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The Development of a Partial Flow Sensor for Tiles

Richard McEver
University of Tennessee, Knoxville, rmcever@utk.edu

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EECS Senior Design

Final Report

The Development of a Partial Flow Sensor for Tiles

Team Members
Austin McEver, Tanner Hobson, Jacob Massengill, Andrew Wintenberg, Tim Lam

Customer
Dr. Papanicolaou

Team FA16-06

25 April 2017

Executive Summary

Our main goal for this senior design project was to design, develop, and build a prototype for a device which is capable of measuring the volumetric flow rate of water through underground pipes known as tiles. Such a device is needed to determine how water is flowing over your land. Such information could potentially be used to better irrigate your land, or to mitigate flooding. The largest constraint on our design was the final cost to build, and is what makes our project both non-trivial and significant. Similar devices already exist in some form, but are exceedingly expensive, making them effectively unavailable to those who need them. Our device was built under a highly constrained budget, allowing future devices to be made for under $30 USD with the right manufacturers.

Due to the nature of our project, our device needed to be robust. The tiles our sensor is supposed to be in are subject to many situations that most electronics are sensitive to. This includes but is not limited to full underwater submersion, freezing, mud, and dirt and debris. All of these factors needed to be considered in our design to be considered successful.

The basic principle of our device relies on a series of wires hanging from the top of the tile, each incrementally getting shorter. When water comes into contact with a wire, our sensor will detect the contact, and signal. This effectively gives us the height of water in the tile. Then through testing and basic physics, we have created a lookup table based on this height which maps water height to the volumetric flowrate. Each tile will need to have a lookup table created based on its diameter and the incline at which it rests.

Currently, we have built our sensor for determining the height of water under our given budget, and have created a lookup table for our first tile. This effectively lays the foundation for all future tile sensors, and proves that our concept works. This was no easy task. Our device overwent multiple complete redesigns throughout the semester. This was caused by incomplete data and unproven concepts. Our initial design included the use of an ultrasonic sensor and pressure transducer. This idea was discarded after finding out our supply of ultrasonic sensors was unreliable, and the pressure transducer was determined to be an impossibility by Dr. Papanicolaou. We then attempted to use another promising sensor, which we will from this point forward refer to as the “Magflux” sensor. The principle behind this sensor is that it would measure the magnetic flux created by the water as it passed through an electric field. This idea needed to be discarded after determining it would not be possible without full flow conditions, directly violating requirement 1.1.1 of the requirements document. Secondly, the sensor would have been exceedingly expensive, being several hundred dollars by itself. We arrived at our current and final design after ruling out several more unrealized designs.

Requirements

1. Capabilities
    1.1. The *device* **MUST** measure the flow of water through a tile.
        1.1.1. The *device* **MUST** be capable of measuring the amount of water flowing through a tile when the tile is partially full.
            1.1.1.1. In full-flow conditions, the device may but is not required to measure the flow.
        1.1.2. The *device* **MUST** be capable of measuring the flow of outward-flowing water under open channel flow conditions in the range of 0 to 180 gallons per minute (gpm).
            1.1.2.1. The maximum possible rate of flow is 350 gpm for 6 inch tiles.
        1.1.3. The *device* **MUST** measure water flow within a degree of accuracy of ± 5 gpm.
    1.2. The *device* **MUST** write temporal water flow data to storage.
        1.2.1. The *device* **MUST** have sufficient storage for lengths of 3 months (90 days) without intervention.
        1.2.2. The *data* **MUST** be easy to transfer to another computer through physical means.
            1.2.2.1. Physical means includes but is not limited to: SD cards, USB flash drives, physical cables, and near-field communication.
        1.2.3. The *data* **MUST** be written in a standard data-describing format.
            1.2.3.1. Some possible data formats include: comma-separate values tables, fixed-width tables, and binary-encoded tables.
        1.2.4. The *data* **MUST** be sampled at an adjustable rate with a minimum of once per minute.
    1.3. The *device* **MUST** be in a watertight container.
        1.3.1. The *device* **MUST** be capable of continuing normal operation while the pipe is in full-flow conditions.
        1.3.2. The *device* **MUST** be undamaged by submerged conditions.
2. Form
    2.1. The *device* **MUST** consist of two distinct parts: the sensor and logger devices.
    2.2. The *sensor* **MUST NOT** restrict more than 50% of the minimum flow out of the tile.
    2.3. The *sensor* **MUST** be installable in tiles with a diameter in the range of 4 inches to 6 inches.
    2.4. The *logger* **MUST** maintain a minimum form factor.
3. Power

