The TP Tracker

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Introduction

1.1 Objective

Every two minutes, enough toilet paper is used to wrap around the Earth. The United States is a major contributor: per person, the United States uses fifty percent more toilet paper than Japan and multiple countries in Western Europe [1]. This has astronomical environmental impacts, especially since most of the paper used is not made from recycled material. The Environmental Protection Agency has long been pushing for the use of recycled toilet paper for its numerous benefits to the environment. If everyone swapped one roll for a recycled roll, 470,000 trees, 1.2 million feet of cubic landfill space, and 169 million gallons of water could be saved [2]. Unfortunately, most people still use paper made from cut trees due to the high cost of manufacturing recycled paper. However, if everyone simply used one less roll, the benefits could be even greater. Part of the problem is that most people simply do not realize how much toilet paper they are using.

We propose a electronically controlled toilet paper dispenser, similar to a paper towel dispenser in a public restroom, which will track toilet paper usage of individuals in a household or private restroom. The dispenser will inform users of their usage and promote more sustainable habits. Our product will allow a user to sign in with an RFID tag, wave their hand to dispense a serving of toilet paper, and then log out after a period of inactivity. The dispenser will track this usage for each user and display total usage since the last reset. Consenting roommates can allow other residents to compare against their own metrics, bringing awareness to toilet paper usage.

1.2 Background

Efforts have been made in a public restroom in China to limit toilet paper usage at the Temple of Heaven Park, one of Beijing's busiest tourist sites. The park has created a dispenser which uses facial recognition to dispense servings of toilet paper to patrons [3]. This is done for economic reasons as excess paper can be expensive overtime. However, this dispenser only limits usage; it does not track usage. At the time of writing, there is no widespread commercial product that tracks an individual's toilet paper usage. Furthermore, alternatives to toilet paper dispensers, such as bidets, have not taken hold in America. Therefore, there is a gap in the market for an electronic toilet paper dispenser and tracker.

In order for our dispenser to be a viable product, our design should be relatively cheap to allow for mass adoption by interested households and businesses. Initial investment in purchasing and installing a dispenser may be greater than purchasing a package of toilet paper, but over time the number of toilet paper rolls saved should be more than worth the cost. Our product must also be energy efficient, entering low power mode when no one is in the restroom such that its usage does not negate the positive impact of reduced paper use.

1.3 High Level Requirements

- Design will dispense a serving of toilet paper when prompted by user, then record this to the user's counter.
- Dispenser will warn when toilet paper roll needs to be replaced.
- The product will attempt to conserve energy by entering low power mode when not in use.

Design

Our design is broken into five components which must interoperate to successfully fulfill the requirements. The Control Unit is the “brain” of the product, controlling many core processes: reading and interpreting data from sensors, controlling the User Interface, and sending the order to dispense. The Mechanical Unit accurately dispenses the toilet paper using a motor (continuous servo, stepper, DC, etc.). The User Interface displays important information and handles user input. The Power Unit keeps the system powered from a wall outlet. It also enables and disables low power mode, which will cut all but the necessary power for the microcontroller when entering sleep mode. The Light Sensing Circuit will determine whether the lights in the restroom are on or off based on an adjustable brightness threshold.

