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Design and Fabrication of a Smart Shopping Cart

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Declaration

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Abstract

Shopping carts are trolleys used by shoppers for transport of merchandise within supermarkets during shopping. Various modifications have been made over the years to improve these shopping carts but the changes have however not been significant. This project focuses on the automation of the shopping cart, modifying it to autonomously follow a shopper while avoiding obstacles and in addition, integrating automated billing with the aim of improving shopper's experience by minimizing their load, especially for the elderly and disabled and minimizing the check out time. The shopping cart entails a tracking subsystem that enables it to track a target in real-time by monitoring ultrasonic signals transmitted by a tracker carried by the shopper. Using the propagation time of the ultrasonic signals, the distance and direction the shopper is with respect to the cart is determined thus enabling the cart to adjust its movement accordingly to follow the shoppers trail. A system of strategically positioned proximity sensors is also included to detect any obstructions within a specific pre-set range from the cart so as to avoid collisions. The shopping cart also entails a billing subsystem which uses radio frequency identification based billing to enable faster tallying of cost of purchased products with minimal human input thus enabling shorter check-out time for the shoppers. The smart shopping cart has been tested and data sets collected to evaluate its performance. It is capable of monitoring the shoppers movements within a range of 4 metres and maintain the same distance or less while carrying a load of up to 4 kg. It is also capable of tallying the cost of items purchased and relaying the data to a computer wirelessly.

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1 Introduction

This chapter contains a brief background on how shopping is currently done, highlights some of the problems encountered during shopping and indicates the objectives illustrating how the project aims to solve these problems. It also indicates the scope within which the project will be undertaken and includes a justification as to why it is necessary to undertake this project.

1.1 Background

Shopping centres are places where individuals physically purchase their everyday necessities. Supermarkets and retail stores usually employ various strategies and methods to ensure a good overall customer experience for their shoppers so as attract and maintain their business. One of the simplest and oldest methods has been the provision of shopping carts to their customers with an aim of helping them store and carry the items which they expect to buy. It consists of only two main parts: a metallic basket and a set of wheels. The basket has a handle attached to it which helps in steering the cart, and it is installed above a set of four small wheels that make pushing, pulling and steering the cart very convenient. It is a simple device, but it is of tremendous assistance to shoppers, enabling them to easily roam throughout the shopping centre as they look for items they wish to purchase, place the items in their carts and thereafter ferry them to the check-out counters for billing and payment. Using shopping carts, shoppers can move a large number of products which they would otherwise not have been capable of carrying.

Though a lot is being done to enhance shoppers overall experience, there is still room for improvement. With regards to the shopping carts, as shoppers add more items into them during shopping, the carts become increasingly difficult to steer as they tends to drift and a larger amount of force is required to move them in the desired direction. This presents a challenge to the shoppers, especially those who are elderly or physically disabled.

Moreover, not all items in a supermarket have their prices indicated or up-to-date. Shoppers normally have to inquire from a shop attendant or alternatively, are surprised during billing when they realize that an item they purchased does not retail at the price indicated in the case of a price update. Most shoppers will also worry that the amount of money brought may not be sufficient to pay for all the items they wish to purchase. They either have to tally the cost themselves prior to checking out or wait until their items are billed at the counter, in which case, if the money carried is not sufficient, will have to return some items, which can be embarrassing to the customer and time-consuming as the cashier deducts the items from the purchase list and the shop attendant returns the items to their respective aisles. In addition, for shoppers to have their items billed prior to payment, cashiers normally utilize bar-code scanners, whereby they scan the bar-code of every single item intended for purchase to determine each customers bill. This is a troublesome and time-consuming process that results in long queues and crowding at the counters. Consequently, many customers tend to abandon their purchases and walk out of the store when faced with such long lines that appear stagnant, resulting to reduced business for the supermarket or retail store [1].

Summarily, there are a lot of areas that need improvement so as to enable supermarkets and large retail stores to offer better services to their clientele.

1.2 Problem statement

In many large shopping centres, a shopping cart is provided for use by customers for transport of their purchased merchandise within the shop. Currently, shopping carts rely on human power for movement. This proves to be a burden to the shoppers where heavy loads are involved, especially for the elderly and the physically disabled. Moreover, the billing process during customer check-out, is a cumbersome and time-consuming process for both the cashier as well as the shoppers and results in the formation of long queues and overcrowding. There is therefore a need to come up with a more convenient and time efficient solution to reduce the load pushed by the shopper as well as minimize the billing time.

1.3 Objectives

The main objective of the project is to design and implement a smart shopping cart that can follow a shopper as well as enable automated billing during shopping.
To realise the main objective, the following specific objectives are defined:

1. To modify the mechanical design of an existing shopping cart to enable electrical actuation.
2. To design and fabricate the electrical circuit that will enable the operation of the smart shopping cart.
3. To design the control algorithm for the smart shopping cart.
4. To test and optimize manoeuvrability of the cart while tracking an individual.
5. To test and optimize the ability of the cart to detect items input into it, tally the cost and relay the information to both the shopper and a remote computer.

1.4 Scope

This project is focused on the implementation of an autonomous shopping cart that will be used in a shopping environment. The cart's design should enable it to track a shopper as he/she manoeuvres through aisles of a supermarket while avoiding any obstacles that may occur. In addition to following the shoppers, the cart will be capable of attaining a record of the items purchased by a shopper and communicating the total running cost to both the shopper and an external device (computer). Considering the given budget, the shopping cart will be designed to have a total loaded mass of about 10 kg, considering the price of motors with speeds and torque ratings sufficient enough to propel a larger weight.

1.5 Justification

Shopping in supermarkets is a common activity for many people. However these shoppers are subjected to poor shopping conditions, be it queueing for long periods of time due to the high numbers of shoppers or pushing heavy carts through the vast supermarkets. These experiences tend to be a nuisance to shoppers and may discourage some from visiting supermarkets. The smart shopping cart aims to enhance the shoppers shopping experience by significantly minimizing the shoppers check out time as well as minimizing labour required to push the purchased goods. It will ultimately lead to the supermarket environment becoming more friendly to their customers and the experience more pleasant.

2 Literature Review

2.1 Background history

The shopping cart or trolley (British English), was first introduced in 1937, by Sylvan Goldman, the owner of the Humpty Dumpty supermarket chain in Oklahoma, United States of America (USA). It was designed as an alternative to carrying shopping baskets and it entailed a metal frame that held two wire baskets[1].

Over the years,the shopping cart has undergone various modifications but the changes however have not been significant. Majority of the supermarkets and retail stores still use the same general design currently, though these designs have their shortcomings, that is the labour required to push them as well as the time-consuming billing process. There has however been a significant amount of research that has been done with the aim of solving the above mentioned shortcomings, some of which have resulted to great progress. These are discussed in this section.

2.2 Existing shopping cart designs

2.2.1 Traditional shopping cart

This entails the normal carts currently used in majority of the supermarkets today. They are either carried by hand or pushed as trolleys.They present a limitation to users who have disabilities or have their hands occupied. In case of a heavy load, they force the shopper to struggle to either carry or push the cart throughout the period they shop.These shopping cart designs are shown in figure 2.1.

2.2.2 Nakumatt motorized cart

Nakumatt Supermarket, introduced the use of motorized shopping carts in some of its major branches in Kenya. These shopping carts provided the physically disabled cus-

Figure 2.1: Traditional shopping cart

tomers with a disability-friendly environment and enhanced their shopping experience by promoting their mobility through the supermarket. The motorized cart comprised of a large shopping basket and a sit for the customer. It was powered by an electric motor and controlled by a steering wheel [2]. Figure 2.2 shows the motorized shopping cart.

The cart's design was however limited to those who had leg-related disabilities and forced an individual to switch from their wheel chair into the carts seat. It therefore could not cater for all individuals due to ergonomic issues.

Figure 2.2: Motorized shopping cart

2.3 Human following robots

Tracking applications have become increasingly popular ever since the concept of wireless sensor networks (WSN) was introduced. Today, various techniques and technologies have been implemented to enable mobile tracking. The selection requirement of tracking systems however varies significantly based on various factors such as the accuracy required, indoor/outdoor environment, positioning techniques, range required, implementation cost etcetera [3]. For human tracking, the techniques implemented consider the subject being tracked as mobile. The most common techniques and technologies that have been implemented for the purpose of human tracking are:

1. Computer vision
2. Received signal strength based tracking.
3. Tracking based on the propagation time of a signal.

2.3.1 Computer vision based human tracking robots

Computer vision (CV) refers to a scientific field concerned with automatic extraction, analysis and understanding of useful information from a single image or a sequence of images so as to determine the operation of a machine [4]. It has numerous applications such as shape recognition, facial recognition and gesture analysis. It entails a sequence of processes, that is; image acquisition, pre-processing and feature extraction.
The image is perceived in either 2D or 3D using a vision sensor such as a light-sensitive camera, infra-red cameras or ultra-sonic cameras. It is then processed to assure that the relevant information can be detected while minimizing false information. Analysis through an algorithm is done so as to detect specific features such as colour, edges, contours, Haar cascade (a flat extensible mark-up language database that contains all the relations of a specific object) etcetera [5]. This occurs at various levels of complexity based on the system of sensors used as well as the processing unit.

Computer vision based human tracking robots have been illustrated in numerous research projects undertaken in universities. An example is in a research project undertaken in the University of Malaysia of a nurse following robot [6]. It involved the use of a 3D motion sensor (kinect sensor), which is a device that can capture motions in 3D and has a software development kit (SDK) that enables it to process colour, depth, and skeletal data. The robot was able to create a skeleton frame of the human. It would follow when the person stood in front of the Kinect sensor for a few seconds with both hands in the air. It then maintained a distance of 1 metre from the individual. This is illustrated in the figure 2.3.

