Smart Coaster

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***Abstract* - To maintain customer satisfaction, a wireless Smart Coaster system will provide wait staff with notifications whenever a customer's drink is near empty. In large, this system will be able to detect and differentiate the volume of a liquid within a cup by measuring weight, allowing the identification of an empty cup in need of a refill. Wireless communication support for multiple coasters will conveniently notify and update wait staff of the drink status of multiple tables through an intuitive and informative user interface. As these coasters are wireless devices that work closely with liquids, having wireless charging capabilities will lend to a more water resistant device. These coasters will alleviate stress for wait staff so that their focus can shift from continuously monitoring customer drinks to other more important tasks.**

I. INTRODUCTION

During the busiest hours of the day, restaurants, pubs, and bars struggle with being able to promptly address customer needs; especially the refilling of drinks which falls down the list of priorities.

A. *Significance*

At restaurants, reputation heavily relies on customer satisfaction and responsiveness of customer service[1]. Waiters/waitresses often juggle serving several tables at the same time, making it difficult to efficiently monitor the needs of each table in real time. Subsequently, managing multiple tables will lead to slower and less responsive service. In these situations, it is likely for at least one of these customers to finish his or her drink without a waiter/waitress to refill the drink in a timely manner.

B. *Context/Existing products:*

In 2017, *New Potato Technologies* released a smart coaster known as the Brio Smart Coaster[2]. The Brio connects through Bluetooth to a smart device and allows the device to receive a notification if a drink has been touched or tampered with (provided the coaster is sitting on top of the drink). The coaster also has 24 LED's lining the edges that will brightly light up so that a drink may be easily found. This coaster is primarily for individual customer use; a customer purchases the coaster and brings it to restaurants/bars for use. Although this device has wireless capabilities, it is not primarily used to detect how full a drink is.

In 2014, a project design team from NYU (Songee Hahn, Dalit Shalom, and Abhishek Singh) developed a coaster known as HYDRATE.ME, a coaster that tracks the amount of water drunk from a bottle. The coaster further notifies the user to drink fluids if the weight of the coaster remains unchanged for an extended period of time.

Notably, this coaster design moderately tracks the weight of a cup and relates the weight to the fullness of the cup. Although the HYDRATE.ME uses low form factor sensors (Force Sensitive Resistors), the rest of the hardware used throughout the design results in a bulky coaster that requires a cable to power an Arduino. This configuration is functional for a single coaster within close proximity to a laptop, but lacks the capability of connecting to multiple coasters wirelessly for use within restaurants.

C. *Societal Impacts*

For decades, wait staff have had the main responsibility of serving customers at restaurants/taverns/pubs. One of the main roles of a waiter/waitress is that they are attentive to the needs of their customers, whether it is food or drinks or desserts - and thus for decades, the waiter/waitress occupation has always been stressful. With the Smart Coaster implemented within restaurant settings, some of the pressure of serving customers is placed on the coaster instead of the waiter/waitress. The coaster will provide convenience when serving drinks to customers and allow waiters/waitresses to focus on other tasks at the same time. While customers continue to use the Smart Coaster, there will be no more craning necks attempting to track down the waiter/waitress for another drink.

D. *System Requirements and Specifications:*

There are a few key specifications and requirements that the Smart Coaster must meet in order to fulfill its job. It has to be accurate enough to be able to distinguish between the different drink levels of a cup (Full, half full, empty); it must last a reasonable time for active use within business hours of a restaurant or pub; it must connect wirelessly to operate in these settings; and ideally it is thin enough to be unobtrusive.

Table I

Requirement	Specification	Value
Accuracy	Empty Glass Detection Rate	≥95% detection ≤1% false positives
	Weight measurement	<10g of error
Usability	Battery Life	≥12 hrs. ≤5 hr. Between charge
	Connectivity	Support for multiple coasters
Form	Thickness	<2 cm thick

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Table I: Requirements and Specifications

II. DESIGN

A. Overview

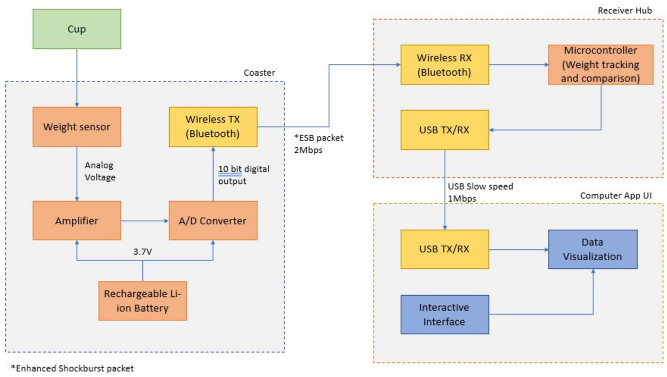

Figure 1:Block diagram of the coaster and hub.