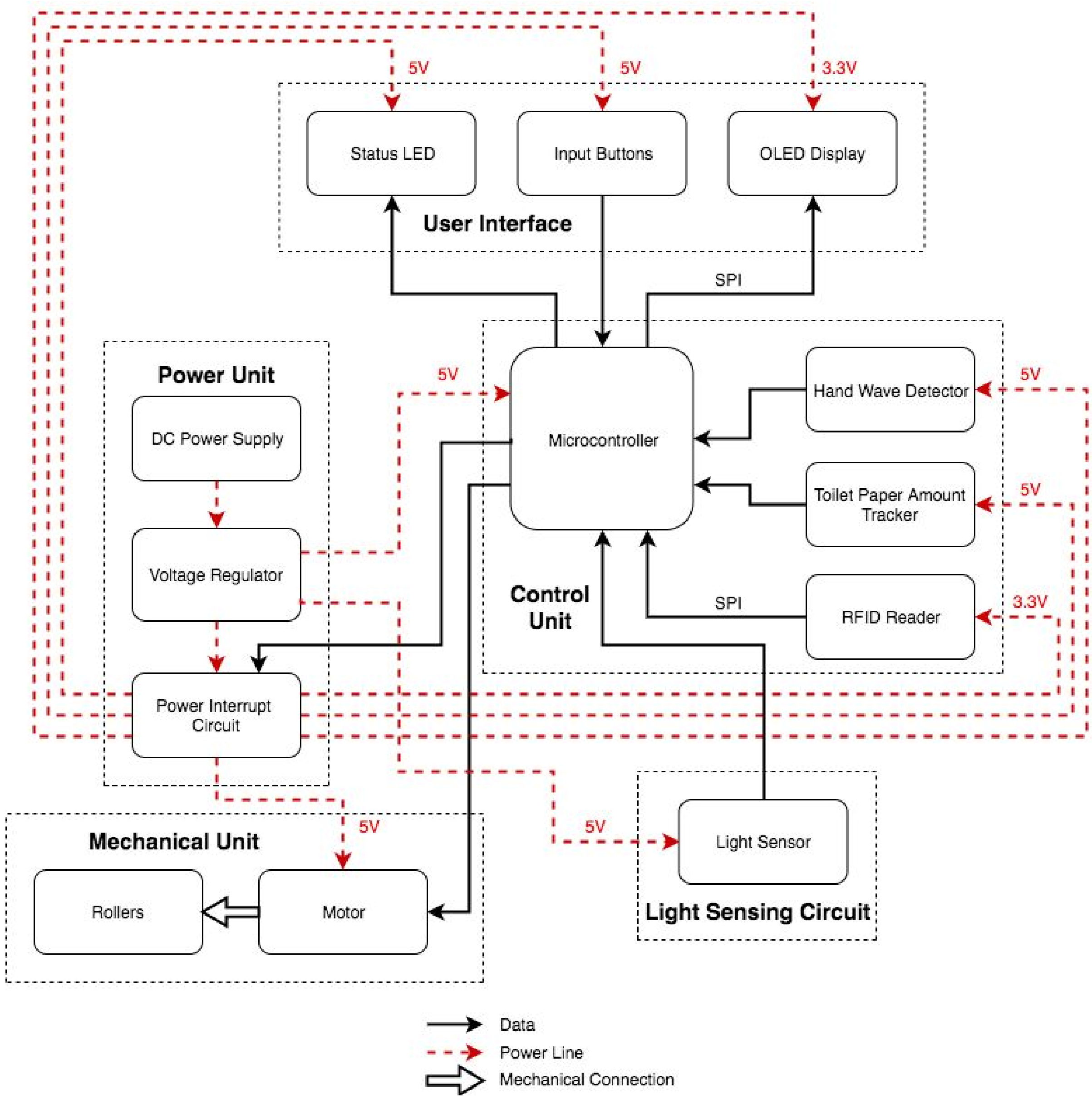

Figure 1: High level block diagram

The components will be arranged in an enclosure broken into three main compartments: extra roll storage, dispensing mechanism, and the PCB/circuitry housing. The side of the compartment will easily open on a hinge so the rolls can be changed easily. The PCB compartment will not be accessible to the user. The top parts of the enclosure will be made of material that is water resistant (not waterproof), so that small splashes of water can fall on it and not damage the device. Figure 2 shows a cross-sectional view from the side of the device.

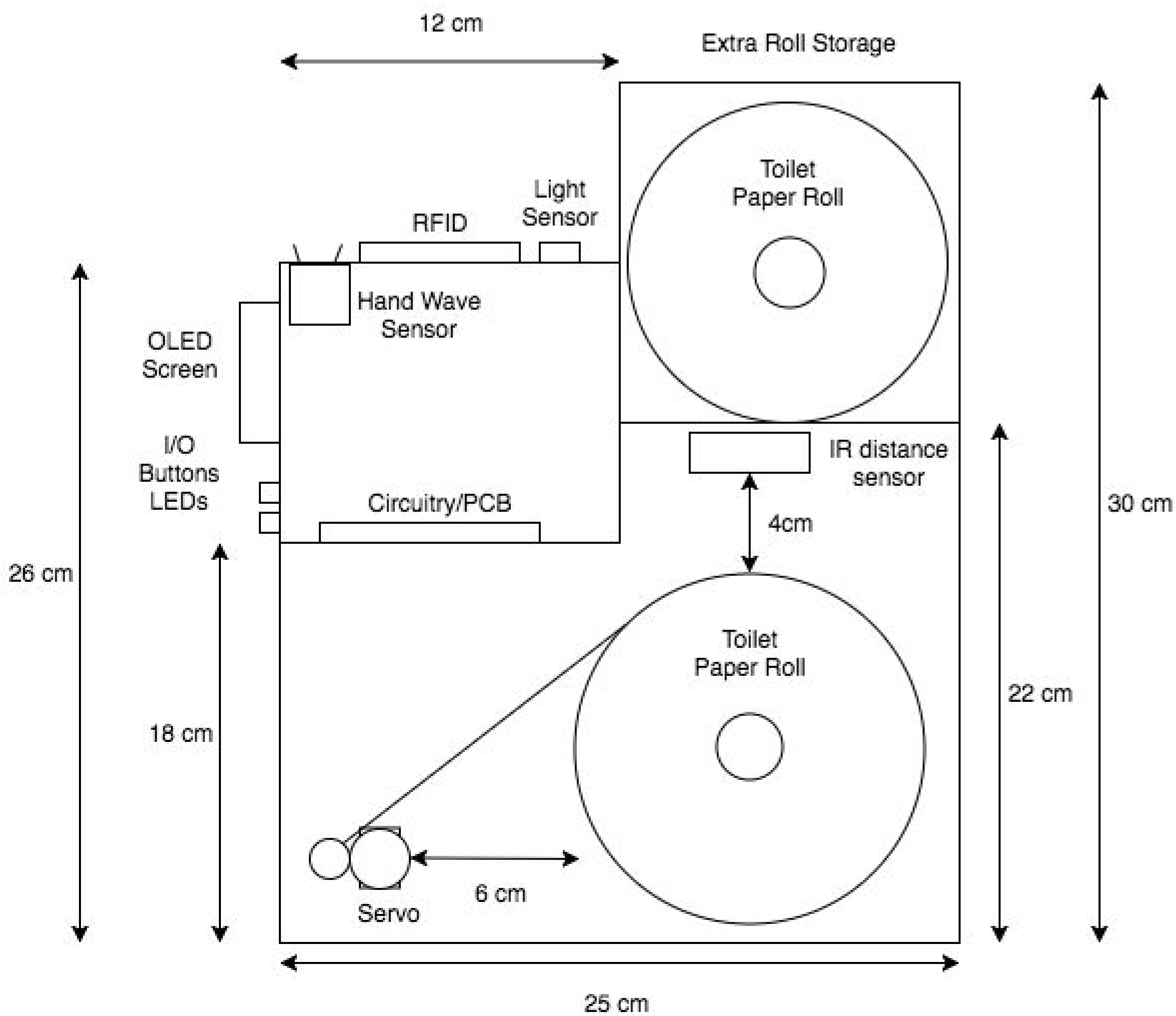

Figure 2: Cross-sectional view of physical layout of design

2.1 Control Unit

The Control Unit consists of a microcontroller, the Hand Wave Detector IR proximity sensor, the Toilet Paper Amount Tracker IR distance sensor, and the RFID reader. The microcontroller connects to the IR sensors, buttons, and LED through its digital pins. It connects to the OLED and RFID reader over SPI bus. The Light Sensing Circuit is connected to The Control Unit detects which user is signed in, dispenses servings of toilet paper, and tracks consumption. The operation of the unit is described by the flow chart in Figure 3. The circuit schematic is given in Figure 4.

2.1.1 Microcontroller

The microcontroller will be the ATmega328P. The microcontroller processes data from the sensors on the product, controls the dispensing motor in the Mechanical Unit, and processes the display of the User Interface. It also stores information on each user in its runtime variables and does data logging to the onboard EEPROM, which stores and retains values for when the device is shut off.

Memory usage breakdown:
The ATmega328P has 2KB of onboard SRAM for runtime variables and 1KB of EEPROM. We want to be able to store usage data on 4 users for up to one month.

A single user entry consists of a username containing a maximum of 10 alphanumeric characters (8 bits per char), a 16 bit unsigned integer for tracking the number of servings used so far in the month (The maximum value of an unsigned 16 bit integer is 65535, which far exceeds the number of servings of toilet paper an average individual user would use in a month.), and a unique 16 bit alphanumeric string that represents the RFID card associated with the user.