3.1. The *device* **MUST** be capable of operating under its own power for a minimum of 3 months without intervention.
3.2. The *device* **MUST** use battery power to provide its energy.
3.3. The *battery* **MUST** be easily replaced or charged.
3.3.1. Charging the device can be but is not limited to: using a solar panel during the day or swapping discharged for charged batteries so that recharging can be done at a separate location.

4. Cost
4.1. The *device* **MUST** not cost more than 500 USD to build.
4.1.1. Ideally, the device will cost less than 100 USD to build.

5. Durability
5.1. The *device* **MUST** withstand temperatures between 0℃ and 30℃.
5.1.1. Standard temperature the device will encounter range from 1.7℃ and 21.1℃.
5.2. The *device* **MUST** withstand below freezing conditions.

Changelog

No changes were made to the original requirements document throughout the course of the project.

Design Process

Our design process included a lot of early prototyping and early failing. This allowed us to try new ideas without becoming stuck with a design which simply would not work. Initially, the team decided to try a pressure sensor and an ultrasonic sensor, but, given advice from the customer, later changed to an electrode sensor. We found success with this design somewhat late in the semester, but the team worked hard to ensure the sensor was in working order by the end of the semester.

Project Decomposition

From the beginning of the project, we knew that our roles would be fairly binary with regards to adhere to the requirements. Andrew and Tim would work together on researching, designing, and building the electronics for the sensor. Then Tanner, Jacob, and Austin would work on the code for the sensor once it was completed. In this way, we were able to decompose the project into two large categories: hardware and software.

Underneath the hardware category, we split up the project into multiple parts again, largely delineated by the necessity of prototyping to test our ideas. The main part of our time and effort was spent on getting the sensor itself working, with the knowledge that we could easily add the data storage, power, and durability towards the end of the project. Over the course of the project, we built prototypes for multiple sensors before arriving on the one we ultimately chose. Once the sensor was chosen and tested, we tested the extra hardware on its own, with a separate Arduino and code base. This was done to limit the number of moving parts while testing, so that we could ensure that any errors during the process were because of the hardware and not because of the way different components worked together.

As noted above, the software for the project was largely composed of small, disparate programs that have one purpose. For example, when testing the SD card, we wrote a small program that only writes to the SD card with fabricated data, which allowed us to isolate the other parts and ensure correctness. In the end, there was not very much software needed for the project, so its decomposition was deemed sufficient.

Project Standards

We held few standards for the project, though the ones we chose to keep were implemented fully throughout. One standard that we adhered to is that we built any hardware components on a Vector Board. This provided extra structure and also allowed us to more easily debug the hardware components because of its organized structure. On the documentation side, we adhered to some conventions in a shared Google Drive folder. In particular, whenever we had any documents we received from the customer of from the TAs, we would put them in a “Given” folder. Additionally, assignments for class went in “Assignments,” documents the customer requested went in “Requested,” notes taken during meetings went in “Notes,” and any pictures we took went in “Pictures.” By having this rigid structure, we were able to more easily store and locate important documents.

We tried to hold a high standard for communication with our customer, Dr. Papanicolaou. We met with our customer and his grad students every Tuesday at 5 p.m. throughout the semester. This allowed us to keep him up to date with our progress, as well as allow him to provide us with valuable feedback. During these meetings, we took detailed and meaningful notes of the events of the meeting, which were distributed no later than the next day. Such standards allowed us to maintain clear communication, as well as hold both parties accountable for any statements made.

