Batteryless Encapsulated Hydrometer

Design Document

Team Number:

SDDEC20-06

Client and Advisor:

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Executive Summary

Development Standards & Practices Used

- Kicad for schematic layout and PCB design
- FreeCAD for housing and mechanical layout and design
- Waterproof and food safe housing capable of IP68 rating standards

Summary of Requirements

- Wirelessly powered
- Batteryless
- Inert
- Wirelessly transmit readings with a minimum frequency of hourly
- Measure the specific gravity of the fluid
- Measure the temperature of the fluid
- Completely encapsulated

Applicable Courses from Iowa State University Curriculum

- EE285
- EE303
- EE452
- EE333
- EE201
- EE230
- IE305
- EE311
- PHYS221
- CPRE 281
- CPRE288

New Skills/Knowledge acquired that was not taught in courses

- Wireless power transfer using matched antennas

- Bluetooth communications on embedded systems
- Tilt hydrometer design and implementation

Table of Contents

List of figures/tables/symbols/definitions (This should be the similar to the project plan)

1 Introduction

1.1 Acknowledgement

We would like to acknowledge Assistant Professor Henry Duwe for his contributions towards our technical design. Professor Duwe works at Iowa State University and focuses on computing and networking systems for secure and reliable computing. One of his current research areas concentrates on wireless energy harvesting and limitations associated with onboard functionality. His research in this area has provided us with the groundwork information that is fundamental in the implementation of our design. He has also overseen all the individual research that our team has compiled throughout this project. We would also like to acknowledge our client Duwe Amalgamated Research Corporation for their sponsorship in this project.

1.2 Problem and Project Statement

In the past decade researchers have been exploring the many facets of wireless energy harvesting. In this process an RF signal is used to wirelessly transmit power to a designated electronic platform. This platform uses either a re-chargeable battery or capacitor to store and distribute the signal energy. Many embedded computational systems are beginning to take advantage of this developing technology but there are many issues surrounding its implementation. Such issues include limited power transfer, signal reception quality, signal strength, etc.

Our project will expand the capabilities of these embedded computational systems and reduce some of the limitations associated with wireless power transfer. To achieve this goal, we will develop a device that can measure the specific gravity within an enclosed container with one hundredth precision. The device will be powered wirelessly by a commercially produced PowerCast transmitter (tx91501b) at 915Mhz. It will remain unpowered until the onboard capacitor his charged to a voltage release point. The stored power will be distributed using an appropriate hysteresis model to power onboard instrumentation. The device will also wirelessly transmit the sampled data to a collection device. The commercial intent of this system is to supply home brewing hobbyists/enthusiasts with a better way to monitor the quality and control of their fermentation process.

In a broader view, it is our hope that our work will inspire others to explore the wide variety of applications that could benefit from our batteryless design. With our design one could easily modify the base level instrumentation to fit their specific application. Other applications could include, oil & gas monitoring, wastewater treatment, chemical plants, etc. These applications are all inclusive of physically restrictive environments that require regular instrumentation monitoring. Overall, this design will enable future applications to mitigate risks associated with firsthand monitoring systems.

1.3 Operational Environment

The intended operational environment for our design is a liquid filled enclosure. This environment is inclusive of high temperatures and liquid exposure. Some of the fundamental aspects to the mechanical portion of our design consists of complete encapsulation(watertight) and temperature resistivity. Other suitable environments for our platform include aquariums, ponds, or any other enclosed liquid environment.

1.4 Requirements

The following requirements have been assigned to this project via Duwe Amalgamated Research Corporation:

1. The transmission signal must be strong enough to travel 2ft beyond the exterior walls to span the diameter of the fermentation tank.
2. The transmission signal must charge an onboard capacitor within a days' time without losing signal quality.
3. The transmission signal must provide enough power for consistent data collection and transmission.
4. The data signal must be able to transmit within the fermentation tank and possibly submersed in liquid.
5. The design must be completely encapsulated and smooth. This will protect onboard electronics and eliminate access for bacteria to collect on the design during fermentation.
6. The design must be temperature resistant. Fermentation temperatures may affect the measurements from onboard electronics.

Any failure to meet of these requirements must be addressed to the client Duwe Amalgamated Research Corporation.

1.5 Intended Users and Uses

The intended end user is the client, Duwe Amalgamated Research Corporation, for measuring a potentially changing specific gravity of a liquid within a sealed container. The sealed liquid container will not be made of metal as that interferes with wireless transmissions. A possible environment could include multiple hydrometers transmitting information to a single base station.