As shown in Figure 1, the Smart Coaster system will consist of the Coaster itself as well as a receiver Hub. The main purpose of the Coaster is to wirelessly transmit the weight of a cup to the Hub. This will require the Coaster to have a weight sensor (load cell and amplifier combination) as well as an Analog to Digital Convertor (ADC). To provide wireless capabilities, a nRF24L01 2.4GHz radio transceiver IC is placed on both the Coaster and Hub to establish Bluetooth communication channels between the two devices[4]. The Coaster will wirelessly transmit a unique identification address as well as measured data to the Hub, where the data is used to determine the drink level on the Coaster. As the Coaster is wireless, it must be capable of operating without charging for several hours and must be charged. When attempting to meet many varied specifications it was necessary to succumb to certain trade-offs. The requirements that conflict directly are the usability and form. In order to realize a designed thickness of <2cm as intended, it was necessary to lower the operating voltage in order to use battery cells with smaller form factors. In addition to this, the enclosure that was developed had a larger radius than initially conceptualized.

B. Block 1 - Coaster

i. Load Cell/Wheatstone circuit

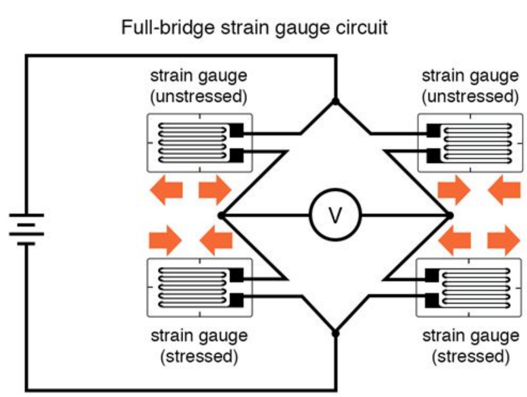

Figure 2: The load cell modelled as a Wheatstone bridge consisting of 4 strain gauges. The difference in stress on each of the strain gauges is translated to differences in the measured voltage V [5].

The load cell is the main sensor unit in the coaster. This device is responsible for providing the translation between the weights of the cups to an analog voltage that can later be used to quantify the capacities of the cups. As shown in Figure 1, the circuit equivalent of a load cell is a Wheatstone bridge with four strain gauges. A strain gauge operates much like a force controlled variable resistor, which means that any stress that is applied to a strain gauge alters the resistance of the device itself. As a force is applied to the load cell, unbalanced stress is placed on the bridge circuit. This unbalanced stress can either pull or compress the individual strain gauges, thus creating an imbalance in the resistance on either branch. By applying a voltage across both branches of the bridge, the difference in resistance of each branch can be found by measuring the difference in voltage between the two strain gauges of each branch as shown in Figure 1. Due to the nature of this design, an advantage to this device is that the difference in resistance is highly accurate and linear with respect to the force that is applied. A disadvantage, however, is that for any supply voltage the difference in voltage between the branches is often extremely small (on the order of millivolts per ten grams). For the range of the load cell that is used for this design, the measured output voltage ranged between about 300µV at less than a gram to over 11mV at over a kilogram.

ii. DC Amplifier

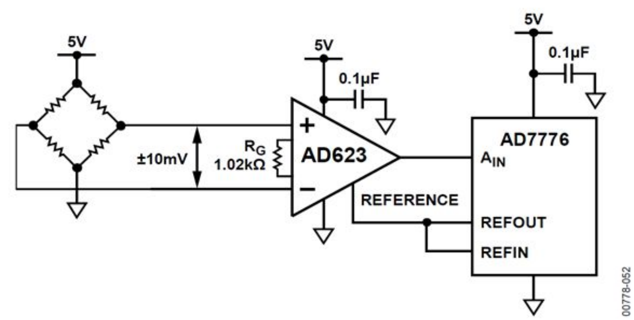

Figure 3: Example wiring diagram of how the output of the load cell can be fed into an A/D converter using a single supply voltage and a single instrumentation amplifier[6].

