. The reason for using the Helmholtz Coil configuration is that Helmholtz coils create a uniform magnetic field between the two coils, as seen in Figure II.C.3, which is vital to sensor accuracy. An air cored coil is used in WaterMania to further eliminate inaccuracies which would occur if an ferromagnetic material were to be used such as an iron core. In turn this forces us to use higher amperage to make up for the magnetic field strength added by an iron core.

In the Helmholtz configuration, the two coils are placed along the same vertical axis spaced a distance of their

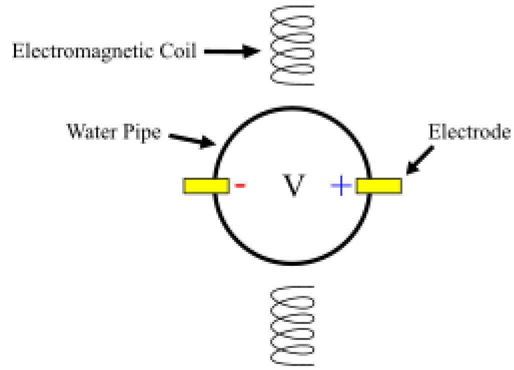


Figure II.C.1: A cross-sectional diagram of the sensor layout. Two coils are placed on top and bottom of the pipe which create a potential difference in flowing water. The difference is then measured by two electrodes placed perpendicular to the coils.

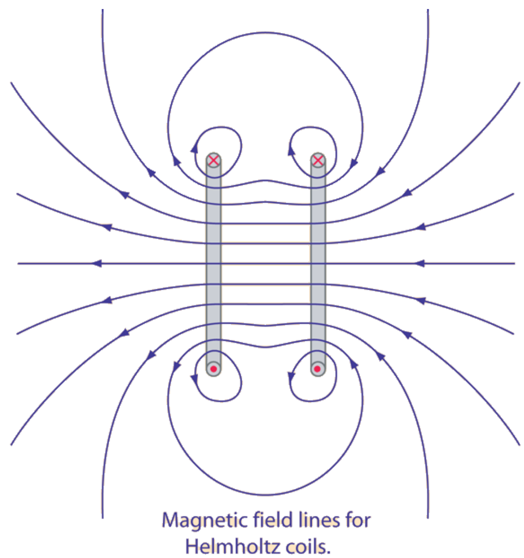


Figure II.C.2: Depicts the uniformity of the magnetic field between two Helmholtz Coils. [3]

diameter apart. The water pipe is centered between the two coils as seen in Figure II.C.1. By centering the pipe between the two coils and having the coils a distance equal to their diameter apart, the equation for their combined magnetic field strength can be simplified to Equation II.1 [4]:

$$B = \frac{32\pi NI \, x10^{-7}}{5(5r)^{1/2}}$$

B = Magnetic Field at Mid-Point (tesla)
N = Number of Coil Turns
I = Amperage
r = coil radius

How the electromagnetic coils are used to measure water flow is based in Faraday's Law. Faraday's Law of Induction states that when a conductor passes through a magnetic field, it creates a potential difference across that conductor. Thus when water, a conductor, flows through the magnetic field created by the coils Faraday's Law can be applied to the system by using equation II.2 [5]:

$$u = kBvd$$
$$u = \text{Induced Voltage}$$
$$k = \text{Device Specific Constant}$$
$$B = \text{Magnetic Field Strength}$$
$$v = \text{Water Flow Velocity}$$
$$d = \text{Pipe Diameter}$$

Equation II.2

The necessary magnetic field strength was then calculated by selecting a desired induced voltage, 25 uV, setting the water flow velocity to 12 feet per second, the maximum velocity possible within our system's pipe diameter of ¾ inch. Thus we determine that the necessary magnetic field strength of the coil is 359×10^{-6} Tesla. Knowing the necessary magnetic field strength we can then use Equation II.2 in conjunction with Equation II.3 to determine the Amperage that will run through the coils from our 5 volt supply. The self-inductance caused by the coils, variable L in Equation II.3, is calculated in Equation II.4 [6].

