RFID AUTOMATIC SELF CHECKOUT BASKET

Final Report for ECE 445, Senior Design, Spring 2026

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Abstract

Standard retail checkout is often slow and labor-intensive, while existing mobile scan-and-go apps rely heavily on the honor system. This project replaces that manual step with a shopping basket that identifies items as they are added. An ultra high frequency (UHF) RFID reader handles tagged products, two load cells track basket weight to flag untagged additions, and an ESP32-S3 microcontroller pulls the data together and sends a live item list to a web application via Wi-Fi. A WS2812B LED strip around the rim provides immediate status feedback to the shopper. Testing of RFID tag reads produced roughly 95% accuracy at an average detection time of 4.47 s, while an aluminum foil lining along the walls contained the signals with 0.5m. The 3.3 V and 5 V supply rails stayed within 0.88% and 0.30% of nominal under load, and load cell readings stayed within 2% of true mass for items under 2 kg.

Contents

1. Introduction

Retail congestion remains a persistent source of inconvenience for customers and operational strain for businesses. Visible checkout delays may discourage customers from completing planned purchases, leading to lost revenue. Traditional checkout systems require businesses to staff multiple registers, increasing labor costs while still failing to eliminate congestion during peak hours.

Existing mobile self-checkout solutions allow users to scan items on their phone; however, there is no system in place to ensure that shoppers are scanning all of their items. While the honor system may work in some capacity, for many retail locations, this is not the case.

As a solution, this project explores an automatic self-checkout shopping basket capable of identifying items as they are placed inside. The shopper places an item inside, and the basket reads the item's tag automatically using UHF RFID technology. Two load cells underneath a false bottom provide a cross-validation with the RFID data, meaning an item placed in the basket without producing a valid tag read is treated as a discrepancy to the shopper rather than leaving it ignored.

The system is divided into six total subsystems, as seen in Figure 1. In the control subsystem, a microcontroller is responsible for all system state, calculations, and communication with a centralized server over WiFi. The UHF RFID subsystem and weight sending subsystem— collectively the sensing subsystem — collect data about the state of the basket and communicate with the control subsystem. The basket provides visual feedback through an LED indicator to inform users of successful reads or potential errors. A public-facing web application allows shoppers to easily see the items in their basket along with their current total price. When the shopper is ready to leave with the desired items, they can pay for the entire basket directly from their phone, removing the need for a final stop at a register or kiosk. The solution removes the need for traditional checkout infrastructure, thus improving the experience for shoppers while simultaneously reducing costs for business owners.

This chapter reveals the motivation behind the project, describes the system architecture at a high level, and lists the performance requirements used to judge whether the product complete. Chapter 2 covers the design procedure of each subsystem as well as specific details. Chapter 3 reports the quantitative test results associated with verification. Chapter 4 details the project budget in terms of parts and labor. Chapter 5 describes the schedule and overall time commitment of the project. Chapter 6 closes the report with a discussion of the project's successes, the challenges encountered during integration, and recommendations for a future iteration of the design.

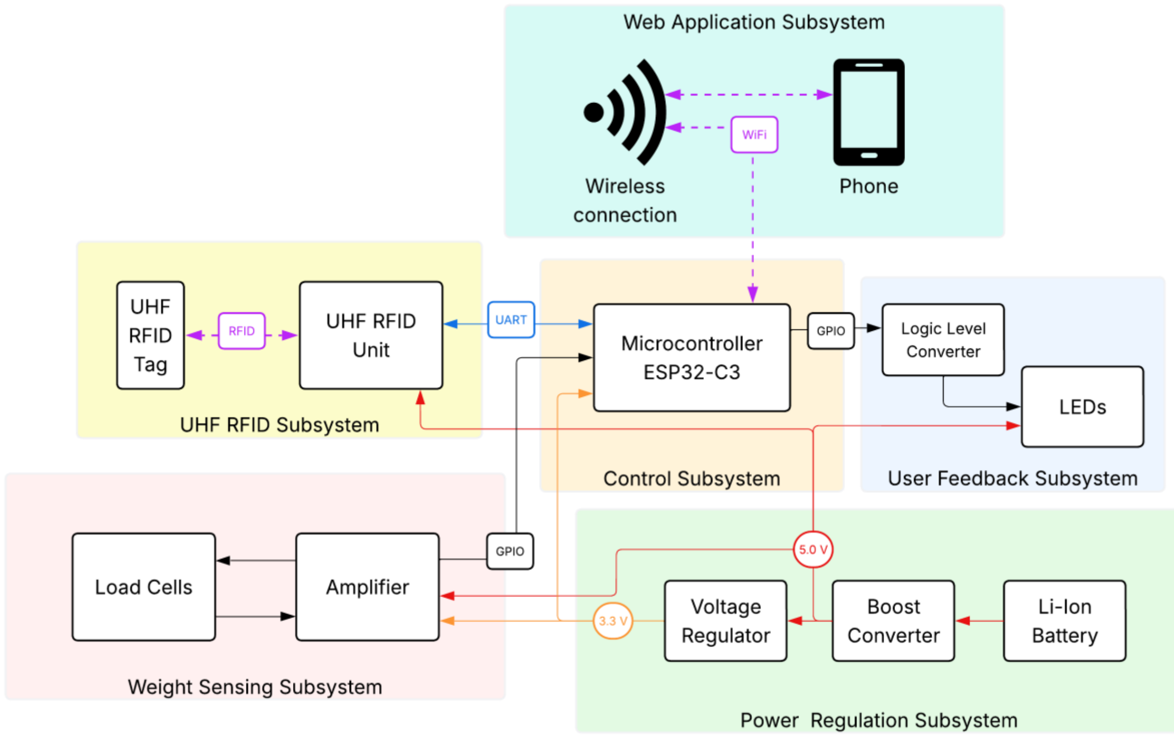

Figure 1. The high-level block diagram of the system. Each subsystem is grouped by a colored rectangle and appropriately labeled. Connections between the subsystems are denoted by labeled arrows. Solid lines represent a physical connection, and dashed lines represent wireless connections.

1.1 High-Level Requirements

1. The basket shall identify at least 95% of RFID-tagged items placed inside within 5 seconds and shall keep unintended reads of items located 0.5 m or further from the basket below 5%.
2. The basket shall detect any item weighing 500 g or more placed inside without a valid tag read and shall notify the shopper through a color change or pulse on the LED strip.
3. The web application shall reflect the current item list and total within 10 seconds of any addition or removal, with no missed or duplicated items.

2. Design

2.1 Sensing Subsystem

The sensing subsystem provides physical validation of the basket's contents to prevent theft or identification errors. It uses an M5Stack U107 UHF RFID module [1] and two 20 kg load cells mounted to a false bottom. RFID identifies tagged items as they enter the basket, and the load cells detect items without a corresponding tag read. UHF RFID is chosen for its abilities to read from a further distance than standard RFID and to read multiple items at once. The particular M5Stack model is chosen for its firmware library, general availability, and documentation. The full schematic for the load cell amplifier is shown in Figure 2. Note that the RFID module's connections can be seen in Figure 3.

2.1.1 UHF RFID

The UHF RFID module detects multiple simultaneous tags in the 860–960 MHz range. It is mounted on the underside of the false bottom in the center pointing upwards. Data from the module is relayed to the control subsystem via UART at a baud rate of 115,200. The transmission power is tuned to 21 dBm, determined to be the minimum power necessary to read all tags placed inside of the basket with at least 95% accuracy. Given HLR 1 described in Chapter 1.1, the antenna must read all tags within 0.25 m of the center of the basket's bottom while not reading any tags that are further than 0.5 m from the same point.