1 user = (username) + (serving counter) + (RFID string)
1 user = (10 alphanumeric characters) + (unsigned integer) + (alphanumeric string)
1 user = (10 char * 8 bits) + (16 bit integer) + (16 bit string)
1 user = 112 bits per user
(4 users) * (112 bits per user) = 448 bits.

Therefore, approximately 448 bits are required to store user data for 4 average users for up to one month.

Usage is also accumulated per day, and stored as a log entry. Log entries keep track of toilet paper usage for a single day for a single user. Each log entry consists of a time_t date and a byte (An 8 bit unsigned integer can count up to 255, which is more than enough servings a single average user would dispense in one day) representing the number of servings the user has used on that day.

1 date log entry = (date) + (number of servings used on that day)
1 date log entry = (time_t variable) + (byte variable)
1 date log entry = (32 bits) + (8 bits)
1 date log entry = 40 bits per log entry

Since EEPROM can hold up to 1024 * 8 = 8192 bits:
(8192 bits EEPROM) / [(40 bits per log entry)*(4 users)] = approximately 51 log entries per user, which is more than enough entries to store a month log of data for four individual users, since 1 month = at most 31 days/entries.

Requirements	Verification
1. Can store usage data for 4 average users for up to one month in EEPROM (based on calculations described in prior).	1. A. Create a program to populate EEPROM with a simulated month's worth of data for four users (based on the calculations described prior). B. Check if the program succeeds with populating the memory by reading the data at each address written to the EEPROM in step A.

2.1.2 Hand Wave Detector

This sensor will be a Sharp GP2Y0D810Z0F Digital Distance Sensor, which has a binary output of HIGH when an object is present in the 2 to 10 centimeter range, and an output of LOW when no object is present in this range. Our device will detect a "hand motion", which signals a request to dispense one serving of toilet paper. A "hand motion" is described as a situation where the sensor has output a binary high signal, followed by a low signal, sampled at a certain time period (Our time period constraint is 2 seconds because this is a reasonable rate of consuming toilet paper servings). The sensor will be mounted in a way such that it is pointing upwards towards the ceiling to prevent false detections of hands and other objects. It is assumed that the product will be mounted in a position such that there is no obstruction of view between the sensor and the ceiling of the room.

Requirements	Verification
1. Outputs HIGH when a hand sized (flat, square 7 cm) object is directly above the sensor at a distance of 2-10 cm, with 98 percent accuracy. 2. Outputs LOW when hand sized object is at a distance outside the distance range of 2-10 cm, with 98 percent accuracy.	1. A. Connect sensor to microcontroller and connect microcontroller to computer through USB. Open a serial connection to computer. Create a software program to display the output value (HIGH/LOW) of the sensor every .25 seconds.

*May output HIGH or LOW when hand sized object is between 10 and 15 cm. **There is a 1 cm tolerance on all measurements in this section.	B. Record 100 samples each for hand sized objects at distances of 3, 5, 7, and 9 cm. Ensure false negative rate is less than 2 percent. 2. A. Repeat step A in part 1 above. B. Record 100 samples each for hand sized objects at distances of 50, 25, and 16 cm. Ensure false positive rate is less than 2 percent.

2.1.3 Toilet Paper Amount Tracker

The sensor will be the Sharp GP2Y0A41SK0F Infrared Proximity Sensor. This short range distance sensor will be used to track the size of the toilet paper roll to determine when the roll is running low (10% remaining). It will be mounted horizontally approximately 4 cm away from the edge of the roll, pointing towards the center of the roll as shown in Figure 2.

Requirements	Verification
1. At a distance of 10 cm from the center of the roll, the tracker will determine percentage of roll left relative to a 5 cm radius standard roll to 10% accuracy.	1. A. Connect sensor to microcontroller and connect microcontroller to computer through USB. Open a serial connection to computer. Create a software program to display the output value (distance) of the sensor every .25 seconds. B. Measure toilet paper roll radius with ruler. Install roll and record output distance shown on serial monitor. Verify the output distance with ruler. C. Repeat for rolls with approximately 10%, 25%, 50%, 75%, and 100% left.

2.1.4 RFID Reader

The RFID reader is used to identify different users by allowing them to login with an RFID card/tag, which has a unique ID string.

Requirements	Verification
1. Must identify the 16B unique ID of multiple unique 13.65MHz RFID cards within a range of 1 to 4 cm, one at a time, each within 5	1. A. Connect sensor to microcontroller and connect microcontroller to computer

seconds.	through USB. Open a serial connection to computer. Create a software program to print the 16B ID value read by the RFID reader to the serial monitor. Hold an individual RFID card parallel to the reader within a distance of 1 to 4 cm. Confirm that a value is displayed on the serial monitor within 5 seconds and record the value displayed on the serial monitor. B. Repeat step A for another RFID card with a different 16B ID value. If the values differ, the reader is functioning properly.

2.2 User Interface

The User Interface displays information such as consumption of each resident, low paper warnings, and other important menus and metrics. It consists of an OLED screen, 4 buttons, and a status LED.

2.2.1 OLED Screen

The Solomon Systech SSD1306 OLED screen will be used to display a text menu to users. The menu will have multiple screens: allow users to sign in manually (if they forget their RFID card), view how many servings of toilet paper the individual user has used, and display percentage of toilet paper is remaining in the current roll. The display has a resolution of 128 x 64 pixels and can communicate over SPI or I2C.

Requirements	Verification
1. Refresh screen at a rate of at least 2 frames per second. This ensures a fluid user interface experience.	1. A. Connect the screen to the microcontroller and connect the microcontroller to a computer via USB connection. Create a software program to move a single 1 x 1 dot in a straight horizontal line from the top left of the screen to the top right of the screen. The screen has a horizontal width of 128 pixels and the program will move the dot one pixel to the right every 0.5 second (500 milliseconds). Therefore the pixel should move two pixels to the right each second, and

	thus will require (128 pixels) / (2 pixels per second) = 64 seconds to move from the left side of the screen to the right side of the screen. B. At the start of the software program, start a software timer in the code. When the pixel reaches the last (rightmost) pixel in the horizontal line, stop the timer. Print the finished timer value to the serial monitor and verify that it is within 64 +/- 1 seconds.

2.2.2 Input Buttons

Four buttons allow the user to control the user interface. Software debouncing code will be written to debounce the buttons so that a button push will not have multiple triggers on a noisy edge transition. This is done by periodic sampling of the input line every 10 milliseconds in our program.