$$V = I((wL)2+R2))½$$
$$V = \text{Voltage}$$
$$I = \text{Amperage}$$
$$W = \text{angular frequency}$$
$$L = \text{Self-Inductance}$$
$$R = \text{Resistance}$$

Equation II.3

$$L = 2□*k*N2*r2/l$$
$$L = \text{Self-Inductance}$$
$$N = \text{number of turns}$$
$$k = \text{coefficient of air}$$
$$r = \text{radius of coil}$$
$$l = \text{length of coil}$$

Equation II.4

The above equations ultimately led to the Electromagnetic Flow Sensor specifications seen in Figure II.C.3.

Specification	Value
Voltage	5V
Amperage	120mA
Magnetic Field Strength	359 uT
Induced Voltage	25uV
Magnetic Wire Gauge	24 AWG
Total Coil Resistance	40 Ω

Figure II.C.3:Electromagnetic Sensor Specifications

2) Electrodes: The electrodes chosen for WaterMania's testing phase was 0.1019 mm copper wire. The material was chosen for its high conductivity and its low-cost. However, in future versions a platinized titanium electrode will be used for even higher conductivity as well as for its resistance to corrosion. The electrodes' output is to the instrumentation amplifier describe in section II.C.3.

3)Signal Amplification: The amplification stage of the Electromagnetic Flow Sensor is a two stage amplifier with a total gain of 1000 times. The first of the two stages is an instrumentation amplifier with a 20db gain as seen in Figure II.C.4. Currently two RC4558P IC [7] are being used in the testing phase to build the instrumentation amplifier. The Op-Amps' on the RC4558P IC specifications are shown in Figure II.C.5. Although a prebuilt instrumentation amplifier will be used in future versions of WaterMania. The reason an instrumentation amplifier was chosen is because it is a differential amplifier as well as it is highly accurate and is the optimal Op-Amp configuration for handling highly sensitive signals due to its high input impedance in excellent CMRR.

The second stage of the amplifier is simply a non-inverting Op-amp with 40db gain as seen in Figure II.C.4.

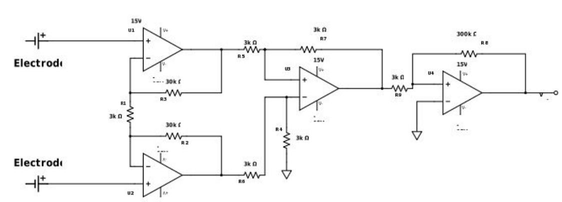


Figure II.C.4: Two Stage Amplifier

Specification	Value
Input Impedance	5MΩ

CMRR	90dB
Vss	15V
-Vss	-15V

Figure II.C.5: RC4558P Specifications

4)Signal Filtering: After amplification there is a lot of high frequency noise to filter out. Thus a four stage low-pass Butterworth filter was built to remove all noise above 100 Hz. In the filtering component the ADA4096-2 IC [8] was used.

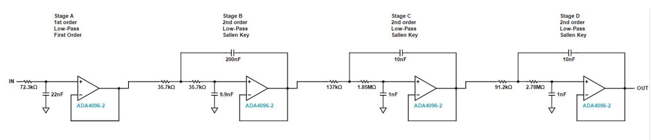


Figure II.C.6: Low-pass Butterworth Filter

D. Water Flow Analysis

The single board computer, Raspberry Pi 3 [9] will receive the filtered signal from the Magnetic Flow Sensor. It will then read the induced voltage and convert said induced voltage into a water flow rate as described below. Periodically the device will save the data locally as well as send the data to a cloud server so that it can be retrieved by the user via an Android Application as described in Section II-E. In both the local and cloud server cases, the data will be placed in a MySQL Database to simplify retrieval. The Raspberry Pi 3 will also periodically analyze the current water flow rate against past data to determine if a pipe within the home is currently leaking or has burst by checking if the current flow rate is anomalous to learnt data. It is important to note that the device will have two separate modes of detection: an At-Home and a Vacation mode. The detection mode will be determined by the user via the Android Application as described in II-E. Lastly in the event of anomalous behavior, the Raspberry Pi 3 will alert the user's smartphone and close the device's solenoid valve if necessary.