In ideal free space, doubling the distance between the antenna and the tag results in a 6 dB drop in forward-link power. Because UHF RFID relies on a two-way backscatter link, the total received signal strength decreases by approximately 12 dB when distance doubles. In the United States, UHF RFID systems operate in the 902–928 MHz band [2]. Assuming operation at the average value of 915 MHz, the wavelength is then $\lambda \approx 0.327\ m$. Based on provided specifications from the tags, the gain is then $G_t = 1\ dBi$. The UHF RFID module does not provide a rating for gain, though given the antenna's footprint of 20 mm by 20 mm and ratings for similar designs, the gain is estimated to be $G_r = 0\ dBi$ [3] [4]. The power received at the tag is thus calculated by the Friis Transmission Equation:

$$P_{tag} = P_t + G_t + G_r - 20\log_{10}\left(\frac{4\pi R}{\lambda}\right) \tag{2.1}$$

$$P_{tag} = 21\ dB + 1\ dBi + 0\ dBi - 20\log_{10}\left(\frac{4\pi(0.25\ m)}{0.327\ m}\right) = 2.348\ dBm \tag{2.2}$$

$$P_{tag} = 21\ dB + 1\ dBi + 0\ dBi - 20\log_{10}\left(\frac{4\pi(0.5\ m)}{0.327\ m}\right) = -3.673\ dBm \tag{2.3}$$

Given the tag's rated sensitivity of -18 dBm, equations (2.2) and (2.3) show that the tag will be read at both 0.25 m and 0.5 m, which was confirmed during initial testing. To ensure that no tags beyond 0.5 m away are read, it is necessary to provide additional attenuation. To mitigate the issue, each of the four walls of the basket is lined with two layers of aluminum foil, which prevents the reading of nearly all tags placed outside of the basket while ensuring those inside remain unaffected.

2.1.2 Load Cells and Amplifier

Each of the two 20 kg YZC-133 straight-bar load cells is connected in parallel to the HX711 amplifier [5], which converts the micro-volt changes from the load cell bridges into a digital signal sampled by the microcontroller. By using two cells in parallel with one placed on each end of the basket, it allows for accurate weight readings regardless of where the item is placed inside. Using one load cell would require centralized placement, making it impossible to place the UHF RFID antenna in its ideal location. Using more load cells would likely provide a more accurate reading, though they would introduce additional mechanical complexity.

To interpret the analog signals from the cells, an amplifier and analog-to-digital converter (ADC) are required. An alternative approach is to use the microcontroller's internal ADC. However, this was rejected because standard microcontroller ADCs lack the resolution to measure micro-volt fluctuations accurately. Instead, the HX711 integrated load cell amplifier was selected. It is desirable because it provides a dedicated 24-bit ADC and an integrated power supply regulator for the load cell excitation voltage, significantly reducing external component count. To ensure baseline reliability, the supporting schematic (Figure 2) for the amplifier was adapted from a standard reference design [6].

The HX711 is connected to both the 5 V and 3.3 V buses. The 5 V rail is used to maximize the full-scale output voltage and improve the signal-to-noise ratio, while the 3.3 V rail is used for the digital logic supply to ensure safe compatibility with the control subsystem. Channel A of the HX711 is used given its gain of 128, providing a maximum differential voltage of ±20 mV. This limit dictates that the selected load cells must have a sensitivity of less than 4.0 mV/V when driven at 5 V, a requirement satisfied by the chosen load cells.

To prove the ADC will not saturate under maximum load, the theoretical maximum full-scale output voltage (V_{max}) of the sensing bridge is calculated using the 5 V excitation voltage (V_{ex}) and the YZC-133's rated sensitivity (S) of $1.0 \pm 0.15\ mV/V$:

$$V_{max} = V_{ex} * S \tag{2.4}$$

$$V_{max} = 5.0\ V * 1.0 \frac{mV}{V} = 5.0\ mV \tag{2.5}$$

The maximum differential signal of 5.0 mV is well within the $\pm 20\ mV$ limit of Channel A at a gain of 128.

Because the two Wheatstone bridges are wired in parallel, their voltage outputs are electrically averaged. This effectively creates a single virtual load cell with a combined capacity (C_{total}) of 40 kg. The applied equation governing the differential signal (V_{sig}) for any applied mass (m) is:

$$V_{sig} = 5.0\ V * 1.0 \frac{mV}{V} * \left(\frac{m}{40\ kg}\right) \tag{2.6}$$

The HX711 amplifies the micro-volt differential signal by a factor of 128 and outputs the 24-bit digital value. The data is sampled by the control subsystem over GPIO at a rate of 10 Hz.

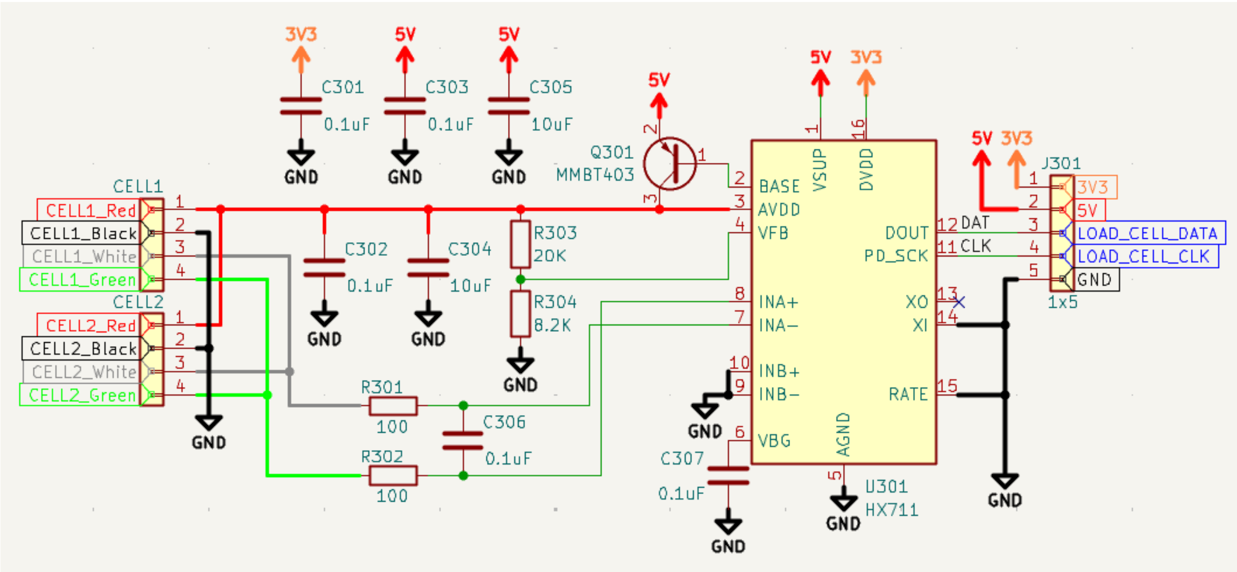

Figure 2. The schematic for the load cell amplifier in the sensing subsystem. CELL1 and CELL1 denote the two connection points for the load cells. The pins labeled in blue represent the connections to the control subsystem.

2.2 Control Subsystem

2.2.1 Hardware

The control subsystem is responsible for maintaining all state information and processing all data received from other subsystems. It is also responsible for communicating the state of the basket, including its contents, with the store's infrastructure via WiFi. Note that in the setup described in this report, the microcontroller acts as a WiFi endpoint. The computer connects to the device's WiFi network, rather than the device connecting to a traditional network. This decision was made due to WiFi access controls in university buildings, though connecting the device to a store's WiFi network instead would be more feasible and reliable in practice.

The subsystem is built around an ESP32-S3-WROOM-1 [7], chosen for its built-in WiFi functionality and general accessibility. Alternative approaches include using other ESP models or STM microcontrollers with integrated WiFi capabilities. To accelerate development and ensure a reliable baseline, the overall schematic architecture was adapted from an existing reference design for a development board [8].

The load cell amplifier (Chapter 2.1) sends a digital signal via GPIO proportional to the mass of the items inside of the basket. It uses GPIO pin 14 as a CLK signal and pin 13 for data transmission. The subsystem also receives UHF RFID tag data from the sending subsystem (Chapter 2.1) via UART, using GPIO pin 11 as RX and pin 12 as TX. Finally, the control subsystem provides data to the LEDs (Chapter 2.5) through a single data line, controlled by GPIO pin 21. To facilitate programming and debugging, a USB-C port is integrated into the design, providing a direct interface for flashing firmware and viewing the serial terminal. The full schematic for the subsystem is shown in Figure 3.