1.6 Assumptions and Limitations

Assumptions:

- Most calculations shall be done on the base station to maximize expandability.
- The hydrometer will operate within a temperature range of 50°F to 80°F.
- The specific gravity measurement should be within 1% margin of error.
- The hydrometer will only need to transmit data once per hour.
- The less space the antenna occupies, the better.
- The hydrometer will be in an environment where the 915 MHz band is unused.

Limitations:

- The system will not use a battery.
- The hydrometer will not be transmitting from a metal container.
- The hydrometer will not be farther than 2 ft from the PowerCast.

1.7 Expected End Product and Deliverables

The expected end product deliverable should be a prototype, fully encapsulated, batteryless hydrometer using a custom PCB. Included with this is the code for our desired base station to communicate with the hydrometer and an analysis of the hydrometer's lifetime reliability. These are to be delivered by November 27th, 2020.

2. Specifications and Analysis

2.1 Proposed Approach

As shown in the conceptual sketch in section 2.1, we will use the power cast as the power transmitter to wirelessly transmit power to the hydrometer. The power harvesting circuitry will power the MCU, sensors, and Bluetooth transmitter. We would like to do most of the computing on-board and but if we don't have enough power, we will send the raw sensor data to the base-station and do the computing on the pi. The micro-controller will continue to collect data and send it until the super capacitors have depleted. Once the base station has received data, it will update UI for the user to be able to see the results.

2.2 Design Analysis

We have mostly done research up to this point. We will soon begin experimenting with the energy harvesting and working on code for the microcontroller and base station. We decided to use a raspberry pi for the base station because of the Bluetooth and WIFI capabilities.

2.3 Development Process

For the mechanical design, we will be using either Solid Works or FreeCAD. For the PCB design, we will be using KiCad. For the Firmware and software, we will be using an SDK from Silicon Labs (Simplicity Studio 4) and the IDE on the Raspberry PI.

