RFID SELF CHECKOUT BASKET

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Project Proposal for ECE 445, Senior Design, Spring 2026

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13 February 2026

Project No. 94

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1. Introduction

1.1 Problem

Retail congestion remains a persistent source of inconvenience for customers and operational strain for businesses. Shoppers are often required to wait in long lines before purchasing their items, transforming a routine task into a time-consuming and frustrating process. In fast-paced environments where convenience is highly valued, visible checkout delays may discourage customers from entering a store or completing planned purchases, leading to lost revenue. As consumer expectations increasingly favor speed and efficiency, prolonged wait times may drive customers toward competitors offering faster checkout options, ultimately resulting in lost sales.

From an operational perspective, traditional checkout systems require businesses to staff multiple registers to manage customer flow. This increases labor costs while still failing to fully eliminate congestion during peak hours. Even self-checkout stations require employee oversight to assist customers, verify purchases, and prevent misuse. These inefficiencies impact both profitability and customer satisfaction, highlighting the need for solutions that streamline the purchasing process without placing additional burden on staff.

Existing mobile self checkout solutions allow users to scan items on their phone and proceed out of the store after digitally completing their transaction. However, there is no system in place to ensure that shoppers are honorably scanning all of their items or entering correct quantities. While the honor system may work in some capacity, for many retail locations, this is not the case.

Beyond convenience, inefficient checkout processes relate to broader societal and economic concerns. Long wait times can reduce accessibility for individuals with mobility constraints or limited time, while overcrowded checkout areas may present safety risks in emergency situations. Addressing checkout delays is therefore not only a matter of convenience but also an economic and safety concern. Improving transaction efficiency can enhance the overall shopping experience, encourage repeat visits, and help businesses operate more effectively in an increasingly competitive retail environment.

1.2 Solution

For a solution to this issue, this project proposes the development of an automatic self-checkout shopping basket capable of identifying items as they are placed inside. The system will primarily use UHF RFID technology to detect tagged products without requiring manual scanning, enabling shoppers to monitor a live item list and running total through a connected web application. A system of load cells will provide weight-based verification to detect discrepancies between expected and measured basket contents. Together, these sensing methods create a verification process that improves reliability.

The system will be coordinated by a microcontroller that aggregates sensor data and communicates with a centralized server over WiFi. Visual feedback will be provided through an LED indicator to immediately inform users of successful reads or potential errors. The basket will connect via WiFi to the store's local servers which will, in turn, display data on a public-facing web application which will allow shoppers to easily see the items that are in their basket along with their current total price. By shifting item identification earlier in the shopping process, the proposed design aims to reduce checkout congestion, lower staffing demands, and improve overall shopping efficiency while maintaining user transparency and control.

1.3 Visual Aid

The following figure provides an illustration of the proposed RFID self-checkout basket within a shopping environment. It highlights how a shopper interacts with the system and how the basket connects to relevant external infrastructure in the context of real-world usage.