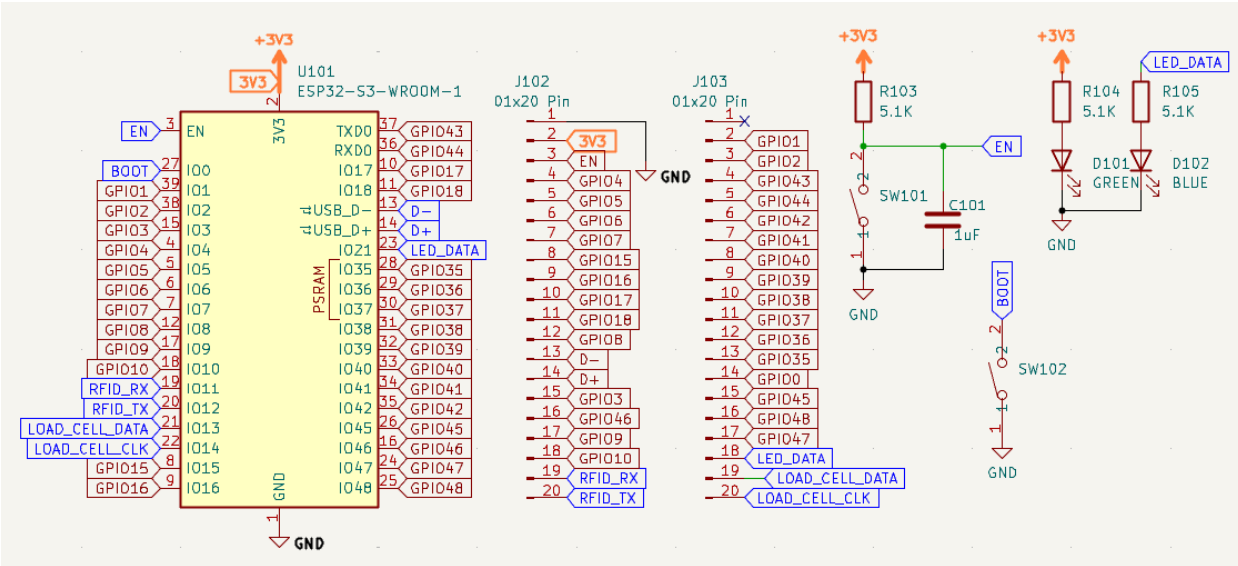

Figure 3. Schematic for the control subsystem. Blue labels denote connections that are used in the system. Red labels denote unused connections. Both D+ and D- signals are shown in Figure 4 and represent connections to the data lines of the USB-C port. SW101 controls the EN signal, used for resetting the microcontroller. SW201 controls BOOT, used for flashing firmware to the microcontroller.

2.2.2 Firmware

Computationally, the control subsystem is responsible for taking data from the sensing subsystem and determining necessary state changes. From the load cell digital signal, the mass is calculated, in kilograms, with a scaling factor and offset, which is further elaborated on in Appendix B: Load Cell Calibration and Accuracy.

For RFID data, the subsystem stores the current tag's IDs in memory. When the subsystem receives the ID of a new tag for more than three consecutive seconds, it is resolved as "inside" of the basket and added to the local list of tags. When the subsystem does not receive an ID of a tag that is currently known to be inside for more than three consecutive seconds, it is resolved as "outside" of the basket.

The control subsystem also consistently validates the weight of the items. The expected weight is determined by a call to an external API which provides a JSON response including each known tag's ID and its corresponding expected weight. Should the actual weight be greater than 100 g over the expected weight of all items known to be inside the basket, the system state enters a "lockout mode," which disallows checking out or the addition of more items.

Based on these states, the firmware drives the LED feedback [9]. When a new item is detected, the control subsystem prompts the LEDs to pulse green. When an item is removed, the LEDs pulse yellow. When the system enters lockout mode, the LEDs pulse red until the system returns to normal state.

Lastly, the control subsystem provides data to web application subsystem (Chapter 2.4) through a websocket. Data is only sent when the state changes, i.e. when an item is added or removed, or when the system enters lockout mode. The control subsystem delivers a JSON payload to the websocket including the current tag IDs, the total weight, and the state of the basket.

2.3 Power Regulation Subsystem

The power regulation subsystem provides stable, regulated operation for all system components using a single-cell nominal 3.7 V lithium-ion battery as the primary energy source. The battery is rechargeable via a USB-C [10] input that safely charges the cell to 4.20 V. The battery output feeds a high-efficiency DC-DC boost converter that generates a regulated 5.0 V rail capable of supporting current up to 1.5 A. The 3.3 V rail powers the microcontroller and is suited to supply 500 mA. Both rails are required to remain within ±5% of the expected voltage under load. This architecture maintains regulation across the battery discharge range of approximately 3.0 V to 4.2 V.

The rating of 1.5 A was determined for the 5 V rail based on 60 LEDs on the strip which pull 60 mA each at peak brightness. Given that the LEDs have been limited via firmware to a maximum brightness of 20%, the actual current draw would be 12 mA per LED, or 720 mA for the strip. The UHF RFID module pulls a continuous current of 200 mA, with a peak pulse current of 260 mA [11]. The current draw from the load cell amplifier is nominal. Given that the 3.3 V rail draws current from the 5 V rail, it is also necessary to account for the microcontroller's current draw. The ESP32 module averages close to 200 mA, though during WiFi transmission it can spike above 500 mA [7]. Thus, the maximum current draw from all subsystems is around 1.48 A.

A resettable PTC fuse is included for overcurrent protection at the USB C input. According to its datasheet, the fuse has a hold current of 3 A and a trip current of 5 A [12]. An ESD protection diode placed at the input clamps transient overvoltage events; the diode avalanches to ground, providing a short connection for clamping voltages of 10.5–11.5 V [13].

The 5 V rail is generated by an ETA9740 power management IC [14], which acts as both a charger for the lithium-ion battery and a power-boost stage. The chip charges the cell to a regulated 4.20 V from the USB-C input and boosts the battery output to a regulated 5 V rail. A 5.6 V Zener diode placed on the 5 V rail [15], together with decoupling capacitors, stabilizes the rail by reducing noise, handling load spikes, and clamping overvoltage events.

The 3.3 V rail is produced by an LM3940 voltage regulator with a 1 A rating [16] operating off of the 5 V bus. Initially, it was planned to use an LDO taking the battery voltage to 3.3 V, though the current rating was too small and caused brownouts. The final schematic for the subsystem is shown in Figure 4.

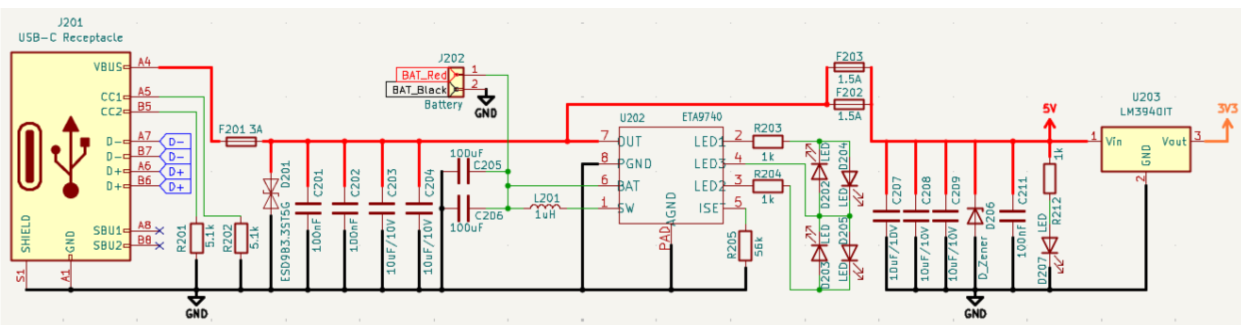

Figure 4. Power regulation subsystem schematic. The ETA9740 power management IC charges the battery from the USB-C input and generates the regulated 5 V rail, while the voltage regulator generates the 3.3 V rail.