2.3.2 Range signal strength indicator (RSSI) based human following robots

This is a tracking method that is based on the use of radio-frequency identification (RFID) which is a technology that exchanges data through radio waves between a reader and an electronic tag which is used for identification and tracking [7]. The RFID systems are usually comprised of two main components: an RFID reader with antennas, and RFID tags. The tags are either passive or active whereby, active tags are connected to a power source whereas passive tags are not. In this case, their power is supplied by the reader. When the tags encounter radio waves emitted from the reader, they get power to energize their circuits. The tags are then able to send their encoded data to the reader. For the

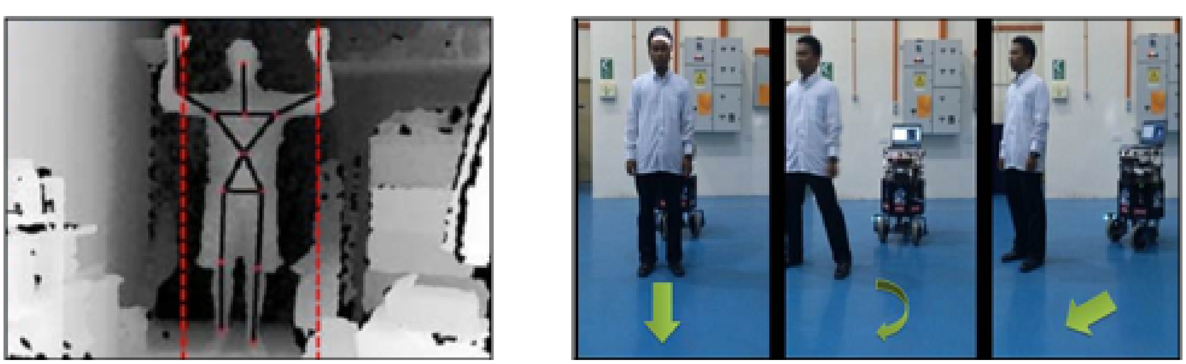

Figure 2.3: Skeletal identification and directional tracking

purposes of tracking, the received signal strength (RSS) of each detected tag is measured in decibels-metre (dBm), which is the logarithmic expression of received power.

Kim, Myungsik et al. [3] proposed a new target tracking and following system using the direction-finding RFID reader featuring a dual-directional antenna. The dual-directional antenna determined the distance of the target from the strength of the RF signals received and the direction of arrival (DOA) of transmitted RF signals based on the ratio of the received signal strengths at two adjacent spiral antennas. This enabled the reader to estimate the direction of the target in real time. With estimated DOA values obtained from the RFID reader, the robot was able to keep track of the transponder and follow it. It was however observed that the ratio was easily deteriorated by environment factors, such as obstacles in the environment, causing it to rapidly fluctuate. The ratio therefore did not consistently give accurate direction. The proposed design is shown in figure 2.4.

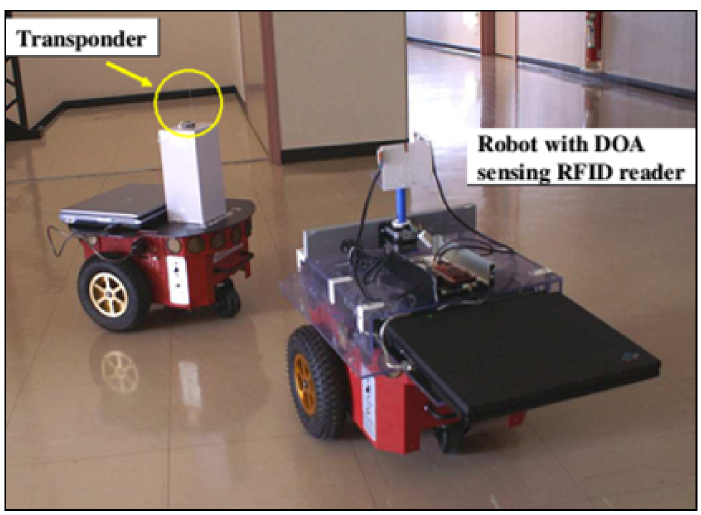

Figure 2.4: RSSI based target tracking robot

2.3.3 Tracking based on the propagation time of a signal

These are based on two main techniques, that is; the time of arrival (TOA) of a signal and time difference of arrival (TDOA) of a signal. TOA involves measuring the arrival time of a signal propagated from a transmitter to a receiver. TDOA of a signal is an improved version of TOA and it involves measurement of the time taken by a signal from the particular signal transmitter to propagate towards multiple receivers. The time difference of arrival between the different transmitters is used to determine direction [8]. Amir Haziful [9] developed an automatic trolley human follower which employed TDOA technique to determine the direction and the distance of a shopper. The robot included a number of ultrasonic receivers placed on the cart and required the user to carry a device that transmitted an ultrasonic signal. The time difference taken for the receivers to receive the transmitters signal enabled the unit to determine the distance. The direction of the individual was then determined based on which ultrasonic receiver received the ping first. The design of the trolley however required the shopper to consistently trigger the ultrasonic transmitters to emit the signal that enabled tracking which would inconvenience shoppers. Figure 2.5 shows the automatic trolley human follower.

A team in Shanghai also built a luggage hauler robot, known as the Cowa Robot, that

Figure 2.5: Automatic trolley human follower

works through the use of sonar sensors to aid the robot to weave through congested concourses and avoid other obstacles as it sticks by the owner's side. The owner wears a bracelet, which when activated, acts as a homing beacon that keeps the suitcase at arms length using the same TDOA technique. If the luggage lags behind, it notifies the user through vibration of the bracelet, so that he/she can go back to retrieve it [10]. Though efficient in person tracking, the Cowa Robot is quite expensive, costing up to KShs 50,000 due to the technology integrated into it. Figure 2.6 shows the Cowa Robot.

2.4 Conventional billing

This is the most widely used billing method in supermarkets. It involves cashiers at a counter using a bar-code scanner to check the price of each item so as to determine the shoppers total bill. The scanner has to be passed over the bar code on each item, thus the process consumes a lot of time especially when dealing with numerous shoppers. Moreover, the position of the bar code may not be easily located and this may further delay the billing process. As a result, shoppers have to queue for long periods of time especially when their numbers are high. Figure 2.7 shows the use of the bar-code scanner.

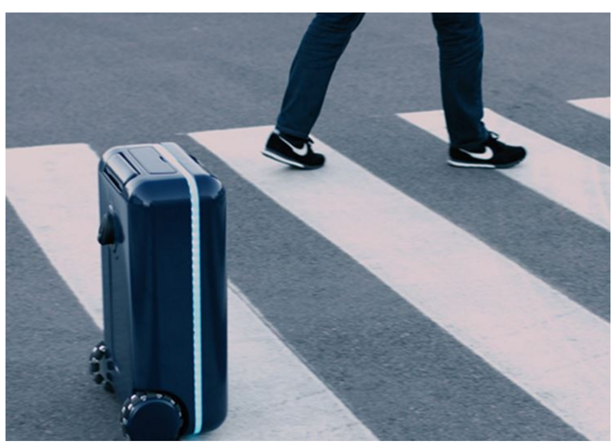

Figure 2.6: Robotic luggage hauler

Figure 2.7: Conventional billing

2.4.1 Panasonic checkout system

Panasonic partnered with a convenience store franchise chain in Japan called the Lawson where they tested and implemented a smart shopping basket system that replaced cashiers. The system detects items in the basket, calculates the bill and automatically bags the merchandise. It uses a unique shopping basket that customers place on an automatic self-registration machine when they are ready to checkout. After the basket is placed in a slot, the bottom slides out and items drop into a bag. The customer is only left with the task of paying for their order. Since the store does not need cashiers to scan the product or pack the bag at the cash register, it has led to reduced labour in the store operations. The unit is however quite expensive [11]. Figure 2.8 shows the Panasonic automated checkout machine.

2.4.2 Amazon Go

The company Amazon unveiled a grocery store without lines or checkout counters. The store, which is located in Seattle, allows shoppers to just grab the items they want and leave; and the order gets charged to their Amazon account afterwards. Once a shopper enters the store, he/she is first required to scan a QR code using their phone, and there after the individual is free to pick the items he/she wishes to purchase. Through the

Figure 2.8: Panasonic's automated checkout system

use of computer vision, machine learning and deep learning to monitor what the shopper purchases. The individual's account is then charged as they walk out the door and a digital receipt is sent to them [12]. The system therefore does not require cashiers as the shoppers serve themselves and leave without queueing. Though revolutionary and futuristic, such a shopping system is quite complex and expensive to implement.

2.4.3 Radio frequency identification based shopping cart

In the research paper RFID Based Automatic Shopping Cart, J. N. Swamy et al [13] proposed the concept of using of Radio-frequency identification (RFID) readers to read and capture information stored on RFID tags attached to products in a shopping centre. The shopping trolley is equipped with an RFID reader on the back panel, such that, after selecting a product, and dropping the product into trolley, the RFID reader reads the tag without requirement of line of sight communication. Figure 2.9 shows the RFID based billing shopping cart.

Figure 2.9: RFID Based billing on shopping cart

2.5 Gap analysis

Majority of the shopping carts currently in use are the normal push carts. These carts present a challenge to the elderly as well as the physically disabled shoppers as they are forced to struggle to push the load throughout the supermarket corridors if they lack a helper, thus denying them a friendly shopping environment. Numerous solutions related to this problem have been proposed, however majority have not been implemented in large scale. This is due to the high price of the proposed solutions or the lack of the proposed solutions' efficiency. Much of these methods proposed are relatively new and require significant amount of research to be done so as to be improved before implementation. It is also important to note that none of the encountered solutions minimized both the shopper's load as well as saved time during check-out simultaneously. There is therefore a niche to implement a solution to solve both challenges.

3 Methodology

This chapter entails a detailed description of the realization of the proposed smart shopping cart. It consists of the factors considered while determining the design and the implementation of the design proposed.

3.1 Design overview

As discussed in the gap analysis in section 2.5, the smart shopping cart should be capable of automatically following a shopper while avoiding obstacles as well as enable automatic billing of purchased items. To achieve this, the design was comprised of three main modules, that is; the mechanical module, the electrical module and the control module.

Each of the modules was further broken down to realize a section of the key functions of the shopping cart, that is the cart's mobility, tracking of the shopper and billing of items intended for purchase. A summarized view of what each of the module consists of is shown in figure 4.12.

3.2 The mechanical module

This entails the general structure of the shopping cart, which comprises of the shopping basket used by the shoppers to carry items, the supporting chassis, wheels and assembly. It also consists of the tracker, a unit that would be carried by the shopper to enable the shopping cart to track his/her movements.