Requirements	Verification
1. Button is pressable.	1. Connect sensor to microcontroller and connect microcontroller to computer through USB. Open a serial connection to computer. Create a software program display the output (HIGH/LOW) of the button to a serial monitor at a 9600 baud rate (9600 bits per second is more than enough speed for a 10 millisecond segment detection of a 1 bit ‘button press’ message). Ensure when the button is pressed there is a smooth transition with no bounce. Check if the serial monitor displays the button press.

2.2.3 Status LED

A status LED will light up when toilet paper roll begins to get low (approximately 10% of paper remaining in the roll).

Requirements	Verification
1. Must be visible from 1 meter away with a drive current of 15 +/- 5 mA.	1. A. Measure current through LED with multimeter. Ensure current is within correct range. B. Ensure easy visibility of illuminated

	LED from 1 meter.

2.3 Mechanical Unit

This subsystem will handle dispensing the servings of toilet paper. It contains the motor as well as the custom-designed mechanical rollers.

2.3.1 Motor

We will use a continuous rotation servo for it's adjustable speed from the microcontroller.

Requirements	Verification
1. Servo will be adjustable from 0 to 1 rotations per second.	1. Attach a marked wheel to the motor. Connect the motor to the microcontroller. Create a software program to rotate the motor at a predetermined speed, and be able to adjust the speed up or down from hardcoded values in the program. Verify rotation speed with stopwatch by tracking how long it takes for the marking to complete one rotation.

2.3.2 Roller

This roller will be used in conjunction with the motor to ensure toilet paper is dispensed.

Requirements	Verification
1. Roller must be able to grip the toilet paper when paired with the motor on the opposite side of the paper.	1. A. Insert roll of toilet paper on to roller. Clamp the beginning sheet of toilet between the motor and the passive roller. B. Create a software program to rotate the motor 5 revolutions. If the paper dispenses easily without much resistance, the roller is working.

2.4 Power Unit

The design will be powered from a wall outlet. The power supply must consist of an AC to DC converter and a voltage regulator to ensure the microcontroller and sensors receive the correct voltage. The AC/DC converter will simply be a packaged 9V converter. This is used instead of batteries for convenience to the user. The Power Interrupt Circuit will receive a binary signal from the microcontroller to enter or leave low power mode. It will also cut the power to all sensors and the motor to eliminate leaked power. In the case that the microcontroller is in low power mode, the Light Sensing Circuit will signal the hardware interrupt pin on the microcontroller, which will in turn signal the Power Interrupt Circuit to leave low power mode.

2.4.1 AC/DC Converter

The converter will change the 120 Volt AC power to a useable DC voltage.

Requirements	Verification
1. The converter must output a voltage of 9+/-1 volts DC.	1. Connect the AC/DC converter to a standard United States household wall outlet (120V 60Hz). Connect a voltmeter to the plug of the AC/DC converter and measure the output voltage.

2.4.2 Voltage Regulator

We will be using two switching regulators to step down the voltage from the DC power supply to 5V and 3.3V respectively. We are using switching regulators instead of linear regulators to decrease power loss when there is low current draw. The circuit is shown in Figure 5.

Requirements	Verification
1. The regulator circuits must output 5 +/- 0.5 V and 3.3 +/- 0.3 V, respectively.	1. Measure voltage output with multimeter when connected to final circuit during both low power and normal modes. Ensure voltage is within specified ranges. Repeat for each voltage requirement.

2.4.3 Power Interrupt Circuit

This consists of a PNP MOSFET between the power supplies and the various sensors which will be turned off in low power mode. They will take a HIGH or LOW digital output from the microcontroller to cut or supply power respectively. See the circuit in Figure 6.

Requirement	Verification
1. Less than 100uA will flow to all connected sensors when HIGH signal is given from microcontroller. Conversely, power will be virtually unrestricted when output is LOW.	1. A. Set input to interrupt circuit HIGH from microcontroller. Read current flow to sensors with a multimeter and ensure it is limited. B. Set input to interrupt circuit LOW from microcontroller. Ensure all sensors run as expected.

2.5 Light Sensing Circuit

2.5.1 Light Sensing Circuit ("Sensor")

The light sensing circuit will consist of a photoresistor which measures the brightness of the room. The circuit will output a binary HIGH if the bathroom is lit, and a binary LOW is the room is dark. The circuit is tunable such that the threshold can be set at any range of the photoresistor using a potentiometer. When the microcontroller is in low power mode, the output of the Light Sensing Circuit will be able to "wake up" the microcontroller because it is connected to a hardware interrupt pin. The circuit is given in Figure 7.

Requirements	Verification
1. Photoresistor circuit can distinguish between an average lit room and average dark room. 2. Light threshold is adjustable such that different brightness thresholds can be set. *What constitutes as a "lit" and "dark" room are up to the interpretation of the user. Lux is used to determine the resistance of different light levels. [4] The user is able to set whatever threshold they want, and whenever the lux is above or below that threshold, the circuit will output a binary (HIGH/LOW) value.	1. Connect circuit output to a multimeter. Turn lights on and off, ensure HIGH and LOW values are output, respectively. Attempt this test in a variety of brightnesses. Tune if necessary. 2. Adjust tuning potentiometer. Ensure both HIGH and LOW can be output from the circuit in dark and light environments of varying brightness/lux.