2.4 Conceptual Sketch

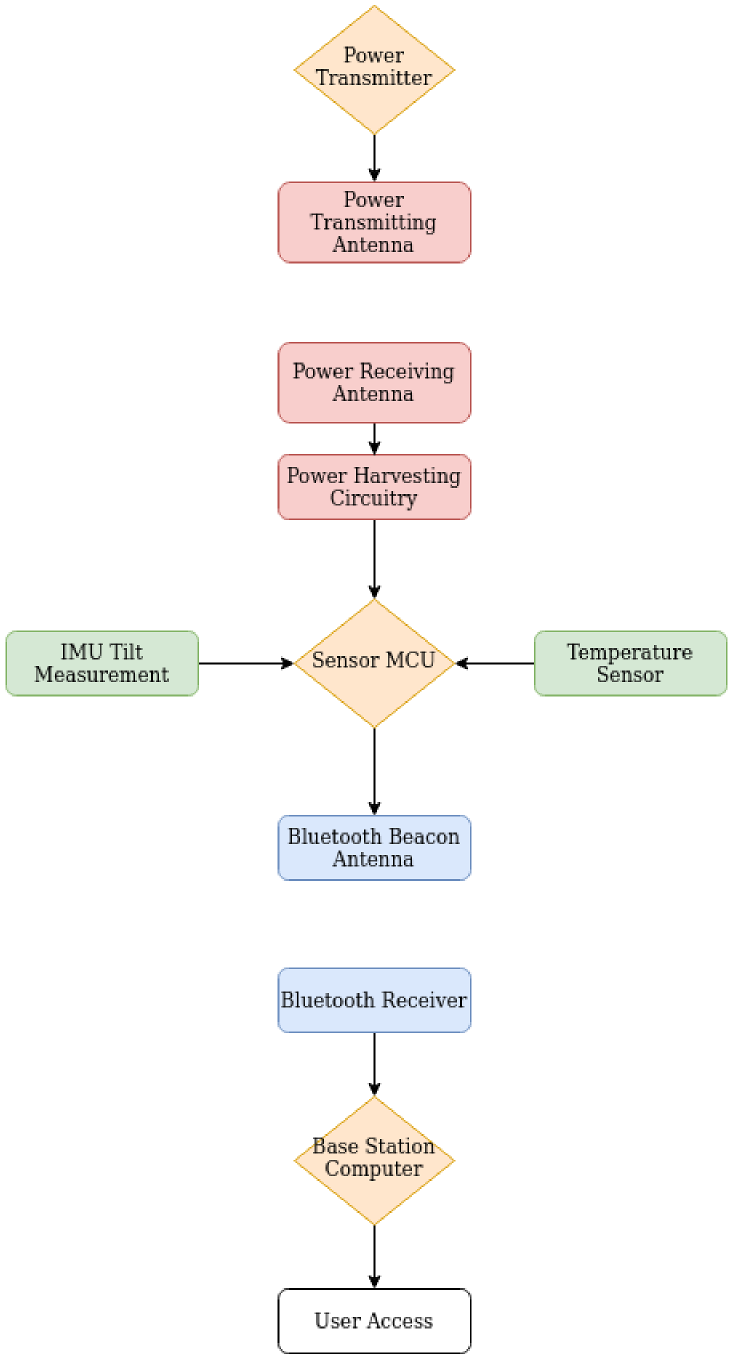

Figure 1

3. Statement of Work

3.1 Previous Work and Literature

There is a product called Tilt Digital Hydrometer and thermometer that has the same functionality we are attempting to achieve. The device allows users to wirelessly read specific gravity and temperature. Specific gravity is measured using an accelerometer on this device. The device is powered with a battery.

The hydrometer we will be developing will not use a battery. It will be able to take the readings that the Tilt hydrometer can take and will have wireless communication with a user interface. Because the hydrometer we have designed is battery less it will implement an energy harvester to wirelessly receive energy. This will mean less user maintenance.

Figure 2 - Tilt Hydrometer

“The Tilt hydrometer lets you instantly read your brew's specific gravity and temperature on your compatible Apple iPhone/iPad or Android smartphone/tablet or Tilt Pi. Most Bluetooth 4.0+ devices will work with the Tilt.”[1] The Tilt hydrometer website tells us the hydrometer communicates with bluetooth.

“The specific gravity is accurate +/- 0.002 within the Tilt's range of 0.990 to 1.120. The thermometer is accurate +/- 1 degree F (+/- 0.5 degree C).”[1] The sensors have the accuracy previously listed.

3.2 Technology Considerations

In comparing our design to the alternative market offerings, the major difference if our lack of having a battery. In the “Tilt” brand hydrometer their unit uses a lithium CR123A battery with an expected lifetime of 3 months in the first generation units and 12 months in the second generation and later units. In comparison our system uses no batteries so it has a lifetime measured in years rather than months. Our battery less hydrometer will not require the user to change the battery or track battery life.

3.3 Task Decomposition

- Layout basic system diagram
- Determine sensors needed
- Select main MCU
- Determine mechanics of tilt system
- Select sensor components
- Design base station layout
- Determine base station hardware
- Write and test some code on 'Gecko' development board
- Gather data on power harvesting capabilities
- Design system schematic
- Design and order prototype PCB
- Determine how to fully encapsulate system
- Design the encapsulating housing
- Order prototype hardware
- Write prototype code
- Assemble prototype
- Test prototype
- Lessons learned and next steps

3.4 Possible Risks and Risk Management

The antenna that will be used for energy harvesting is 6 inches and we are not sure if it will work when it is submerged in water. 95% of the Tilt hydrometer is submerged in water so this may lead to some issues for our implementation. The cost of the energy harvesting circuit is also a concern. The price of our device needs to be around $140 and we are concerned with this extra functionality driving up our cost. If the antenna cannot operate in water, we are concerned with how accurate our device will be with 6 inches of it above water.

3.5 Project Proposed Milestones and Evaluation Criteria

Milestone 1 (Wireless Power Harvesting): Determine the environment that the device is capable of harvesting energy in (water, air, plastic shield, etc.).

Tasks:

- Confirm functionality of power harvesting circuitry in different environments
- Design power harvesting circuitry based on the designs provided by client
- Transmit 915 MHz signal through empty plastic container (amount of time for LED to turn on)
- Transmit 915 MHz signal through plastic container with water (amount of time for LED to turn on)

- Based on the results of the above tests determine an optimal design for the power harvesting circuit

Milestone 2 (Power system function): Analyze the power supply circuitry of our circuit and determine the functional time our microcontroller will have to collect data, perform the necessary calculations, and transmit the data back to the user interface over Bluetooth. Determine the optimal voltages to switch the circuit on and off.

Tasks:

- Determine an optimal capacitor based on cycle life, charging time, and discharge rate
- Measure the discharge rate of the capacitor
- Measure capacitor charging time

Milestone 3 (Microcontroller Function): After determining how much time the microcontroller will have to perform calculations we will need to confirm that the hardware can complete it in the given allowed time. Additionally, we need to consider the memory we need for the code.