3.2.1 Cart structure

In the design of the general shopping cart's structure, the following were the main factors considered;

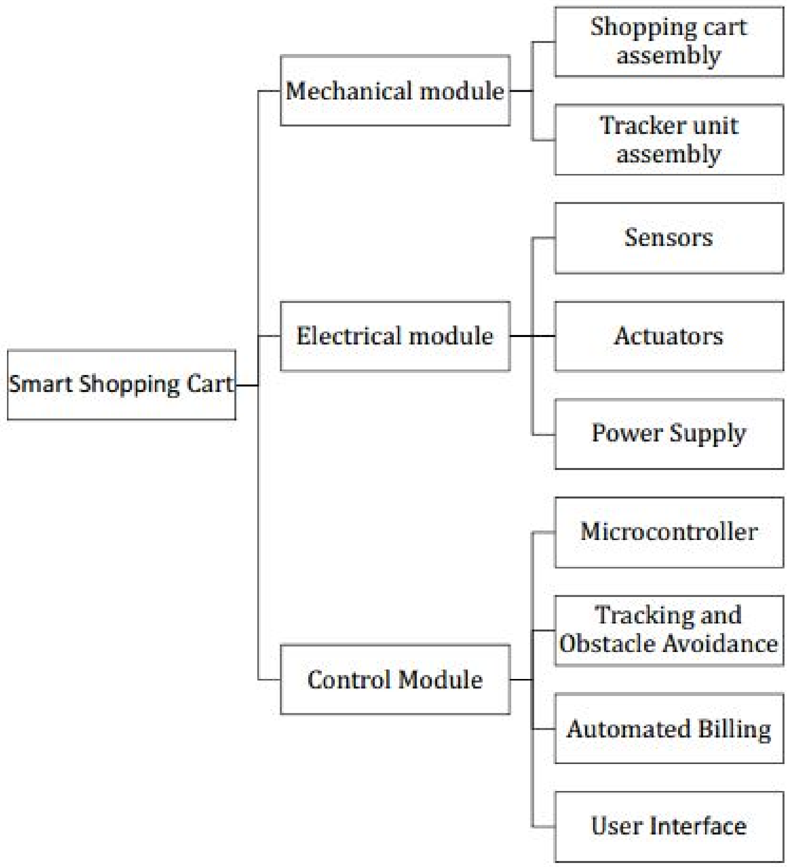

Figure 3.1: Smart Shopping Cart Modular Breakdown

1. **Weight.** The cart was required to be as light as possible, so as to maintain the torque demand required to propel it forward at a minimum. A light cart would minimize the cart's power demand as well as simplify the process of attaining motors that match the cart's requirements.

2. **Structural integrity.** The cart's structure was required to be sturdy enough to support its own weight as well as the load of the purchased goods without failing.

3. **Aesthetics.** The cart was required to be appealing to the users.

4. **Cost.** The price of fabricating or acquisition of the cart was to be affordable enough such that the project would be maintained within budget.

Based on the factors above, two approaches were considered and compared, that is modification of an existing shopping cart or fabrication of a cart. This comparison is illustrated in table 3.1.

Since the existing carts have been in use for many years, their design has been significantly optimized over time and they meet most of the design considerations. To avoid the high cost of purchasing a cart to be modified, a second-hand cart was selected costing KShs 1000, which was relatively lower than the cost of fabricating one. The smallest variation was chosen so as to ensure the general cart structure remained as light as possible.

3.2.2 Steering mechanism

The steering mechanism refers to the mechanism that was used to enable the cart to change direction as it follows a shopper and avoids obstacles. In selection of the type of steering mechanism to be used, the following factors were put into consideration;

1. Steering accuracy: This refers to the measure of manoeuvrability that could be

Table 3.1: Shopping Cart design considerations and comparison

Design Options	**Modifying existing cart**	**Fabricating a cart**
Weight	7 Kgs - 15 Kgs	Varies based on materials used in the design as well as the size of the cart
Structural Integrity	High, as they have been improved over years of use	Varies based on the design
Aesthetics	Highly attractive	Varies based on the design
Cost	A second-hand cart is relatively cheap (Kshs 1000)	Varies based on the design and material to be used. Would cost more than Kshs 1000

achieved by the steering system. Considering the narrow arrangement of supermarket aisles, the cart was required to be capable of making sharp turns.

2. Durability: A steering mechanism with minimal moving parts and maintenance requirements was considered ideal.

3. Complexity: This refers to the ease of implementation of the system. A simple mechanical structure and control system for steering was considered ideal.

Based on the described factors, two steering methods were considered and compared, that is differential steering and servo-based steering.
Differential steering involves the use of two motors whose control is independent of each other, and free-moving wheels (caster wheels). If both wheels turn in tandem, the cart would move in a straight line, and by rotating the motors at different speeds, the cart would change direction towards the slower-moving wheel. Servo-based steering on the other hand, would involve the use of a single motor for propelling the cart forward, and two servo-motors at the front wheels to enable change in direction. The comparison of these two systems is shown in table 3.2.

Based on these considerations, the mode of steering selected was differential steering, as it enabled easy to control, is accurate, durable yet relatively simple to implement.

Table 3.2: Steering system consideration and comparison

Design Options	**Differential steering**	**Servo-based steering**
Steering accuracy	Accurate, can make sharper turns	Slightly more difficult to manoeuvre
Durability	High, as its simple with less parts	Many parts, most of which are moving
Controllability	Simple to control	More difficult to control, requires complex mechanical design for controllability

3.2.3 Mechanical assembly of the shopping cart

Modification of the cart's mechanical structure was done so as to enable the cart's movement to be achieved through electrical actuation. It entailed the removal of the rear caster wheels so as to replace them with motor-actuated wheels. An angle bar was welded across where the caster wheels were initially mounted so as to provide housing for the motors to be used for actuation. The design of the motor housing was determined based on the dimensions of the motors to be used. The motors were then secured to the housing using brackets bolted onto the housing The figure 3.2 illustrates the design of the motor housing.

Considering the environment the shopping cart would operate in (a smooth cemented or tiled surface), trolley rubber wheels were selected as they would provide sufficient traction with the ground. To allow sufficient clearance from the ground, the selected wheels had a diameter 150 mm leaving a 50 mm clearance between the motor's housing and the ground. The wheels were then directly coupled to the motors' shafts to ensure efficient

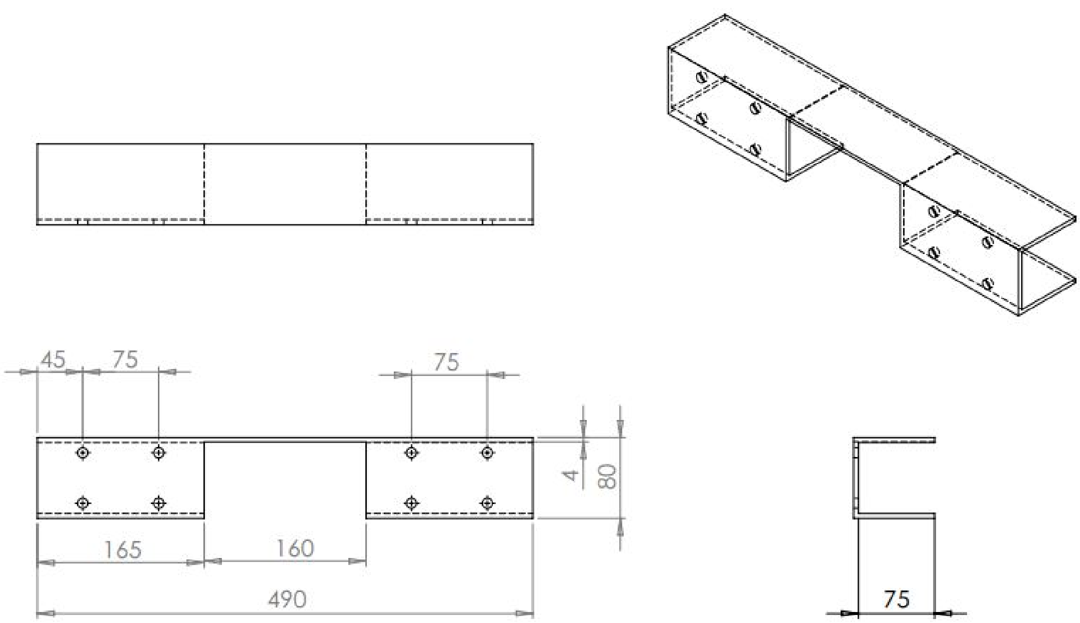

Figure 3.2: Motor housing design

power transmission. Since the wheels acquired were designed for trolleys, they had ball bearings where a shaft would normally be mounted as shown in figure 3.3, which would compromise on the actuation of the wheels by the motor. The ball bearings were therefore welded to wheels' rims so as to permanently fix their movement to that of the wheels.

To couple the wheels to the motors' shafts, motor hubs were specifically designed for the selected motors and wheels for 3D printing. The hubs' dimensions were therefore based on the dimensions of motors' shafts and the internal diameter of the wheels to be used. The motor hubs had a subtle taper so as to enable force-fitting on a small section thus ensuring a secure fit. A threaded hole was also added to enable the wheels to be further secured on to the hub using a bolt and washer. Another threaded hole was added to be used when mounting the motors' shafts, such that a screw would be used to firmly secure it to the hub, thus minimizing any play as the shaft rotates the wheels. The figure 3.4 illustrates the design and dimensions of the motor hubs.

3.2.4 Tracker unit mechanical design

This is the unit that would be carried by a shopper to enable the shopping cart to track his/her movements. It comprised of a 3D printed casing for housing of components used to enable tracking. The components included an Xbee radio module, an ultrasonic

Figure 3.3: Trolley wheels

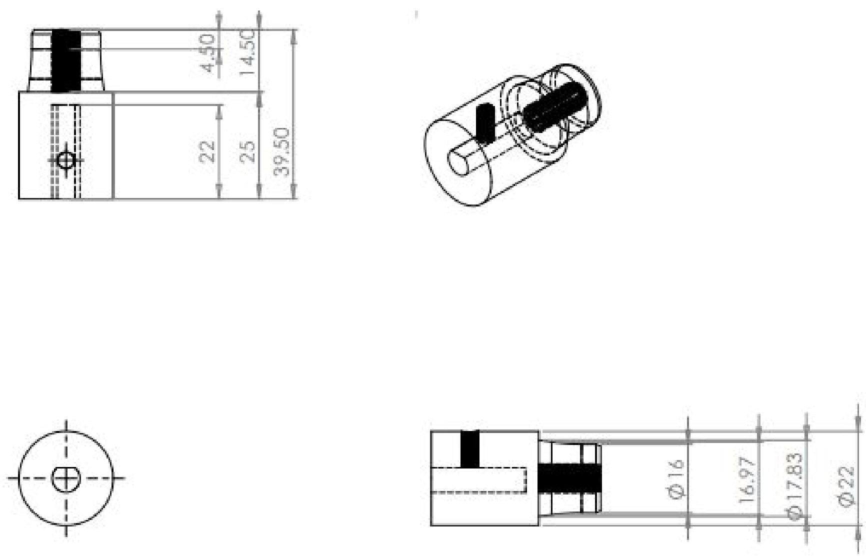

Figure 3.4: Motor hub design

transmitter, a 9V battery and a circuit board. The selection criteria of these components is discussed later in this chapter.