In order to take advantage of the accuracy and linearity of the load cell, the output range must be scaled to the full range of the A/D converter. To be consistent with both the supply voltage of the microcontroller and the supply voltage of the load cell, an amplifier that can operate on a single rail is desired. This means that the negative supply of the amplifier, VSS or -VS, must be connected to ground. Some additional requirements include:

1. High common mode rejection
2. Low power consumption
3. Low output noise

Both the high common mode rejection and low output noise directly affects the effective resolution of the A/D converter. Since the difference is on the order of millivolts, any amplification of the common mode voltage reduces the measured difference in voltage per gram of the sensor. Similarly, high output noise could cause the output of the ADC to vary drastically for a given input.

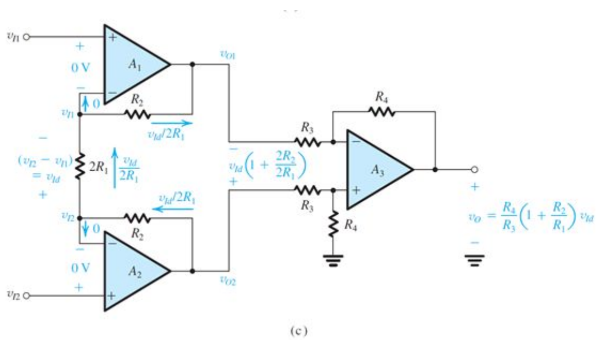

Figure 4: Model of a general instrumentation amplifier[7].

The solution that met all the specified requirements is the instrumentation amplifier. Due to their design, these devices are known to have a very high common mode rejection ratio (CMRR) as well as excellent differential amplification capabilities. Shown in Figure 3, a typical instrumentation amplifier consists of three op-amps. The two input amplifiers, A_1 and A_2, provide a large input impedance to maximize the differential gain between the two inputs v_{I1} and v_{I2}. The third stage provides even further amplification of the differential voltage v_{O1} and v_{O2}. Something to note is that a common mode input, i.e. $v_{I1}=v_{I2}=v_{ICM}$, will remain the same at the output of the first stage due to the symmetry of the input stage. In other words, the common mode input voltage will only be amplified by A_3 while the differential input will be amplified by both A_1 or A_2 and A_3. Additionally, the gain of the overall amplifier "can be varied by changing only one resistor, $2R_1$," which can greatly simplify the overall design of the coaster[7].

The amplifier that was selected for this design is the AD623, as shown in Figure 2, which met all of the specified requirements[6]. Provided in the datasheet, the gain of the amplifier can be determined using the following equation

$$V_O = \left(1 + \frac{100\ \text{k}\Omega}{R_G}\right) V_C \quad (1)$$

To take advantage of the full range of the ADC, the output voltage range of the load cell must be amplified to match the range of the ADC's reference voltage, which is between 0V-5V. As shown in Figure 3, using a gain of 1000 V/V would have provided a range of about 0g to about 700g for the coaster. Taking into account the measured weight of a standard full glass being about 700g, this would have been sufficient. However, if different glasses were used or different drinks were taken into account, the nonlinearity that appears at the output after 700g may prove to be an issue. In order to use the full range of the load cell, the gain of the amplifier was reduced to about 700 V/V by increasing the resistance of the bias resistor R_G. In doing so, the output of the amplifier now remains linear for the full range of the load cell.