1) Flow Rate Conversion: The ability to determine the current flow rate within the main water line lies within Faraday's Law of Induction as stated in II-C [4]. Knowing this we can use the equation [10]:

$$u = kBvd$$

u = Induced Voltage
k = Device Specific Constant
B = Magnetic Field Strength
v = Water Flow Velocity
d = Pipe Diameter

Equation II.2

In this equation, the induced voltage, u, measured in volts is the potential difference of the ions within the water between the two electrodes created by the magnetic field. The device specific constant, k, is a constant programmed within the device which is determined experimentally to adjust the device for accuracy. The magnetic field strength, B, is the magnetic field strength between the two coils. The water flow velocity, v, is measured in meters per second and is the rate at which the water is flowing through the cross sectional area beneath the coils and between the two electrodes. Lastly, the pipe diameter, d, is the width of the pipe, measured in meters or the approximate distance between the two electrodes.

By manipulating equation II.1 we can determine the flow rate of the water in meters per second:

$$v = \frac{kBd}{u}$$

Equation II.2

The velocity of the water found in Equation 2.2 is then converted to a volumetric flow rate by multiplying the velocity by a factor of 0.075295. The new volumetric flow rate is now in units of U.S. Gallons per second.

2) Saving Data: The volumetric flow rate will be saved in two separate MySQL databases. The decision to have two separate databases was made for three reasons. First, saving a small amount of data of time period x locally will allow the device to respond quicker to anomalous patterns by reducing the time taken to retrieve said data than retrieving the data from the cloud server. As of now the exact length of the time period x is to be determined later in testing. Secondly, the local data will allow the device to continue operating in the event that the user loses connection to the internet. Lastly, the use of a cloud server grants the user easier access to their water consumption data by allowing WaterMainia to store a larger amount of the user's consumption data as well as allows the user to access their consumption data without the user forwarding ports to WaterMainia. In the event that WaterMania was to be accessed remotely by the user, WaterMania would have to act as a server and thus would need to have port 80 forwarded to the device. Aside from the obvious problem of forwarding ports being confusing for the average user, it can also open vulnerabilities in the user's network if they do not know what they are doing and thus deters us from allowing direct access to the WaterMania device.

The volumetric flow rate will be saved to both databases every 60 seconds. The data will be saved within the MySQL database in two fields: U.S. Gallons per Minute and a Time Stamp. The Time Stamp will allow the user to download and display their water consumption via the accompanying Android Application as described in II-E.

3) At-Home Mode Detection: Figure 2.D.1 shows the logic for determining if there is a leak or pipe burst within the user's plumbing system.