The main factor that influenced the selection of the design of the tracker's housing was the dimensions of the aforementioned components with the aim of keeping it as small and portable as possible while maintaining its aesthetic appeal. The design was also required to be easy to disassemble and assemble so as to allow for easy placement of components. It therefore included internally threaded columns to allow the use of screws for the assembly of the various parts it was composed of. These parts included the main housing, the upper rear cover that covered the components and the lower rear cover that covered the battery. Slots were also included to be used for the placement of the ultrasonic transmission cap, status LEDs and an on/off slider switch. Figures 3.5, 3.6 and 3.7 illustrate the various part designs that make up the tracker assembly and figure 3.8 illustrates the tracker assembly.

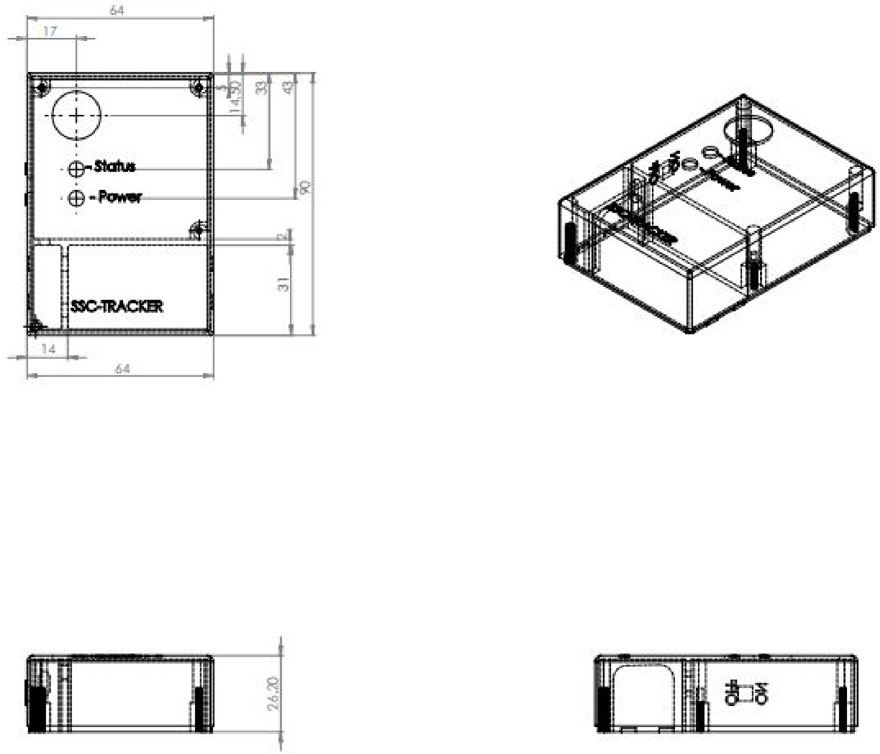

Figure 3.5: Main housing

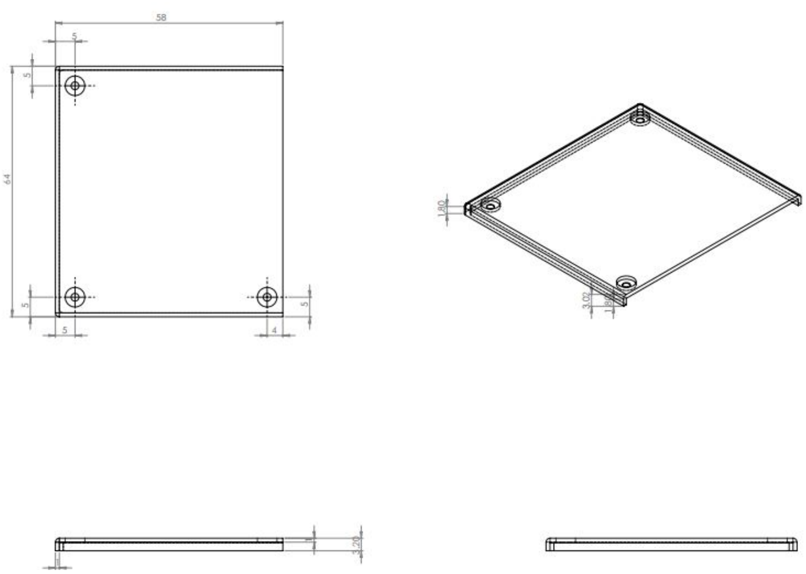

Figure 3.6: Rear upper cover

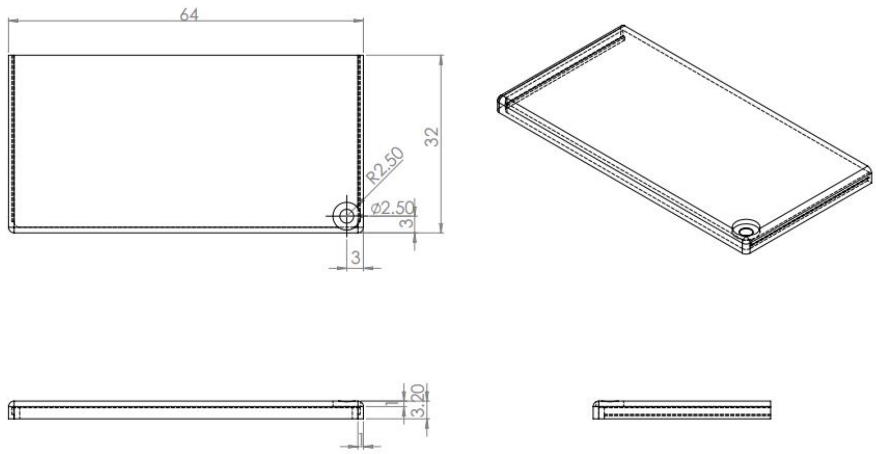

Figure 3.7: Battery cover

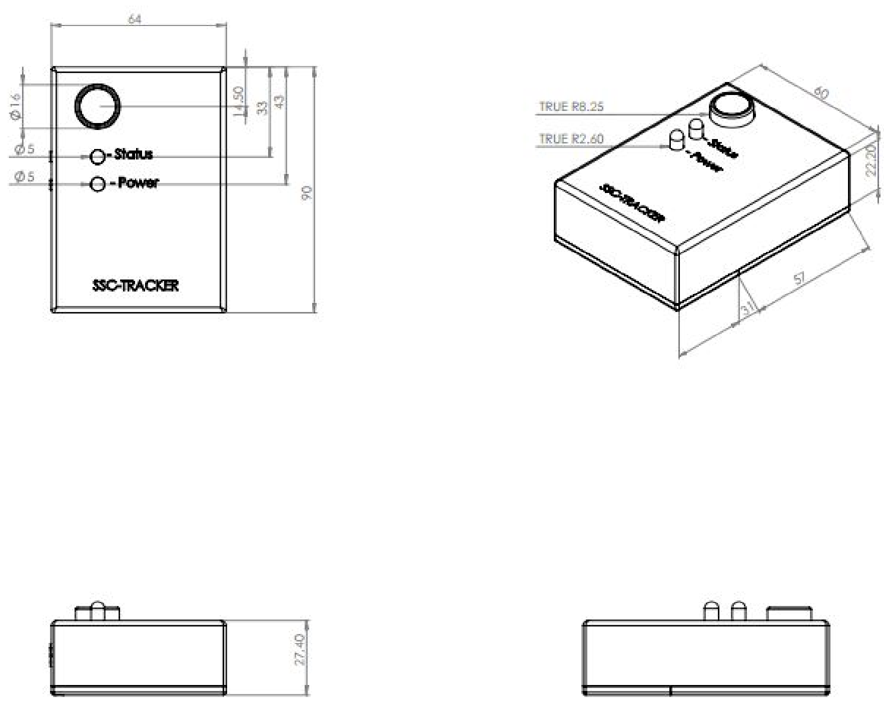

Figure 3.8: Tracker unit assembly

3.3 The electrical module

This module entailed the selection and implementation of the appropriate sensors and actuators for the various functions the smart shopping cart was to execute, the user interface and the power supply unit.

3.3.1 Person tracking sub-system

This refers to the means through which the smart shopping cart determined the position of the shopper relative to its position. This entailed the detection of distance between the shopper and the shopping cart as well as the direction the shopper was relative to the cart. The following factors were considered in selecting the technique used for person tracking:

1. **Accuracy:** The sensor or method used was to be capable of determining the true position of the shopper, relative to the cart.

2. **Range:** The sensor was to be capable of accurately tracking the shopper within a range of at least 3 metres.

3. **Invasiveness:** This refers to whether the shopper was required to wear a tag or carry a device so as to enable tracking. The technique used ideally should not have required the use of such devices to improve convenience to the shopper.

4. **Processing time:** The method used was required to enable fast analysis of data from the sensors so as to generate relevant output signals for actuation.

5. **Price:** The method used was to be within budget.

The techniques discussed in section 2.3 (computer vision, RSSI of a radio signal and propagation time of a signal) were considered and compared. Table 3.3 illustrates the results of the comparison.

Based on the considered factors, an RGB-D camera (camera capable of perceiving depth) would have been ideal as it would enable highly accurate, non-invasive tracking and would be capable of differentiating between different individuals. Such a camera was however

Table 3.3: Person tracking considerations

Design Considerations	**RFID, with active tags**	**Camera**	**Propagation time of a signal**
Accuracy	Accuracy is highly dependent on control algorithm	Highly accurate	Accurate
Range	High, upto 50m	High, but limited to cameras with depth sensor	Approximately 3m - 6m
Invasiveness	Need to wear tag/device	No need to wear a tag/device	Need to wear tag/device
Processing time	Depends on the of tag	Relatively slow	Fast
Cost	Kshs. 3,000 - Kshs. 6,000	Kshs. 8,000 - Kshs. 16,000	Kshs. 3,000 - Kshs. 4,000
Complexity of control	High	Based on camera	Relatively simple

well beyond the set budget, with the cheapest, the kinect sensor, costing KShs 16,000. The technique selected was therefore the propagation time of a signal. This entailed the use of ultrasonic sensors which operate based on the principle of TDOA to determine distance and direction of the target, as discussed in section 2.3.3.