2.4 Web Application Subsystem

The web application serves as the shopper's primary interface, allowing them to view a live, synchronized list of items in the basket and the running total price. It establishes a real-time, bidirectional communication link with the basket's microcontroller subsystem via a websocket connection over the local WiFi network hosted by the basket's access point. In a production retail setting, the basket would instead connect to the store's WiFi, though this was impractical during prototyping.

The architecture is divided into a Flask-based data backend and a dynamic frontend. The system operated on an event-driven model instead of polling. Upon session start, the frontend establishes a websocket handshake with the microcontroller. Whenever the microcontroller detects a state change, it immediately broadcasts a JSON to the frontend; state changes include events such as a new RFID tag being detected or a weight fluctuation. The application then cross-references the received RFID tag IDs against the backend item database to retrieve the corresponding names and prices. It then calculates the running total and updates the UI item list.

If the websocket connection is interrupted or the microcontroller fails to connect, the frontend enters an error state. This alerts the user via a displayed connection loss. Figure 5 shows the flowchart for the user-facing web application.

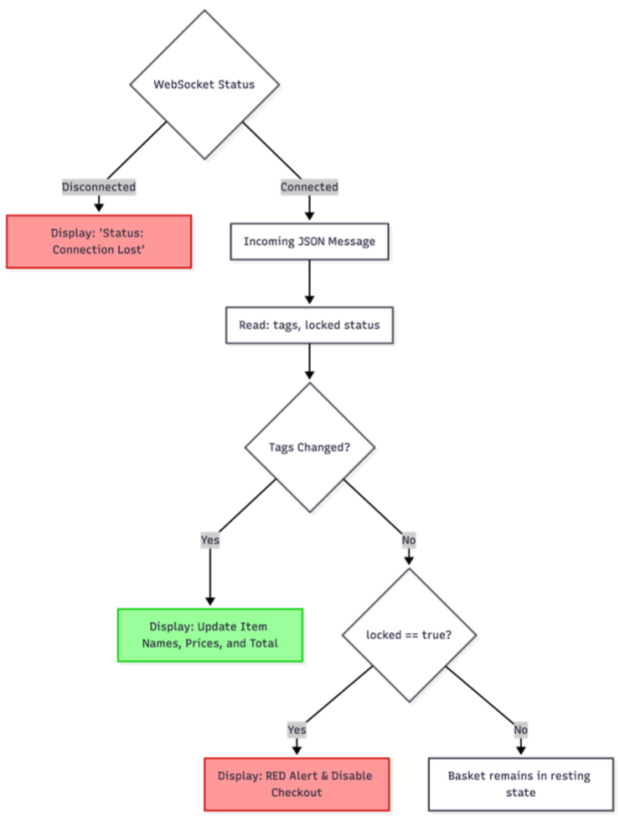

Figure 5: Flowchart for the web application.

2.5 User Feedback Subsystem

The user feedback subsystem provides immediate visual confirmation of the basket's state to the user without requiring them to look at the mobile application on their phone. The display has three distinct states which include the following: solid white indicates "ready," a green or yellow pulse indicates "success" during addition or removal of an item respectively, and a pulsing red indicates a "lockout" such as weight increase without a corresponding RFID read.

The subsystem uses a WS2812B RGB LED strip driven by the microcontroller. The WS2812B requires a 5 V data line, but the ESP32-S3 GPIO outputs at 3.3 V; the data line is therefore routed through a 74HCT245 logic level shifter to ensure 5 V signal integrity. The LEDs are required to remain visible under standard store lighting and at distances up to 1 m away, and the subsystem is constrained via firmware to draw no more than 720 mA from the 5V rail during peak operation to prevent power instability. The schematic is shown in Figure 6.

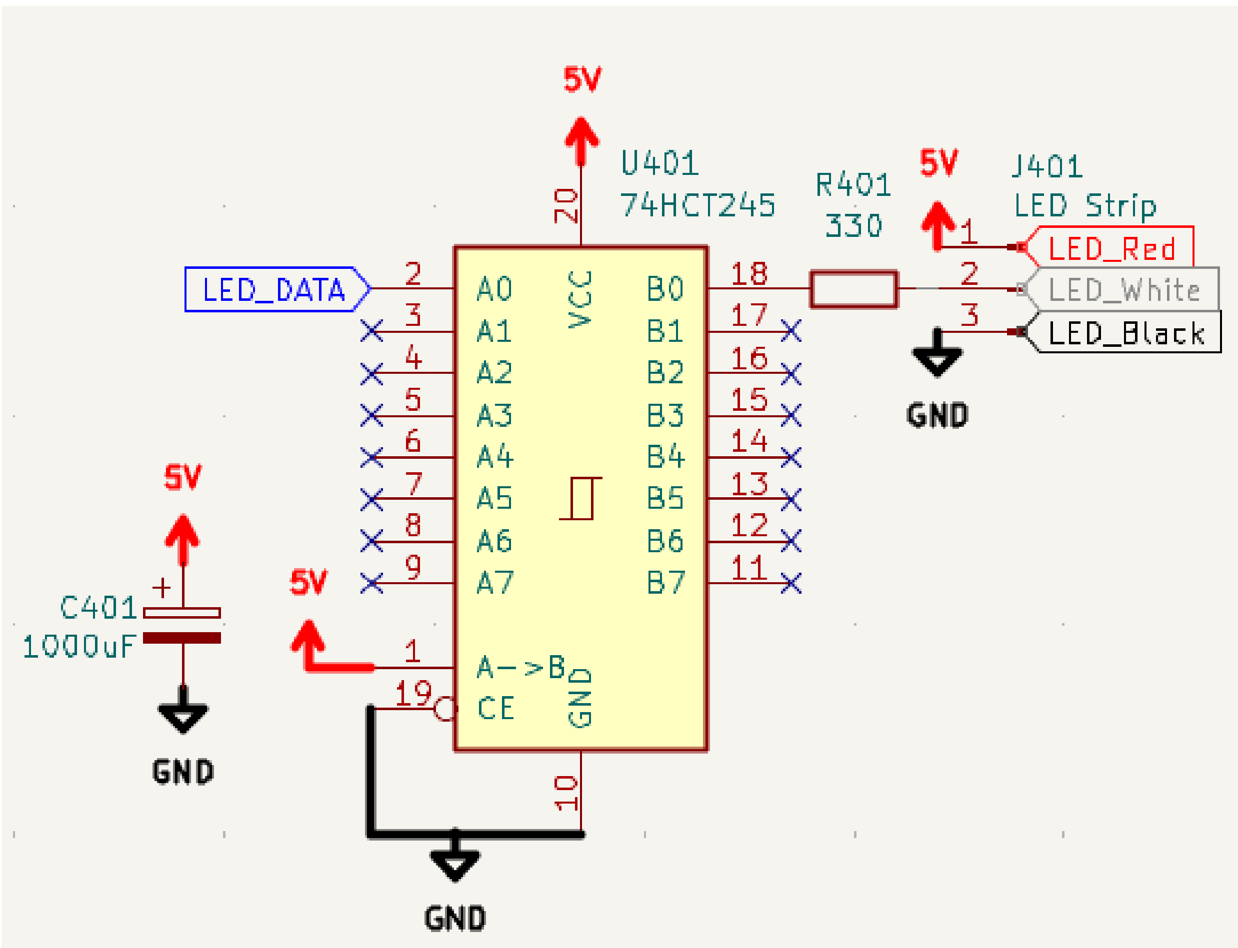

Figure 6. The schematic for the user feedback subsystem. The J401 Connector is where the LEDs are to be plugged in, while the pin labeled "LED_DATA" goes to a GPIO port on the microcontroller.

3. Design Verification

This chapter presents the testing performed on the completed system to verify that the design requirements were met. Each subsystem was tested individually before integration, and the integrated basket was then tested against the three high-level requirements established in Chapter 1.1. The full requirement and verification table for all subsystems can be found in Appendix A.

