March 19, 2015

Dr. Andrew Rawicz
School of Engineering Science
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Burnaby, BC
V5A 1S6

Re: ENSC 440W Design Specification for the LiteSpeed Gate

Dear Dr. Rawicz,

Please find the enclosing design specification for our LiteSpeed Gate project designed by ShopLite Solutions. Our LiteSpeed Gate is a retail store gate system allowing merchandise to be scanned wirelessly. The LiteSpeed Gate enables consumers to instantly pay for their items without going through the cashier using Radio Frequency Identification (RFID) technology.

Our design specification document details the technical guidelines for the design of the proof-of-concept LiteSpeed Gate. Some of the technical design details of the final LiteSpeed Gate are discussed as well. This document will be used by all of the engineers involved in the completion of the project.

If you have any questions or concerns, please feel free to contact me by email at nbalzer@sfu.ca.

Sincerely,

Noah Balzer

Noah Balzer
Chief Executive Officer
ShopLite Solutions

ShopLite Solutions

Design Specification for LiteSpeed Gate

A pleasant, fast and light shopping experience

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Submitted to:
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Executive Summary

The design specification of the LiteSpeed Gate (LSG) provides the design details for the development of the proof-of-concept device. Since this document is primarily concerned with the design of the proof-of-concept device, only those functional requirements specified in the document *Functional Specification for A LiteSpeed Gate* [1] under the I and II classification (minus R66-II) will be discussed.

Besides outlining the design of the LiteSpeed Gate, this document also provides justification for specific design decisions. The proof-of-concept LiteSpeed Gate consists of a wooden gate which has an antenna mounted on each side and a scale at its base. Stepper motors automatically adjust the orientation of each antenna to increase scan accuracy. A central reading unit activates the antennas which scan items presented to the gate. The scale located at the base of the LiteSpeed Gate retrieves the total weight of the items. A core system computer reads the inputs of the central reading unit and scale, produces commands for the micro-controller to activate the stepper motors, and displays the output on the user interface unit. The user interface unit consists of a screen and a variety of buttons for user input.

This document describes the technical details of the components chosen and outlines any selection criteria used in decision making. Software infrastructure details and a flowchart of the main process is also included. Finally, a description of the test plans for each of the subsystem units as well as the integrated system is outlined.

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Glossary

CPU Central Processing Unit

CRU Central Reading Unit

LFT Legal for Trade

LSG LiteSpeed Gate

MVC Model-View-Controller

OS Operating System

POC Proof of Concept

RAM Random Access Memory

RFID Radio Frequency Identification

SNR Signal to Noise Ratio

TCP/IP Transmission Control Protocol/Internet Protocol

UHF Ultra High Frequency

UI User Interface

WPF Windows Presentation Foundation

1 Introduction

The LiteSpeed Gate is a retail store gate system which allows for customer's merchandise to be wirelessly scanned. The LiteSpeed Gate enables consumers to instantly pay for their shopping items without going through the cashier using Radio Frequency Identification (RFID) technology. Our goal is to reduce checkout wait times in stores and thus improve the overall shopping experience. This design specification outlines the technical details for the design of each subsystem in the LiteSpeed Gate.

1.1 Scope

This document outlines the design of the LiteSpeed Gate specified in the *Functional Specification for A LiteSpeed Gate* [1]. The design specification presents the technical details of all the major subsystems for a proof-of-concept device as well as some of the design details of the final product. Since this document is primarily concerned with the design of the proof-of-concept device, only those functional requirements under the I and II classification (minus R66-II) will be discussed.

1.2 Intended Audience

The specification is intended for all of the engineers at ShopLite Solutions. This document will be referred to as a design guideline during the implementation phase in order to ensure that all of the requirements are met. This document will also be used during the testing phase to ensure proper functionality.

2 System Specifications

The LSG will automatically scan through all the items that are present at the gate through RFID technology. The system process initiates when a customer approaches the gate and places their items or cart on the scale. The LSG then scans all of the items using the RFID module and adjusts antenna angle to improve accuracy.

Scan results are used to obtain information from the database, including the item name, price, and weight. Verification compares the sum of the item weights with the output from the scale.

3 Overall System Design

This section provides a high-level design of the entire LSG system. The major design details of the LSG system common to all of the subsystems will be discussed, and subsequent sections will describe the specific design details of each subsystem.

3.1 Structural Design

Figure 1 shows the proposed structural design for the LSG.

Figure 1: Structural Overview of the LSG

The LSG structure will be made from readily available recycled wood due to budget constraints. According to the functional specs, the wood structure must be strong enough to support the mounting of all of the subsystems and withstand moderate incidental contact [1].

Table 1 summarizes the physical dimensions of the LSG structure. These dimensions were chosen to accommodate the chosen antennas and standard shopping carts [2] as specified by RS6-II and RS7-II in the functional specification.

Table 1: Summary of Physical Dimensions

Component Description	Dimensions (Length x Width x Thickness)
Ramps (x2)	25” x 42” x 3.5”
Base	42” x 42” x 3.5”
Sides (x2)	60” x 20” x 2.5”
Location Controller Opening	18” x 18” x 4.5”

In future development iterations, more criteria will be used to select the appropriate materials for the structure of the LSG. Properties such as recyclability, cost, and ventilation will be considered. Physical requirements will include rounded edges for safety and aesthetics. Finally, the chosen material should have a negligible effect on antenna radiation patterns.

