Sustainable Hi-Traffic Toilet Redesign

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***Abstract*— The Sustainable-Hi Traffic Toilet Redesign employs improved sensing technologies to decrease water usage and improve maintenance of restrooms. The SHTTR system employs battery free RFID sensors to monitor room occupancy, toiletry usage to determine how the toilet was used, as well as trigger the toilet to be able flush accordingly. This system provides an improved model on the self-flushing toilet, with proper dual flush significantly saving on water usage. The system monitoring and triggering the wireless sensors also acts to supply analytical data for improved maintenance scheduling and supply monitoring to improve upkeep of public restrooms.**

***Index Terms*—RFID, Toilet**

I. Introduction

THE initial idea behind the SHTTR system came from concerns over issues with both mistimed or ineffective self-flushing toilets. Since the average person uses the bathroom thousands of times a year, even small improvements in commercial waste technologies can grossly impact the amount of water wasted when applied at a large scale. The system is composed by a few parts. Firstly, there is a toilet paper usage sensor, with the plan to detect toilet paper usage within a 5-sheet range. The system then includes a simple door latch sensor to determine when the restroom stall is occupied. There is a sensor relay to trigger the type of flush necessary per the bathroom usage instance, and finally there is a wireless monitoring system that triggers proper responses for the toilet based on input information from the door and toilet paper usage sensors. By designing a retrofittable solution, the approach allows for realistic installation in existing bathrooms. Using a wireless system, the solution allows for simple a scalable variable size implementation with the ability to expand modularly if more sensor capabilities are developed.

II. Design Requirements

In order to satisfy the accuracy necessary to create the SHTTR system, it necessary to constrain the solution. This requires that the toilet paper usage sensor is accurate to realistic toilet usage, the wireless monitoring system is polling at proper intervals, and that door latch sensor provides accurate feedback in bathroom occupancy.

For the toilet paper usage sensor, the intended accuracy of the design is within 5 sheets of paper. As the majority of toilet clogs come from the paper usage, it is important that the system can accurately determine the amount of toilet paper used to the extent that a high volume or low volume flush is triggered. In order to obtain this accuracy, the plan is to use a load cell to measure downwards force applied to the roll of toilet paper. This works in two ways, both to measure the time that a user is pulling downwards to retrieve sheets of paper as well as a rudimentary scale. Using the load cell as a scale, the precision is based on the following equation:

$$Resolution = \frac{Load\ Cell\ Max\ Weight\ (g)}{ADC\ Resolution * ADC\ Gain * Load\ Cell\ Sensitivity\ (mV/V)}$$

$$Resolution = \frac{500g}{2^{16\ bits} * 0.128 * 0.7mV/V} = \pm 0.085g$$

In general, the real-world ADC has a resolution of 24 bits, but however, because of some general noise, it is generally given that only 16 of these bits should be taken as completely accurate for the measurement. This resolution of the scale is well within the defined parameters of +/- 5 sheet accuracy of the toilet paper usage sensor.

The intended accuracy occupancy of the system is reliant on how often data is collected in order to make decisions based on the current state. The goal of the occupancy sensing is to determine within 5 seconds whether or not a single toilet stall is in use. Both the door latch sensor and the toilet flushing trigger are not time cycle dependent and can be read from remotely as the rate of the system polling. The toilet paper usage sensor, once activated, will be updated at a rate of 60 Hz then sending the results to the monitoring system. In order to complete this monitoring reliability, the system will read from the proper tags every 80ms as well as writing to tags when necessary in 80ms. This will allow for accurate occupancy sensing while not wasting power by constantly polling as often as possible.

In addition to these requirements, we also need the system to be reliable for long term use. With some basic calculations with a sage but naïve power usage, the intended battery powered portion of the sensor could operate for 46.92 hours until the battery dies. However, by using a battery free wireless sensor as a wakeup relay, the sensor will not be powered on while the room is not occupied, so there will be no power wasted. Assuming that a single stall is occupied for around 1 hour a day, then the battery life of the toilet paper usage sensor extends to over a month.