3.1 RFID Identification and Isolation (HLR 1)

Verifying that the basket correctly identifies at least 95% of RFID-tagged items placed inside within five seconds involved the use of 20 total uniquely tagged items. The basket was first placed on a surface with nothing inside and connected to the user-facing web application. The verification began by placing six individual items inside of the basket and monitoring how long until the web application displayed the update. Table 1 shows the average amount of time per item. The overall average time was 4.47 s.

Verification continued by repeatedly placing items inside of the basket and verifying that the item displayed on the frontend was the item actually placed inside. Some items were placed individually, and some were placed simultaneously. Throughout verification, each time an item was not successfully identified within 10 seconds, it was counted as a miss. Among 150 total items placed inside of the basket, 142 items were correctly identified, resulting in 94.67% read accuracy.

It is important to note that the read accuracy can be strengthened by increasing the transmit power of the UHF RFID module, though this results in a higher number of unexpected reads, i.e. items outside of the basket.

Table 1. Time Until Object Recognition

Item	Center	Corner 1	Corner 2	Corner 3	Corner 4	Average
Candle	4.7 s	5.5 s	4.8 s	4.7 s	4.9 s	**4.9 s**
Jar of Peanuts	4.6 s	4.7 s	5.2 s	4.9 s	5.2 s	**4.9 s**
Deodorant Stick	3.3 s	4.6 s	5.3 s	5.2 s	2.6 s	**4.2 s**
T-Shirt	4.6 s	4.7 s	4.9 s	5.1 s	5.0 s	**4.9 s**
Plastic Cup	2.4 s	4.7 s	2.7 s	2.5 s	2.6 s	**3.0 s**
Soap Bar	5.1 s	5.0 s	5.0 s	4.9 s	4.8 s	**5.0 s**

To ensure that less than 5% of items placed further than 0.5 m away were read, the basket was placed on a flat surface with no items inside. A ring with a 0.5 m radius was marked on the surface. The basket was placed exactly in the center. A diagram of the setup can be seen in Figure 7. Eight items were placed along the marked ring. Every ten seconds, the items were rotated by approximately 90 degrees to ensure that the angle did not affect the reading.

Throughout all 20 items being placed around the ring in different orientations and at different locations, none of them were read. Thus, it can be deduced that the basket reads 0% of items that are placed at 0.5 m or further.

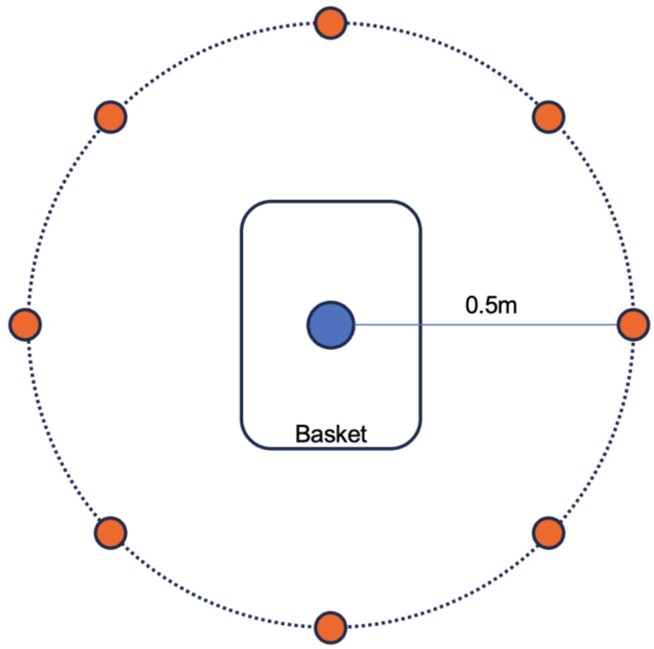

Figure 7. The setup used for verifying the number of unexpected RFID reads for items outside of the basket.

3.2 Weight Threshold and Visual Feedback (HLR 2)

Is it required that the basket recognize any item weighing at least 500 g that does not have a tag and notify the user via the LED strip and the web application. In order to verify the functionality, the basket was first connected to the web application. A 500 g item was placed inside, and the basket and web application gave the expected lockout message.

Further testing was conducted to ensure that items would be recognized even if the basket is full. Seven tagged items with weights ranging between 0.18 kg and 2.46 kg were placed inside the basket one at a time, followed by the untagged 500 g item. In each case, the basket correctly identified that there was an untagged item inside of the basket.

During development, the decision was made to lower the weight threshold to put the basket into lockout mode. After a firmware change, any item weighing more than 100 g will be recognized by the basket. Afterwards, the same process as above was repeated with a 100 g item in place of the 500 g item.

Verification was conducted with a variety of weights already inside before the unexpected item was placed in, ranging from 0.18 kg up to 6.42 kg. In each case, the basket correctly identified the untagged item through both the LEDs and the web application. Based on the binary results of the testing process — observing whether the item was detected or not — the basket correctly identified items weighing at least 100 g with 100% accuracy regardless of the existing weight inside.

More information related to the calibration of the load cells and the observed accuracy can be found in Appendix B: Load Cell Calibration and Accuracy.

3.3 Web Application Latency and Accuracy (HLR 3)

To verify that the web application was correctly updated within 10 seconds of a new item being placed inside or an existing item being removed, the same testing process described in Chapter 3.1 was used. The only difference in testing is the fact that the basket was connected directly to a computer via USB C to monitor the serial port at the same time. During all 150 tests of items being added and removed, the web application correctly updated nearly simultaneously with the serial port. The web application also displayed the correct state and items 100% of the time. Due to the fact that the testing in Chapter 3.1 was reliant on the items updated on the web application within 10 seconds, it is sufficient to state that this high-level requirement passed.

3.4 Critical Low-Level Requirements and Deviations

There were no major deviations in terms of testing, though some tests were conducted in tandem. For example, it was determined that the load cell amplifier gave the correct and expected weight within an acceptable tolerance. Thus, it was not necessary to prove that the digital signal was linearly correlated to the mass, because that was already known. No parts of the overall system failed verification.

3.4.1 Power Regulation Requirements

As the most important subsystem, it is necessary to validate that the power supply remains stable on each voltage bus. The power regulation subsystem was tested under load to verify that both rails met their voltage-stability requirements. The 3.3 V rail produced by the voltage regulator was brought from no load up to 0.5 A while the rail voltage was monitored. The 5 V rail was swept from no load up to 1.2 A while output voltage and delivered power were monitored. The curves for both rails are shown in Figure 8. It should be noted that although the data ends at 1.2 A, the 5 V rail was tested to 1.5 A.

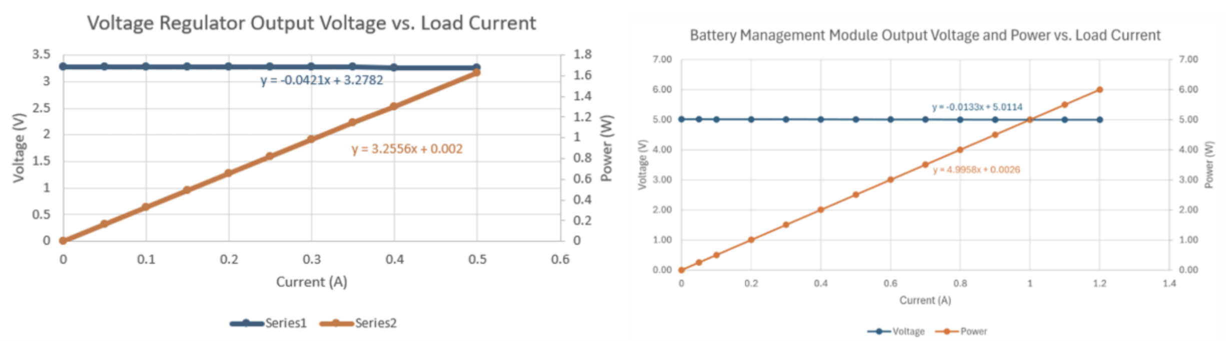

Figure 8. (a) Output voltage and delivered power on the 3.3 V rail produced by the XC6206-series LDO, measured across a load sweep from 0 to 0.5 A and (b) output voltage and delivered power on the 5 V rail produced by the ETA9740 battery management IC, measured across a load sweep from 0 to 1.2 A.