The tracking system thus entailed ultrasonic receivers mounted on the cart and a tracking unit comprising of an ultrasonic transmitter, to be carried by the shopper. When the transmitter sends out ultrasonic ping signals, the time taken for the receivers to detect the signals enabled the controller to determine the distance between the shopper and the cart.

The time difference of arrival of the ultrasonic ping signal between the two receivers was also used to determine the direction the shopper with respect to the cart.

$$\Delta t = t_r - t_l. \tag{3.1}$$

Whereby;

- t_r was the transmission time for the right ultrasonic receiver,
- t_l was the transmission time for the left ultrasonic receiver,
- Δt was a measure of direction, such that if $\Delta t = 0$, the shopper was exactly ahead of the cart, if $\Delta t > 0$, then the shopper was towards the left of the cart and if $\Delta t < 0$, the shopper was towards the right of the cart.

As the transmitter and the receivers were independent of each other, for time of transmission to be comparable to the times the signals are received, a wireless means of synchronising the operation of the ultrasonic devices was deemed necessary. A pair of Xbee series 1 radio modules was selected to be the wireless means of initiating a synchronised transmission of the ultrasonic pings as they had a significantly high speed of communication between each other thus little delay. One was configured as a transmitter and the other as a receiver so as to synchronise the ultrasonic devices' operation. The Xbee wireless transmitter sent a request packet to the Xbee receiver. Once the request was received, the Xbee receiver on the tracker subsequently triggered the ultrasonic transmitter to send an ultrasonic ping. The time of transmission of the ultrasonic signal was therefore determined as follows;

$$Transmission\ time = Xbee\ transmission\ time\ + Xbee\ delay\ time\ .$$

However as the Xbee modules utilize RF for communication, the delay is negligible as RF transmission is significantly faster than ultrasonic waves.

The ultrasonic sensors used were the HCR-SRO4 sensors as they were affordable and had a great range. As the HCR-SRO4 sensors entail both a transmitter and receiver on one unit, the transmitters were removed, that is, for the ones to be placed on the cart, and the receiver removed from the sensor that was to be carried by the shopper. The HCR-SRO4 ultrasonic sensor and Xbee module are shown in figure 3.9. The placement of the two receivers was at the front of the cart, because the shopper led the cart from the front, and the cart was be programmed to always orient itself to face the shopper. The receiving sensors were positioned as far apart from each other as possible so as to increase resolution in detection of direction as well as increase the field of view within which the cart was capable of detecting the shopper. The figure 3.10 shows the position of the ultrasonic receivers on the cart.

Figure 3.9: Ultrasonic sensor and Xbee wireless module

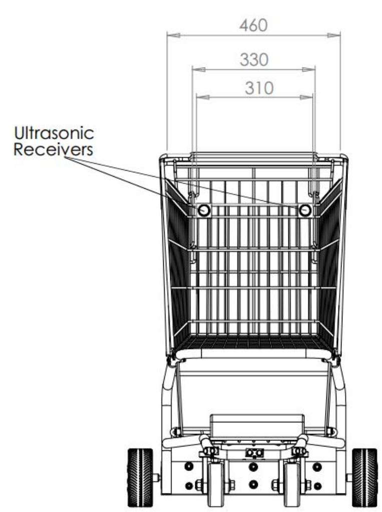

Figure 3.10: Ultrasonic receiver placement positions

3.3.2 Obstacle avoidance sub-system

This consists of the sensors that enabled the smart shopping cart to avoid obstacles or collisions with people, other carts and objects in its path. For the selection of the sensors to be used, the following consideration factors were made:

1. **Accuracy and precision:** The sensors were required to give true and consistent readings of the distance between the cart and any obstacles.
2. **Range:** The sensors were to be capable of detecting obstacles within a 0.5 m range.
3. **Interference:** The sensors' operation was required not to be influenced by the tracker transmission.
4. **Cost:** The sensors should be within budget.

The sensors which were considered were the ultrasonic sensor and infrared sensors. The table 3.4 illustrates the comparison of the two.

Due to its accuracy and affordability with respect to range, the use of ultrasonic sensors was again selected. This would have ideally entailed the use of five ultrasonic sensors, strategically positioned to detect and avoid collision with obstacles in the direction of motion of the cart. The placement was therefore selected as follows;

Table 3.4: Obstacle avoidance considerations

Design Considerations	**Ultrasonic Sensor**	**Infra-red Sensor**
Accuracy and precision	Highly accurate	Accurate
Range	High (0.02m - 6m)	Relatively lower (up to 2m)
Interference	Accuracy reduces for sound absorbent material	Effect of interference is low. Affected by strong lighting
Cost	Cheap	More expensive as range increases

- 1 sensor at the front to detect obstacles in front of the shopping cart.
- 2 sensors at opposite ends at the front of the shopping cart, each at 45^0. These will be responsible for the detection of obstacles as the cart turns while moving forward.
- 2 sensors on the sides towards the rear end of the cart to avoid obstacles as the cart makes sharp turns.

This is illustrated in the figure 3.11. The sensors would be positioned at a low position so as to enable detection of low lying obstacles.
The use of ultrasonic sensors for both tracking and obstacle avoidance would have however presented a challenge as the ultrasonic transmitter responsible for tracking would interfere with the operation of the ultrasonic sensors responsible for obstacle detection. As a result, the obstacle avoidance sensors positioned at the front entailed the use of infra-red sensors, which cost slightly higher, but cannot be affected by the ultrasonic transmitter used for tracking. The obstacle detection sensors on the sides were however ultrasonic sensors since from their position there was no interference from the the tracking ultrasonic transmitter.

The ultrasonic sensors selected for the purpose of obstacle avoidance were therefore the HR-SR04 ultrasonic sensors. This is because they have a sufficient range of 5 m, are easily available and inexpensive. The infra-red sensors to be used for the front facing obstacle detection sensors are the GP2Y0A21YK infra-red sensors, with a range of 0.8 m, which

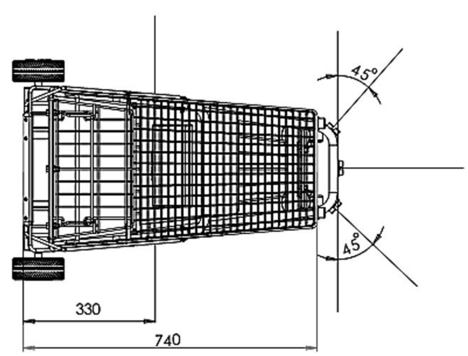

Figure 3.11: Obstacle avoidance sensors placement

is sufficient for obstacle avoidance. The infra-red sensor to be used is shown in the figure 3.12.

Design modification

The set-up selected for placement of the obstacle avoidance sensors was revised as a result of noise. The utrasonic sensors placed on the sides were a source of noise to the ultrasonic receivers responsible for tracking, especially in enclosed spaces where their signal was reflected against walls. In order to avoid noise, two of the infra-red sensors to be used at the front replaced them, therefore only three sensors were used for obstacle avoidance.

3.3.3 Automated billing

Automated billing refers to the subsystem responsible for costing the shopper's purchased goods and subsequently communicating the goods' total price to both the shopper and the shop's server. The subsystem was therefore required to be capable of monitoring the items the shopper fed into the cart, determine the price then finally communicate the same to the shopper as well as the supermarket server.

Item detection

The following factors were considered to determine the technique to be used for this monitoring system:

1. **Read rate:** The billing technique was required to be capable of reading the item data at a fast rate.

Figure 3.12: GP2Y0A21YK Infrared Sensor

Figure 3.13: Radio frequency reader module

2. **Security:** The billing technique was required to be capable of reliably monitoring items placed and removed from the cart so as to avoid a shopper from tricking the system and avoiding payment of an item.

3. **Implementation complexity:** The technique used was required to be simple to design and implement.

4. **Implementation cost:** The technique used was required to be affordable.

5. **Human capital:** The technique used was to require minimum amount of human capital while billing.

The system considered two methods, that is the use of a bar-code scanner mounted on the cart and an RFID based billing system, whereby each item in the supermarket was tagged and read by an RFID reader mounted on the cart. A comparison to distinguish the more favourable of the two techniques was done and is illustrated in table 3.5.

From the comparison, RFID based billing was selected as the better choice between the two, as it would be convenient to use and required very little input from the shopper. Considering factors such as cost and availability, the RF reader selected was the 125 KHz RFID Reader Module. This is shown in figure 3.13. The RF readers were rated to have a range of 10 cm, therefore more than one was required to enable monitoring of items input from any direction. Considering the dimensions of the small-sized cart basket, three readers were to be used to detect when items were fed or removed from the cart. The RF readers were to be placed along the inner wall of the cart. The range within which they could theoretically detect RFID tags is illustrated in the figure 3.14.

As each of the RFID tags cost Kshs 100, only four were purchased for demonstration purposes. To avoid the detection of items along aisles adjacent to the cart, the RF readers used were shielded from the RF signals external to cart using aluminium foil, which is light yet effective in blocking RF signals, thus limiting detection within the cart.

Design modification

On purchasing and testing of one of the 125 KHz RF readers, it was realized that they had limited range and required near contact range with the RF tags in order to identify

Table 3.5: Automated billing comparison

Design Considerations	RFID	Bar-code
Read rate	High throughput	Very low throughput
Orientation of placement	Can be put into cart in any orientation	Bar-code scanner requires a line of sight with the bar-codes
Security	High. It would be difficult to trick the system to avoid cost	Low. Dependent on shopper integrity
Ease of control	Complex to implement	Implementation is straight forward
Human Capital	Once running, system is completely automated	Shopper must scan each tag
Implementation cost	Requires the use of RFID tags which are relatively expensive	Uses bar-code tags which are cheap

them. They also took multiple reads when a tag was close to them over a long period of time which interfered with effective billing. Alternative RFID readers were therefore selected. These were the EM-18 RF readers. The readers have a consistent reading range of 8 cm and did not take multiple reads on a single pass of an RF tag. The figure 3.15 illustrates the EM-18 RF reader. Of the three EM-18 RF readers purchased, one was defective. Because the readers were imported, replacement of the defective one was a challenge. This therefore constrained the design to using two RFID readers.