Open Questions

One of the largest open questions we had to answer was: why is there not a sensor like this already? The idea--using a sensor to detect the volumetric flow rate of water through pipes--had already been applied in other scenarios and other countries, but none of the existing solutions were cost effective or easy to install in the field. During our research, we found a sensor that aimed to solve our problem, but fell short on the cost effectiveness we aimed to address.

After determining why a similar device device does not already exist, we needed to question, *how do we measure the volumetric flow rate of water*? We first approached this question from a physics standpoint, and realized we just needed to know a few answers to a few basic questions; the depth of the water, the velocity of the water, and the diameter of the tile were all we needed to know to calculate the flow rate. Since the diameter of the tile is both constant and known, we could ignore that aspect of the question and focus on the depth and the velocity of the water. Knowing about the installation, diameter, and shape of tiles gave us a lot of room to work with: we really only needed to measure the water depth. We then researched sensor types that could answer each of these questions. Because of our prior knowledge, we opted to only measure the height of the water, and use a lookup table (which we have called our "calibration curve") to determine the flow rate based on that height.

Alternatives Explored

In a sense, our project consisted almost solely of the testing of different alternatives and evaluating their effectiveness. For example, the sensor component of our project was finalized in the last few weeks, though we had spent the weeks up to that point testing all different manner of sensors. We initially tested a pressure transducer, which would measure the depth of the water via the water pressure at the bottom of the tile, then it would convert this depth into a flow rate through a lookup table that we referred to as a "calibration curve." Ultimately, despite some early successful tests, this alternative did not pan out because our customer preferred we spend our time on the other possibilities.

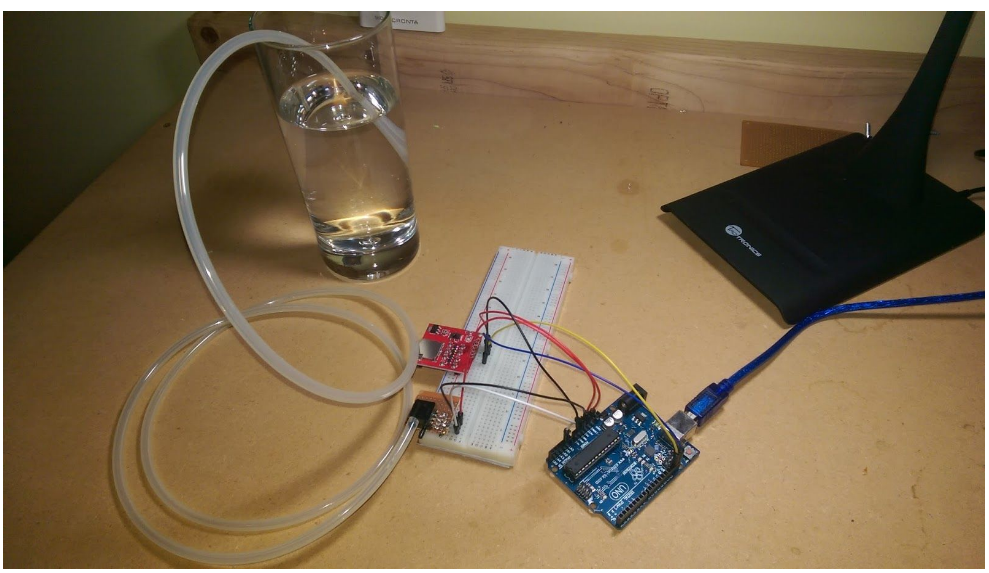


Figure 1: An early prototype using the pressure transducer.

In addition to the pressure transducer, we also tested a waterproof ultrasonic sensor. The idea behind this method is that we would use an ultrasonic transceiver to emit a high pitched sound at the top of the tile, then measure the time it takes for the pulse to reflect off of the surface of the water. This time can be directly converted into a measurement of distance based off of the speed of sound through air. Initially, we were concerned about whether an ultrasonic pulse would actually reflect off of the surface of water, but after initial testing with a non-waterproof sensor, we concluded that it should work. However, once we began implementing the waterproof variant, we realized that we would need a custom amplifier to power the transceiver. Implementing this amplifier would have greatly increased the time needed to build the prototype, and as we realized later on, the selected solution provides comparable accuracy, which was one of the main draws to the ultrasonic sensor.