Finally, the monitoring system must be able to relay important information in real time to the necessary parties. Using an online database, maintenance schedules will be able to see details such as the amount of toilet paper remaining in specific rolls as well as the amount of times a toilet or bathroom was used.

III. Architecture and/or Principle of Operation

From a system architecture standpoint, the SHTTR system has several key parts.

Central to the wireless functionality and the cohesive hub of the system is a ThingMagic M6e-Nano EPC-C1G2 RFID Reader. This reader both allows for the powering of the battery free wireless sensors and relays as well as being able to read and write values to and from the same sensors. The reader will be controlled by a Raspberry Pi 3B+. This then gives the system the ability to communicate with a separate server over the internet to post log data from the sensors. The computer will be responsible for logging the information from the reader to a server, as well as processing the information and making the necessary decisions to give commands for the reader's write commands. The M6e-Nano Reader was chosen because of its capability to perform the necessary requirements of the design while still being in the feasible budget range of the class.

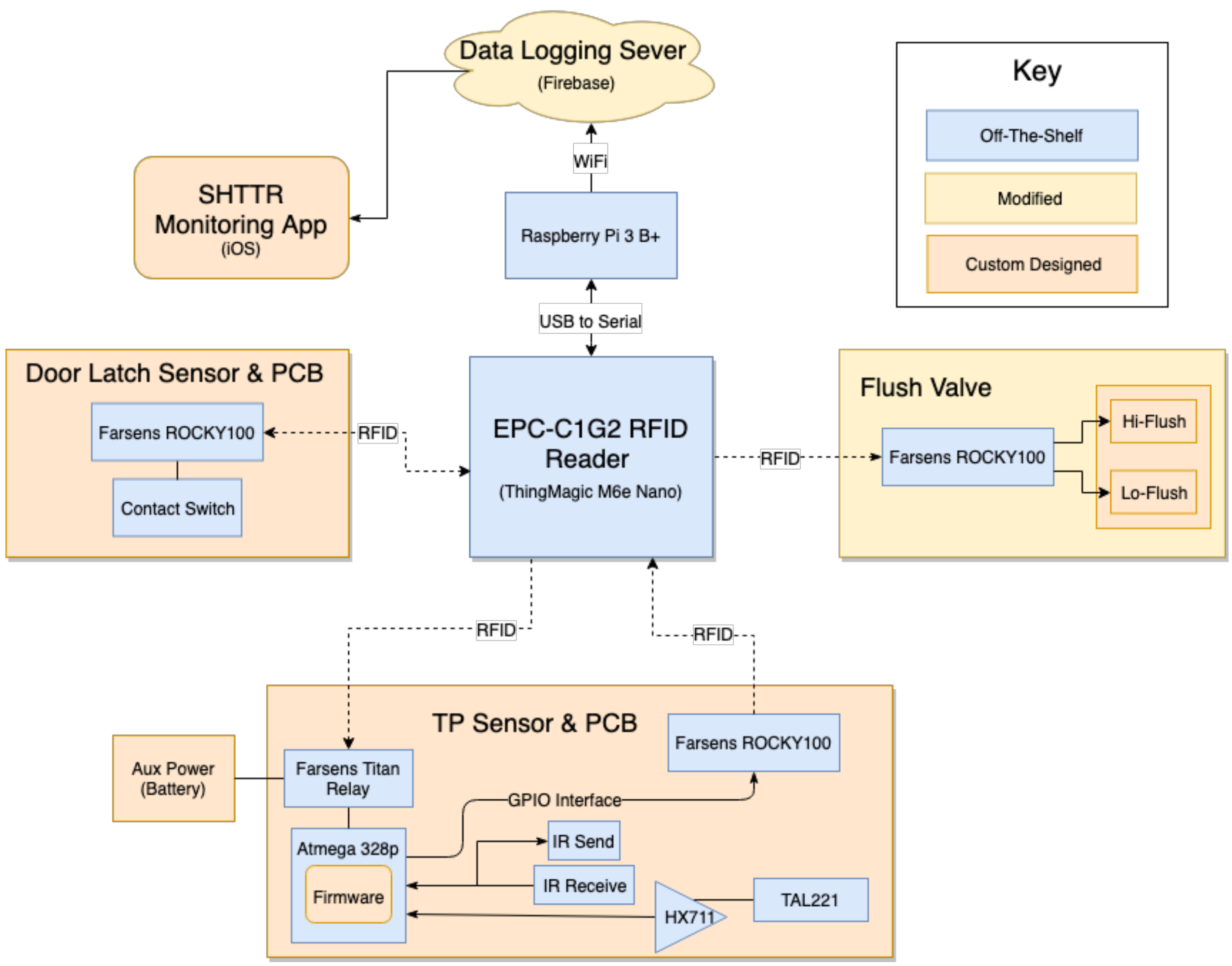

Fig. 1. System Block Diagram

In addition to the RFID reader polling from this server, there will be a separate cell phone application that acts as a way for a human readable monitoring system. This will give maintenance workers and schedulers access to the information read from the sensors to inform for proper decision making. The plan with this is to give alerts for when

The Door Latch Sensor is architecturally rather simple. The position of the physical locking of the door latch will be detected with a simple contact switch, as these are the only two states that the door may be in, necessary to the operation of the SHTTR system. This state is then communicated to the RFID reader by a Farsens ROCKY100 wireless sensor. This allows the reader to process the information and determine the state of the system.