Transmission of item data

Communication of items' details and the total cost to the shopper was done using an LCD

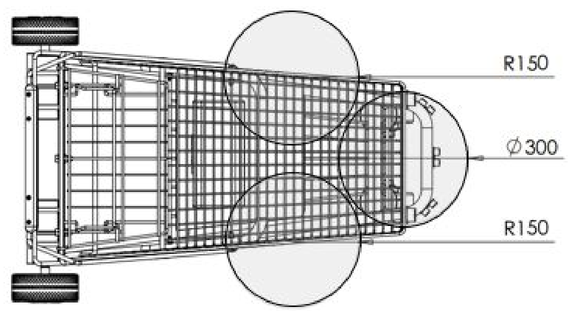

Figure 3.14: Radio frequency reader placement

Figure 3.15: EM-18 RF reader

screen. Communication to a remote computer so as to enable charging of the shopper for the purchased goods, was however required to be done wirelessly. For this process, various wireless modes of communication were considered, that is; the use of bluetooth and WiFi connection. The factors considered for selection of the mode of communication were speed of communication, ease of use and data representation. Considering these factors, the use of a WiFi module to communicate data to the server was selected. This was because the WiFi module would provide an internet connection and would enable the data to be sent to a cloud-based database from where data of the items purchased as well as total cost could be accessed through a computer. The use of such a database would enable presentation of data in an understandable tabular format. Though transfer of the data can be achieved via Bluetooth, the process of presenting the data in an easily readable format would have been relatively more challenging. The speed of connection is also relatively slower for Bluetooth as it would require pairing of the Bluetooth modules, that is, between the cart's module and the computer. A cloud-based platform known as ThinkSpeak was selected where data would be transmitted from the micro-controller through a WiFi module, (ESP8266) and accessed remotely from the cashier's computer.

Design modification

During implementation, it was realised that the cloud-based platform that was proposed was primarily for representing graphical data from analogue readings and the process of attaining tabulated data was complex. The module selected also presented a challenge in transmission of data wirelessly, having a tendancy of corrupting the data. An alternative method was therefore used that involved the use of an ethernet shield and a small wireless router. The data from the controller was uploaded onto a locally hosted website through an ethernet shield connected to a router set up as a WiFi network repeater. The website's local host shared the same Wifi network with the repeater. A WiFi shield was considered in place of the ethernet shield and router, however it was significantly more costly relative to the selected transmission set-up.It cost Kshs 5,000, yet the ethernet shield cost Kshs 1000 and router was already available.

3.3.4 Actuation

3.3.5 Motor drive selection

The factors considered for the selection of the motors were as follows:

1. **The weight of the cart.**This was used to determine the motor torque ratings.
2. **The required speed of the cart.** This was used to determine the required motor output speed.
3. **Manoeuvrability .** The motors selected were required to allow easy speed control.

The following parameters were assumed to determine the selection of the motor:

1. A small-sized cart would be used with a loaded weight of 10 Kgs.
2. A desired maximum speed of 1.4 m/s. This was based on the average walking speed of a human.
3. A wheel diameter of 0.13m. The diameter was equivalent to the standard size of a small-sized shopping cart.
4. The surface of operation was to be smooth, and would have a 0 degree angle of inclination. This was in-line with the surface of the supermarket environment.
5. The inertia of the wheels and air drag were considered negligible.

Motor speed ratings.

The motor speed ratings were be determined as follows;

$$n_w = \frac{velocity}{wheel\,circumference} \tag{3.2}$$

$$n_w = \frac{v_{max}}{2\Pi\,(R_w)} \tag{3.3}$$

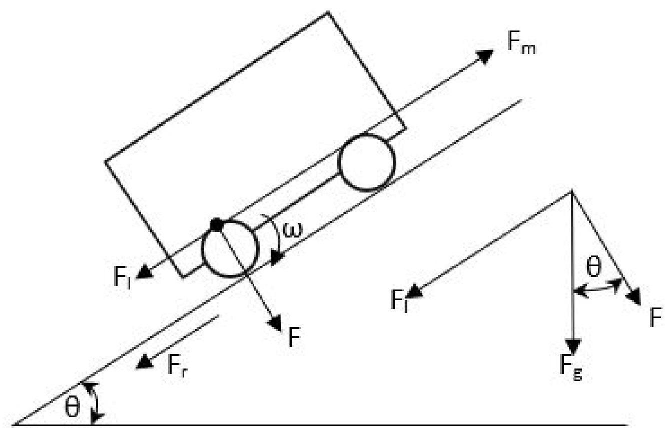

Figure 3.16: Free Body Diagram

$$n_w = \frac{1.4}{2\Pi\,(0.065)} \text{x} \frac{60}{1} = 205.68\,rpm$$

The no-load speed (n_0) rating of the motor was therefore required to be greater than 205.68 rpm, so as to compensate for loss of speed due to the added weight of the cart, load and friction. Therefore, considering an efficiency rating of 75 percent, the minimum motor speed rating was calculated as follows:

$$205.68\,\text{x}\,\frac{100}{75} = 274.24\,rpm$$

Motor torque and power ratings.

For the torque ratings for each motor, the figure 3.16 was considered.

It was assumed that when the cart is moving, its weight would be divided into two components: one perpendicular to the surface, which was responsible for the friction force, Fr , and the other, Fl , which was as a result of gravity F_g. The motor force was required to equal all forces in the opposite direction.

$$F_m = F_r + F_l \tag{3.4}$$

The normal force F and the load pulling force F_l were computed as follows:

$$F = F_g\, cos\theta \tag{3.5}$$

$$F_l = F_g\, sin\theta \tag{3.6}$$

whereby θ was the slope of the surface. The gravitational force F_g was given by;

$$F(g) = m\, g \tag{3.7}$$

where m was the loaded mass of the cart and g was gravitational acceleration. The frictional force was given by;

$$F_r = \mu\, F \tag{3.8}$$

whereby, μ was the coefficient of friction.

Having attained the value of F_m, torque was therefore given by;

$$T_m = F_m\, r \tag{3.9}$$

whereby, r was the radius of the wheels coupled to the motor.

Therefore;

$$F_g = 10\text{x}\, 9.81 \;=\; 98.1\, N$$

$$F = 98.1\, cos(0) =\; 98.1\, N$$

$$F_l = 98.1\, sin(0) = 0\, N$$

$$F_r = 0.4\text{x}\, 98.1 =\; 39.24\, N$$

$$F_m = 0 \,+\, 39.24 \;=\; 39.24\, N$$

$$T_m = 39.24\text{x}\, 0.065 \;=\; 2.5506\, Nm$$

Considering that two motors were to be used as it is differential steering system, the minimum torque to be supplied by each motor was given by;

$$T_m = \frac{2.5506}{2} \;= 1.2753\, Nm$$

Summarily, the base motor ratings and specifications were to be;

Figure 3.17: Tsiny DC Geared Motor

1. A loaded speed of at least 274 rpm.
2. A loaded torque of at least 1.2753 Nm.
3. Easy speed control, as differential steering is used.

Considering the above factors, DC geared motors were selected. This is because their speed is easily varied using a motor speed controller and they are capable of achieving high torque ratings at a relatively high speed as compared to motors such as stepper motors and servomotors. Geared motors also do not require one to develop a gear reduction system as the gear reduction is already done internally within the unit. Therefore, they were considered a better alternative relative to using a DC motor and fabricating a gear reduction system. The DC geared motor selected was the Tsiny DC Geared Motor which is shown in the figure 3.17. It has a voltage rating of 12 V, speed rating of 280 rpm, a torque rating of 1.5 Nm and a stall current of 5.5 A.

For the variation of speed, a dual H-Bridge motor controller was considered ideal as a single unit would enable the independent variation of speed of the two motors. The motor controller's operation would be controlled by a micro-controller, such that by varying the voltage supplied to the individual motors, their speed would be varied. The motor controller was required to be capable of supplying the relevant voltage to the motor

Figure 3.18: Monster Moto Shield Motor Controller

considering the desired speed and supplying a current no less than the stall current. Considering these factors, the motor controller selected was the Monster Moto Shield motor controller, which could deliver a maximum current of 30 A to the motors, a continuous current of 14 A and a maximum voltage supply of 16 V. The motor controller is shown in figure 3.18.

3.3.6 Power supply unit

There were two independent power supplies that were implemented to enable the operation of the smart shopping cart. These were; the shopping cart's power supply and the tracker's power supply.

1. **Shopping cart power supply**

   As the smart shopping cart was expected to be mobile, a DC power source was selected to power the components. The battery pack capacity was determined based on the current ratings of all the electrical and electronic component and total operation time required. The highest voltage rating of the components used was also considered to determine the minimum voltage supply of the battery pack. This was the motor's voltage rating. Since the shopping cart was to be mobile and motors rated 12 V had been selected, a 12 V DC supply was considered as ideal.

   Therefore, for the system to operate for at least 20 minutes (primarily due to the budget), the battery pack capacity (C) was calculated as follows;

$$C = I_{tot}\,\mathrm{x}\,t \tag{3.10}$$

To determine the total current required, the major component's working current were considered. This is shown in table 3.6.

Therefore, considering equation 3.10, the capacity was determined.

$$C \ = 11,163\,\mathrm{x}\frac{20}{60} = 3,721\,mAh$$

So as to avoid total drainage of the battery as well as to reduce the rate at which the number of charge cycles left declines, the capacity for an 80 percent discharge was considered. An 80 percent operation efficiency was also considered for the calculation of the total battery capacity, which was obtained as follows:

$$C \ = \ \frac{100}{80}\,\mathrm{x}\,\frac{100}{80} = 5,814.06\,mAh$$

The battery types considered for this application were lithium-ion batteries, lithium polymer batteries and lead acid batteries. The factors used to determine the selection of the battery included weight, battery capacity, voltage maintenance and cycle life. Table 3.7 shows the comparison between the different battery packs.

Table 3.6: Power Bill Calculation

Component	**No.**	**Working Current (mA)**	**Total**
Motor	2	5,500	11,000
Monster Moto Motor Controller	1	36	36
Zigbee Transmitter	1	17	17
Ultrasonic Sensors	4	15	45
Infrared sensors	3	5	25
RF Readers	1	20	20
WiFi Module	1	20	20
Total Current			11,163

From the comparison, the battery selected was the Lithium polymer battery. Though it is relatively expensive when compared to the other batteries, it met most design considerations. The Lithium battery selected was therefore a Gens ace Lithium Polymer Battery which has a capacity of 5,500 mAh, 14 V and a weight of 200 g.