The final alternative sensor we looked into was a bobber connected to a linear or rotary potentiometer. By using the bobber, we have a reference point to the surface of the water to ultimately determine the depth of the water. This would be done by measuring the height and angle of the bobber, and doing a short calculation. This idea was discarded only because we found our final selected solution to be significantly easier, cheaper, and more intuitive.

Another feature of our device that had multiple possible solutions was the manner in which we stored the data collected by the sensor. There were two main possible formats, each with a list of pros and cons. These two possible formats were binary, and CSV. With binary storage, reading and writing data to and from our software would be easier, and we would be able to store more data in the same amount of storage space when compared to CSV; as opposed to the CSV format, which had the significant benefits of being a universal format and human readable. These benefits were decided to be more significant than the superior storage optimization offered by the binary format, as we are not collecting enough data for there to be a significant difference in data size. Our decision to use CSV over binary also means the potential of using analytics tools such as Microsoft Excel to perform more advanced statistical analysis, without the need for us to create custom software to do so.

Our powersource was also another component of the project which had a few different potential solutions. We knew we needed a battery, and we knew we wanted to use a sealed lead acid battery, as it would provide us with the most power for the lowest cost. What we did not know was if that was going to be our only power source. We had discussed the augmentation of solar panels to the device with our customer. This would potentially give our device complete self-sufficiency when combined with a lower power microprocessor, but we ultimately decided not to pursue this route. We came to this decision based on the resource and time limitations of the project. We finally decided to use just a simple, non-rechargeable solid lead acid battery in our final design.

The last module of our device which had multiple possible solutions was the processor. For this, we had essentially three options: Use the Arduino Uno from testing in the final prototype, or use the ATTiny or Atmega microcontrollers. We quickly discarded the Arduino for two reasons, namely that it added about 20$ USD to the final design and their could potentially be legal issues with using the Arduino in a product intended for the market. We decided to use the Atmega for this prototype, as it retains the memory bandwidth of the Arduino, but at a significantly reduced cost. In the future, we would like to switch to the ATTiny, as it would both reduce the final cost by about $1 USD and be much more power efficient; the ATTiny could potentially add months to the battery life of our device. The main issue with the ATTiny is that it has a much less memory than the Atmega, and as such will require more time devoted to software optimization than what we currently have.

Selected Solution

We have temporarily named our final design the Electrode Sensor. This device consists of a series of incrementally shorter wires hanging at the top of the tile towards the bottom. In this system we measure the depth of the water in order to determine the volumetric flow rate. We measure the water's depth by taking advantage of the conductivity of water (especially with sediment in it); we put a positive voltage at the bottom of the tile and measure how many contacts are submerged under the water. If a contact is submerged, it will receive a voltage reading and be given an "on" reading, otherwise it will receive no voltage and be given an "off" reading. Calibration curves are then created through testing and measurement and used to convert water depth to flow rate. Initially, we tested this concept using individually soldered wires, then switched to a ribbon cable once we were confident this solution would be our final solution.

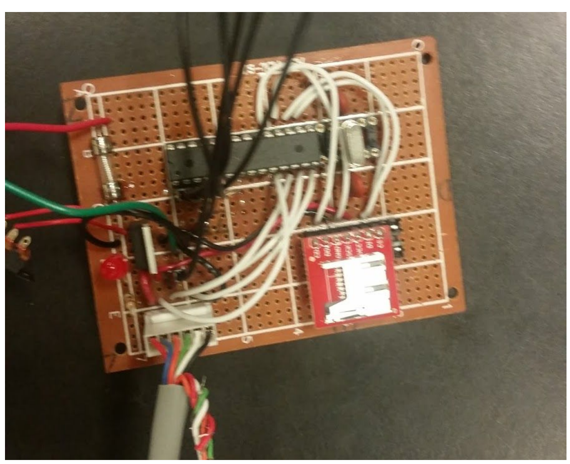


Figure 1: Control board of the selected solution.