The Flush Valve is similarly relatively simple from an electronic design standpoint. The ROCKY100 sensor waits for a state to be written from the RFID reader and activates a simple digital button signal for either a high-volume flush or a low-volume from a dual flush valve.

Finally, the toilet paper usage sensor. The sensor is powered on and off remotely from a Farsens Titan Relay. The system is controlled by an Atmega328p microcontroller powered by auxiliary power in the form of a battery. The TAL221 load cell is connected to the microcontroller via the HX711 load cell amplifier which allows the microcontroller to interpret the signal being received from the load cell and process information accordingly. In addition, there is an IR LED as well as an IR receive diode. These are used to determine physical rotation of an access. Through a GPIO interface from the microcontroller, another Farsens ROCKY100 communicates the state of the toilet paper sensor to the central RFID reader.

IV. Design Trade Studies

When selecting components for our project, there were two major pieces we had to decide on: Load Cells, and the RFID Reader to use as the basis for the system. Each of these required unique considerations, and the results of these trade studies are described below.

TABLE I. LOAD CELL OPTIONS

Model	***Capacity (g)***	***Sensitivity (mV/V)***	***Resolution (g)***
TAL221-100	100	0.6	0.020
RB-Phi-203	100	0.6	0.020
TAL221-300	300	0.7	0.051
TAL221-500	500	0.7	0.085
Seeed 114990100	2000	2	0.119
TAL221-1000	1000	1	0.119
TAL220-3000	3000	1	0.358
TAS606	5000	1.5	0.397

A. *Load Cell Selection*

When deciding on load cells, we had to consider two major factors: maximum capacity and resolution when coupled with our HX711 load cell amplifier. The options show above are the cells that we initially considered. Our main goal was to have as precise of a resolution as possible. However, we had to rule out all load cells with a capacity under 500g, as they would not be able to handle the weight of the toilet paper. After looking at these options and calculating theoretical resolution when paired with the HX711, it became clear that the TAL221-500 was the best load cell for our design. It combines adequate capacity with ±0.085g resolution, enough to measure with sub 5-sheet accuracy.