Tasks:

- Determine microcontroller on/off functionality
- Determine the size of written code for calculations and sensor libraries
- Cycle the microcontroller on and off and test functionality

Milestone 4 (Sensor Accuracy): In order to provide a device that is accurate the sensors may need to be calibrated. For example, if the temperature of the accelerometer increases this may affect the way that calculations must be done to determine an accurate position reading. The accuracy will also be heavily influenced by the mechanical design of the battery less hydrometer so before calibration can be finalized, we need to finalize the mechanical design.

Tasks:

- Calibrate Sensors
- Test operation of the accelerometer in different temperature environments
- Test operation of the accelerometer in mechanical design

Milestone 5 (PCB Layout/Chip pinouts): Decide on IC's and associated circuitry that will be used for all functional areas of battery less hydrometer. Design circuitry and layout PCB of battery less hydrometer based on chosen IC pinouts and associated circuitry as well as desired mechanical functionality.

Tasks:

- Choose IC's
- Design circuitry (Simulate and test everything that is possible to)
- Layout PCB
- Test individual IC's that are possible to test without PCB
- Test PCB functionality

Milestone 6 (Mechanical): The hydrometer must tilt based on the density of the liquid that it is in. This seemingly simple task will be quite challenging. We must consider weight, buoyancy, and the shape of the mechanical design.

Tasks:

- Design container
- Test operation of the accelerometer in mechanical design

3.6 Project Tracking Procedures

We will use the milestones discussed in the 3.5 as well as the Gant chart from 4.1.

3.7 Expected Results and Validation

The desired outcome is an accurate battery less hydrometer capable of energy harvesting that communicates data to the user using Bluetooth communication. The cost of this device needs to be below $140.

Measurements displayed on the user interface will correspond to the temperature and specific gravity of the environment being used to test the battery less hydrometer.

4. Project Timeline, Estimated Resources, and Challenges

4.1 Project Timeline

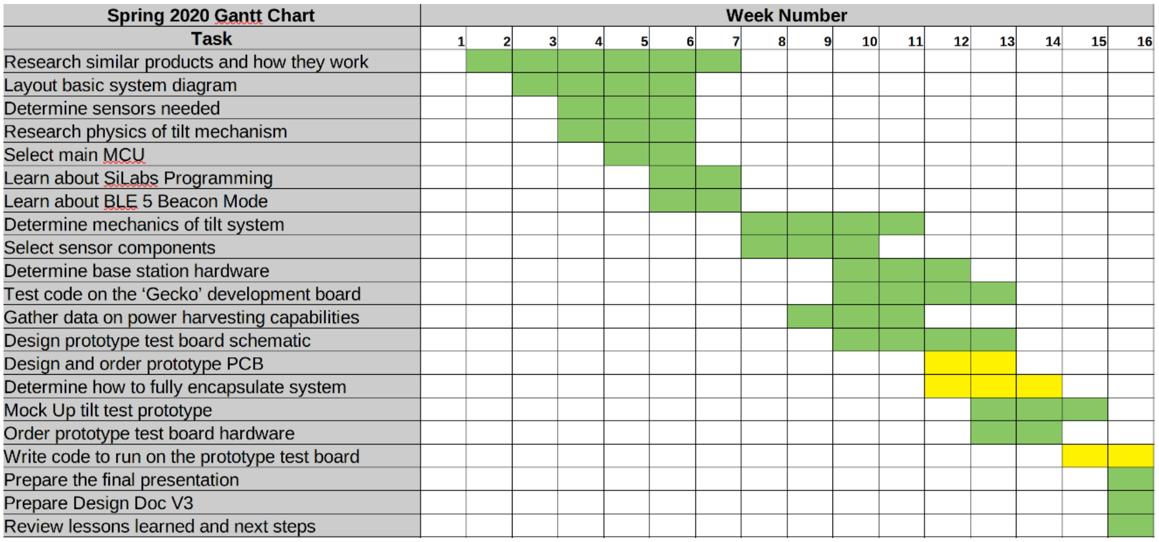

Figure 3 - Project Timeline

In this timeline you can see that we focused on making sure that we developed sound solutions for our project before purchasing components and trying to build a prototype. Also, within this Gantt chart you can see that we progressed methodically through the project and planned out design and build timelines for different aspects to finish around the same times so that we could try to avoid anyone ending up with time spent waiting for other team member to finish their parts. The green represents tasks we were able to complete while the yellow is for a few of the items that we started but were unable to complete according to schedule. Our intentions at the beginning of this semester were to have a finished initial prototype version by the end of the spring but due to the pandemic we had some significant challenges when it came to accomplishing a lot of the hardware work. With this being the case, we have quite a bit that has gotten shifted to be worked on over the summer and next fall.