This solution aids our customer's desire for denser, more accurate, measurements near bottom of the tile than at the top. We also were able to use shift registers to limit the number of wires that need to be routed from the sensor to the microcontroller, which in turn makes our system more robust with fewer possible points of failure. To control the device, we used an ATMega328p processor; this component required adding timing crystals, but was ultimately beneficial because it allowed us to reduce our overall cost without sacrificing power. To store data, we used a standard micro SD card adapter to to record data in CSV format.To power the sensor, we used a sealed lead acid battery without solar charging. We originally contemplated adding solar panels to increase the battery life of our sensor (perhaps even making it self-sufficient), but due to time and resource constraints, we decided it was against our best interests. Finally, to secure the device from water and other elements, we are using a waterproof project box to store everything in. This will ensure our device lasts as long as possible in the elements.

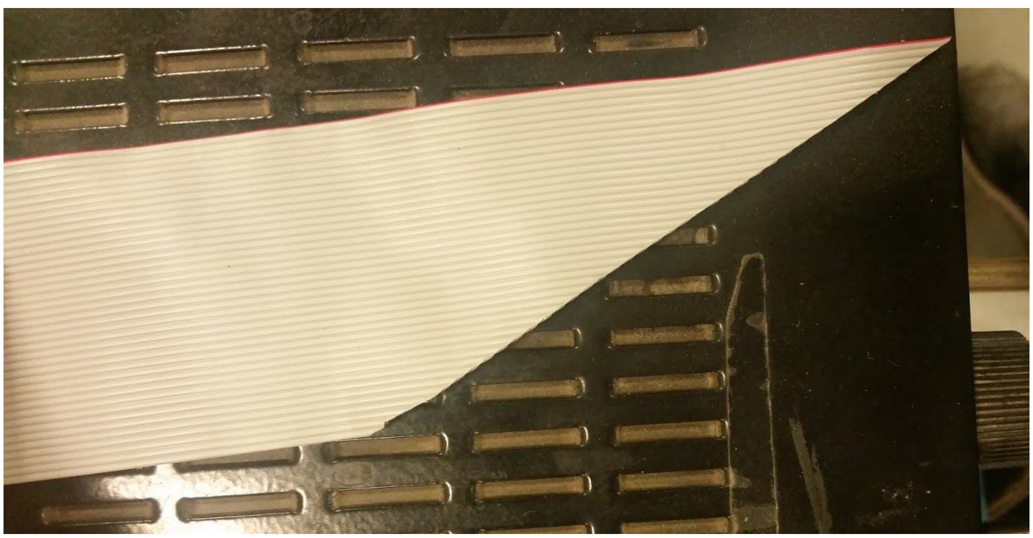


Figure 1: The ribbon cable used for the electrode sensor. Note the diagonal cut that demonstrates our ability to allow variable resolution in the tile.

Requirement Satisfaction

In order to ensure that all requirements were met, we tested each of the requirements against the actual performance of our device. For example, we were able to test that requirement 1.1 was satisfied by placing the device in an open channel flume and determining that unique height values were being given for varying depths of water. Another example is how we checked requirement 2.2 by verifying that our sensor was not restricting water flow by more than 50%. All other requirements were checked in this manner.

Implementation Verification

In order to ensure our project wes a success, we needed to ensure that as we proceeded through each step of the project (requirements, design, implementation, testing, and evaluation), that the work produced was verified against the outcomes of the prior phases. We began this process early on in the requirements phase, and have continued until the end.

For the requirements phase, we ensured our success by keeping our requirements as general as possible. This allowed as much flexibility as possible when it came time for the design phase. An example of this generality can be seen in requirement 1.1. We did not restrict ourselves to any one way of detecting the water flow rate. In turn, this allowed us to rapidly prototype multiple designs, and did not force us to specify exact design specifications such as the number of wires the ribbon cable must have.