B. *RFID Reader Selection*

TABLE II. RFID READER COMPARISONS

Model Name	***Maximum Transmit Power (dBm)***	***Antenna Support***	***Price***	***Interface***
ThingMagic M6e-Nano	27	1	$224	FTDI/Serial
ThingMagic USB Pro	30	1	$695	USB
ThingMagic M6e	31.5	4	$795	UART/USB
ThingMagic Sargas	30	2	$1,190	Ethernet/USB
ThingMagic M6	31.5	4	$2,090	Ethernet/USB/Wifi
IMPINJ Speedway R420	32.5	4 (32 expandable)	$2,365	RS-232/Ethernet/USB

Selecting the RFID Reader was a critical part of the design of this project. The RFID Reader sits at the heart of the SHTTR system and working with the UHF spectrum using EPC-C1G2 necessitated looking into high-powered commercial readers. Being on a relatively tight budget, we were fairly constrained, though that didn't stop us from looking at the options on the market. In the end, we decided on the ThingMagic M6e-Nano, mainly due to the fact that its $224 price fit well within our budget, compared to the next cheapest reader at $695. This is not to say that it doesn't fit our use case. For this iteration of the SHTTR system, the range afforded by the M6e-Nano's 27dBm maximum transmit power provides more than adequate range to cover a single stall. Another major benefit is compatibility with the ThingMagic MercuryAPI, the standard API for interfacing with EPC-C1G2 readers over USB/Serial/Ethernet. If SHTTR were to be expanded to a full bathroom install, either the ThingMagic M6e, or IMPINJ Speedway R420 would be the reader of choice. The full M6e board would allow for four antennas, and with the maximum transmit power of 31.5dBm, would allow for four circrcles of 16ft overage, enough for most single-gender restrooms. For an even more robust installation, the IMPINJ Speedway R420 could be used for its expandability, using up to 32 antennas to cover an entire suite of restrooms, such as a men's and women's room in close proximity. Additionally, its ethernet connectivity would allow it to be controlled over the network, removing the need for a local Raspberry Pi or similar microcomputer for command management and data logging.

V. System Description

A. *Toilet Paper Sensor*

The Toilet Paper Sensor involves processing the rotation of and force on the roll in order for the microcontroller to process and determine the number of sheets of toilet paper used and what flush volume to use.

For the rotational portion of the roll, in order to communicate specific rotation, the system is using an infrared LED as well as an infrared receiving diode to process a simple physical signal. Inside the cardboard tube of a roll, a reflective surface in the form of a small square of foil is placed in specific position along the side of the roll. The IR LED is constantly sending the exact same magnitude, and the IR receiving diode is waiting to receive a specific amount of the signal back. When the foil is directly under the IR LED, the diode will receive a much large value than usual received when the diode is reflecting against the bare cardboard that is around the rest of the inner circumference of the roll. As the toilet paper is in an enclosed space, the light pollution for the IR sensor is at a relative minimum compared to being present in an open room.

The load cell exists to act as a force sensor. This accomplishes two goals of the design. Firstly, it acts as a relatively precise digital scale (resolution determined via trade study). This information is necessary to process the amount of toilet paper left on the roll, which in turn helps the system determine how many sheets are used per a rotation of the roll. The load cell also includes a secondary functionality. When a user pulls downwards on the roll to obtain sheets of toilet paper, then a downwards force is applied to the roll. By measuring the amount of time, the force is applied, we can have a secondary sensor in the system to improve upon accuracy. This is useful as a fallback in case the real-world resolution of the load cell system is not sufficient for ~5 sheet accuracy.

The load cell has to be connected to a load cell amplifier. The basic functionality of a load cell is communicating force into a variable resistance. The HX711 amplifier runs a voltage through the load cell (a Wheatstone bridge) and is able to amplify that voltage to the microcontroller. The microcontroller then determines the amount of force that correlates with the voltage excited from the load cell based on a calibration factor.

The microcontroller, an Atmega328p, is responsible for controlling the TP sensor and relaying the information to the Farsens ROCKY100 in order to facilitate RFID communication with the main reader unit. The microcontroller takes in the before and after weight of the toilet paper roll, the force applied to it while pulling, as well as the rotation logged and uses that information to decide whether the flush should be Hi or Lo. This information as well as the percent remaining of toilet paper is communicated to the ROCKY100 over GPIO and so it can be read by the reader.