Additionally, the specificity present in our Gantt chart will helped us stay focused on what tasks needed to be taken care of. With the unexpected change in schedule, the current plans for next fall now include making the initial prototype early in the semester that can be easily disassemble with a fully sealed unit to come later in the fall. We will also have a significant amount of testing that will need to be done so it will be important that we make some progress on software over the summer so that we have enough time in the fall to accomplish everything we're hoping for.

4.2 Feasibility Assessment

From our investigations thus far, this project is feasible with a few key challenges. The main challenge will be harvesting enough power from the transmitter to consistently and reliably transmit data. This will be added to by the possibility of the sensor being placed in a metal tank which could make the power harvesting unfeasible in some situations. The other challenge will be properly designing the mechanics of the tilt to ensure that the sensor tilts enough for highly accurate specific gravity measurements while also not restricting the power harvested by tilting the antenna too much. Additionally, a new challenge we had was needing to adjust the schedule and tasks to deal with the pandemic as being unable to work in the labs has greatly limited our hardware development.

4.3 Personnel Effort Requirements

Table 1 - Project Roles

Task	Member Responsible	Effort Required
Research Workings of Similar Products	All	Fair; but a very important task to make sure we understand the functionality
Layout basic system diagram	Jensen	Significant; but brief to get the layout done.
Determine sensors needed	Chris M.	Fair; takes some time to reconcile the diagram with available sensor types.
Research Tilt Mechanism Physics	Jensen	Significant; it was challenging to find information on utilizing tilt in such an application.
Select the main MCU	Griffin	Significant; due to the abundance of options.
Determine mechanics of the tilt system	Tilden	Very challenging; as there is little information available about it.
Select sensor components	Griffin	Fair; to determine the proper packages and specifications.
Determine the base station hardware	Jensen	Fair; required finding hardware capable of our requirements.
Write and test some code on 'Gecko' dev board	Josh	Significant; required writing custom Bluetooth beacon code.
Gather data on power harvesting capabilities	Chris P.	Straightforward; but time consuming to collect data.
Design prototype test board schematic	Griffin	Challenging; needed to take all parts and properly layout circuitry.
Design and order prototype PCB	Griffin	Very challenging; required very specific design choices.
Determine how to fully encapsulate the system	Tilden	Challenging; required looking at novel manufacturing methods.
Mock Up tilt test prototype	Jensen	Significant; required finding creative solutions for a manual measurement method

Order prototype hardware	Chris P.	Straightforward; just a matter of ordering the BOM from Kicad.
Write the prototype board code	Josh	Challenging; required highly efficient and fast code for the sensor.
Final Presentation	All	Significant; the final presentation will be important to demonstrate our progress.
Design Document V3	All	Fair; this document builds upon the other versions with added updates.
Review lessons learned and next steps	All	Significant; this will be important for our overall success in the fall.

As can be seen in this table, I focused on tasks that are highly important for our Gantt chart. This encompasses the entirety of the project and helps us focus in upon the specific items that we can expect to struggle with. Knowing in advance that we will have challenges with certain tasks allowed us to have more success in completing them.

4.4 Other Resource Requirements

Apart from financial resources we will need the following resources:

- Lab Access to the power harvesting development kits.
    - It is necessary to gather data on the power harvesting capabilities of these modules.
    - It will be extremely useful to have hands on experience with these modules before building them into our sensor.
- Equipment for building our sensor.
    - Our prototype and final designs will require the use of a reflow oven to properly construct.
    - To encapsulate the system, we will likely need a molding setup and a 3D printer to make a functionally accurate prototype.
- Time
    - We will need to make time available outside of our work schedules to contribute to this project.
- Software Access
    - We will be using Kicad for PCB design.
    - We will be using Solidworks for the mechanical design.

4.5 Financial Requirements

For our project we have the following cost estimate of what it will take to go from the initial design at this point to a final product at the end of next fall. These numbers are very rough at this point but will become fine-tuned as we get farther into the project.

Table 2 - Financial Analysis

Testing Hardware	$30

Initial Prototype • PCB - $15 • Electrical Components - $100 • Housing - $20	$135
Base Station with Power Transmitter	$150
Miscellaneous	$50
Project Total (Estimate)	**$365**

5. Testing and Implementation

The batteryless, encapsulated hydrometer has numerous parts that need to work simultaneously for the product to function properly. This includes the mechanical tilt, measurement of the angle of tilt, computation, energy harvesting, and wireless communication back to the base station. In order to facilitate the success of this product, extensive testing will be necessary for each of the components.