Design modification

During implementation, the Li-po battery attained was found to be defective (had two dead cells) and the cost of purchasing a new one was too high, with the one with the desired specifications costing KShs 6,500. A small-sized lead acid battery with nearly similar specifications (12 V rating and 5 Ah capacity) was therefore purchased and used instead. The figure 3.19 shows the led-acid battery used.

Power circuit

A power circuit was used to convert the power supplied to the specific voltages

Table 3.7: Comparison of Different battery types

Design Considerations	**Lithium-ion Battery**	**Li-Po Battery**	**Lead Acid Battery**
Weight	Light	Lightest	Heavy
Discharge	Can be discharged by 100 percent	Can be discharged by 100 percent	No more than 50 percent discharge is encouraged
Voltage maintenance	Maintains voltage throughout discharge cycle	Maintains voltage throughout discharge cycle	Drops during discharge
Cycle Life	Long (5000 cycles or more)	Long (5000 cycles or more)	Short (400-500 cycles)
Cost	Expensive	Slightly more expensive	Cheap
Capacity	Relatively lower	High	Low

Figure 3.19: 12 V 5 Ah led acid battery

ratings of each of the components. The power was supplied to the motors from the motor controller, which was directly connected to the battery. The power supply to the micro-controller however entailed a voltage regulator to step down the voltage to the ratings required by the 9V-rated micro-controller. The LM78xx series of voltage regulators was used for this purpose. The sensors used were then powered through the micro-controller. In the design of the power supply circuit, capacitors were used for decoupling so as to ensure a smoother power supply was achieved. LEDs were also used as indicators for fault detection. The figure 3.20 illustrates the electrical schematic for power supply to the cart's components and the figure 3.21 illustrates the printed circuit board that was fabricated based on the schematic.

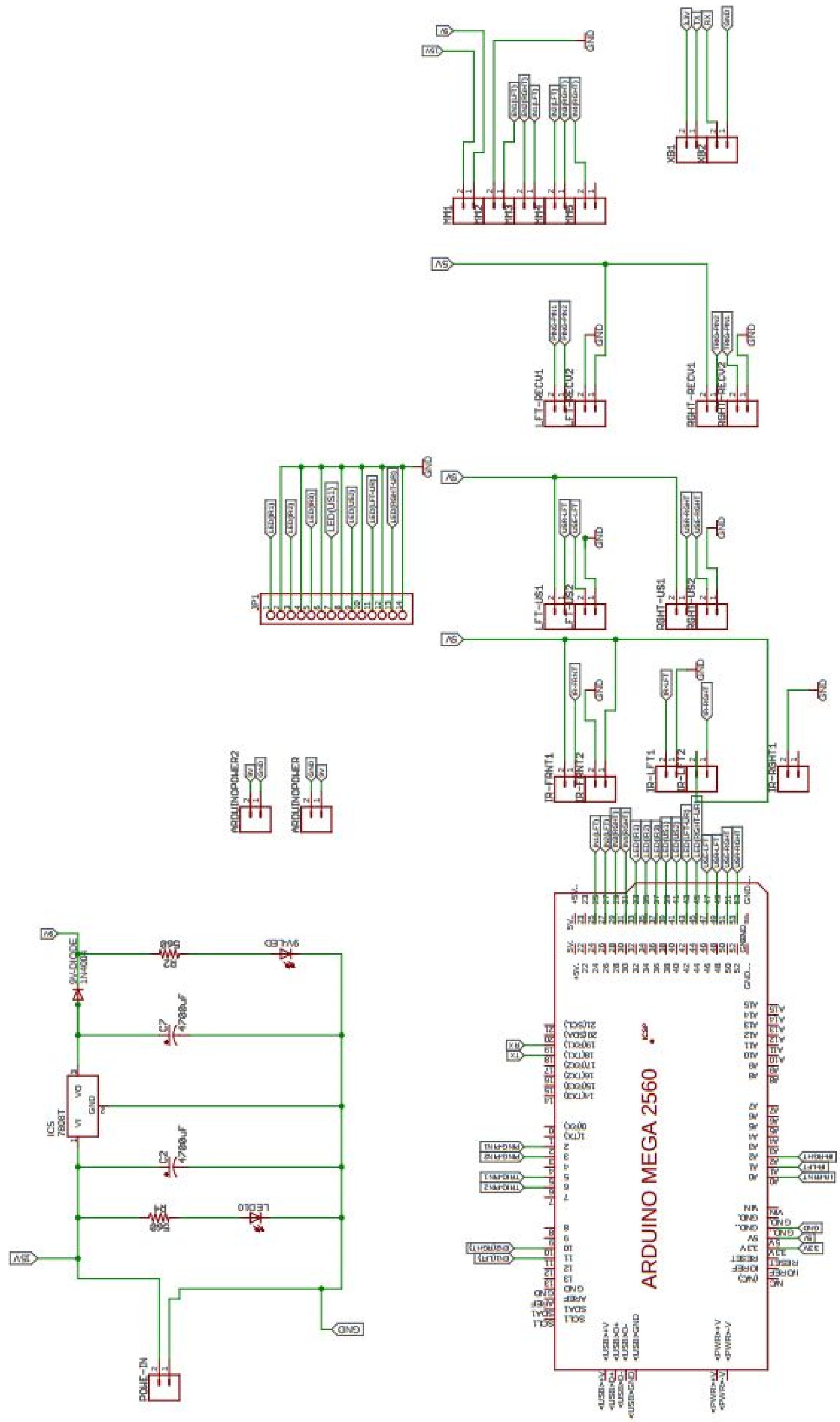

Figure 3.20: Power Supply Circuit

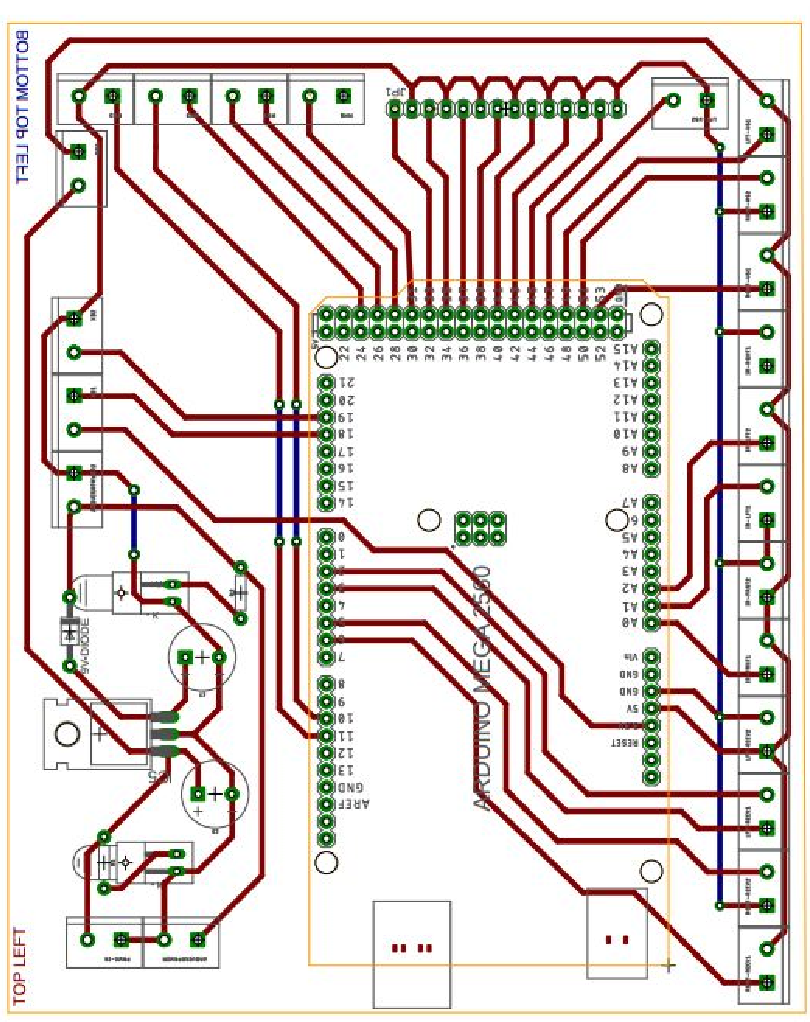

Figure 3.21: Power Supply Circuit

2. **Tracker power supply**

The tracker power supply was primarily used to power two main components, that is the Xbee series 1 radio module that was to act as the receiver, and the ultrasonic transmitter. The power demand was therefore calculated based on their working current ratings as illustrated in the table 3.8.

Therefore, considering equation 3.15, for operation of up to 1 hour, the capacity was determined as follows.

$$C \; = 55 \,\mathrm{x} \frac{60}{60} = 55 \, mAh$$

A 9 V rechargeable Eveready battery was selected to provide power to the electronic components. The battery has a capacity of 175 mAh and therefore from a single charge, it could power the tracker for about 3 hours.

$$\frac{175}{55} = 3.18 \, h$$

As the ultrasonic transmitter required has a voltage rating of 5 V and the Xbee module had a 3.3V rating, a 5 V voltage regulator was used to step down voltage supplied to the ultrasonic transmitter and a 3.3 V zwener diode was used to further drop down the voltage to 3.3 V for power supply to the Xbee series one module. For the ultrasonic transmitter to send an ultrasonic ping, its trigger pin was required to be set high for a period of between 10 to 15 microseconds. The time interval the pin stayed high was set by the controller at the shopping cart remotely. Two LEDs were used to indicate the operation of the tracker. One was used to indicate that

Table 3.8: Tracker Power Bill Calculation

Component	**No.**	**Working Current (mA)**	**Total**
Ultrasonic transmitter	1	15	15
Xbee receiver module	1	40	40
Total Current			55

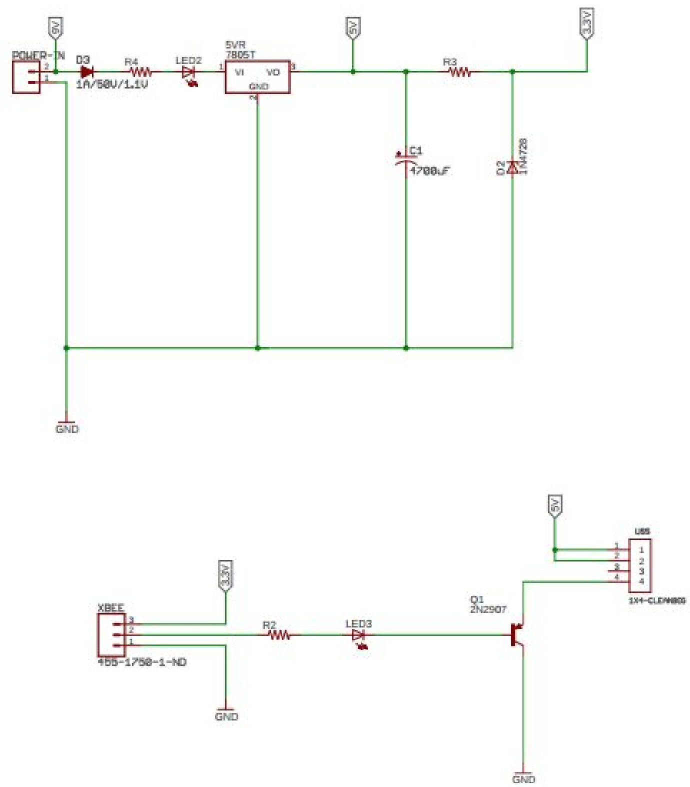

Figure 3.22: Tracker power supply circuit

the tracker was on and the other was used to indicate that the tracker was receiving radio signals prompting it to transmit ultrasonic pings. The figure 3.22 illustrates the tracker's electrical schematic and the figure 3.23 illustrates the tracker's circuit board.