To ensure our design matched our requirements, we checked that our design would pass each of the requirements before moving into the implementation phase. For example, for each design, we kept a running total of the cost of each component so we would have a running total cost. This ensured that none of our designs violated requirement 4 of our requirements documents.

During the implementation phase, we ensured that our design and requirements were maintained by keeping the implementation strict to the design. This meant finding parts which were at or under our projected budget, and which would be robust enough to survive the underwater conditions our device is subject to.

For testing, we simply verified that our prototype survived each of the requirements tests. We again verified that each part remained at or under our projected budget, and that the prototype could survive underwater conditions. We did this by submerging the device for 30 minute periods and determining full functionality was maintained. We repeated this process in the evaluation phase, by determining whether or not our tests were accurate, and by submitting our device to harsher tests. In the end, we were able to stay inline with our original requirements by maintaining our consistency throughout each step of the project.

Project Results

We built a sensor to the specifications of the requirements document. Although there were some hiccups, the overall concept and implementation were sufficient to meet the customer’s needs. Over the whole semester, we tested many variations of sensors in order to arrive at the one that provides the most benefits for the lowest cost. Ultimately, we tested our sensor in both standing water in the lab, and running water in a simulated tile in an open channel in the H&S Laboratory, and in both scenarios, we were able to accurately measure the flow depth. When we computed a calibration curve to map the flow depth that we read with the sensor to the flow rate from the open channel, we obtained a consistent and reproducible calibration curve. We also demonstrated that the sensor can operate under its own power and verified that the SD card is suitable for long term storage. Overall, we can conclude that we have fully met all of the requirements agreed upon with the customer.

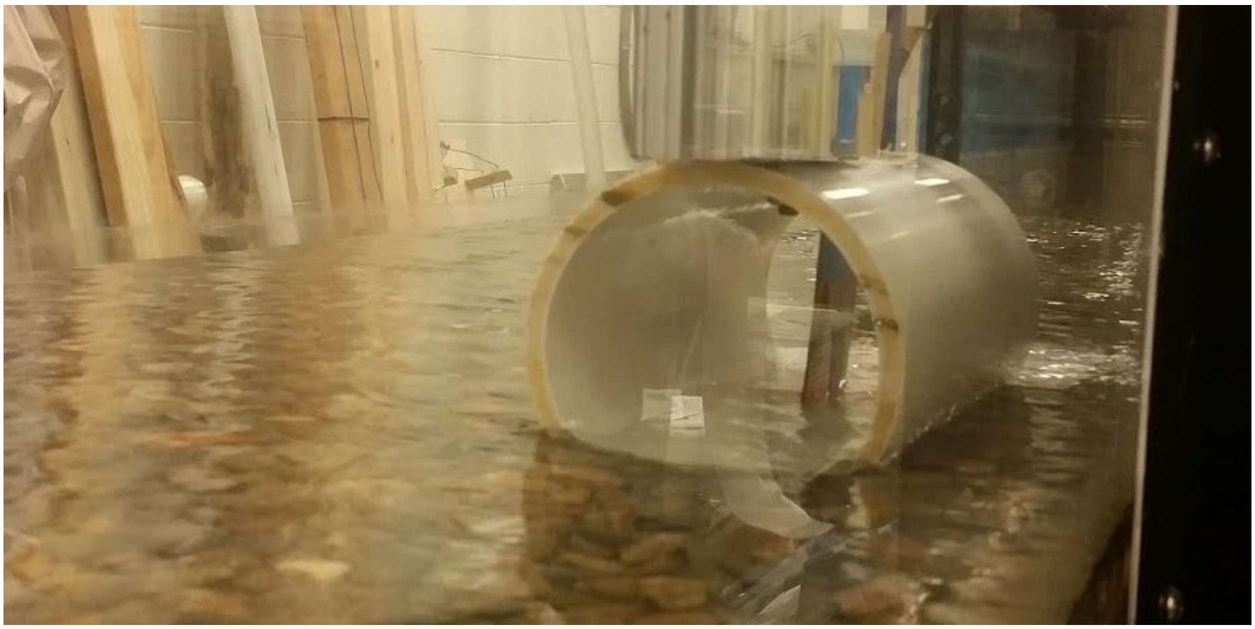


Figure 1: The section of tile used in the H&S Lab to test our final sensor.