Power is a concern in this system, as battery replacements cause inconvenient maintenance overhead. For this reason, we have decided to integrate a battery-free RFID triggered relay, the Farsens Titan into the TP sensor to allow it to be powered off when the stall is not occupied. This relay connects a battery to the Atmega328p and, based on our initial calculation: $\frac{1000mAh}{13mA} = 79.92hrs$, a low-power Atmega328p could run on a 1000mAh battery for 76.92 operating hours. Estimating bathroom usage of a single stall of the UC first floor, this would be 20 visits per day, with a 4 min per-visit average time, that equates to roughly 2 months of battery life. This is linearly related to battery capacity, so fitting the stall with a 2000mAh battery would yield a ~4-month battery life, requiring changes only 3 times per year.

B. RFID Reader System

The chosen RFID reader uses the ISO standard EPC-C1G2 set of commands. This is the standard for almost all commercial UHF RFID readers, and also the standard that the Farsens tags communicate on. While there are many commercially available readers that are compatible with EPC-C1G2, many of these are far outside the realm of possibility for this project based on cost alone. The M6e-Nano does not have an impressively extensive range in its communication abilities using the built-in antenna, nor support for multiple external antennas. However, it will be capable of providing the intended functionality of the design for a theoretical single-stall installation, with the possibility to attach a single external antenna is need be for range extension purposes. If the design were to be adapted to a full-restroom use case, an EPC-C1G2 reader with support for higher transmit power and multiple antennas would be used, allowing the system to be controlled from a single reader unit with multiple TP sensors, Door Latches, and Flush Valves, as readers on this specification support up to 150 individual EPC tags.

The commands will be given to the reader over FTDI via a serial-to-USB module connected to the USB of the Raspberry Pi 3B+. The reader is able to read a specific tag within 7ms of the given command (150 tags/sec), and able to very quickly relay this information to the Pi. The Raspberry Pi is then responsible for parsing all incoming data from the reader. On board, it is responsible for determining the next state of the SHTTR system. The computer gives the necessary read and write commands to the reader for continued operation as well as logging the relevant data to the Firebase server.

C. Communication Server

The server provides a common interface for the SHTTR system to communicate information. It is responsible for both receiving the current state of the supplies and bathroom usage as well as integrating the ability to relay maintenance analytics of this information. It is integrated using the Firebase Realtime Database framework.

The Raspberry Pi will be responsible for communicating with the server over Wi-Fi interface. The main functionality of the server is to be a constant log for the information being received from the RFID reader. The stall occupancy data, as well as flush frequency/volume, and toilet paper remaining will be logged to the Firebase server for access by the app.

The server also is connected to the companion SHTTR application. The SHTTR app provides an easily readable, formatted version of the information that can act to inform maintenance workers of the proper actions to take in response to the current state of the bathroom.

D. Door Latch Status Sensor

Mechanically, the door latch sensor is relying on a standard contact switch. The switch is in an “off” position when the latch on the bathroom stall door is not locked. When the latch is engaged, the switch makes contact and sends and “on” signal. The latch is connected to a ROCKY100 Farsens RFID tag. The information of the state of the latch is read by the ROCKY100 and transmitted to the base station when the read command is sent, roughly twice every second to ensure quick detection of occupancy and boot-up of the TP sensor via the Titan Relay.

E. Flush Valve

The flush valve is another relatively straightforward component of the overall sensor system. This component mainly consists of a ROCKY100 adapted to send a signal to a commercial dual-flush valve for either a Hi or Lo volume flush. Due to budget constraints, a real valve will not be used, instead 2 LEDs will illustrate either a Hi or Lo flush.

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H. *SHTTR App*

Using iOS frameworks, the application uses the built-in communication protocol to access information over any connected network (Wi-Fi, cellular data, etc.) Because the server is using the Firebase framework, it only updates the information on the phone as information in the database changes. This way, less information and processing power are waster in constantly polling the entire database. It can also allow for multiple access points of the same information, so in essence, an unlimited number of phones could access the information.

VI. Project Management

A. *Schedule*

Please refer to the Figure X at the end of the document for the image of the updated schedule. In general, the schedule has changed throughout some time as some of the general design of the SHTTR system has gone through some revisions.