2.6 Software Flow Chart

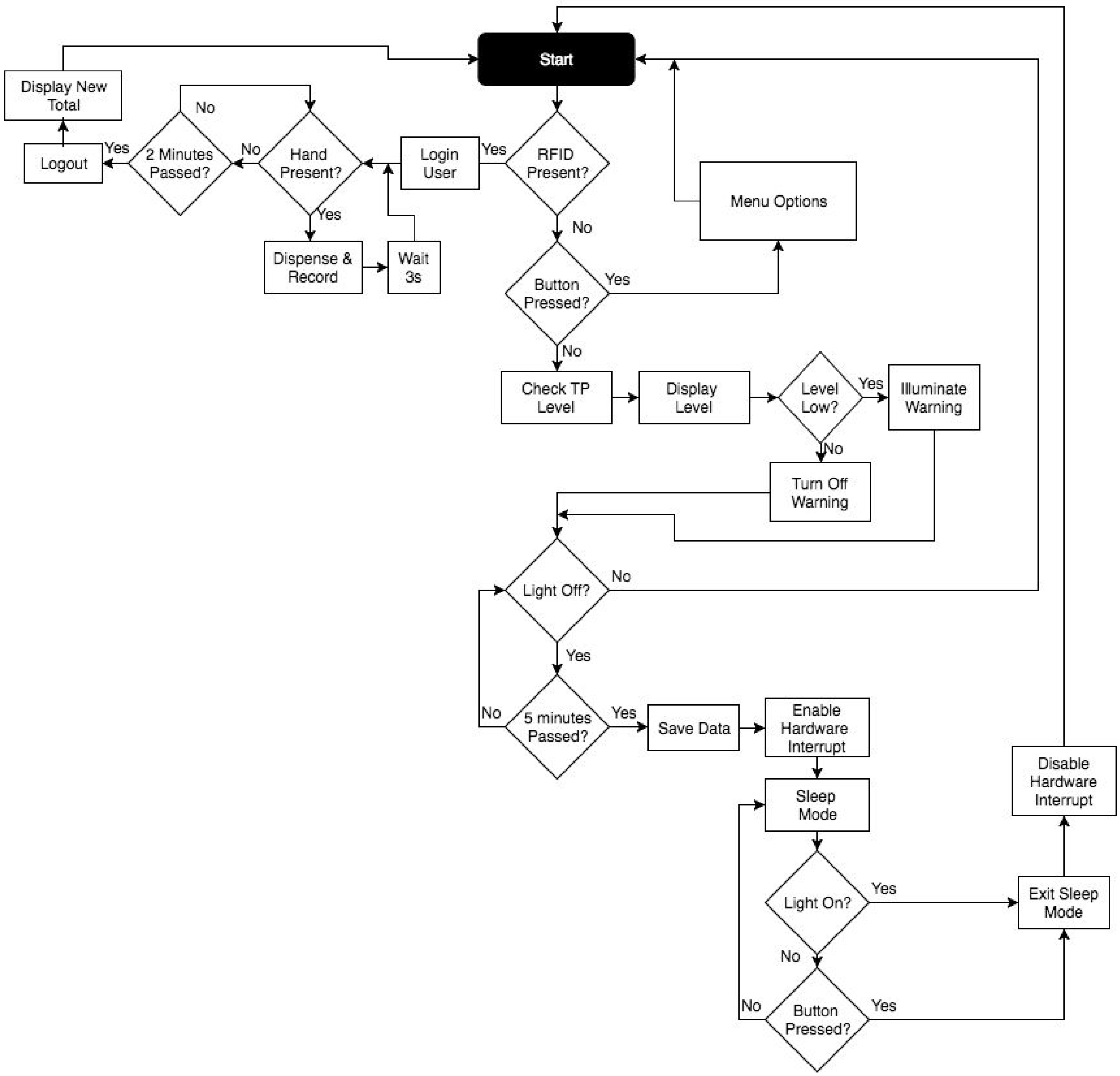

Figure 3: High Level Unit Operation Flow Chart

2.7 Schematics

To clarify signals in the schematics, certain nets have been labeled. The outputs of the 5V and 3.3V voltage regulators are labelled as 5VOUT and 3.3VOUT respectively. The 5V and 3.3V interruptible signals are labeled as 5VINT and 3.3VINT. These are the outputs from the Power Interrupt Circuit. The output from the microcontroller which controls this is labeled as P_SAVE. Finally, the output from the Light Sensing Circuit is labeled as L_SENSE.