3.1.1 Other Designs

While designing the structure of the POC LSG, other building materials were considered, such as metal and plastic. Large metal surfaces, however, may alter the antenna’s radiation pattern or reduce its bandwidth [3]. Because plastics are more expensive and difficult to manipulate, wood was selected due to availability. The use of plastic, however, will be reconsidered when designing the final LSG as it could potentially reduce the material costs substantially in mass production.

3.2 High-level System Design

This section presents a high-level overview of the entire system. Figure 2 below illustrates how inputs are received and how subsystems interact with each other in order to produce an output.

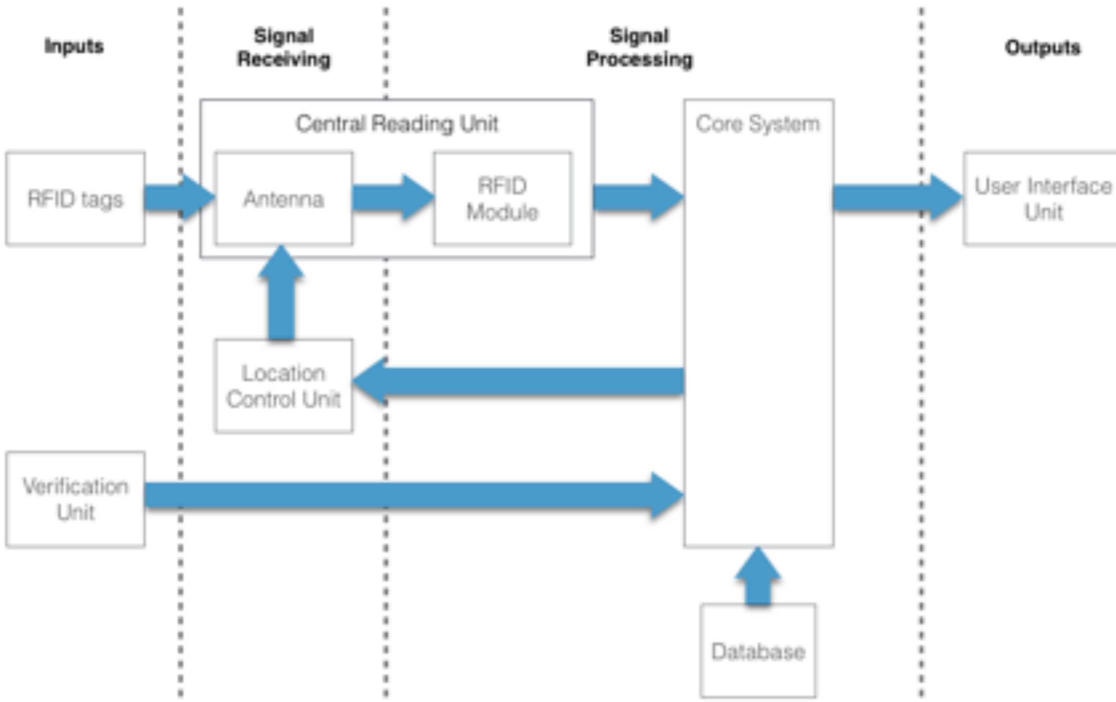

Figure 2: System Block Diagram

3.3 Subsystem Placement

The LSG is composed of the following subsystem units:

- Central Reading Unit (RFID Module and antennas)
- Core System
- Database
- Location Control Unit (Micro-controller and motors)
- Verification Unit (Scale)
- User Interface Unit (Screen)

Figure 3 highlights the placement of the different subsystems in the LSG.