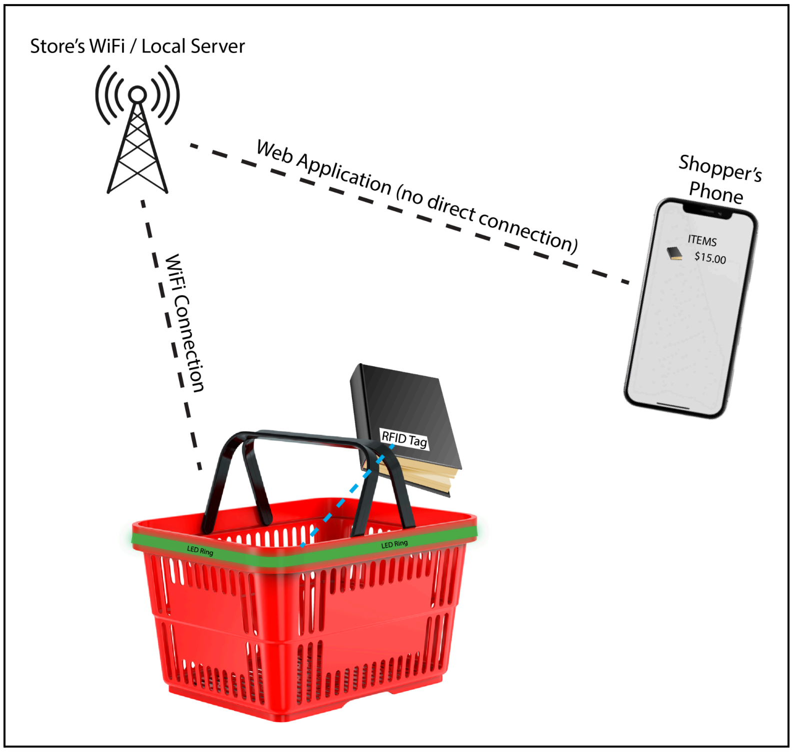

Figure 1 High-level representation of the proposed RFID self-checkout basket in context, illustrating its interaction with key external systems and the user

1.4 High-Level Requirements List

- The system shall automatically detect and correctly identify at least 95% of RFID-tagged items placed inside the basket within 5 seconds of insertion, and shall accurately distinguish items inside the basket from those outside by limiting unintended RFID reads to less than 5% for objects located more than 12 inches away.
- The system shall successfully identify when an item weighing at least 0.5 pounds has been placed inside of the basket but an RFID tag was not recognized and notify the user via a pulse or color change of the LED light.
- The system shall update the user-facing web application with the current item list and running total with 100% accuracy within 10 seconds of any item being added or removed from the basket.

2 Design

2.1 Block Diagram

Our proposed high-level block diagram is shown in **Figure 2**, providing an overview of the interactions between the system's primary subsystems:

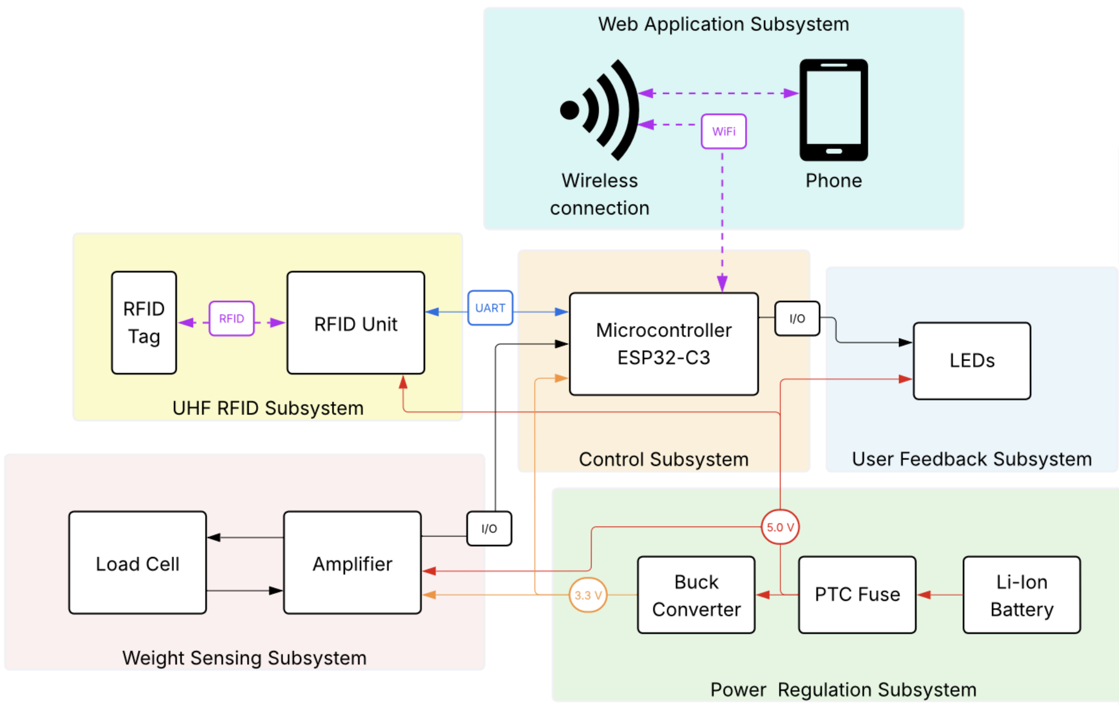

Figure 2 High-level block diagram of the RFID self-checkout basket system illustrating how the major subsystems integrate to support overall functionality

2.2 Subsystem Overview

2.2.1 UHF RFID Sensing

We will make use of UHF (Ultra High Frequency) RFID due to the fact that it is able to detect multiple tags "piled" on top of one another and has an increased range over standard RFID. Using a M5Stack UHF RFID Unit (JRD-4035) as the reader module, we will access the data via the UART connection. Each individual item will have a unique RFID tag (1568-27180-ND or similar part number). We will also tune the power (attenuation) of the RFID reader such that it only detects items inside of the basket. This subsystem is critical for enabling automatic detection of items and forms the foundation of the self-checkout functionality.

2.2.2 Control: Microcontroller

The microcontroller (ESP32-C3-DEVKITM-1-N4X) will use input from the RFID subsystem to keep track of every items' unique tag and determine which are in the basket. With WiFi and bluetooth connectivity, it will communicate with the store's infrastructure (or in our case an emulation on a laptop computer). The microcontroller acts as the central processing unit, integrating sensor data and coordinating communication between all subsystems to ensure accurate tracking and system operation.

2.2.3 Weight Sensing: Load Cells

Approximately two load cells (1528-4543-ND), each supporting 10kg, will be placed at the bottom of the basket in order to provide another layer of input validation. If an increase in weight is detected by a new RFID tag is not detected, this will alert the user of an error. Additionally, an amplifier (1568-13879-ND) will be used to ensure the signals can be picked up by the microcontroller. The load cells provide a secondary verification mechanism to improve reliability and prevent errors in item tracking.

2.2.4 Power Regulation

The power subsystem ensures stable and reliable operation of all electronic components. Power will be supplied through a rechargeable battery pack (a 3.7V Li-ion or something similar to support 1-2 hours of shopping), connected to a USB-C breakout board with proper configuration channel (CC) termination. The battery voltage will feed into a boost/buck converter system to provide a regulated 5V supply at adequate current. The 5V rail will directly power high-current devices such as the RFID reader and LEDs. Bulk (470 µF) and decoupling (0.1 µF) capacitors will be placed near these components to mitigate voltage dips caused by transient current draw during startup.

A buck converter, such as the MP1584EN module, will step the 5V input down to a regulated 3.3V rail for the microcontroller and low-power sensors. This separation reduces electrical noise and prevents instability in sensitive logic devices. Additionally, a resettable PTC fuse will be incorporated to provide overcurrent protection by limiting excessive current flow during fault conditions. Together, these components create a robust distribution network capable of supporting simultaneous subsystem operation. This subsystem ensures that all electronics operate reliably and safely throughout the shopping process.

2.2.5 Web Application

A web application (running via smartphone emulator on a laptop) will connect to the device via the “store’s” infrastructure (WiFi), allowing a shopper to see a live list of the items in their basket and a running total. The web application will connect to a centralized server (emulated on a computer) and access the information via API, meaning that shoppers do not need to use a bluetooth connection which poses security risks. The web application provides the shopper with real-time visibility and control over their basket contents, enhancing usability and transparency.

2.2.6 User Feedback: LED Status Indicator

The basket will be equipped with RGB LED lights (WS2812B) that can be set to multiple colors. This will be able to display different colors in different patterns (strobing, pulsing, etc.) based on different statuses of the basket: solid white to indicate the basket is ready, pulsing red to indicate there was an error with the item, or a green pulse to indicate a successful reading of an item. The LED will be controlled by the microcontroller. The LED subsystem ensures immediate user awareness of basket status, contributing to a smooth and error-minimized shopping experience.