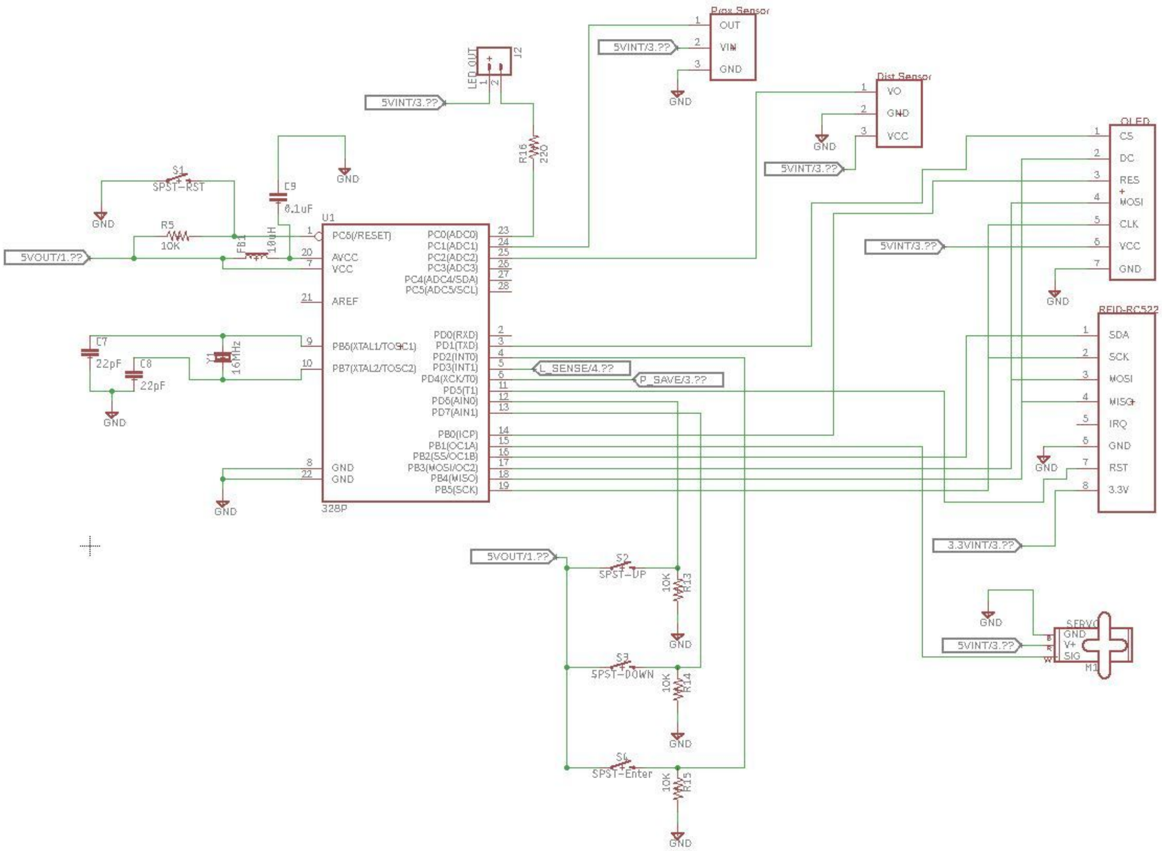

Figure 4: Control Unit, User Interface, and Mechanical Circuit

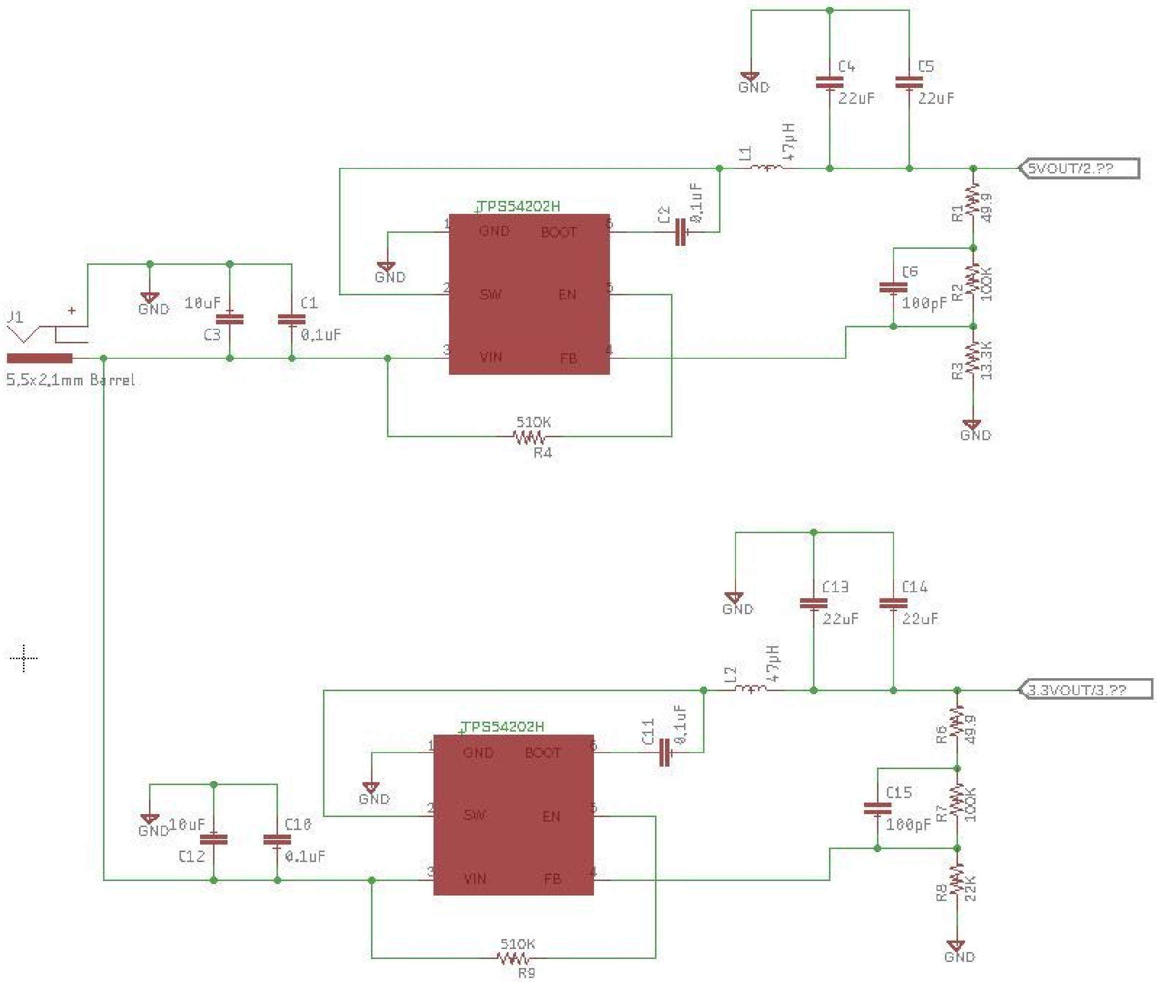

Figure 5: Voltage Regulator Circuit

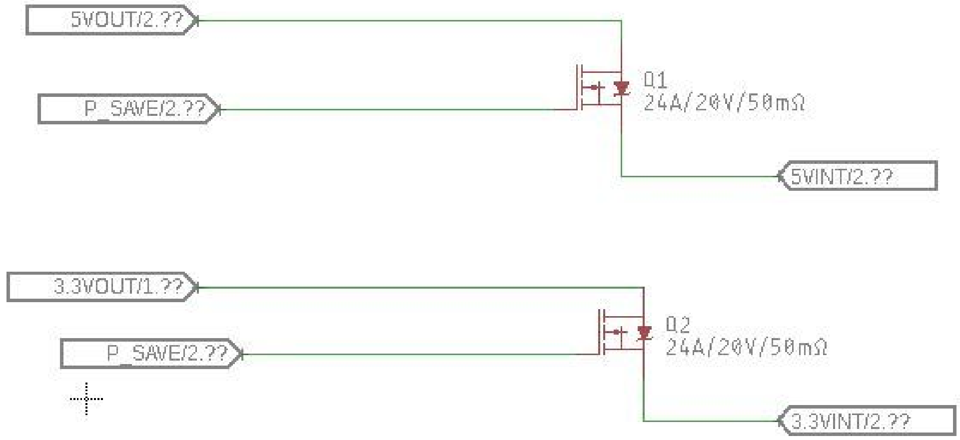

Figure 6: Power Interrupt Circuit

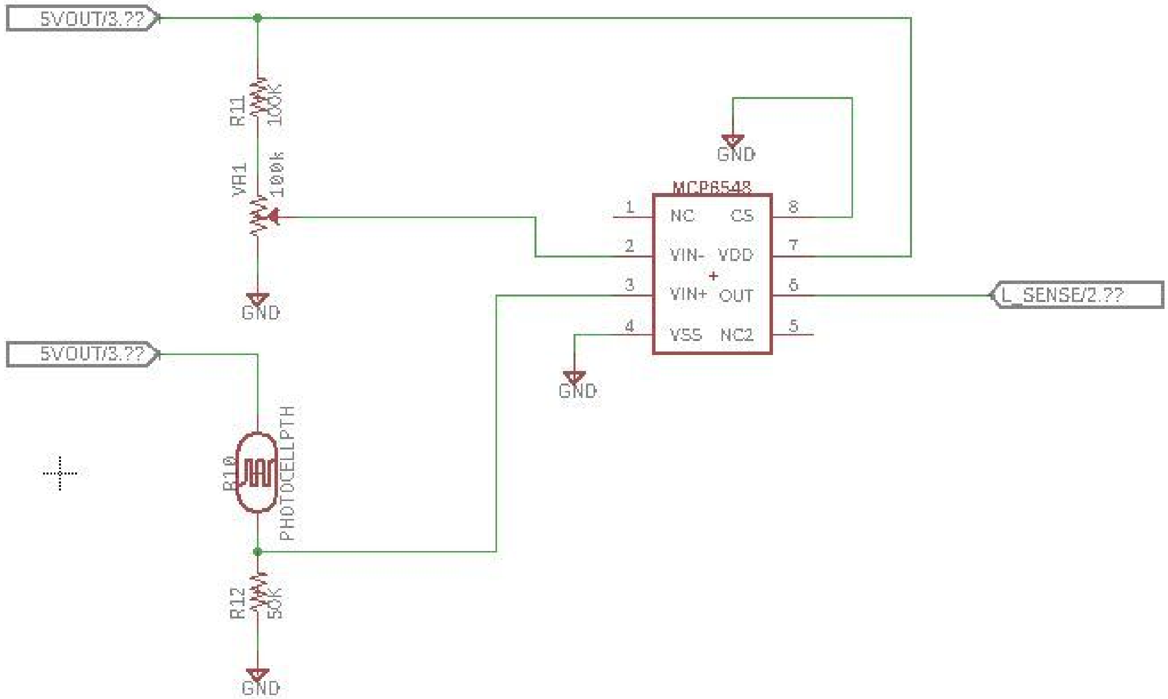

Figure 7: Light Sensing Circuit

2.8 Tolerance Analysis

We will be examining the IR distance sensor in the toilet paper (TP) remaining measurement block. More specifically, we will analyze the tolerable noise level on the analog input pins. We would like to report the amount of toilet paper remaining to an accuracy of ten percent. This can be taken as the area of the roll edge to tube edge, compared to the standard 5 cm thick roll. Our standard roll has a tube radius of 2.25 cm, and a roll radius of 7.5 cm. The percentage of toilet paper left can be taken as:

$$TP\% = \frac{(Outer\ Radius)^2 - (2.5\ cm)^2}{(7.5\ cm)^2 - (2.5\ cm)^2}$$

Outer Radius	Percent Left	Distance Tolerance (10% change in TP)
7.50 cm	100%	.35 cm
7.16 cm	90%	.36 cm
6.80 cm	80%	.38 cm
6.42 cm	70%	.40 cm
6.02 cm	60%	.43 cm
5.59 cm	50%	.47 cm
5.12 cm	40%	.51 cm
4.61 cm	30%	.58 cm
4.03 cm	20%	.68 cm
3.35 cm	10%	-

Table 1: Distance Tolerances