5.1 Interface Specifications

The major consideration with interfaces in this product is concerned with power consumption. In order to limit the power consumed, the communication between devices will need to be fast. A model of total time required to complete the communication in each cycle should be made.

- There will be serial communication via an I2C bus between the microcontroller and the accelerometer and temperature sensor. The functionality of this serial bus will need to be evaluated and modeled.

There will be wireless communication with the base station via a connectionless Bluetooth transmission. The current consumption and time required to transmit should be measured. Additionally, the environment it will be transmitting from is near fluids which can limit signal integrity. The ideal transmission power (in dBm) should be selected based on test results.

5.2 Hardware and Software

The hardware for this product will exist on a printed circuit board (PCB) that hosts the embedded system. This will include the energy harvesting subsystem, the power management circuitry, the microcontroller and sensors, and the wireless communication subsystem. The software will include sensor data collection, calibration, computation, wireless communication, and an exit flag.

Hardware:

1. Energy Harvesting:

   The product will utilize a PowerCast system that operates in the 915 MHz frequency band. The energy harvesting dipole antenna is designed by the PowerCast Corporation along with the P2110B PowerHarvester Receiver.

2. Power Management:

The power management circuitry exists on the P2110B module. Once the voltage across the capacitor reaches a selected value, the voltage regulator will be activated until either the voltage drops too low or the shutdown flag is activated.

3. Microcontroller and Sensing:

The microcontroller (MCU) selected for this product is the EFR32BG13. This product offers low power consumption along with fast boot times. Additionally, it has an integrated Bluetooth 5 physical layer (PHY) and 2.4 GHz transceiver. The sensors that will be selected will utilize an I^2C serial bus for communication with the MCU. There is a 6-axis accelerometer and temperature sensor on the device which will be utilized in the calculation of the specific gravity of the current fluid to within ±0.001 [g/cm^3] accuracy.

4. Wireless Communication:

The wireless communication will utilize a connectionless Bluetooth session called a Bluetooth Beacon. In this configuration, the product will transmit the data at 2.4 GHz under the Bluetooth 5 protocol without connecting to the base station.

Software:

1. Sensor Data Collection:

The software will collect sensor data using the I^2C protocol and existing libraries. The libraries used to access the sensor functions will be modified versions of existing code to minimize memory utilization on the device.

2. Calibration:

The calibration of the measurement data will be housed on the base station and not on the product. This will allow for the user to calibrate data in the field without accessing the PCB directly. This calibration process will be designed to be accurate to within ±0.001 [g/cm^3].

3. Computation:

The computation of the specific gravity will be performed on the base station. As a result, the hydrometer will transmit raw sensor data for calculation and calibration to be performed by the end-system.

4. Wireless Communication:

The wireless communication will be performed over a Bluetooth 5 Beacon and will require all relevant libraries to be stored in on-chip memory.

5. Exit Flag:

One of the pins on the MCU will be a dedicated exit flag that will kill the power to the microcontroller once all necessary operations have been completed. There is a pin on the

P2110B module to perform this operation. This will allow for the power management circuitry to charge faster since the device will only consume the power it requires and not all available power.

5.3 Functional Testing

1. Energy Harvesting:

   The energy harvesting antenna and P2110B PowerHarvester Receiver will need to be profiled together for efficiency, gain, polarity, and power harvesting under various conditions.

2. Power Management:

   An analysis of power consumption of the entire product will need to be made and adjustments to the activation threshold will need to be made. Additionally, an appropriate capacitor size will need to be selected to act as the power source for the product.

3. Microcontroller:

   The microcontroller will be tested for startup time, power utilization during sensor measurement, power utilization during computation, and power utilization during Bluetooth transmission.

4. Wireless Communication:

   The transmission will be characterized by measuring the transmission time and current consumption during transmission. Transmissions will also be tested for received data integrity under various conditions to determine the minimum transmission power level. Additionally, the RF impedance matching circuit will be analyzed to ensure that the impedance is within 5% of the required 50Ω impedance of the chip antenna.

5. Sensor Data Collection:

   The sensors will be tested for wakeup time, measurement time, and power consumption during measurement and idle. Testing will also be done to ensure that full functionality is maintained through the reduction of the device libraries.

6. Calibration:

   This calibration process will be designed to be accurate to within ±0.001 [g/cm3] and verified through testing.

7. Wireless Communication:

   The software will need to be ensured that it can fit into the on-device memory.