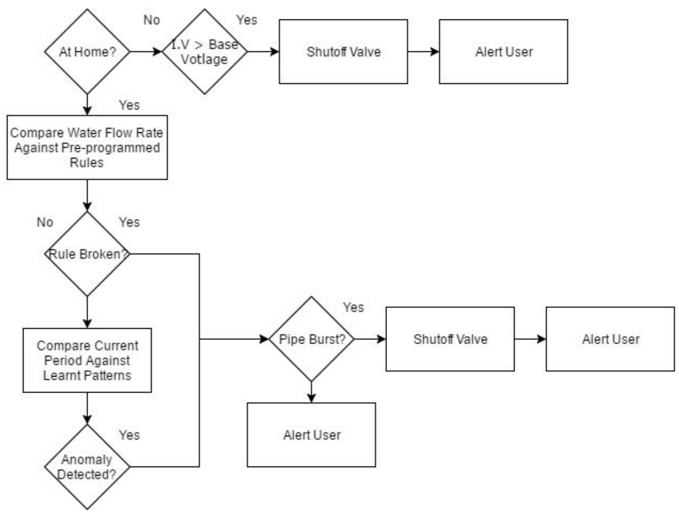


Figure II.D.1: Pipe Leak and Burst Detection

If the user has the device set to At-Home Mode, then the device first compares the user's current water consumption against a set of pre-programmed rules. These rules act as the baseline for WaterMania while it is learning the user's water consumption patterns. If any of these rules are broken then the device will then proceed with the appropriate response to the rule broken. The rules which will be pre-programmed into the device are:

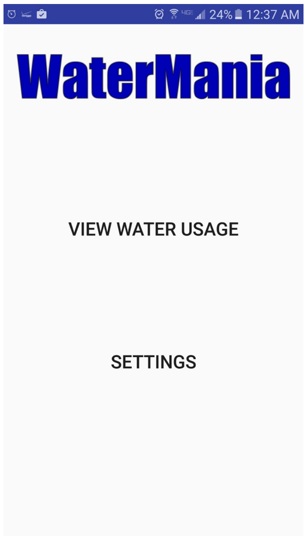
- The water flow rate shall not exceed 75% of the maximum flow rate of a ½'' pipe for more than 2 minutes. Breaking this rule will be treated as a pipe burst and will cause the solenoid valve to be shut and the user to be alerted. The reason for using half inch pipe as the basis is because most plumbing fixtures use half inch fittings and a half inch pipe is more likely to burst than a larger diameter pipe due to a smaller amount of water needing to be frozen to burst the pipe. It is important to note that the maximum flow rate of a half inch pipe is 14 U.S. Gallons per Minute, 0.233333 U.S. Gallons per Second [11].
- A low flow rate should not occur for more than one hour. Breaking this rule will be treated as a pipe leak and the user's smartphone will be notified so that he may take the correct course of action. A pipe leak is determined to be a small hole in one of the plumbing pipes, a leaking faucet, a faucet left dripping or a leaking fitting.
- Water Flow has been detected within the last 24 hours. If this rule is broken then the user will be asked if he would like to switch to Vacation Mode. The reason for this rule is to help WaterMania react more quickly to pipe bursts in the event that the user is in fact away from home for a long period of time and simply forgot to switch WaterMania into Vacation Mode.

4) Vacation Mode Detection: When the user is away from home he has the ability to switch WaterMania into Vacation Mode. In Vacation Mode, WaterMania will treat any change in water flow rate as a potential pipe burst or leak and will immediately shut the solenoid valve and notify the user to mitigate damage.

E. Android Application and Remote Access

The Android Application as well as the cloud server has been designed to enable the user to intuitively use WaterMania and access their water consumption data. The reason an Android Application was chosen is to allow the user to be able to remotely control WaterMania and receive alerts even when they are not home. While the cloud server was implemented to allow the user to access their water consumption data even when their device is temporarily disconnected from the internet and to remove the need to forward your router's ports to WaterMania.

1) Android Application: As seen in Figure II.E.1, the Android Application for WaterMainia features two main activities: the View Water Usage Activity and the Settings Activity. In Figure II.E.2, you can see that the user is presented with two sets of date and time pickers. These date and time pickers allow the user to choose the period of time which they want to retrieve their home's water consumption data. The first set of date and time pickers is for the start date and the second set is for the end date. Upon picking your desired time interval and hitting submit, a request to run a PHP script is sent to the cloud server and the data is then echoed back from the MySQL database to the user's application.