2.3 Subsystem Requirements

2.3.1 UHF RFID Sensing

The UHF RFID sensor is crucial to the overall design as it allows the system to detect the presence of individual RFID tags. This subsystem is the sole source of determining which item has been placed inside of the basket. It must be able to provide enough “wake-up” power to any tag within this range, otherwise the tag will go undetected.

- The subsystem shall reliably detect passive UHF RFID tags located within 0.25 meters of the antenna with at least 95% read probability within 2 seconds.
- The subsystem shall not detect tags located further than 0.5 meters from the antenna.
- The subsystem shall support simultaneous detection of at least 5 tags all in the basket at the same time.
- The subsystem shall operate at 915MHz.
- The subsystem shall provide sufficient power to activate tags with sensitivity of at least -18 dBm within 0.25 meters from the antenna.

The subsystem will operate off of a 5V power supply. It shall communicate with the microcontroller subsystem with UART (baud 115,2000bps) to communicate tag ID information in 96-bit format. The subsystem will further be attenuated, if necessary, by means of metal shielding to ensure that tags are properly read within the specified distance range.

2.3.2 Control: Microcontroller

This 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. Failure of this subsystem results in no other subsystem being able to intercommunicate and a total loss of functionality.

- The subsystem shall receive tag data from the UHF RFID subsystem via UART (baud 115,200bps)
- The subsystem shall process and log new tag reads within less than 200ms of data reception.
- The subsystem shall maintain an internal list of active tags that are currently inside of the basket.
- The subsystem shall support tracking of at least 25 unique tag IDssimultaneously.
- The subsystem shall correctly determine items that have been removed and items that were newly added based on read persistence.
- The subsystem shall filter reads shorter than 200ms in order to prevent the false addition of an item that was not fully placed in the basket.
- The subsystem shall update the state of the basket within 1s of an item being added or removed.

The subsystem will operate off of a 3.3v power supply. It will communicate with the RFID subsystem via UART, the load cell subsystem via an amplified signal from a two-wire interface (RXD, TXD) and sample at a rate between 5-20 times per second. It will connect to the web server via WiFi, and connect to the LED subsystem via single-wire digital control.

2.3.3 Weight Sensing: Load Cells

Load cells will be responsible for measuring the total weight of the items the basket contains and send this data off to the microcontroller in order to further verify validity of the tracking. The weight information will be used to confirm whether items have been added or removed from the basket detected by the RFID subsystem. It will also detect potential mistakes, untagged items, or misreads.

- The subsystem shall measure weight of each individual item and output overall weight as summation of every item.
- The subsystem shall communicate weight data via amplified voltage measurement connected to a GPIO port of the microcontroller subsystem.
- The subsystem shall be able to read a maximum weight of at least 20 kg.
- The system amplifier shall operate at 3.3 V.
- The system's load cell receives excitation voltage (5.0 V) directly from the amplifier component.

If this subsystem fails, we will have lost some reliability of valid detection.

For the purpose of design, convenience, and effectiveness, the basket will incorporate a false bottom platform in order to measure the weight of content inside without sacrificing accuracy if done otherwise. The basket handles will be mechanically connected to a structural frame that transfers the full basket weight to through the load cells.

2.3.4 Power Regulation

The power regulation subsystem will be responsible for the distribution of correct electrical power to each different subsystem in a stable manner. This will be done with an initial Li-ion cell (5V) that is connected to a PTC fuse for an extra measure of safety. The PTC then outputs 5V which is connected to select subsystem modules and a buck converter. The buck converter will output 3.3V which is then connected to the remaining subsystem modules.