B. *Team Member Responsibilities*

Brian is primarily responsible for the SHTTR Application development as well as the usage of the server. He will be working on the front end as well as integrating real time data.

James is primarily responsible for the development and usage of the software on the Raspberry Pi responsible for giving commands to the RFID reader, as well as being the primary one working on RFID tag read and write control. He will be working with Brian to manage the Data upload to the server with the information from the RFID sensors.

David will be working on the initial prototype for the rotational sensor and the initial circuit prototype with the door latch sensor. He will be working with James to integrate Farsens tags with these sensors as well as the physical enclosures.

The group will be working together to perform final verifications and piecing together things as issues arise.

C. *Budget*

Refer to figure X for the expense document for this project. Much of our costs were inelastic, as Farsens is the only company making battery free wireless RFID sensors commercially. The rest of the costs were determined via our Design Trade studies.

D. *Risk Management*

From the design phase, there was some initial risk management in the initial project design. It is important to be ambitious enough with the design to engineer something original and interesting but not too ambitious such that the project is unfeasible. This continued into the realization of the final design as the project was refined. This involved avoiding spending too much time on unnecessary portions to the idea of the project as a system, such as abandoning goals to improve occupancy sensing, which is essentially a solved problem.

Throughout this, there were several phases of design decisions made in an effort to minimize risk. First, instead of trying to create our own battery free wireless sensors, we have decided to use commercially available sensors. This limits the risks that would be inherently present when building complicated systems.

Second, we thought about the skills within our team before proceeding with our project. David largely has experience with high-level design of hardware systems. David was largely the architect of the overall system and understand the commercial and non-commercial components we needed for the project. Further, he does great hands-on work such as fitting sensors. James is a great low-level coder and is largely doing much of the interfacing with our RFIDs using a Raspberry Pi. Brian is handling much of the data logging, as he has good networking databasing, and networking experience. While challenging, each part of the project seemed well within the purview of at least one of our group members.

Third, we chose to research each proposed technology to make sure that it fits our requirements. For example, with our TP load sensor, we made sure that the granularity of the weighing system actually fits our needs and isn't too inaccurate. Another example is with the RFID writing: we are generally worried about the undefined behavior of writing to a switch sensor tag. As such, we are actively investigating alternative solutions for writing before an implementation has unexpected behavior or, worse, renders the tags unusable. This foresight has been integral in our project being as far along as it is.

Fourth, we have been active about speaking to experts in the particular areas that worried us most. Speaking with Professor Rowe a handful of times with regards to things like occupancy helped us clarify the most effective way to approach that problem and saved us time, money, and headache from picking an inferior solution.

Fifth, we made sure to pick solutions in our project that are cost-effective. We understand that our budget is $600 and picked technologies that both did the job and would not push our budget to the limit. We are doing quite well with this administrative aspect which can haunt a team down the line if handled incorrectly.