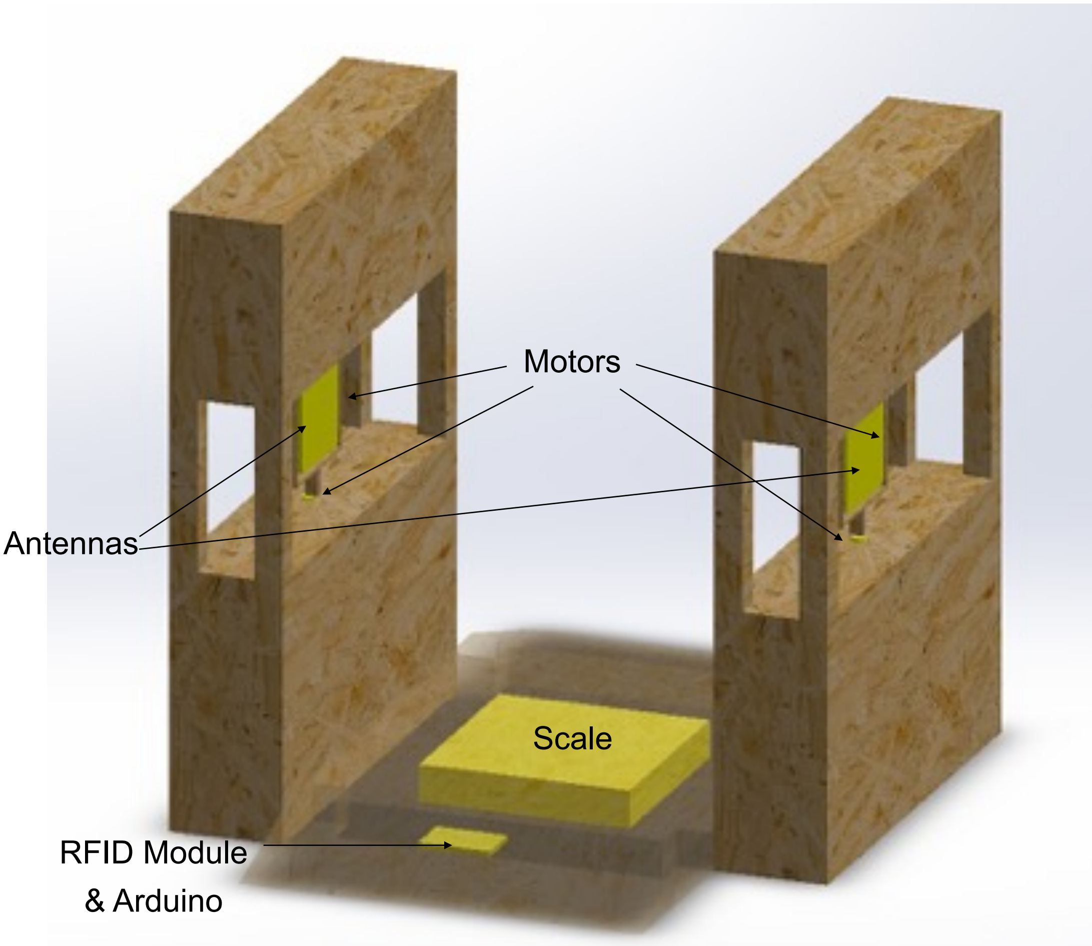

Figure 3: Subsystem Placement in the LSG

3.4 Safety Considerations

Safety will be enforced in the LSG in order to protect users and developers by taking the following precautions:

- Proper insulation of wires
- Use of an emergency shut off switch
- Careful routing of wires
- Stable structural construction

In the final LSG, the location control unit components and antennas will be enclosed to ensure user safety during operation as seen in requirement R56-III. For the POC device, however, the location control unit will not be enclosed due to time and budget constraints, and also to demonstrate its functionality.

4 Core System

The design of the core system processing unit for the LSG is described in this section. The following subsections outline the design considerations for the core system hardware and sequence flowchart.

4.1 Core System Hardware

For the POC device, a Samsung 550P7C laptop will be used as the hardware for the core system. This laptop was chosen as it offers all of the ports needed to interface with the different subsystems as well as the processing power to run the main application. This laptop also allows for demonstration of the UI and was readily available to use for the POC device at no extra cost. Table 2 summarizes the applicable specifications:

Table 2: Samsung 550P7C Specifications

Component	Specification
CPU	Intel Core i7-3610QM @ 2.30GHz
RAM	8 GB
OS	Windows 7 Home Premium
Ports	USB and Ethernet

In the final LSG, the core system hardware will feature a touchscreen device meeting the minimum processing requirements, and with the ability to interface all of the subsystems and inventory database of the store.

4.2 Main Process

The main process of the core system handles the central reading unit and verification unit outputs and sends commands to the location controller to adjust the angular orientation of the antennas. The flowchart of the main process is shown in Figure 4.

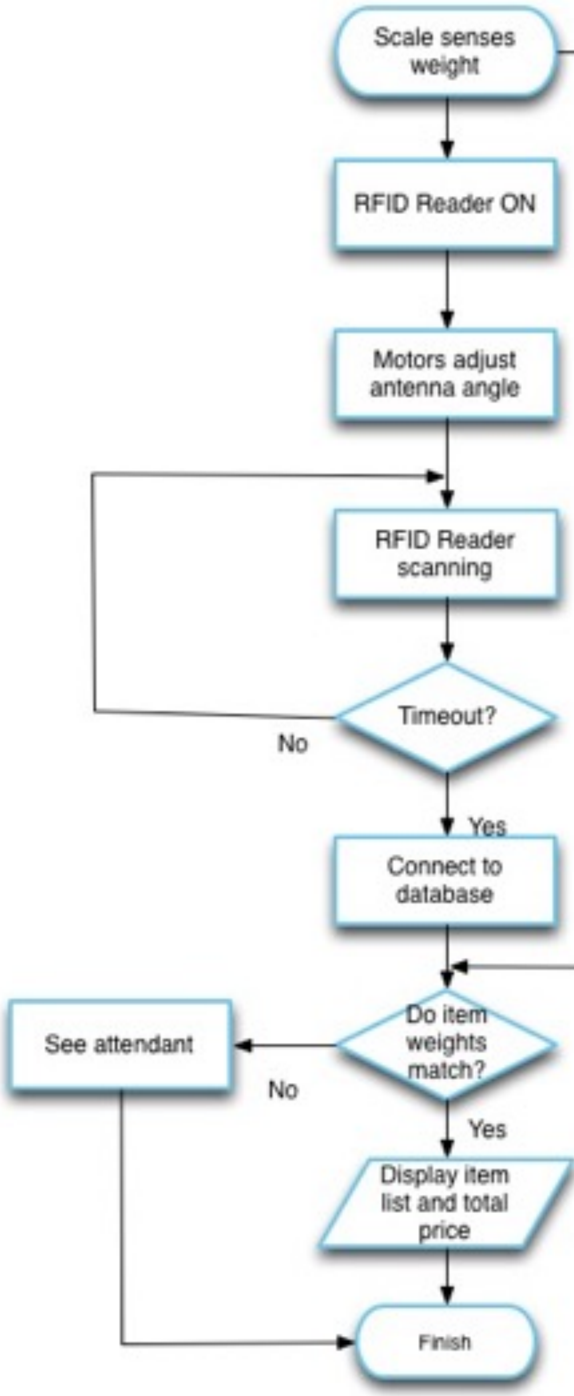

Figure 4: Flowchart of Main Process

5 Central Reading Unit

The central reading unit (CRU) is responsible for identifying the tags presented in the LSG and sending this information to the core system.