The 3.3 V rail held between 3.279 V and 3.250 V across the full load range, a total deviation of $\Delta V = 0.029$ V, or approximately 0.88% of nominal. This is well within the ±5% specification for the rail.

The 5 V rail held between 5.011 V and 4.996 V across the full load range, a total deviation of $\Delta V = 0.015$ V, or approximately 0.30% of nominal. Delivered power scaled approximately linearly with load current up to 1.2 A, indicating that the boost converter remained in its regulated operating region throughout the test. This is also well within the ±5% specification for the rail.

4. Costs

4.1 Parts

Table 2. Cost Breakdown by Part

Part	Manufacturer	Retail Cost	Bulk Cost	Actual Cost
Black Shopping Basket	Regency Mobile Products	$6.49	(12) $69.99	(1) $6.49
U107 UHF RFID Module	M5Stack Technology	$79.00	N/A	(1) $79.00
2pk 20 kg Load Cells	Wishiot	$11.99	N/A	(1) $11.99
SW2812B Strip LEDs	Shenzhenshi Coyu	$7.99	N/A	(1) $7.99
2011 Battery	Adafruit Industries LLC	$12.50	N/A	(1) $12.50
MMBT4403LT3G Transistor	onsemi	$0.16	(1000) $39.20	(1) $0.16
RK73B2ATTD563J Resistor (56kΩ)	KOA Speer Electronics, Inc.	$0.10	(1000) $8.24	(1) $0.10
RMCF0805FT13K7 Resistor (13.7kΩ)	Stackpole Electronics Inc	$0.10	(1000) $6.97	(1) $0.10
RG2012P-203-B-T5 Resistor (20kΩ)	Susumu	$0.10	(1000) $58.06	(1) $0.10
RMCF0805FT8K20 Resistor (8.2kΩ)	Stackpole Electronics Inc	$0.10	(1000) $6.97	(1) $0.10
CRCW0805100RFKEA Resistor (100Ω)	Vishay Dale	$0.10	(1000) $13.29	(2) $0.20
MLZ2012M3R3ATD69 Inductor (3.3uH)	TDK Corporation	$0.32	(1000) $175.98	(1) $0.32
MLZ2012N1R0LTD25 Inductor (1uH)	TDK Corporation	$0.12	(1000) $64.60	(1) $0.12
C0805C104K5RACTU Capacitor (0.1uF)	KEMET	$0.13	(1000) $28.77	(5) $0.65
16TPV1000M10X10.5 Capacitor 1000uF	Rubycon	$1.54	(100) $69.32	(1) $1.54
DX07S016JA3R1500 USB-C Receptacle	JAE Electronics	$1.91	(500) $615.36	(2) $3.82
1812L300MR Fuse	Littelfuse Inc.	$2.12	(500) $514.72	(1) $2.12
ESD9B3.3ST5G ESD Protection	onsemi	$0.21	(1000) $51.61	(1) $0.21
ETA9740 Power IC	etasolution	$1.34	(500) $79.30	(1) $1.34
MMSZ4689-E3-08 Diode	Vishay General	$0.55	(1000) $142.86	(1) $0.55
Resistor 5.1kΩ	ECE E-Shop	N/A	N/A	(7) N/A
Resistor 1kΩ	ECE E-Shop	N/A	N/A	(3) N/A
Resistor 10kΩ	ECE E-Shop	N/A	N/A	(1) N/A
Resistor 330Ω	ECE E-Shop	N/A	N/A	(3) N/A
74HCT245 Logic Shifter	ECE E-Shop	N/A	N/A	(1) N/A
Capacitor 10uF	ECE E-Shop	N/A	N/A	(7) N/A
Capacitor 1uF	ECE E-Shop	N/A	N/A	(1) N/A
ESP32-S3-WROOM1	ECE E-Shop	N/A	N/A	(1) N/A
Total				$129.40

4.2 Labor

Table 3. Itemized List of Labor Hours

Item	Hours	Price	Total
Group Member Labor	450	$54/hr	$12,150
Machine Shop Labor	5	$30	$150
		Total:	**$12,300**

Note: Estimating approx. 2.5 hours of work per member per day, 30 total working days, 3 team members.

5. Schedule

Table 4. Week-by-Week Schedule per Team Member

Week	Task	Person
February 22nd - February 28th	Finalize component selection and place orders	Jada
	Complete KiCAD Load Cell Amplifier and MCU KiCAD	Jacob
	Work on Power Subsystem KiCAD	Oscar
	PCB FIRST ROUND ORDERS - Load Cell Amplifier Breakout Board and MCU Breakout Board	Everyone
March 1st - March 7th	Work on Power Subsystem KiCAD	Oscar
	Breadboard Testing: MCU logic and UART communication	Jacob
	Breadboard Testing LED Logic: Verify 3.3V to 5V signal shift via 74HCT245	Jada
	PCB SECOND ROUND ORDERS - Power Subsystem Breakout Board	Everyone
March 8th - March 14th	UHF RFID Tuning: Calibrate RFID frequency and test tag IDs	Jacob
	LED Pattern Testing: Code/test Green, Red, and White pulses on breadboard	Jada
	Verify LED Subsystem design	Oscar
	PCB THIRD ROUND ORDERS – LED/User Feedback Subsystem Breakout Board	Everyone
March 15th - March 21st	**SPRING BREAK**	
	Leave basket with Machine Shop to be worked on over Spring Break	Everyone
March 22nd - March 28th	Solder PCBs: ESP32, and Load Cell Amplifier	Jacob
	Solder PCB: Power Subsystem	Oscar
	Test LED patterns based on simulated sensor triggers	Jada
	PCB FOURTH ROUND ORDERS – Fully Integrated PCB	

Table 4 continued: Week-by-Week Schedule per Team Member

March 29th - April 4th	Build Web Application UI and Backend (API/WebSocket setup)	Jacob & Jada
	Web App Testing: Verify 720x1280 resolution responsiveness	Jada
	Battery Life Testing: Verify subsystem draw supports shopping duration	Oscar
April 5th - April 11th	Firmware Integration: Link RFID tag detection to Weight Sensing logic	Jacob
	System Calibration: Ensure 0.5lb weight change triggers error if no tag read	Jada
	Cable Management: Secure all 5V/3.3V wiring within the basket frame	Oscar
April 12th - April 18th	Final Mounting: Place PCB and LED strip (WS2812B) into the basket	Everyone
	Accuracy Test: 95% identification accuracy for 10+ items	Jada
	Verify Web App refresh rate and updates within specified time frame	Jacob
	Resolve any "false positive" RFID reads outside 12-inch range	Oscar
April 19th - April 25th	**MOCK DEMOS – Did not participate**	Everyone
	Line basket with aluminum foil to limit outside tag reads	Everyone
April 26th - May 2nd	**FINAL DEMOS**	Everyone
May 3rd - May 6th	Final Paper	Everyone
	Finalize Lab Notebook	Everyone

6. Conclusion

6.1 Accomplishments

The completed system delivered the functionality outlined in the design document. The basket's overall structure effectively matched the design stage exactly with no major changes made between design and demonstration, and all subsystems were built and connected as originally planned. The minor changes that did occur, namely the LDO swap and the addition of an aluminum foil liner on the inner basket walls, were incorporated without altering the block-level design. This foil lining, combined with the tuning the module's power, allowed the system to condense and amplify the signal to reach nearly 100% RFID read accuracy by the conclusion of the project. Additionally, the load cell amplifiers were highly successful, outputting the correct mass within a -2% margin for items under 2kg. This was a significant improvement over the quotes +/- 10% accuracy and remained consistent even after movement and power cycles. We viewed these as our major successes.