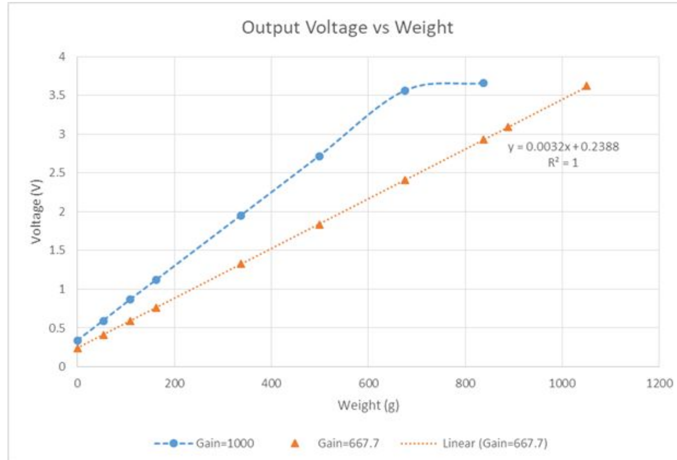

Figure 5. Measured output voltage of the AD623 vs weight applied to the load cell using 2 different gain settings. Note that when the gain is approximately equal to 1000 V/V, the voltage saturates around 3.6V before the maximum capacity of the load cell is reached.

iii. ADC

To measure the amplified analog voltage of the load cell, an Analog to Digital Converter (ADC) is used. The ATMEGA168, placed on the coaster PCB, has an ADC that can map an analog signal between 0 and 5V to a digital equivalent using 10 bits[8]. With 10 bits of resolution, the analog signal can be represented as digital values between 0 to 1023. In this way, the analog resolution of the ADC is 5V/1023 = 4.89mV/ADCvalue. To find the resolution of the weight measured from the load cell, consider the amplifier output range of 0.24V to 3.62V that respectively corresponds to the load cell weight range of 0g to 1000g. Weight per volt is calculated 1000g/(3.62-0.24V) = 0.296g/mV. Multiplying this by the previous volt resolution of 4.89mV/ADCvalue, each ADC value is capable of measuring a weight with precision: 0.296g/mV * 4.89mV/ADCvalue = 1.45g/ADCvalue. Assuming the ADC is sampling an ideal (noiseless) voltage, the interpreted weight will have a maximum error of 1.45 grams.

iv. Noise Effects

Considering the weight accuracy required of the coaster in order to differentiate drink levels, the effect of noise should be considered. With the ADC sampling directly at the output of the instrumentation amplifier, any noise amplified or generated by the amplifier will affect the sampled amplifier voltage. With this in consideration, the output of the amplifier is measured (with constant weight applied to the weight sensor) using an oscilloscope as shown in Figure 6:

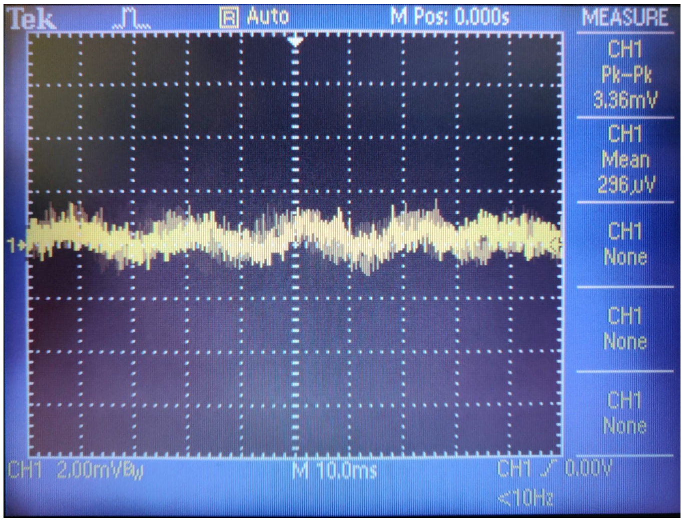

Figure 6. Screenshot of the maximum measured noise at the input of the ADC pin of the microcontroller.

The peak to peak noise is measured to be 3.36mV. With the ADC capable of measuring voltages with a resolution of 4.89mV/ADCvalue, ideally, the ADC will not be affected by the noise generated by the amplifier. However if the measured voltage lies directly on the threshold of 2 ADC values, then the noise will push the ADC value between the 2 values, corresponding to up to 1.45g in error, which is well under spec.

C. Block 2 - Bluetooth communication

Coasters will regularly transmit updates to the hub quasi-asynchronously using a 2.4Ghz radio. The possibility of interference due to two coasters transmitting simultaneously is negligible due to the extreme ratio between transmission time and update period. Each coaster will transmit updates at 0.5 second intervals. Each update is a four-byte transmission, consisting of a single-byte ID and a three-byte value from the sensor.