5.1 Central Reading Unit Hardware

The CRU includes the radio-frequency identification (RFID) module and two antennas to communicate with any passive RFID tags within range. The RFID module is a frequency transceiver operating at ultra-high radio frequency to retrieve tag serial numbers. The passive RFID tags have radio frequency circuitry, which is activated through induction by the magnetic fields generated by the antennas.

5.1.1 RFID Module

The YR8600 ultra-high frequency RFID reader was chosen for our design. This reader consists of one RF transceiver Indy R2000 chip and four ultra-high frequency channel ports. The ports are designed for the use of both TCP/IP and RS232 data line interfaces. The YR8600 connects with up to four antennas to allow flexible scanning coverage.

In the LSG, the YR8600 reading module will connect to two antennas and operate in the ultra-high frequency range, specifically between 860Mhz and 960Mhz. This frequency range allows the central reading unit to read up to 700 tags per second, which guarantees an acceptable performance for our final product as specified by RS47-III [4]. The reading parameters of the YR8600 are shown in Table 3 below:

Table 3: YR8600 Details and Specification [15]

Operating Voltage	3.7V - 5V	Output Power Flatness	+/- 0.2 dB
Standby Mode Current	< 50mA	Receive Sensitivity	< -85dB
Sleep Mode Current	< 100uA	Peak Inventory Speed	> 700 tags/sec
Operating Current	1.2A +/- 10%	Tag Buffer Size	1000 tags @ 96bit EPC
Operating Temperature	-20° - 55°	Spectrum Range	860MHz - 960MHz
Humidity	< 95%	Output Power	20 - 33dBm

5.1.2 Antennas

The LSG CRU is composed of two 9.2dbi UHF RFID antennas, which provide relatively high signal strength at a range of 2-3 meters. These antennas both generate magnetic fields, and serve as a channel allowing data transfer back from the tags [4]. The relevant parameters are summarized in Table 4 below:

Table 4: 9.2dbi UHF RFID Antenna Specification [16]

Frequency Range	840 - 960MHz
Gain	9.2 dBi
Horizontal -3dB beamwidth	70°
Vertical -3dB beamwidth	70°
Front-Back	> 25dB
Impedance (Ω)	50
VSWR	< 1.3
Maximum Input Power (W)	200
IM.3rd Order(2x43dBm)	< -150dBc
Dimensions	260x260x40mm
Weight	0.6kg
Radome Material	ABS/Glass fibre reinforced plastic
Working Temperature	-25° - 85°

5.2 Central Reading Unit Software

Reader methods were provided in a dynamic link library, reader.dll, by the vendor. The library includes a list of Application Programming Interfaces (APIs) that allow communication between laptops and the YR8600 module. To use the provided library, a customized multi-threading application will be implemented in C#. This application includes a user-friendly interface to interact with customers. More details will be presented in the user interface unit section [4].

6 Location Control Unit

The location control unit described in this section is used to automatically reorient the antennas between successive readings in order to increase overall reader accuracy.

6.1 Physical and Mechanical Design

The location control unit has undergone redesign compared to what was written in the functional specification. The functional specification stated that improved reader accuracy would be achieved by actuating each antenna so it could move along the frame of the gate. This was to gain additional antenna vantage points, assuming that some tags would be scannable with particular geometric configurations.

Through preliminary experiments, however, it appears that the additional vantage points tested convey no measurable advantage in reader accuracy . Instead, reader accuracy was found to increase with proximity and power. This is likely due to the inversely proportional relationship between range, r, and power delivered to the tag, P. This is governed by [5]:

$$P = P_0 g_t g_r \left(\frac{\lambda}{4\pi r}\right)^2$$

Thus moving the antennas to the top of the gate, a height of approximately 7 feet, effectively increased r, and therefore decreased power to the tag by a factor of $\frac{1}{r^2}$. The strength of the returning signal with this orientation is reduced compared to the having the antennas immediately adjacent to the side of the cart, since r is smaller in the latter case. With decreased signal strength, the SNR also decreases. Reader sensitivity is given by [5]:

$$Sensitivity = SNR_{\min} kTB(NF)$$

Since the sensitivity of the reader is proportional to the SNR, a reduced SNR results in reduced reader sensitivity. So there was no advantage in changing the geometry while simultaneously decreasing sensitivity by moving the antennas further away from the tags. In the LSG, we will therefore position both antennas as close as possible to the shopping cart. The easiest method is to have the antennas along the right and left sides of the cart, as opposed to positioning them at the top or bottom. This is depicted in Figure 1 and 3. Having the antenna structure on top might obstruct a person from walking through the gate, while having it on the bottom might obstruct a cart.

Changing geometry while avoiding a reduction in sensitivity, on the other hand, appears to improve reader accuracy. Reader performance was likely improved due to the changing angular orientation of the reader relative to the tags. Antennas project fields in the shape of lobes in 3-dimensional space, called a radiation pattern [6]. In the example below, the lobes represent areas of antenna sensitivity, while the null space around the lobes are insensitive.