Lessons Learned

Throughout this project, our team as a whole learned how to work on a project with many people and many moving parts. We also learned how to communicate with a customer on a large project and the importance of clear communication. This project was not trivial for any of us, and we encountered many hardships along the way which have made us better engineers overall. Many lessons that were learned throughout this course could not have been taught to us in any other manner.

Unexpected Events

Our team had the unique challenge of having to change its structure from the previous semester, as we lost one member and gained two more. This was a challenge for us, as we had to quickly get to know one another while also trying to complete assignments and make deadlines. More pressingly, there were several unexpected inconveniences throughout the semester. These inconveniences were caused by miscommunications and unavoidable happenstance.

One such major inconvenience was with regards to our original design. We believed fully that we were on pace to finish our original design fast, and then would have many weeks to test and polish the system. However, due to a miscommunication between our team and our customer's team, we were actually building a sensor which would not work. This was quickly pointed out by Dr. Papanicolaou, and we revised our design afterwards. We ensured no such similar events would happen again by establishing a strict note-taking policy for our meetings, and maintaining an open line of communication between us and Dr. Papanicolaou's team.

Another issue we had and may face again in the future deals with the physical nature of our device. We had issues with loose wires, breaking parts, and parts exposed to water in the initial prototypes of our final sensor. These issues have been mitigated through more robust construction, but cannot be outruled as a potential problem in the future.

Future Changes

There are several changes we would like to see happen for this project. One such change would be to optimize the self-sufficiency of our device. We can do this by reducing the overall power consumption, and by allowing the device to produce its own power. Our extended plans would be to change our microprocessor from the ATMega to the ATTiny. This new microprocessor is much more power efficient, and could potentially improve our battery life by a matter of months. However, this processor has less memory for us use, and as such we will need to spend significant time optimizing the software to make it work. To allow the device to operate under its own power would involve us adding solar panels to the device. We didn't add this component for two reasons: we didn't want to spend too much time on the power source until we were sure our sensor would work, and by the time we realized our sensor was going to work it was too late to order the panels.

As far as our team goes, we wish we had held ourselves to stricter deadlines and more clearly defined team roles and responsibilities. We often found our work would run over time, and we would not have customer approval in time for submission. This resulted in us submitting documents without customer approval until later. We also ran into the issue of being confused as to who was doing what and when. This was caused by us not strictly giving tasks for each of us to complete and leaving our roles ambiguous.

Relevant Coursework

We do not believe that any one particular class or previous coursework project contributed to the success of our project, but that collectively, all of our classes have taught us the skills we have needed. Developing the Arduino software used general programming skills taught in CS102 and CS140. Though no class teaches the Arduino language, it is similar to the C++ that is taught in most lower division CS courses. Implementing the sensor took knowledge from physics courses such as PHYS231, as well as general power electronics classes, such as EE335 and EE336.

Team Member Contributions

Throughout this project, all members contributed in different ways; some contributed more in the technical aspects of the device, while others contributed more to reports and documentation. All team members played a key role in the success of this project.

Individual Responsibilities

Tanner is a computer science major and as our leader, was responsible for managing the team and for writing MBO reports. He was also responsible for drafting, revising, and sending emails to the customer, instructor, and TAs. Tanner acted as the first liaison to Dr. Papanicolaou, and assisted in the creation of the custom software needed for our device.

Jacob, another computer science major, acted as our lead researcher. He was responsible for searching for different sources of information online and sharing what he found with the rest of the team. Jacob acted as a second liaison to Dr. Papanicolaou as well. He assisted in the creation of the software for the project. Finally, Jacob took notes for each of the meetings and distributed those notes afterwards.

Andrew, an electrical engineering major, elected to be our team’s solutions architect. He was responsible for the design and construction of our device. As one of the people most familiar with the type of electronics we would need for this project, he was responsible for helping explain different electrical concepts or problems to the customer as needed.