D. Block 3 - Hub

i. Software functionality

The Hub constantly listens for updates from coasters and stores them in memory. An array of structs is used to index current coaster values by the corresponding coaster IDs. An update with an un-indexed ID is given an entry in a free slot in the array if available; subsequent updates change the existing extry. During calibration mode, the hub will store two values from the first-connected coaster when each of two button presses occur. These recorded values serve as the minimum and maximum values expected from the coasters when they are supporting a drink. During normal operation, the “percent full” of the first-connected coaster is displayed by illuminating a similar percent of LEDs connected to the hub. To determine the “percent full” represented by a coaster value, the hub linearly interpolates between the recorded calibration minimum and maximum. Additionally, all coaster updates, including calculated “percent full”, are put into text and transmitted over the wired serial connection to the computer.

III. THE PRODUCT

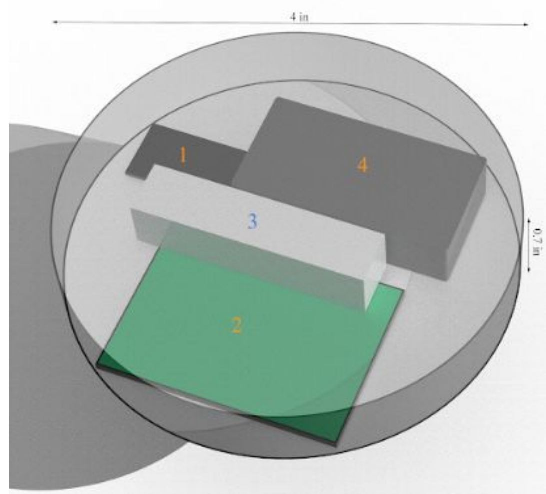

Figure 7. Smart Coaster product sketch. Shown within the coaster is (1) the nRF24L01 2.4GHz radio transceiver, (2) PCB, (3) 1 kg load cell, (4) Li-ion battery cell enclosure

A. Product Overview

The intended layout of the Smart Coaster is depicted within Figure 7. The coaster enclosure consists of two 3D printed plastic dishes, similar in shape to petri dishes. The top dish has a larger radius than the bottom dish, allowing the bottom dish to fit loosely into the top dish such that a water resistant cavity is created. This cavity will be used to store electronic components. The load cell, used to measure weight, is anchored to the bottom dish as well as the top dish. It is important that the load cell is the only means of supporting the top dish since it must provide weight measurements of any object or cup placed on the top dish. In this way, the top and bottom dishes are designed with a 1mm gap anywhere between both dishes. Design of coaster thickness is reliant on this enclosure design. The enclosure design must take into consideration the thickness of each electronic component especially since the top dish of the enclosure cannot be supported by any other dish or component excluding the load cell.

The load cell is wired to the coaster’s PCB, containing the surface mounted instrumentation amplifier and microprocessor. As the load cell output voltage is on the scale of millivolts, the amplifier is necessary to provide an analog voltage in the range of 0-5V to the ADC located within the microprocessor. Weight accuracy is considered here by controlling the gain of the amplifier and by observing the effects of amplifier noise. The gain of the amplifier is selected such that the linear voltage response of the load cell is scaled as close to the range of the ADC input as possible. Noise effects are reduced through the use of low pass filters (large capacitors).

To maintain portable and wireless utility, a Bluetooth transmission chip (the nRF24L01) is connected to the microprocessor to allow wireless communication to the receiving Hub. The nRF24L01 has the capability for 8 channels of communication at a time, allowing the communication of multiple coasters.

To power the PCB (including microprocessor, amplifier, load cell, and wireless chip), two rechargeable Li-ion AAA batteries are used. The capacity of these batteries along with the current drawn from the PCB determine the amount of time that the coaster can be used without charging. Ideally, the coaster should be able to last throughout the business hours of a restaurant, which the coaster is capable of drawing 14mA from the two batteries for up to 24 hours between charges.

B. Electronic Hardware Component

During prototyping, circuit design was realized through breadboards to prove the design's functionality. This step determined initial numbers for instrumentation amplifier gain, operating voltage, and capacitors. After this step, the circuit design was transferred to printed circuit board design software, Altium. In consideration of fabrication time, Altium designs were prioritized; once the first PCB design was sent for fabrication, a second was immediately designed in order to accomodate any original design issues.