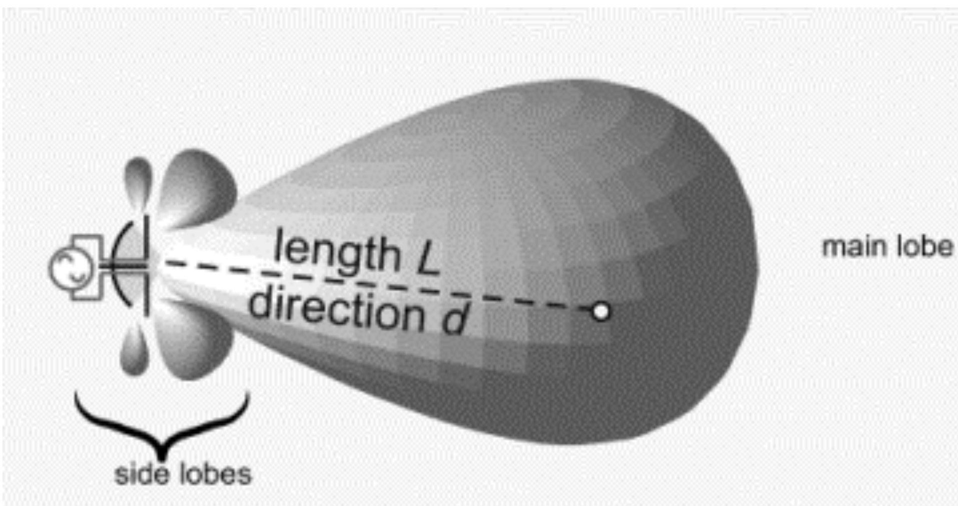

Figure 5: Example radiation pattern of an antenna [7]

The presence of null space outside the lobes [6], necessitates either the reorientation of our two antennas to sweep a larger volume with the lobes, or the usage of multiple antennas for more lobes. Of these, the reorientation option is a more cost-effective solution due to the low cost of motors compared to antennas ($3 for an adequate stepper motor, versus $70 for another antenna). Thus, our complete solution is to change the angular orientation of the antennae between readings, while keeping a fixed translational frame of reference close to the sides of shopping carts. Angular rotation will be accomplished with a bracket and an actuator allowing the antennas to rotate about the y-axis. Another actuator rotates the entire antenna-bracket structure about the z-axis of the antennas. This is depicted in the figure below. The top of the bracket will attach to an axial bearing.

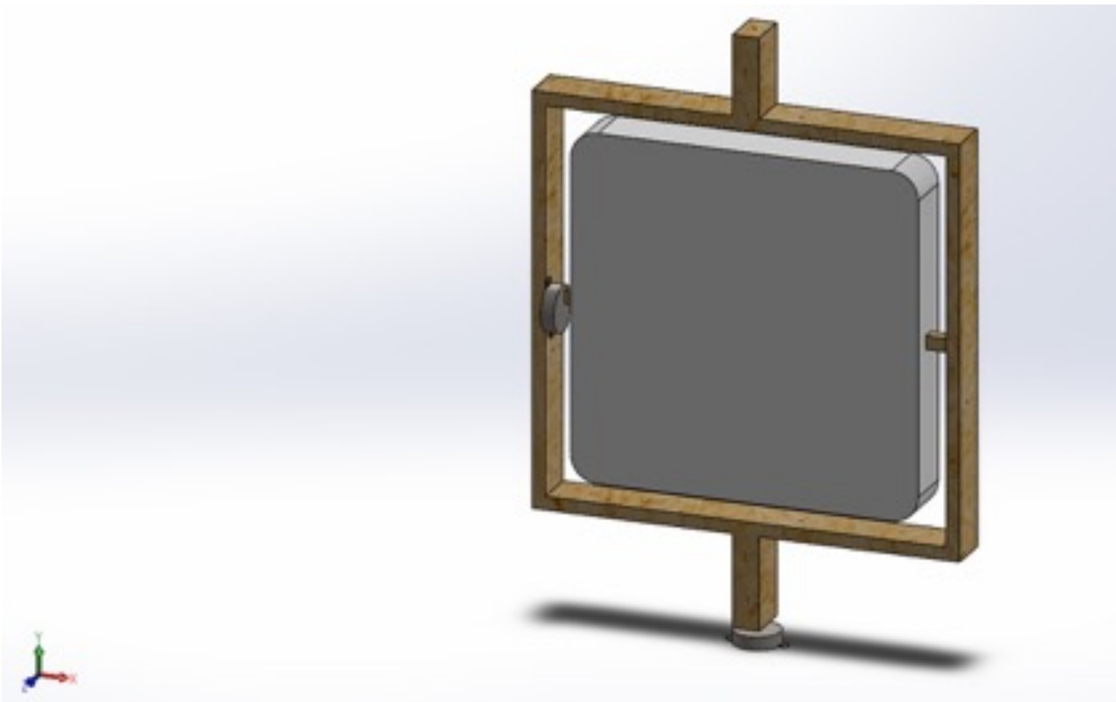

Figure 6: Antenna-Bracket Structural Overview

6.2 Electronic Design

The actuator (28BYJ-48 stepper motor) will be controlled by a micro-controller (Arduino Uno) and motor driver (UNL2003). Two motors attached to the same antenna will rotate at different speeds in order to sweep a larger volume with the antenna's field. From the median position depicted in Figure 6 above, the motors will allow a total of 180 degrees rotation about their respective axes. Since the 28BYJ-48 motor has a step size of 5.625 degrees, angular position is easily calculated by counting the number of steps taken by the motor and performing the appropriate conversion.