Austin, our final computer science major, was our lead reporter. He was responsible for creating first drafts of any documents needed for class, to give us a base to work from. Later, when the papers were finished, he would go back over them and ensure they kept a common style. Austin also assisted in the creating the software for the project.

Tim, our other electrical engineering major, acted as our lead tester. He was responsible for working with Andrew on any designs and implementation, but also for coming up with the plans we used to test our device and running through them once the device was finished.

Individual Contributions

Tanner supported the team by creating the MBO reports we needed, and by managing us. He kept track of deadlines for us, and orchestrated online meetings via Slack. Tanner also created a significant portion of the software for this project. Since Tanner had the most experience with creating software for similar projects, he was able to help Austin and Jacob understand and build the needed software. Tanner also brought the team donuts as motivation for doing good work.

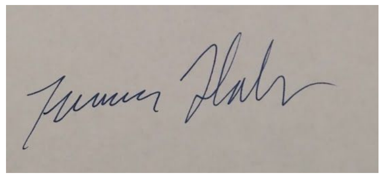
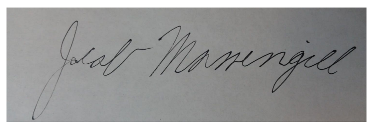
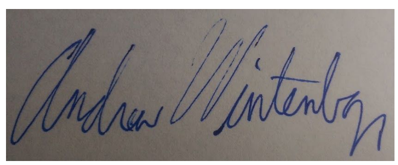
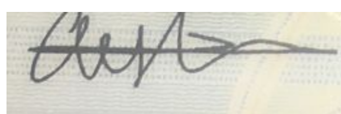
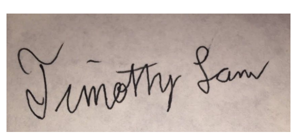
Jacob advanced the team's collective knowledge by researching potential designs for the sensor, as well as potential vendors from which to purchase parts. Jacob was the first one to discover the promising Magflux sensor. He was also responsible for note-taking during meetings, as well as the distribution of said notes afterwards. Jacob assisted in general debugging of hardware and software as well.

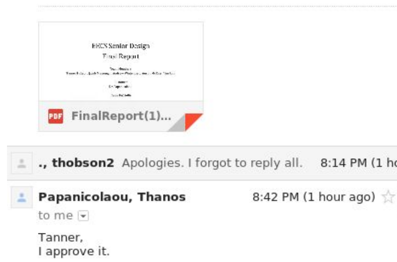
Andrew handled most of the physical and electrical aspects of the sensor as the primary builder of the unit, selector of parts, and technical designer. He created the schematics for the sensor and assembled the sensor from battery to microcontroller to electrode sensor. He also assisted with reports and did preliminary tests as he was assembling the sensor. Andrew also contributed concrete designs for the electrode sensor soldering the first iteration and using a ribbon cable for the final prototype.

Austin provided valuable design ideas, contributed to reports, assisted with presentations, and aided in the development of the sensor software. He first contributed the idea of the electrode sensor, and while the team initially pursued the ultrasonic and pressure sensors, the electrode sensor ended up providing the most elegant solution. He also maintained his role as lead report writer, ensuring all team documents met requirements in a timely manner. Austin documented the testing through video and pictures and helped prepare presentations. Finally, he contributed to the code base.

Tim aided with the design of the power supply and distribution of the sensor. He also helped with all of the reports and was very instrumental in providing technical insights to the customer. As one of our electrical engineering students, Tim helped design the final sensor. In the final weeks, he aided in the production of a functional schematic of the electronics. Additionally, he helped facilitate team meetings and ensured that everyone who was available could come to the meetings.

Team Member and Customer Approval

Name (print)	Name (signed)	Date
Tanner Hobson		4-25-17
Jacob Massengill		4-25-17
Andrew Wintenberg		4-25-17
Austin McEver		4-25-17
Tim Lam		4-25-17

Dr. Papanicolaou		4-25-17