8. Exit Flag:

The exit flag must be tested to ensure that it operates as designed. An analysis should be performed to determine how much time and energy is saved from using the exit flag versus allowing the available power to be consumed.

5.4 Non-Functional Testing

Performance:

- The exit flag must be tested to ensure that it operates as designed. An analysis should be performed to determine how much time and energy is saved from using the exit flag versus allowing the available power to be consumed.

Compatibility:

- The device should be tested to ensure that its Bluetooth 5 Beacon capabilities are compatible with previous versions of Bluetooth.

5.5 Process

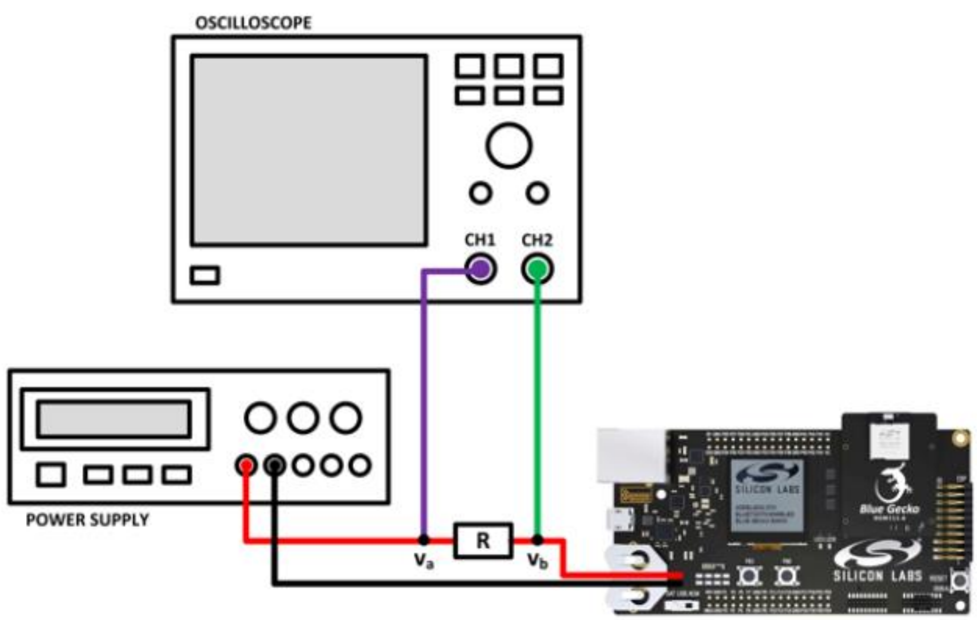

Figure 4 - Power Consumption Test Configuration

- Power Consumption Tests:

  A 1Ω resistor will be placed in series with a power supply and the microcontroller. The voltage across the resistor will be collected on an oscilloscope and stored in a .csv file. The voltage across the resistor is reflective of the current consumed during operation.

- Transmission Power Level Testing:

  The EFR32BG13 development board shall be placed in a watertight container and powered by a battery for this test. It will be programmed to transmit from 0 dBm to 19 dBm with increments of 1 dBm at a time. Received power will be measured from the base station in various environments including a fluid to introduce interference. The base station and transmitter shall be 1.5 meters apart. The minimum power level necessary without compromising signal integrity should be selected.

- Startup/Wakeup Times:

  The wakeup times will be determined based upon the amount of energy we are able to harvest. An optimal time interval between transmissions will be selected to balance a consistent time interval with the ability of the device to harvest enough power within the allowable range.

5.6 Results

In the early testing stages we have utilized the P2110 evaluation board to obtain results. The first test that we have run on this device is to see the effect distance from the PowerCast transmitter has on circuit activation. This evaluation board harvests the transmitted energy, blinks an LED, and then shuts down the circuit. The results of this test can be seen in Figure 5 - Average Period vs. Distance.