6.2.1 Stepper Motor

Angular rotation should be relatively slow for both axes, allowing the antennae time to perform multiple scans at each angle. The antenna may be thought of as an addition to shaft inertia, since rotation will be directly coupled to the motor shaft. The additional inertia, L, is approximated by:

$$L = \frac{Ml^2}{6}$$

Where M is the total mass of the antenna, and l is its length. The calculation is simplified by assuming the antenna has uniform density, and also negligible thickness compared to it's length and width. The bottom motor must also rotate the frame and another motor, and the additional inertia is assumed to be negligible. With negligible load and inertial properties combined with low RPM requirements, the specs for the actuator are minimal. Thus we utilize the cheapest stepper motors available for the POC, because of their cost-effectiveness compared to AC, DC, and hybrid motors. Although the stepper motor only allows discrete movements, a step size of at most 15 degrees should allow the entire volume within a shopping cart to be swept. Thus the 28BYJ-48 motor is suitable because its step size is 5.625 degrees. Finally, the stepper motor was also selected for ease of use and implementation, as well as being within noise level requirement R14-II specified in the functional specification.

6.3 Control Hardware

The stepper motor will be controlled by the driver through 4 input pins. Powering any 2 of the pins allows up to 8 different combinations, and thus 8 rotation phases. The driver has 4 input pins and 4 output pins, and the output pins are connected to the stepper motor and the input pins are connected to Arduino.

The driver amplifies the signal from the Arduino so that the supply voltage to the stepper motor is 5-15V. Angular position is determined by counting the number of steps, while stepper speed is controlled by the frequency of the pulses. Figure 7 below shows the stepper motor and driver.

Figure 7: Stepper Motor and Driver [8]

Table 5 summarizes the specifications.

Table 5: BYJ48 Stepper Motor Specification

Rated Voltage	5V DC
Number of Phases	4 or 8
Speed Variation Ratio	1/64
Frequency	100Hz
Friction Torque	600 - 1200 gf.cm
Pull in Torque	300 gf.cm

6.4 Control Software

The control software for the stepper motor consists of 2 main parts: the program on the Arduino micro-controller and the main process on the core system. The program on the Arduino receives instructions from the core system throughout the main process and operates accordingly.

These instructions are transmitted via serial port, and control whether the motor is on or off as well as motor speed. The additional complication of controlling Arduino from the core system rather than simply running Arduino's code constantly, is to have the ability to switch the motor on and off in order to save power. The motor will turn on when the scale senses weights and shut off when scanning is complete.

7 Verification Unit

The verification unit consists of a scale which interfaces with the core system. The primary function of the scale is to measure the total weight of the merchandise and output this to the core system. The core system will compare this weight with the expected weight calculated using the database in order to verify that all of the merchandise has been scanned.

7.1 Verification Hardware

Due to budget constraints, the scale used in the verification unit for the POC device will be the Salter Bracknell PS500 which was graciously lent to us by BC Scale Co Ltd. This scale is battery powered, has a 250 kg capacity with an accuracy within 0.1 kg, and has a standard serial interface which makes it suitable for our POC device [9].

In the final LSG system, more stringent criteria will be used to select the appropriate scale such as LFT and level III classification [9]. Furthermore, in the final system the scale will be built into the floor, making the ramp unnecessary, and have a weighing surface accommodating standard shopping cart size [2] as specified in the functional requirement by RS65-III.

7.2 Other Designs

Another design considered for the verification unit was use of an additional portable antenna which could be used to probe the customers shopping bag or cart in order to ensure that all of the tags had been correctly scanned. But more verification measures would need to be implemented in order to ensure that users or store attendants sufficiently probed the bag or cart in order to retrieve all of the item serial numbers. Furthermore, the process of thoroughly probing the user's shopping cart or bag proved to greatly reduce the checkout speed of the LSG and therefore negatively impacted the overall benefit of the LSG. Thus weighing the items, a method traditionally used in express lanes, made the most sense for its ease of implementation and speed.

8 User Interface Unit

The user interface unit includes a software UI and hardware indicating the status of the checkout process. It also allows users to interact with the backend control system and create a customized checkout process if desired.

8.1 Software Components

The signal processing and output stages seen in the system block diagram in the POC project are integrated into a single C# project. The project was designed following the MVC architectural pattern [10]. Therefore, the software user interface represents the view part of the system as seen in Figure 8 below:

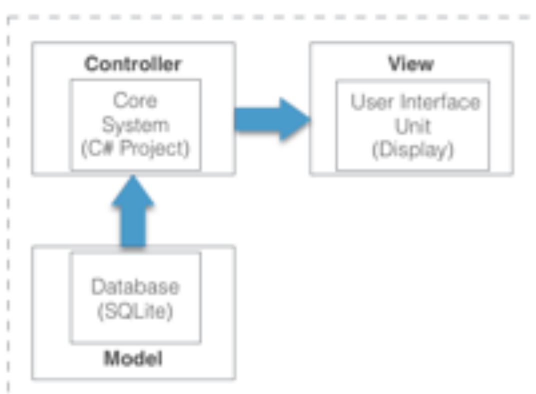

Figure 8: MVC Architecture Implementation

The CRU scans RFID tags and sends the information in message blocks to the core system. The core system then processes the messages and updates the UI after checking the database. The following flowchart describes the logic behind UI updates:

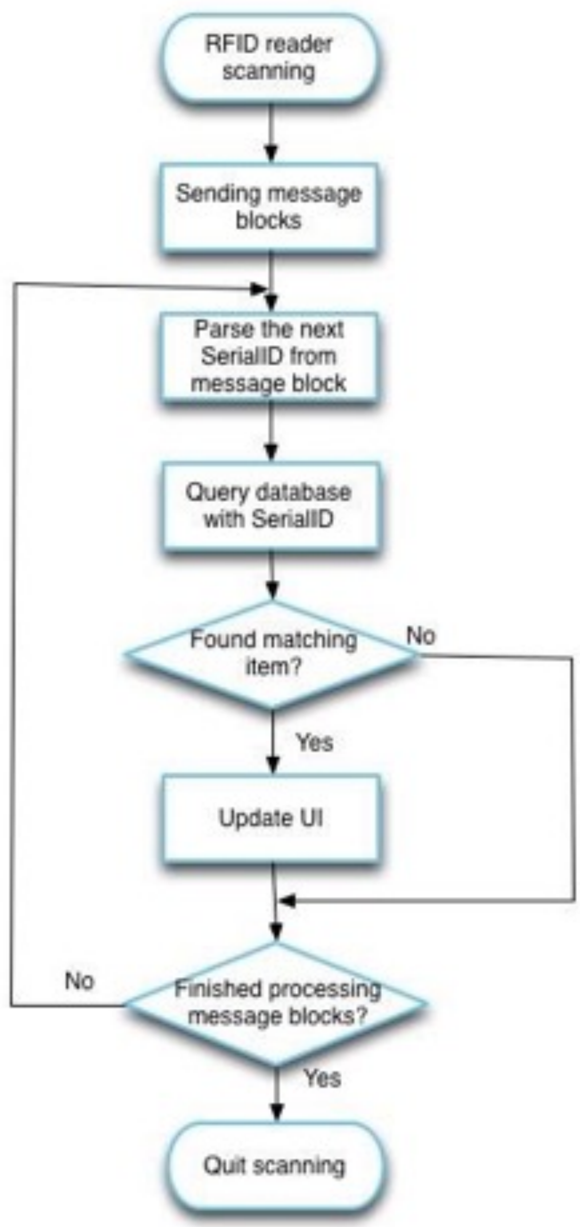

Figure 9: UI Updating Logic Diagram

8.1.1 Display

For the POC device, the user interface software is constructed using the WPF framework. The UI displays a list of scanned items (including their details) and the total price. In the final LSG, the touch screen device will give users the ability to preview item details, remove items from their list, and call for assistance. The sample screen is shown below:

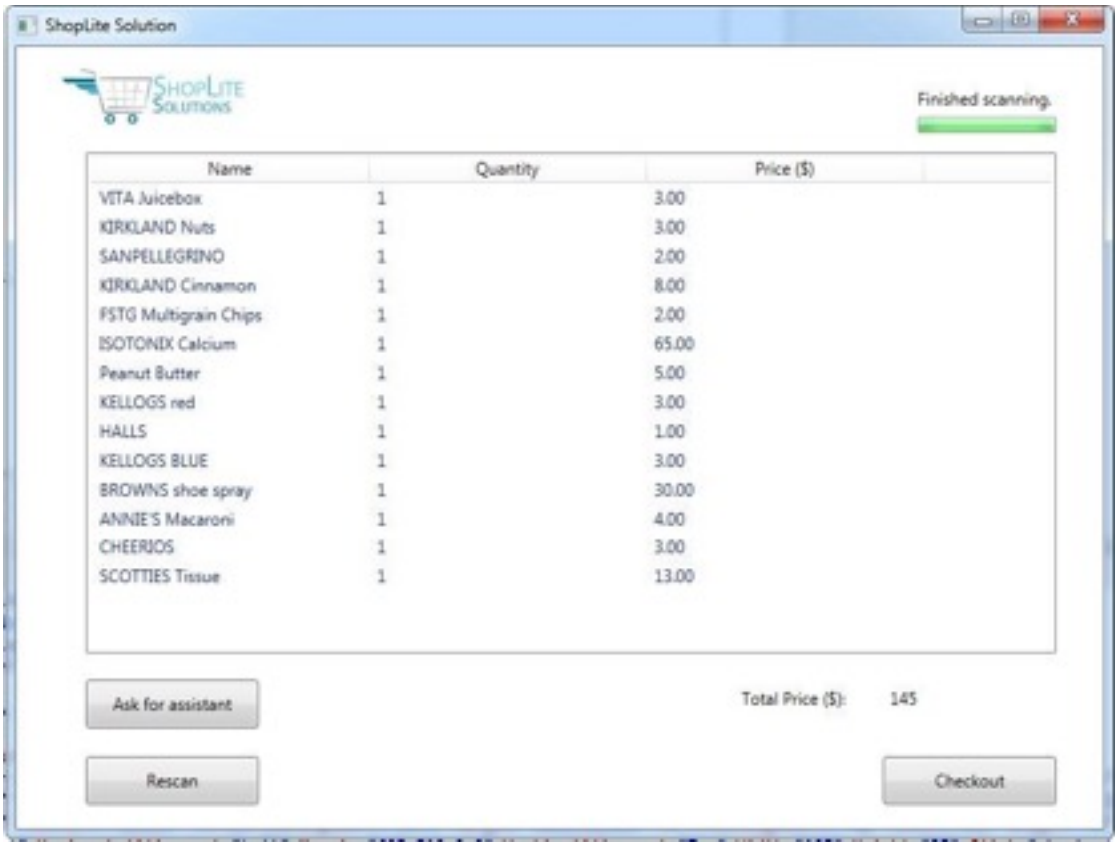

Figure 10: Sample User Interface

8.2 Hardware Components

For the POC, the interface shown above will be displayed on a laptop. The final product's UI consists of a touch screen, a payment device, and coloured LEDs.