Design of the PCB considered that each component would be hand soldered to the board. Larger SMD resistors and capacitors were used throughout the design to reduce the amount of time spent soldering components to the board. This would provide more flexibility when debugging and allowed jumped cable connections between soldering pads if needed.

To confirm functionality of the circuit board, voltages at each node of the PCB were compared to the breadboard prototype as an initial check that traces were correctly placed. Components such as amplifiers, diodes, and voltage regulators were tested individually and as a system by powering the board with the selected rechargeable batteries and checking that each functioned as intended. Through this process, it was discovered that there was an extra connection to ground than originally intended, causing the amplifier to have a limited output voltage. The issue was resolved by removing the amplifier and removing a soldering pad that was unintentionally grounded.

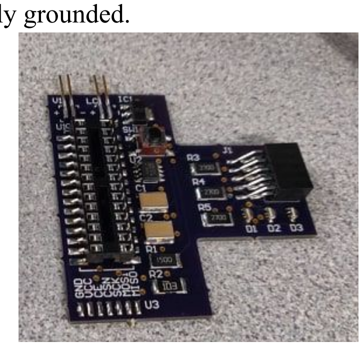

Figure 8. Smart Coaster Populated PCB

Shown in Figure 8 is the final PCB design before modifications were made to accommodate the extra ground connection. The right (square) portion of the PCB is a basic programmer used to embed code into the chip. Once the code is embedded, the programmer on the right side of the board is cut off to allow the PCB to fit within the coaster enclosure. As seen for this design, the microprocessor has a DIP packaging that is attached to the board through a 28 pin Dual Leaf connector. This design uses a DIP microprocessor so that it may be freely removed, programmed on a breadboard, and reconnected to the PCB in the case that the programmer did not function correctly. Although functional, the PCB design displayed in Figure 8 would ideally have used a TQFP SMD microprocessor to further reduce the size of the PCB.

C. Product Functionality

i. Volume Sensing

As shown in Figure 5, the weight sensing circuit was able to provide a highly accurate, highly linear measurement of the weight of the glass including its contents as a measurable voltage. When digitized by the onboard analog to digital converter of our microcontroller, we were able to obtain an error of 3±1.45g from the actual weight, which is directly proportional to the volume in milliliters of water.

ii. Wireless Communication

The wireless transceivers on both the coaster and the hub were functioning at the time of CDR. At close range, the hub was able to receive the packet containing the device ID and the ADC code from two independent coasters models with minimal loss.

iii. Software

At the time of CDR, the software for the hub interface was functional but at times lacked responsiveness. Although it was shown to update the volume measured by each coaster in real time, there were a small number of times where it showed noticeable signs of unresponsiveness when, for example, a glass was removed from the coaster. This was partly fixed by increasing the polling rate on the hub to shorten the intervals of measurement, which helped to make the experience smoother for the user.

D. Product Performance

i. Accuracy

The main specification, 95% detection rate, was supported by using the same weighted objects in enough trials to support this percentage. This was confirmed by using a seperate scale to verify that the weight was correct and should be considered full or not. There were no issues of false positives thanks to initial calibration of the expected weight range for a glass, and through trial we found that this specification really was a non-issue.

ii. Battery

To charge a single coaster from a dead li-ion battery (3V) to a fully charged 3.6-3.7V cell (not including overcharging/Up to 4-4.2V) could be done in under 2 hours, easily meeting the specification for charging, and the 2 cell coaster used for CDR was capable of running for an expected 25 hours with our circuit drawing an expected 14-15ma of our batteries possible 350mah. Post CDR we had planned to bring our circuit down to operate on a single 3.7V cell, however the battery life would have remained the same as our 2 cell configuration was a series connection.

iii. Form

Our requirements of form and usability directly conflicted, as we intended on a very compact and practical design. In order to remain under 2cm as intended, it was necessary to lower the operating voltage in order to require less battery cells, we were unable to get to this stage, and the dimensions of the prototype enclosure were a little off, making it unusable, so this specification can not reasonably be considered to have been met. However we believe that with just some slight adjustments this specification could have been met, and with a little work hopefully could have looked like a real product.