- The subsystem shall receive DC input from Lithium-ion battery source
- The subsystem shall provide overcurrent protection
- The subsystem shall generate a stable 5.0 V output (DC)
- The subsystem shall generate a stable 3.3 V output (DC)
- The subsystem shall include appropriate decoupling capacitors to smooth out voltage dips and filtering to minimize interference with other subsystems
- The subsystem shall operate for a minimum of X hours on a charged battery (X to be decided later)

The PTC fuse was included in the original design due to the initial idea of powering the entire system via USB-C cable. This allows some room in the future for potential power source alternatives.

2.3.5 Web Application

The web application serves as the interface between the shopper and the basket, displaying real-time item information and totals. It contributes to the high-level requirement of accurate, timely item tracking. The subsystem requirements are as follows:

- The web application shall display each item added to the basket within 20 seconds of successful detection with 95% accuracy.
- It shall provide a running total of the basket contents, updating with each new item addition or removal.
- The application shall communicate with the microcontroller/server via WiFi using an HTTP REST API or WebSocket with a minimum 1-second refresh rate.
- The interface shall remain responsive on standard smartphones or tablets, supporting a minimum resolution of 720×1280 pixels.
- 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.

The subsystem receives item ID and status data from the microcontroller/server. Additionally, it sends user commands (e.g., remove item, complete checkout) back to the server. These requirements ensure that the web application provides real-time, actionable feedback for the shopper, enabling transparency and confidence in the checkout process.

2.3.6 User Feedback: LED Status Indicator

The LED status indicator provides instant visual feedback to the shopper about the state of the basket, contributing directly to the consideration for accurate and fast error detection. Requirements for this subsystem are as follows:

- The LED system shall change color within 5 seconds of an item being added or removed.
- A green pulse shall indicate successful detection of an item.
- A red pulse shall indicate an error, such as a missing RFID tag or weight discrepancy.
- A solid white shall indicate the basket is ready for use.
- LEDs shall be visible under standard store lighting and at distances up to 1 meter from the basket.
- The subsystem shall consume no more than 500mA on the 5V rail during peak operation to prevent power instability.

The subsystem receives commands from the microcontroller regarding item status and error conditions via single-wire digital control. It also uses the same 5V rail as the RFID system but must not interfere with RFID read reliability. These requirements ensure the shopper can instantly recognize the basket's status, reducing confusion, and allowing for immediate corrective action if an error occurs.

2.4 Tolerance Analysis

A critical risk to the completion of this project is proper calibration of the RFID read zone and ensuring that the reader is capable of reading multiple devices piled on top of one another. It will be necessary to limit the range to only within the basket with a very small tolerance of just a few inches. Should the range be too high, the basket will incorrectly read items that are nearby, but not in the shopper's basket. Should the range be too low, the basket will not identify all of the items inside.

The basket shall have a signal strong enough to "wake" a tag at the furthest spot from the reader ($d_{max} = 0.25\ m$), yet the signal must be weak enough outside of the basket's range ($d_{lim} = 0.5\ m$).

In free space, doubling distance 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.

Given that UHF RFID operates between at 915 MHz, the wavelength $\lambda \approx 0.33\ m$. Based on the specifications of the reader, the minimum power (P_t) is 18 dBm. We will assume that the gain of the reader and tag respectively $G_t = G_r = 1\ dBi$. The sensitivity of the tags is approximately -18 dBm.

Based on the Friis Transmission Equation $P_{tag} = P_t + G_t + G_r - 20log_{10}(\frac{4\pi R}{\lambda})$, the power received at the tag with the reader on its lowest setting at a distance d_{max} is then:

$$P_{tag} = 18\ dB + 1\ dBi + 1\ dBi - 20log_{10}(\frac{4\pi(0.25m)}{0.33}) \approx 0.43\ dBm$$

Given that the tags' sensitivity is -18 dBm, this is enough power to activate the tag. At d_{lim}, only an additional 12 dB of additional loss occurs, meaning that through free-space, the system would still transmit enough power to read a tag.