6.2 Uncertainties and Unsatisfactory Results

While the weight sensing subsystem passed the baseline requirement of ±10% accuracy, testing revealed a quantifiable negative scaling bias at higher loads. Specifically, measuring a 2.466 kg mass resulted in a percent deviation of -9.5%. The data indicates that as the applied mass increases, the calculated weight consistently underestimates the true physical mass. This deviation is likely attributable to a rounding truncation in the hardcoded scale factor (56908.0) within the firmware, or physical flexing of the basket's false bottom at higher loads, which mildly attenuates the mechanical force transferred to the load cells. Because the deviation remained within the acceptable operational threshold, the scaling mathematics were not adjusted.

6.3 Ethical considerations

The basket was designed in alignment with IEEE Code of Ethics Sections I.1 and I.2 [17]. Electrical safety is enforced through ±5%-regulated 5 V and 3.3 V rails, a resettable PTC fuse and ESD diode at the input, and a lithium-ion charging path consistent with UL 1642 [18] and UL 2054 [19]; the casing prevents user access to exposed conductors in line with OSHA electrical safety principles [20]. The UHF RFID subsystem operates within the 902–928 MHz ISM band authorized under FCC Part 15 Subpart C [2], with transmit power held below the permitted maximum and stray emissions further reduced by the aluminum foil basket liner. Privacy is addressed through data minimization: only item identifiers and the running total are transmitted, with no shopper-identifying data collected.

Cross-verification between the RFID and weight subsystems mitigates adversarial misuse such as tag shielding or load-cell manipulation, with discrepancies surfaced through the LED feedback rather than silently accepted. Beyond technical safety, several broader ethical considerations were identified. The widespread expansion of this product has the potential to reduce entry-level and low-skill job opportunities within the retail sector. Additionally, the current concept of carrying the basket is not the most accessible for the elderly or persons with disabilities who may have limited reach or mobility. Finally, environmental impact is a concern because product end-of-life disposal creates electronic and battery waste. A production version would need to be designed specifically for easier component separation to facilitate the proper recycling of the lithium-ion cell and mixed electronics.

6.4 Future work

Several improvements would extend the basket beyond what was demonstrated. The most useful is the addition of external verification, such as in-store cameras or shelf sensors, to cross-check the basket's item readings. This approach is already used by existing operations such as Amazon Fresh and would provide a second layer of verification independent of the basket's own readings. The weight sensing subsystem could also be improved through better calibration, allowing the basket to be carried without disturbing readings, and through support for items priced by weight such as produce. The RFID subsystem could be expanded by using tag types designed for metal containers or liquid items, since neither was tested during the project.

Future revisions of the hardware should use a lighter, sturdier false bottom with more clearance to the basket walls, since the platform occasionally caught on the sides and gave inconsistent readings. Additional overvoltage protection on the 5 V rail would also help prevent damage to the RFID module, which was destroyed once during testing and delayed integration.

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Appendix A. Requirement and Verification Table

Table 5. Requirements and Verification Table

Requirement	Verification	Verification status
Load cells and amplifier output a digital data signal proportional to the mass.	• Connect the load cell amplifier to both 3.3V and 5V power. Ensure no mass on the load cell(s). Connect CLK (J1, Pin 4) to a pulse generator to provide a clock. • Using a multimeter, read the voltage between GND and AVDD (JP4, Pin 5) and log this in a table of mass vs. AVDD, Digital Output • Using a logic analyzer, capture the 24-bit logical output from DAT (J1, Pin 3) during a clock cycle. • Repeat the above two steps for multiple masses placed on the load cell(s). Plot mass vs. AVDD and ensure it is constant (trendline with slope 0 ± 0.125). Plot mass vs. DAT (as a number) and ensure the relationship is linear (linear trendline with $R^2 > 0.95$)	**PASS**
Subsystem reliably detects passive UHF RFID tags located within 0.25m but not further than 0.5m from the antenna with at least 95% read probability within 2 seconds.	• Connect to the MCU via USB-C to gain access to debugging information, including tags that are currently within range. • Ensure no tags are within 3 meters of the RFID antenna. • Place one UHF tag inside of the basket as close as possible to the antenna and ensure that the correct tag ID is read and visible by the MCU within 2 seconds. • Using a meter stick with one at as close to the antenna as possible, slowly move the tag away until it reaches 0.25m. Ensure the tag is still read at all times. • Continue past 0.25m and ensure that the tag is no longer read somewhere between 0.25m and 0.5m. • Repeat the above steps in multiple directions/axes (above, in front, behind, etc.) • During all movements, hold the tag still for 10-20 seconds every 5-10cm. Verify that the tag is read correctly during at least 95% of all total hold time.	**PASS**

Table 5 continued: Requirements and Verification Table

Microcontroller correctly communicates with the LED Subsystem to produce the expected colors on different data signals from the Sensing Subsystem: Solid white indicates the basket is ready for use A green pulse within 5 seconds of an item being placed indicates successful detection of an item A red pulse within 5 seconds of an item being placed indicates an error, such as a missing RFID tag or weight discrepancy	• Ensure the basket is empty and the system is powered on • Visually confirm the LED strip is set to a constant Solid White pattern • Add a tagged item to the basket • Visually confirm the LED strip displays a green pulsing pattern within 5 seconds • Place an untagged weight into the basket to trigger a "Weight Mismatch" • Visually confirm the LED strip displays a red pulsing pattern within 5 seconds	**PASS**
Microcontroller provides update to TCP server within 20 seconds with 95% accuracy based on input from Sensing Subsystem.	• Ensure the basket is empty (no items inside). • Place a tagged item inside of the basket and start a stopwatch. • Verify that the “server” has received the correct item ID via WiFi within 20 seconds. • Repeat multiple times to ensure accuracy.	**PASS**
● Microcontroller recognizes when an item has been placed in the basket (determined by weight) but an RFID tag has not been recognized by the Sensing Subsystem within 20 seconds with 95% accuracy.	• Ensure the basket is empty (no items inside). • Place an item weighing at least 500g with no RFID tag inside of the basket and start a stopwatch. • Verify that the “server” has received a “missing item” signal via WiFi within 20 seconds and that the LEDs correctly display the expected result (as described above) • Repeat multiple times to ensure accuracy.	**PASS**
The microcontroller correctly detects the expected weight ±10% at least 95% of the time	• Connect to the MCU via USB-C to gain access to debugging information; specifically, the weight information from the Sensing Subsystem. • With an empty basket, power on the system and check that the basket shows 0kg • Add an item with a known weight and verify that the detected weight matches with ±10% of the kg • Repeat the above step with multiple items to ensure that overall accuracy remains.	**PASS**
The microcontroller shall provide a data update to the backend at a frequency of approximately 1Hz (once per second) to maintain real-time synchronization	• Connect the MCU to the laptop’s emulated backend server • Record the arrival time of 10 consecutive data packets • Verify that each interval of package arrival falls within the acceptable range of 1.0s±0.2s	**PASS**
The microcontroller shall be capable of transmitting a list of at least 15 unique tag IDs simultaneously without data corruption	• Place 15 tagged items into the basket • Observe the JSON output on the emulated laptop backend server • Verify all 15 unique IDs are listed in the data array and match the physical tags	**PASS**