IV. CONCLUSION

The Smart Coaster project is currently in a good state of production, The main coaster and its connection to the Hub have been realized and now it is a matter of adding both very useful and necessary functionalities to the project's success. In addition it will be transformed into an attractive and presentable product. This will be achieved through the same good work that all team members have been putting in up to this point, with the goal of making a very good final product. The new designs elements that have been added will pose some extra issues early on. However, with the planning that has gone into these new ideas, as well as further research and prototyping, the result should be exactly what we aim for.

ACKNOWLEDGEMENT

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APPENDIX

A. *Design Alternatives*

The main design alternatives considered were for the way that weight would be measured in the Coaster. Originally "Force Sensitive Resistors" were considered the number one choice[9]. However after receiving and testing these sensors it was found that they did not fit the needs of this project, drifting too far from their initial value and being unable to maintain a stable/measureable resistance. So this was discarded for the final decision to instead use a load cell. The load cell proved to be a very good choice that exceeded the accuracy that we originally intended, as well as being a good fit all around for the design.

B. *Technical Standards*

- USB 2.0: used for serial communication between the hub device and a PC
- 2.4 GHz ISM Band: frequency band allocated by the FCC for short range communications. This is used for wireless communication between the coaster and the hub

C. *Testing Methods*

The main experiments performed were those that validated the functionality of the coasters and their connection to the Hub. This includes trying various weights both inside and outside the range of weights that we wish to be able to detect and catalogue on the Hub. Objects of varying weights were used to test the accuracy of the load cell by comparing the results on the Hub to the actual weight, verified using a lab scale. In order to test for the confidence intervals that we set, we ran many trials with the same objects, as well as different ones. We ran these trials and logged the measurements they produced until there was enough data to confirm these two specifications for the 95% confidence intervals. Again the two lab scales were used to confirm that the results were accurate.

After setting up a 2nd 'dummy' coaster we were able to validate the Hub's ability to connect to and receive data from multiple devices without having negative effects on the accuracy of measurements. Further tests will need to be performed once the coasters are complete to verify that they can meet the specification set for battery life and charging time.

C. *Team Organization*

The team is organized as a combination of 3 EE students, and one CSE student. The team has been working well, with one or two missteps in communication that has been continually improved upon. Josh is the most specialized of the members, being an expert in programming and the wireless communication that is needed for this project. The team has worked well together assisting each other in numerous sections of the project (coding, wiring). Angus has done the majority of coordinating with our Advisor Professor Yang. Jonathan has done the coordination with evaluators Professors Polizzi and Eslami in planning PDR and MDR, as well as reserving conference rooms.

D. *Beyond the Classroom*

Jonathan: This project has and will continue to help develop my skills as I become a professional EE. Being in charge of the power aspects of the project have helped me to expand my limited knowledge on power systems. This expansion in the topics I have experience in has proven useful while talking to working professionals in interviews. Beyond this, having a hand in the full scope of the project, from conception to final product, is another important part of this project. Chuck Malloch was a good resource for me when researching potential options for the battery supply of the coaster.

Joshua: Software development has been, and will increasingly be dependent on the hardware being programmed on/for. This has caused me to learn to develop with a more modular style to reduce the impact and additional work induced by hardware changes. I'll note that while working on this project, I've gained not only technical skills, but also skills in communication, team organization, and presentation. A big part of my work was learning to use the code library that made using the nRF24L01+ radio much less cumbersome. I can definitely see my experience with that learning process coming in handy in the future.

Angus: As an EE, being able to translate signals from a sensor into useful information that can be manipulated is an important skill. Throughout the early stages of the design of the prototype I was able to make use of the manufacturer's datasheets as well as our own empirical measurements to develop a compact and stable design to connect our sensor to our microprocessor together. For this task, having datasheets for each of our components, sensors and our microprocessor was a helpful guide in providing some design suggestions.

Tim: Although the project is an ECE Design Project, one of the more important skills used for this project is communication rather than engineering (but still necessary). In a team of four, there are four sets of good ideas that can be applied to the project. Not all of the ideas will be used in the end, but communicating why each idea will work brings both diversity and innovation to the table. Communication is also important in maintaining project progress. By setting reasonable deadlines and assigning main responsibilities between teammates, the project is tackled with ease.