To ensure that the system does not read a tag at d_{lim}, we will therefore control the orientation of the antenna to face strictly upwards (given that the antenna is directional) and add shielding to the basket to provide the necessary minimum of 6dB of additional loss. It is also necessary to note the system will not be performing in true free-space and it is impossible to accurately estimate the attenuation provided by the basket alone without shielding. But, even when assuming free-space, the addition of just a thin layer of aluminum would provide between 5 and 10 dB of additional attenuation, making the overall tuning of the system feasible.

2.5 Optional Goal: Camera-Based Item Verification Subsystem

As an optional extension to the system, to be completed if time allows, a camera-based verification subsystem may be incorporated to assist in identifying items that do not contain RFID tags. While the primary design will still rely on UHF RFID and load cell measurements for automatic detection, certain retail products such as fresh produce or unpackaged goods may not be easily tagged. The camera subsystem would provide an additional sensing modality capable of recognizing these items through image processing techniques.

The camera would be mounted along the interior rim of the basket and oriented downward to capture images whenever a weight change is detected without a corresponding RFID read. Captured images would be transmitted to the microcontroller and processed locally or forwarded to a server for classification using a lightweight computer vision model. If an item is successfully identified, it would be added to the user's virtual basket; otherwise, the system would alert the shopper through the LED indicator and web application.

This proposed camera subsystem would need to satisfy the following requirements in order to function effectively within the overall design:

- The subsystem shall operate from the regulated 5V or 3.3V power rail without introducing harmful electrical noise to other components.
- The subsystem shall capture an image within 5 seconds of a detected weight change that is not matched to an RFID read.
- The subsystem shall communicate captured image data to the microcontroller or server with an end-to-end latency of less than 10 seconds.
- The subsystem shall function under typical indoor retail lighting conditions without requiring external illumination.

The subsystem would receive trigger signals from the microcontroller when a weight change occurs without an associated RFID tag. It also would send captured image data to the microcontroller or centralized server for processing. It would communicate classification results back to the microcontroller so the item list can be updated in the web application. These interfaces would ensure seamless integration with existing sensing and processing subsystems while preserving the core structure of the design.

3. Ethics, Safety, and Societal Impact

The proposed smart basket must operate accurately to prevent billing errors that could negatively impact customers or businesses. The system will be designed with redundant verification through RFID detection and weight sensing to minimize false readings. Extensive testing and calibration will be conducted to reduce the likelihood of incorrect item identification.

Safety considerations are also critical in the physical and electrical design of the basket. All circuitry will operate within regulated voltage levels, and protective components such as a resettable fuse will help prevent overcurrent conditions that could cause overheating or fire hazards. Wiring will be insulated, secured within the basket structure, and positioned inside to avoid user contact or mechanical strain. Additionally, the basket will be made out of a durable plastic material that does not pose an immediate threat to the user and is safely able to support a minimum of 30 pounds.

From an ethical standpoint, the system will avoid collecting unnecessary personal data. Communication between the basket and the web application will transmit only item-related information, reducing privacy risks. Transparency will also be emphasized by allowing shoppers to view their item list and running total in real time, helping users identify mistakes before checkout.

The societal and economic impacts of this technology are largely positive. By reducing checkout times, the system may improve accessibility for individuals with limited mobility or time constraints while enhancing overall customer satisfaction. Businesses could benefit from improved operational efficiency and reduced congestion without fully replacing human workers, instead allowing employees to focus on customer assistance and higher-value tasks. Environmentally, the system encourages efficient store layouts with less physical space dedicated to checkout infrastructure and reduced paper receipt usage when paired with digital transaction records.

Potential misuse must also be considered. Users might attempt to bypass detection by shielding RFID tags or manipulating basket weight. To mitigate this risk, the design incorporates cross-verification between sensing methods and error notifications when inconsistencies arise. While no automated system is entirely immune to misuse, these safeguards promote responsible operation and align with professional expectations for trustworthy engineering design.