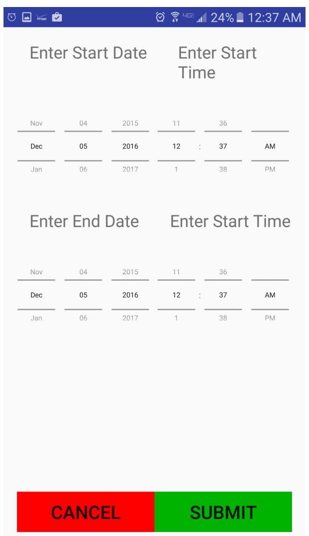


Figure II.E.1: Main Menu *Figure II.E.2: Date Selector*

Upon receiving the data, the android application compiles said data into three types of graphs which are capable of displaying varying information about your water consumption as seen in Figure II.E.3.

Graph Type	Time Stamp	Flow Rate	Total Water Usage	Special Events
Table	x	x	x	x
Line	x	x		
Pie	x		x	
Scatter	x	x		x

Figure II.E.3: The types of graphs included in the Android Application and their contents.

The first type of graph is a table much like the one pictured above in Figure II.E.3. The table will consist of four columns: time stamp, volumetric flow rate, cumulative water usage, and special events, where the first entry is the initial time selected and the last entry is the final time selected on the previous screen. Figure II.E.4 gives a description of what each column contains.

Column Title	Description
Time Stamp	Contains the date and time which a particular entry corresponds to.
Volumetric Flow Rate	Contains the water flow rate at a particular time in U.S. Gallons per Minute
Cumulative Water Usage	Contains the total amount of water which the user has used since the start of the time period in U.S. Gallons (The first entry will have 0 gallons used).
Special Events	Contains whether or not an alert was sent to the user and whether it detected a pipe leak or burst.

Figure II.E.4: Android Application Table Column Description

The Line Graph, Pie Chart and the Scatter Plot's data descriptions are the same as the Table's data description in Figure II.E.4, however the Line Graph visually displays changes in flow rate, while the Pie Chart visually displays total water used in intervals one size smaller than the interval picked, ie if the user selects data across one week than the Pie chart will be split into seven intervals to represent each day of the week. However, the user will be able to customize the intervals using a user interface to shrink or enlarge the time period of each interval. Lastly, the Scatter Plot will show the volumetric flow rate as well as the times where pipe leaks and bursts have been detected. Although the Scatter Plot does encompass all of the information which the Line Chart does, we have decided to include both types of graphs because the two graphs compliment each other's strengths and weaknesses. That is that the Line Chart does a better job at displaying trends in data points when there are less data points, while the Scatter Plot does a better job at displaying trends amongst large amounts of data.

The second Activity, the Settings Activity, is where the user remotely controls WaterMania from their Android Device as seen in Figure II.E.5. From this screen WaterMania is initially connected to the user's WiFi via Bluetooth; the user can remotely control the device's solenoid valve by either overriding the solenoid's state to open or close, or by allowing WaterMania to control the solenoid. Next, the user can set the device's current mode of operation to either At-Home Mode or Vacation Mode.

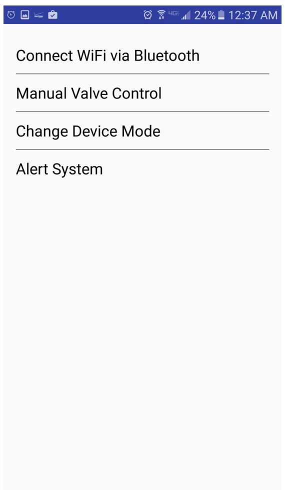


Figure II.E.5 Settings Activity

Lastly, the user can choose which types of alerts WaterMania will send to him in the event of a pipe leak or burst. The user can choose either SMS messaging, push notification or both.

2) Cloud Server: We are currently using HostGator as the service for the cloud server as it allows us to host a MySQL database as well as run PHP scripts remotely. Inside the server a MySQL database contains all of the flow data dating back until the start of the device where each entry consists of four fields: a time stamp, volumetric flow rate, a boolean determining if an alert was sent and a string which contains what type of alert was sent.