Table 5 continued: Requirements and Verification Table

The subsystem shall recharge a 3.7 V Li-ion battery using a 5.0 V ±5% USB-C input and regulate the battery voltage to 4.20 V ±5%, preventing over-charging.	• While plugged in, USB-C board will confirm power delivery to load (battery) via LEDs • Measure charging voltage at +/- terminals and examine the voltage rises to correct level. Monitor battery voltage and charge current using multimeter. Confirm whether we read 4.20 V ±5% and reach 0A at full charge. • The battery will be discharged to approximately 3.0 V prior to testing. A regulated 5.0 V ±5% input will be applied via the USB-C connector. Battery voltage and charging current will be continuously monitored using a digital multimeter and/or oscilloscope.	**PASS**
The subsystem shall provide a regulated 5 V ±5% output rail capable of supplying up to 1.2A continuously	• The 5 V output will first be measured under open circuit conditions to confirm nominal regulation. A programmable load will then sweep current from 0 A to 3 A while output voltage is monitored. Voltage must remain within 4.7 V to 5.3 V across the full load range. A transient 3 A load pulse will be applied to simulate RFID burst current demand. Output voltage will be observed using an oscilloscope to confirm that droop remains within acceptable limits • Measure the output with no load attached right after USB-C has been unplugged with a multimeter to ensure a (±5%) 5.0 V is being outputted	**PASS**
The subsystem provides a regulated and stable DC 3.3V ±5% + maximum of 500mA rail for appropriate loads	• The 3.3 V output will be measured under open circuit conditions and then tested. Output voltage must remain between 3.3V with ±5% error. The 3.3 V rail will also be monitored during 5 V transient load events to confirm no coupling-induced instability	**PASS**
Provides a running total of the basket contents, updating with each new item addition or removal.	• Add three items with known prices to the basket • Verify that the UI total equals the sum of those items • Remove one item and confirm that the total reflects the summation of the prices of the remaining items	**PASS**
The interface shall remain responsive on standard smartphones or tablets, supporting a minimum resolution of 720×1280 pixels	• Load the app on an emulator set to 720x1280 resolution • Visually verify that all UI items are visible, aligned, and functional	**PASS**
Failure to update the item list within the time window, or failure to synchronize with the basket, shall trigger an error notification on the UI	• Power off the basket while the web application is active and connected • Confirm that some type of error alert appears on the application interface within 20 seconds	**PASS**

Table 5 continued: Requirements and Verification Table

The expected LED color is produced when a simulated data signal is sent to the Data Line	• Connect the GND pin of the ADALM1000 to the GND rail of breadboard • Connect Channel A (Orange) to the ESP32 side of the 74HCT245 (3.3V input) • Connect Channel B (Blue) to the LED side of the 74HCT245 (5V output) after the resistor • Upload a "Solid White" test script (Hex: 0xFFFFF) to the ESP32 to create a consistent, repeating pulse train on the data line • Open the Oscilloscope tool in Scopy and enable both Channel A and Channel B • Use the Measure panel to add "Max Voltage" for both channels. Confirm that Channel A reaches 3.3V (±10%) and Channel B reaches 5.0V (±10%) to check the level shifter • Observe the physical LED strip to see if it flows White • Update the ESP32 code to "Solid Red" (0xFF0000) and visually confirm that it turns Red • Repeat for Green (0x00FF00)	**PASS**
LEDs shall be visible under standard store lighting and at distances up to 1 meter away	• Activate the LED under standard overhead fluorescent lighting • Stand 1 meter away from the LED and confirm the color and state are clearly distinguishable	**PASS**
The subsystem shall consume no more than 500mA on the 5V rail during peak operation to prevent power instability	• Set the LED strip to White (R, G, and B, each at 255) • Measure the current draw on the 5V rail using a multimeter in series • Confirm the current draw is ≤ 500mA	**PASS**

Appendix B: Load Cell Calibration and Accuracy

To ensure accurate mass readings from the parallel load cell configuration, the sensing subsystem requires software-level calibration to account for the physical weight of the basket (tare) and the specific voltage response of the dual-Wheatstone bridge. This calibration relies on two primary variables within the firmware: the `offset` and the `scale_factor`.

B.1. Automated Zero-Offset (Tare) Initialization

The `offset` represents the baseline raw digital output of the HX711 amplifier when the basket is entirely empty. Because mechanical drift or temperature changes can slightly alter the load cells' resting resistance, this value is not hardcoded.

Instead, the firmware dynamically establishes the zero-offset every time the system boots. During the initialization phase, the microcontroller allocates a 20-second window to allow the load cells and amplifier to thermally stabilize. During this period, the firmware continuously polls the HX711 and accumulates the raw digital readings. At the end of the 20 seconds, the readings are averaged to establish the `offset` variable, filtering out transient electrical noise before the system goes live.

B.2. Scale Factor Determination

The `scale_factor` is the mathematical constant that converts the raw, zero-adjusted digital output of the ADC into physical kilograms. It is experimentally derived using a known physical calibration mass.

The calibration procedure requires placing a verified mass (e.g., a 0.500 kg test weight) into the basket after the zero-offset has been initialized. The scale factor is then calculated using the following relationship:

$$ScaleFactor = \frac{Data_{craw} - Offset}{Mass_{known}} \qquad (B.1)$$

Where $Data_{raw}$ is the stabilized 24-bit output from the HX711 with the test weight applied, $Offset$ is the previously established zero-load value, and $Mass_{known}$ is the exact mass of the test weight in kilograms.

Through experimental batch testing of the assembled basket, the scale factor was determined and hardcoded into the firmware as 56908.0.

B.3. Real-Time Mass Calculation

During standard operation, the firmware continuously samples the HX711. To calculate the preliminary physical weight of the basket's contents in real time, the microcontroller applies the calibrated variables using the following operational equation:

$$Weight = \frac{Data_{current} - Offset}{56908.0} \qquad (B.2)$$

This preliminary calculation yields the measured mass in kilograms. To prevent false readings caused by environmental factors, the firmware then passes this calculated mass through a 1.5-second settling delay and a dynamic walking-variance filter before validating it as the final, official system weight.

B.4. Load Cell Accuracy Verification

To verify the accuracy of the mass-sensing subsystem and the firmware's calibration logic, the system was tested using seven known test masses ranging from 0.180 kg to 2.466 kg. The objective was to ensure the calculated weight provided by the microcontroller remained within a ±10% tolerance of the true physical mass, which is the required threshold to reliably cross-reference items with the external database.

Each item was weighed five times in different locations in the basket, then averaged together. The percent deviation for each test item is plotted in Figure 9. The data confirms that the subsystem successfully met the accuracy requirement across the tested range, with all readings falling within the upper (+10%) and lower (-10%) bounds. The maximum observed error occurred during the testing of Item 7 (2.466 kg), which yielded a percent deviation of approximately -9.5%.

While the system passed verification, the data reveals a minor negative scaling bias. As the applied mass increases, the percent deviation trends downward, indicating that the system consistently calculates a slightly lighter weight than the true mass. This behavior is likely attributable to a minor rounding truncation in the hardcoded scale factor (56908.0) or slight physical flexing of the basket's false bottom at higher loads, which mildly attenuates the mechanical force transferred to the load cells. Because the deviation remains within the acceptable ±10% operational threshold, no further adjustments to the scaling mathematics were required, but future iterations could implement a dynamic, multi-point calibration curve to flatten this deviation at higher masses.

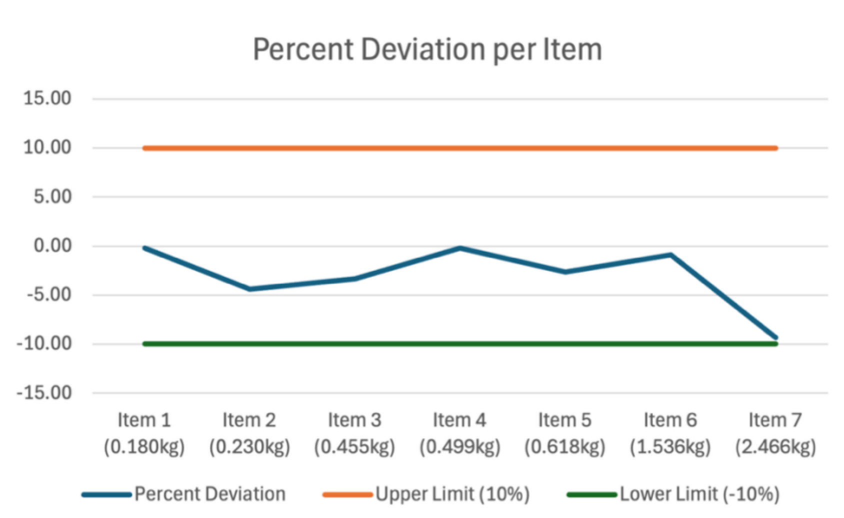

Figure 9. The percent deviation of each item versus the known mass.