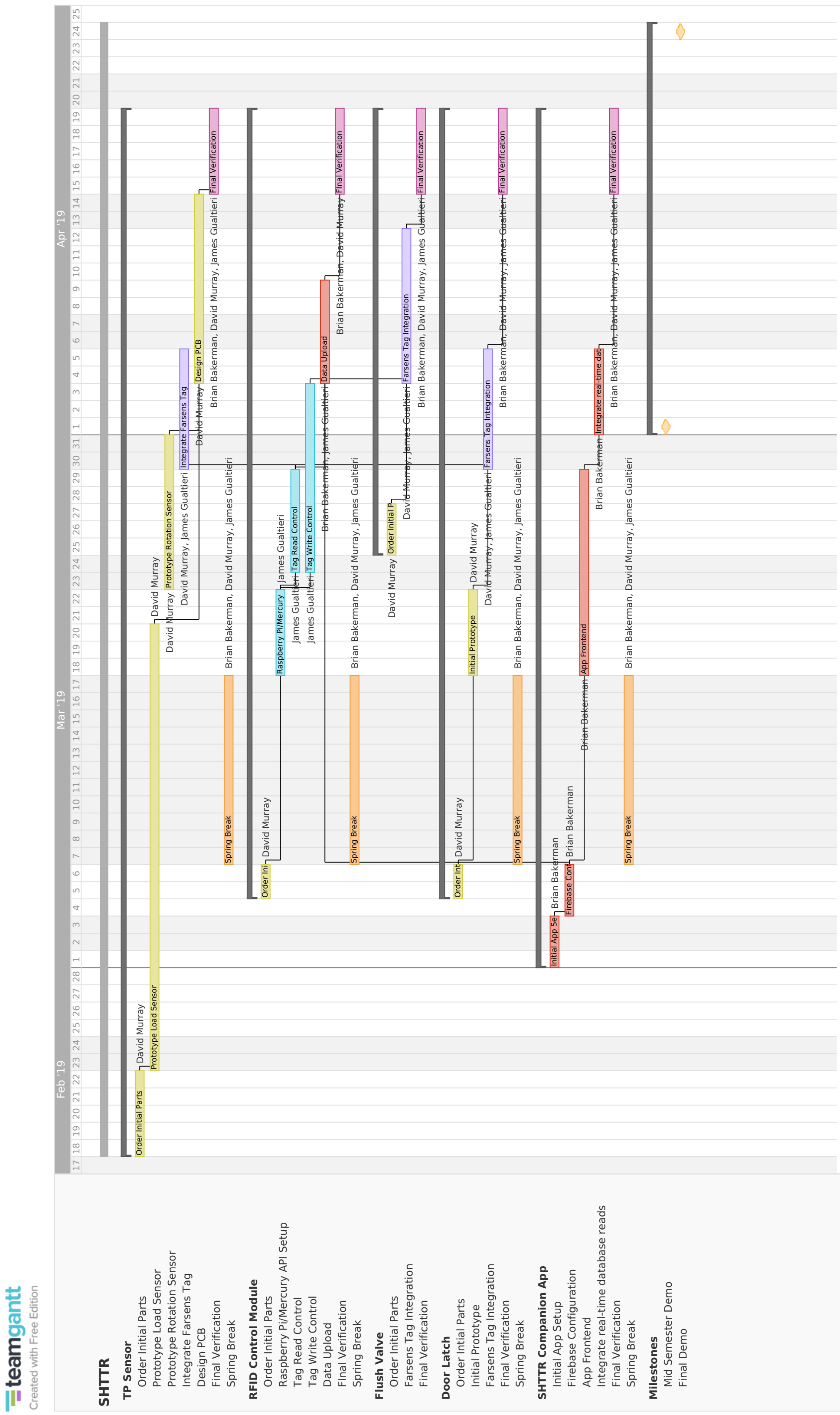

Fig. 2. Updated Schedule

Part	Use	Supplier	Quantity	Price/ea	Cost
500g Load Cell	Load Cell	SparkFun	2	$9.95	$19.90
HX711	Load Cell Amp	SparkFun	1	$9.95	$9.95
Arduino Pro Mini 5V	Microcontroller	SparkFun	1	$9.95	$9.95
FTDI Breakout	Programming Arduino	SparkFun	1	$14.95	$14.95
Breadboard PSU	Powering Arduino	SparkFun	1	$11.95	$11.95
Shipping 1	Shipping	SparkFun	1	$13.28	$13.28
RFID Reader	Read/Write tags	SparkFun	1	$224.00	$224.95
Serial to USB	communicate with reader	SparkFun	1	$7.95	$7.95
RFID Tags	test tags	SparkFun	1	$1.95	$1.95
Shipping 2	Shipping	SparkFun	1	$13.28	$13.28
EVAL01-X5-R	Battery-Free Switch Sensor	Farsens	2	€40.00	$90.64
Shipping 3	Shipping	Farsens	1	€20.00	$22.66
Assorted M3 Bolts/Spacers	Mounting	Amazon	1	$11.99	$11.99

Fig. 3. Expense sheet.