However, the cloud server does not solely act as a point for data retrieval, but also acts as the middle-man for transferring commands between WaterMania and the user's Android Application. From WaterMainia's end, WaterMania polls the server every 60 seconds to check for any settings changes made by the user. It does this at the same time that data is uploaded so that the device does not have to separately connect to the server and thus wastes as little processing power as possible. If a command is found then the command is downloaded and executed by the device and is then deleted from the cloud server. WaterMania also routes all push notifications through the server by running a PHP script located on the cloud server to send the alert to the user's Android Device.

From the Android Application end, the Android Application pushes all commands onto the cloud server where they will be stored until the user's device polls for the commands.

F. Solenoid Valve

We chose to implement our water main shutoff with an electronic solenoid valve controlled by a solid state relay. This valve is being driven directly from a residential standard 120VAC receptacle. For convenience and with power consumption in mind we chose US Solid Solenoid Valve. [12] This valve only has an 18W power rating and manual override providing safety for our system. With temperature tolerances of 14-248 degrees fahrenheit we are well within our extreme tolerances of residential water temperature, making this valve a perfect fit. Simulations and testing proved this valve to be exactly what we needed.

III. Project Management

We have accomplished all of the goals we set out to achieve for MDR. We enabled our flow meter electrode voltage to increase with a greater flow rate and decrease with a lesser flow rate. Our single board computer is measuring the voltage from the flow meter and communicating with the solenoid valve; closing the valve when the flow meter passes the threshold voltage we set.

Our slated CDR goals are to have general mode implemented with fully parameterized flow data being read from the flow meter being the input for data analytics on the software side and for the whole of the system to be integrated and compacted i.e. all signal filtering and power systems on custom PCBs with everything ideally fitting into an enclosure so our system could easily be installed and tested outside of the home plumbing simulation.

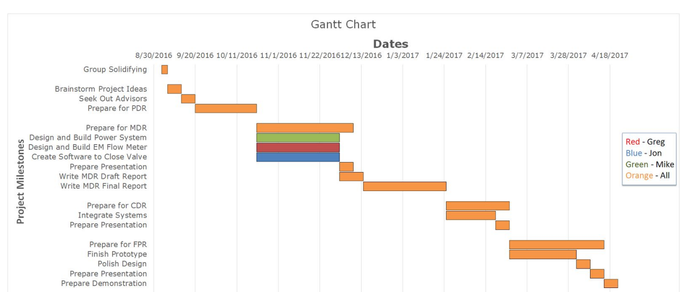


Figure III.1: Gantt Chart

IV. Conclusion

At this point in time our project consists of a simulation system built with the flow meter fastened onto it and the flow meter's electrodes feeding into the computation system. We got to this point by building the three main parts separately, connecting them together and consequently dealing with the myriad of unforeseen issues that popped up. Now that all of these issues have been dealt with we can build upon our system; our full goals are within our reach.

Our immediate plans are to revamp the flow meter to make it induce a greater voltage by using an iron core for the magnetic coils which will create a larger voltage range. With this we can associate the variable flow rate, create an enclosure for the flow meter to hinder any outside inductive interference, change the power system to input a modified sine wave into the coils to disperse any kind of ion buildups, refine our current analog amplification and pulse shaping to further eliminate noise and make the signal more clean and consistent, coding in the data analysis systems with which we will be able to start detecting smaller leaks and implement standard mode, and an expansion of the android app where the end user can access their water record and data.

An issue that we foresee popping up is difficulty creating a small very accurate parameter between water flow and induced voltage in the flow meter. Another possible issue is preventing false positives with the general mode functionality, where the user would use large amounts of water (I.e the washing machine, two sinks, and flush every toilet in the house) could possibly trip the shutoff valve threshold.

Acknowledgment

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