To account for oversized rolls (6+ cm radius from tube), we will position the edge of the tube 10 cm from the proximity sensor. The average roll edge is then approximately 5 cm from the proximity sensor. We will take linear approximations of output voltage slope over 1 cm distance, and map this to the ATmega328P’s analog input pin resolution to find the distance resolution. See Figure 8 for output voltage vs distance chart. The analog inputs have a 10 bit input resolution. Over 5 volts, this is a voltage resolution of about 5 mV. Values marked with a “-” are marked so due to the “don’t care” nature of those values, as we assume the roll is oversized.

Distance to Sensor	Roll Outer Radius	Output Slope(V/cm)	Ideal ATmega Distance Resolution	Distance Tolerance/ Resolution
3.5	-	-.30	.017 cm	-
4.5	7.5	-.35	.014 cm	25
5.5	6.5	-.35	.014 cm	28
6.5	5.5	-.25	.020 cm	23.5
7.5	4.5	-.20	.025 cm	23.2
8.5	3.5	-.18	.028 cm	25

Table 2: Sensor Output Voltage Response and ATMEGA distance resolution

Using the above information, we can allow for noise approximately 20 times the voltage resolution of the ATmega328P. This is noise of approximately 0.1V. It is doubtful we would reach this level of random noise, however improper toilet paper roll placement on the order of 0.5 cm could offset our results by this level.