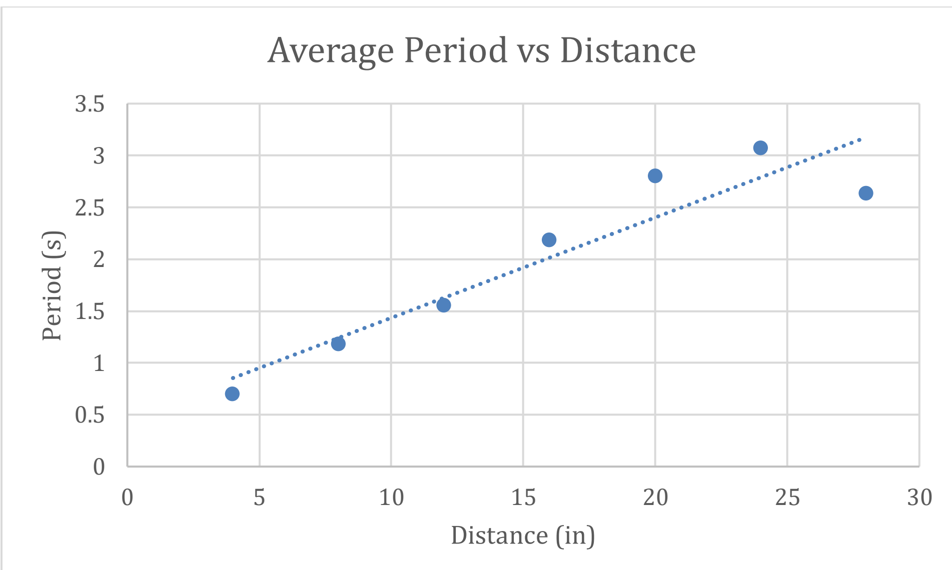

Figure 5 - Average Period vs. Distance

The effect of distance on the power harvested can be seen to be linear from this test result. The one outlying datapoint, at 28 inches from the transmitter, the period between LED flashes is actually shorter than the previous closest data point. This is thought to be a result of reflection and a new set of tests are planned to be performed pending lab access.

In our next test we had to ensure that our encapsulation prototype would depict the physics of a tilt hydrometer. In this test we constructed a tilt mechanism out of household materials that proportionally aligns with the physical elements of our encapsulation prototype. We then set the tilt mechanism a float within a Tupperware container filled with 10 cups of tap water and recorded the baseline tilt. Next, we added ¼ cup of sugar until we reached 5 cups (½ the volume of the baseline water). Each time we added a ¼ cup of sugar the degree of tilt was recorded.

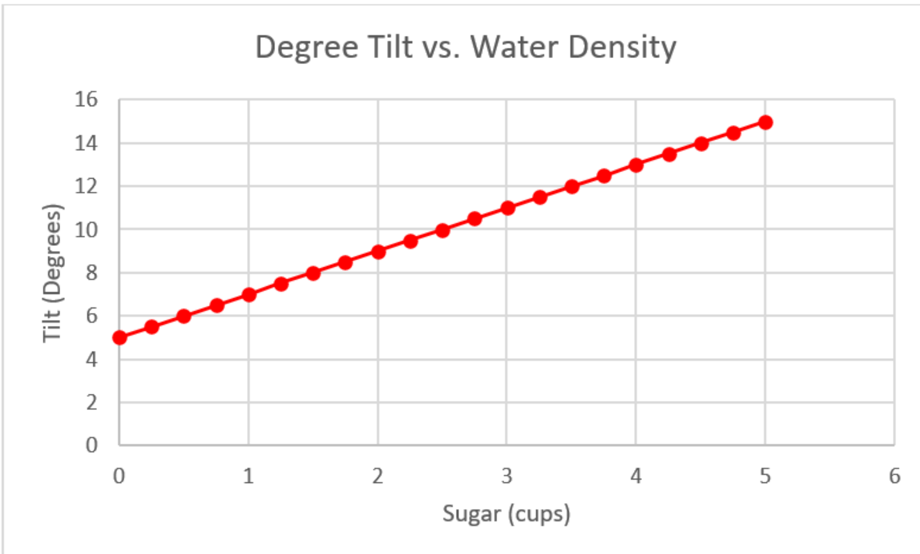

Figure 6 - Average Period vs. Distance

In our experiment we found that there was a linear relationship between the degree of tilt and specific gravity of a fluid. As we increased the specific gravity of water by adding sugar to the system the tilt mechanism displayed a greater degree of tilt. Overall, this experiment proved that our prototype encapsulation will generate a linear relationship between axis tilt and the specific gravity of whatever fluid it is immersed in.

6. Closing Material

6.1 Conclusion

With the project just getting kicked off, we have yet to make significant progress in prototyping. We have instead spent our time thus far accomplishing planning and design tasks to set out a specific and achievable plan for the rest of the semester that can smoothly carry over into next fall. Going forward we plan to begin testing with and collecting data with our development tools available to us and then we will get into the design and prototype phase as the semester goes on. This focus will be the best setup for allowing us to successfully have an initial working prototype at the end of this semester.

6.2 References

1 https://tilthydrometer.com

2 Journée J. M. J., and W W. Massie. *Offshore Hydromechanics*. Delft University of Technology, 2001.

6.3 Appendices

No further appendix information at this time.