The payment device will accommodate cash, credit and debit card purchases, and conform with Payment Card Industry Data Security Standards [11]. LEDs are used to indicate status, and the final system will use an intuitive colour mapping. For example, green will indicate line available, yellow will indicates processing customer, and red will indicates transaction error. In the case of red, a store employee will resolve the problem. All of the devices will be properly synchronized so the checkout experience will be intuitive.

9 System Test Plan

First, individual testing of the different unit systems will be conducted to verify that their respective performances match the requirements laid out in the functional specifications. After unit tests are complete, testing and verification will be done on the entire system by simulating several normal and extreme conditions. This includes the system's response to shoplifting, which is a serious problem for retailers [12].

9.1 Central Reading Unit and Core System Test Plan

The function of the CRU is to wirelessly scan multiple items in a given period of time. To confirm that the CRU is operational, a performance test will be conducted. Different quantities (10 and 25) of passive RFID tags will be placed near the antennas. After the central reading unit is activated, all tags should be detected in less than 10 seconds, which will be verified by checking the serial number of the tags and comparing them with the serial numbers read into the core system.

In addition, integration of the CRU with the core system and verification system will be tested. When a shopping cart is pushed onto the scale, the core system should activate the central reading system and begin a scan.

9.2 Location Control Unit Test Plan

The location control unit increases the accuracy of the whole system by rotating the antennas. The unit consists of four stepper motors, four motor drivers and a micro-controller. To confirm the functionality of the location control unit, the following tests will be performed:

1. A simple software testing framework will test each motor individually for appropriate responses to input from the micro-controller and the driver.

2. Motor torque will be tested by verifying that the two stepper motors can rotate the antenna with respect to the x and y axes (Figure 6).
3. Place the stepper motors into the location control unit, and verify the maximum rotation range by activating the micro-controller and observing the range.
4. Verify that the micro-controller can rotate the two antennas concurrently in a parallel pattern.

9.3 Verification Unit Test Plan

The Verification Unit consists of a scale and ensures the accuracy of the LSG. To confirm the functionality of the verification unit, the following tests will be performed:

1. Put a known weight or several known weights onto the scale and verify the accuracy of the scale.
2. Connect the verification unit to the core system and verify that the value of the weight is received by the core system.

9.4 Database Test Plan

The database stores item information, including weight, price, name, and serial ID. As all items will have tags with unique IDs, the accuracy of the database will be tested by scanning individual items and checking that the correct information is retrieved.

9.5 User Interface Unit Test Plan

The following tests will be conducted to verify the functionality of the user interface unit:

1. Verify that the right information is displayed on the user interface unit. The name and price should be displayed correctly on the interface when the corresponding item has been scanned by the gate.
2. Verify that items cannot be cancelled from the interface except by the system administer.
3. Test that the correct functional abilities are displayed by the interface, and verify that the user can checkout or ask for assistance by clicking the corresponding buttons on the UI.
4. Check that a status indicator properly conveys a completed transaction as well as a failed one.

9.6 Normal Case 1: Light Shopper (10 items or less)

User input: A shopper places a bag on the scale to start the scanning process.

Conditions: The bag contains 10 items.

Expected Results: The central reading unit powers up and initializes the scanning process, the location control unit rotates both of the antennas, and the verification unit outputs the total weight of the items.

The LSG should detects all of the RFID tags attached on the items and also obtains the total weight of the items in less than 10 seconds. There should be an accuracy of 100%. The serial numbers of the tags will be output to the core system, and corresponding item information will be retrieved from the database. The information includes item name, unit price, and total price, which are then displayed on the UI.

9.7 Normal Case 2: Heavy Shopper (25 items or more)

User input: A shopper pushes a cart onto the scale to start the scanning process.

Conditions: The cart contains 25 items.

Expected Result: The central reading unit powers up and initializes the scanning process, the location control unit rotates both of the antennas, and the verification unit outputs the total weight of the items.

The LSG should detects all of the RFID tags attached on the items and also obtains the total weight of the items in less than 10 seconds. There should be an accuracy of 100%. The serial numbers of the tags will be output to the core system, and corresponding item information will be retrieved from the database. The information includes item name, unit price, and total price, which are then displayed on the UI.

9.8 Extreme Case 1: Tag has been removed from an item

User input: A shopper pushes a cart onto the scale to start the scanning process.

Conditions: One item tag has been removed.

Expected Result: The central reading unit powers up and initializes the scanning process, the location control unit rotates both of the antennas, and the verification unit outputs the total weight of the items.

During the scan, the actual weight obtained from the verification unit system will be compared with the total weight calculated from the scanned tags. Though the CRU will miss an item, the scale will have measured its weight. Since the numbers will not match, a message will appear on the user interface indicating that store personnel will be called.

9.9 Extreme Case 2: Shoplifting

User input: A shopper pushes a cart onto the scale to start the scanning process.

Conditions: One of the items is in the shopper's pocket.

Expected Result: The central reading unit powers up and initializes the scanning process, the location control unit rotates both of the antennas, and the verification unit outputs the total weight of the items.

During the scan, the actual weight obtained from the verification unit system will be compared with the total weight calculated from the scanned tags. As the item in the shopper's pocket will be scanned by the central reading unit but not weighed by the verification unit, the weights will not match. Since the numbers will not match, a message will appear on the user interface indicating that store personnel will be called.

10 Conclusion

This document has discussed in detail the proposed design of the proof-of-concept LiteSpeed Gate and each of its subsystems in order to meet the functional specification. Furthermore, considerations involved in the design decisions as well as justification for each of the components chosen is given. During development and implementation, this design specification will be referred to in order to meet the functional specification. Finally, through the test plans outlined, required functionality will be ensured.

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