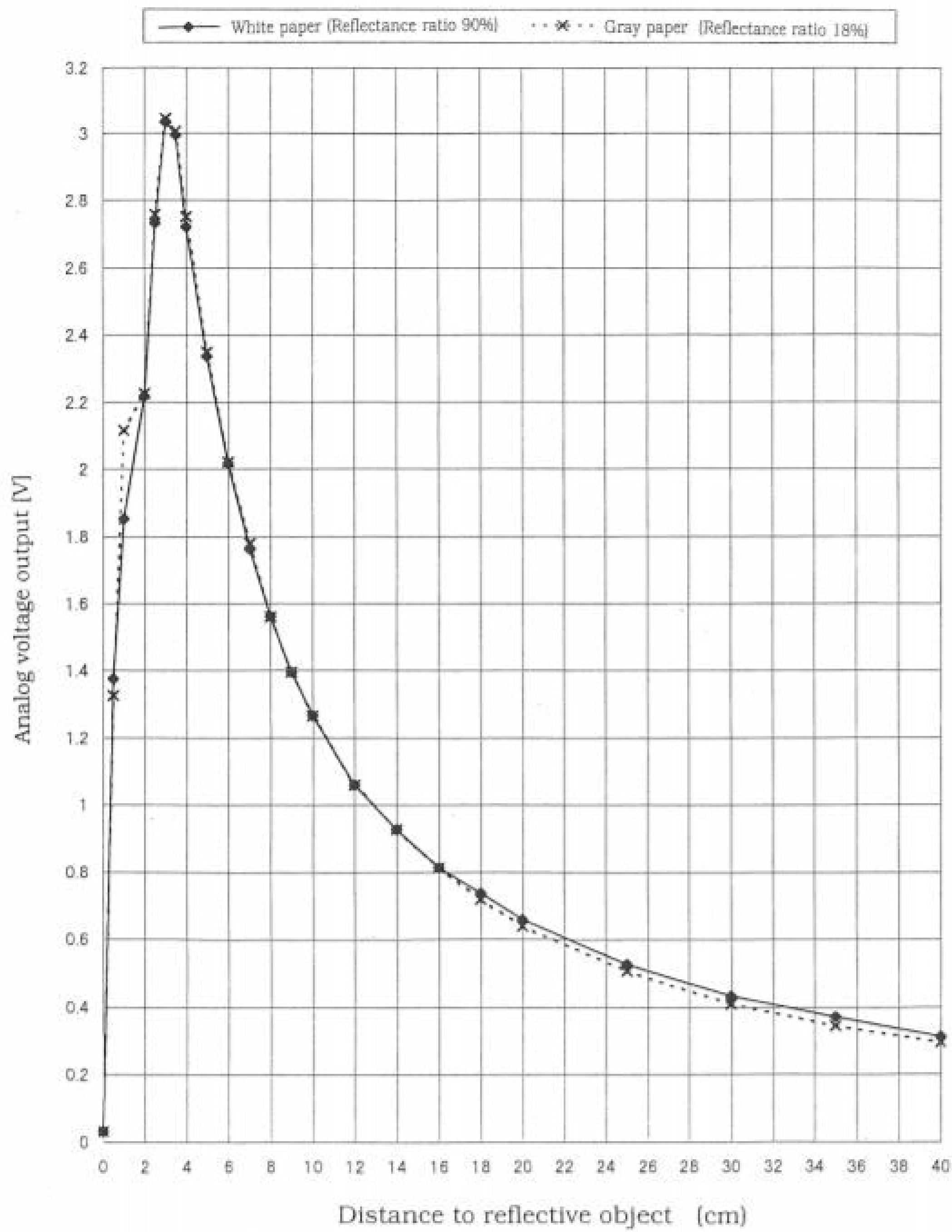

Figure 8: Output of the IR distance sensor.

Cost and Schedule

3.1 Labor

We assume a labor cost of $35 hourly. Estimating 10 hours of work weekly per person, with 10 full weeks of work in the semester after project approval. This is a labor cost of:

$$2 * \frac{\$35}{hr} * 2.5 * \frac{10hrs}{week} * 10\ weeks\ =\ \$\,17{,}500$$

3.2 Parts

We only are calculating the cost of parts for producing one prototype. Bulk ordering of components would significantly reduce the costs, possibly up to 30% or more.

Component	**Manufacturer**	**Serial**	**Price($)**	**Quantity**
IR Prox Sensor	Sharp	GP2Y0D810Z0F	$5.95	1
IR Distance Sensor	Sharp	GP2Y0A41SK0F	$14.00	1
Microcontroller	Atmel	Atmega328P	$3.00	1
OLED Screen	Solomon Systech	SSD1306	$9.99	1
Continuous Rotation Servo Motor	Adafruit	FS90R	$7.50	1
RFID reader	Mifare	RC522	$6.00	1
RFID card	QIAOYUAN	-	$0.80	5
Photoresistor	API	PDV-P8001	$0.95	1
Potentiometer	Bourns	3362P-1-104LF	$1.02	2
Comparator	Microchip	MCP6548-I/P	$0.58	1
Pushbutton	-	-	$0.50	4
Voltage Regulator	Texas Instruments	TPS54202H	$1.69	2
MOSFET Interrupt	Fairchild	FQP27P06	$0.95	2
Assorted RLC	-	-	$3	1
Enclosure Wood	-	-	$5	1
TOTAL			**$69.29**	

* " - " indicates irrelevant/unavailable field

3.3 Grand Total

The grand total of parts and labor then becomes $17,569.29 to create a working model of the project.

3.4 Schedule

Week	Will	Kevin
2/19/18	Prototype servo mount and roller. Construct prototype enclosure. Order Components.	Begin developing OLED display code with microcontroller.
2/26/18	Begin breadboarding Light Sensor, Power Interrupt, and Voltage Regulator.	Continue developing user interface menus. Begin programming button input and RFID Reader.
3/5/18	Start PCB Design.	Wrap up development user interface menus and button input. Finish RFID integration. Begin developing motor dispensing code.
3/12/18	Complete PCB Design. Submit for fabrication. Develop code for IR distance sensor for roll thickness.	Develop code for integrating IR proximity sensor for hand wave detection and IR distance sensor for tracking roll thickness. Finish motor dispensing code.
3/19/18	Revise PCB design if necessary. Combine all components to single breadboard. Begin testing unit.	Finish developing detection/sensor codes. Develop code to integrate Power Interrupt Circuit with hardware interrupt pin.
3/26/18	Develop sleep mode code. Test low power mode. Integrate all developed code thus far into simple working model.	Conduct unit tests, feature tests, and integrated black box system test. Begin developing code for interfacing with EEPROM.
4/2/18	Tune all parts, general product debug.	Fine tune serving amount and user interface menus. Experiment with different positions for roll thickness IR sensor, attempt to increase accuracy of thickness.
4/9/18	Assemble PCB, Debug.	Finalize modifications to the physical enclosure and sensor placement.
4/16/18	Continue Debugging. Make enclosure water resistant.	Fix bugs and clean up code. Complete documentation.
4/23/18	Prepare final presentation and write final report.	Prepare final presentation and write final report.

Safety and Ethics

There are a few safety concerns our team will have to worry about. First, we would like to avoid our users getting their fingers stuck in the dispensing mechanism. High powered mechanical components can cause harm to a user if not properly shielded. For this reason we will incorporate a low powered motor and will place a guard in the opening such that it is difficult to reach any moving parts. The opening will be thinner than the average finger width in order to prevent users from sticking their fingers up the dispensing opening. The second safety concern is that in a bathroom setting, there will likely be water splashed on the product. We will shield all connections as best as possible and only work with 9VDC or less within the enclosure, preventing electrical danger to our users. The entire enclosure will be sealed and as water resistant as possible. Since we will be using a wall adapter to bring in DC power to the device, there is an inherent risk: misuse could lead to shock. For safe operation, the enclosure must be properly mounted. If pulled off the wall, there would be a possibility for injury.

In terms of ethics, there is the issue of potential harm to others through disclosure of information [5] [6]. This is touched upon in IEEE Codes 2 and 9, which state that an invention should avoid conflict and avoid injuring users. We believe this includes not only physical safety, but the security of information and personal privacy of our users. We will include a visibility setting for each user so they may decide whether or not to display their consumption to other residents. However, we cannot control external peer pressure from roommates to share the said information; we can only provide the option of restricting visibility. This product is designed such that everyone can become more aware of their own usage, not for purposes of spying or regulation. Participation should be voluntary. Another ethical issue brought up is that female users may generally have higher toilet paper usage than males. We do not want to violate IEEE Code 8 and discriminate against any gender. This product is designed for use as a personal tracker. If one would like to share their usage voluntarily, this is an option, but it is designed primarily for personal tracking and improvement. Therefore, there should be no inherent gender-based discrimination.

References

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