3.3.7 User interface

The smart shopping cart was required to display the product price of each item, the number of items as well as show the total cost of the products within the cart, as a shopper loaded items into it. It was also considered ideal that the smart shopping cart provide an auditory feedback indicating that an item has been added or removed from the cart. The factors considered for selection of the display were display size and affordability. As a

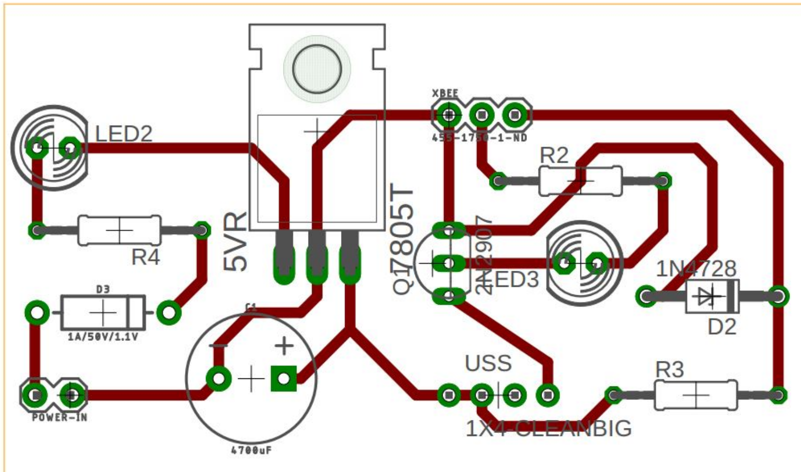

Figure 3.23: Tracker circuit board design

result, a 16 x 4 LCD display was selected to communicate the relevant information to the shopper. The display was large enough to display all the required information and was easily available and affordable. A buzzer was also included such that it beeped whenever an RFID tag was detected by any of the RF readers. The display and buzzer selected are shown in the figure 3.24.

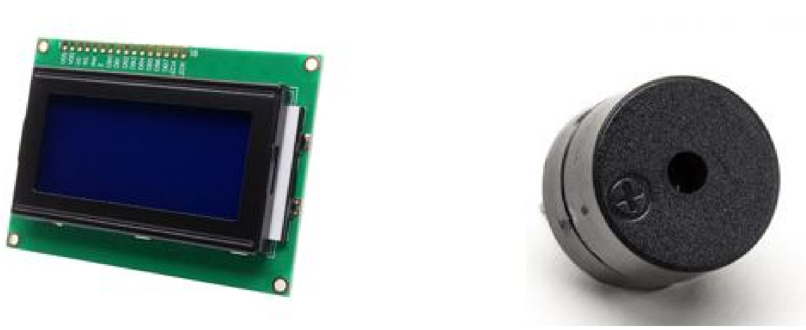

Figure 3.24: The LCD Display.

3.4 The control module

This module was concerned with the algorithm with which the smart shopping cart was expected to operate and achieve its functions. The algorithm was programmed into a micro-controller which determined the operation of the smart shopping cart actuators based on the input from the sensors. The main function of the micro-controller was to coordinate the operation of person tracking and obstacle avoidance as well as automated billing. The following considerations determined the selection of the micro-controller to be used.

1. **Number of pins:** The micro-controller was to have a sufficient number of pins to enable communication with all the sensors and actuators of the smart shopping cart, which are a significant number.

2. **Processing speed:** The micro-controller was required to be capable of processing all the input data from the sensors and determining a relevant output within the shortest time interval for smooth operation of the system.

3. **Control complexity:** The micro-controller was required to be simple to use and program so as to enable easy and fast modification of the program code.

Considering the above factors, the micro-controller selected was the ATmega 2560, mounted on an Arduino Mega micro-controller platform. Other than having a sufficient number of pins (54) and a sufficient clock-speed of 16 MHz, the Arduino Mega board enables programming of the micro-controller chip through a simple integrated development environment (IDE).

Since the person tracking function and obstacle avoidance function involve actuation of the same motors, the micro-controller was responsible for determining which function was ran, with obstacle avoidance taking a higher priority.

The control strategy that was used in the person tracking function was a negative feedback control, whereby, an error signal was computed, and the motors' speed controlled proportional to the error. Two errors were calculated, that is:

1. The difference in distance between the pre-set distance the smart shopping cart should maintain from the shopper to the distance the cart was, at an instance. This was used to determine the motor speed.

2. The TDOA of the ultrasonic signal from the tracking ultrasonic transmitter as indicated in equation 3.1. This was used to determine the relative speed of the motors, with respect to each other, enabling turning.

Whenever an obstacle was detected, the obstacle avoidance function took over control and stopped the cart if detected ahead of it, or caused it to swerve away from an obstacle if detected on one side. In order to avoid compromising on the operating speed of the person tracking and obstacle avoidance processes, an additional micro-controller was used to coordinate the automated billing process. This was possible because automated billing did not involve the use of the key actuators used for person tracking and obstacle avoidance (the motors). The micro-controller used for this purpose was the ATmega328p, mounted on an Arduino UNO micro-controller board. This micro-controller has relatively fewer pins than the ATmega 2560, though they were enough to connect to the inputs (RFID readers) and outputs (display panel) and WiFi module used in automated billing. The micro-controller boards to be used are shown in figure 3.25.

The figure 3.26 illustrates the program flow chart for person tracking and obstacle avoidance, and the figure 3.27 illustrates the program flow chart for automated billing.

Figure 3.25: Arduino Mega and Arduino Uno Micro-controller Boards

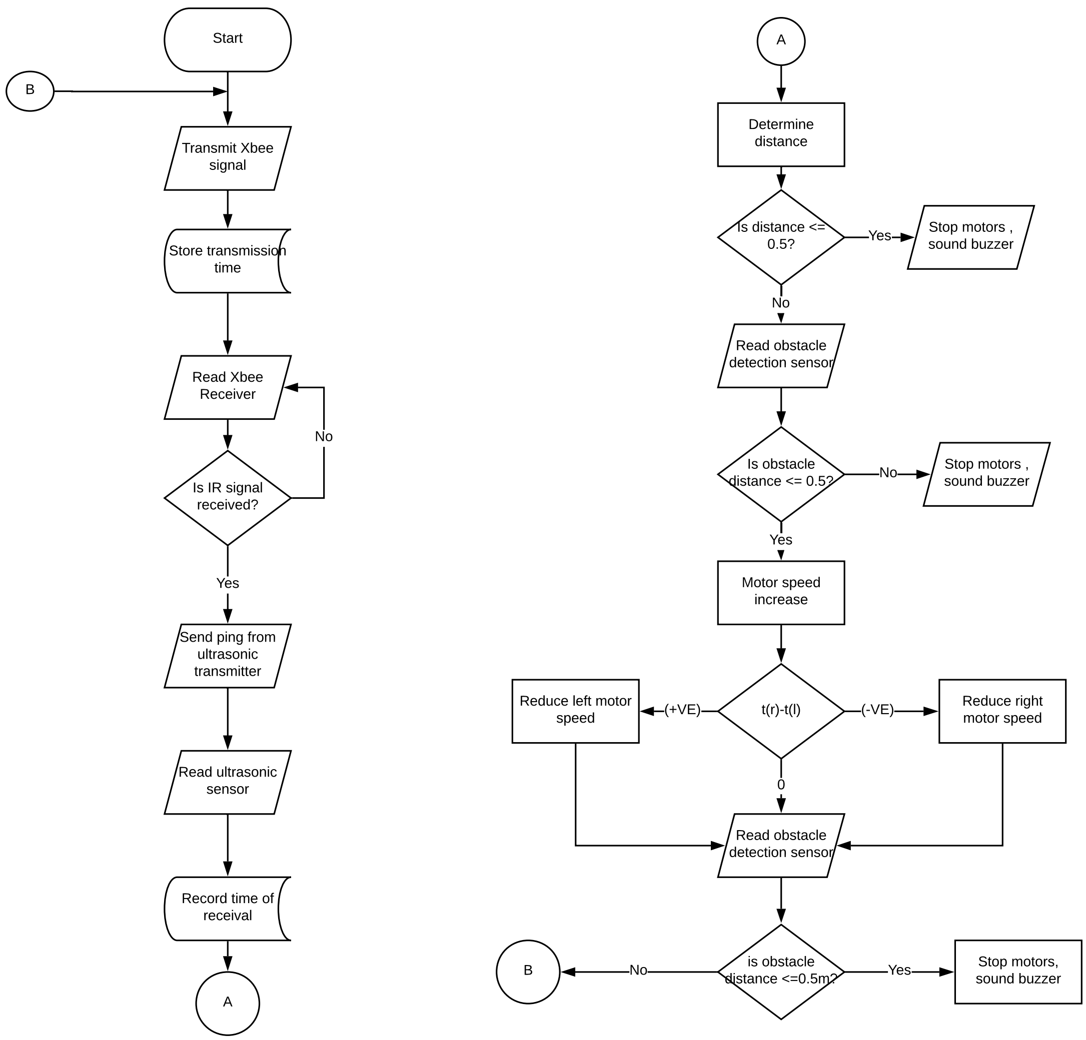

Figure 3.26: Person tracking and obstacle avoidance program flow

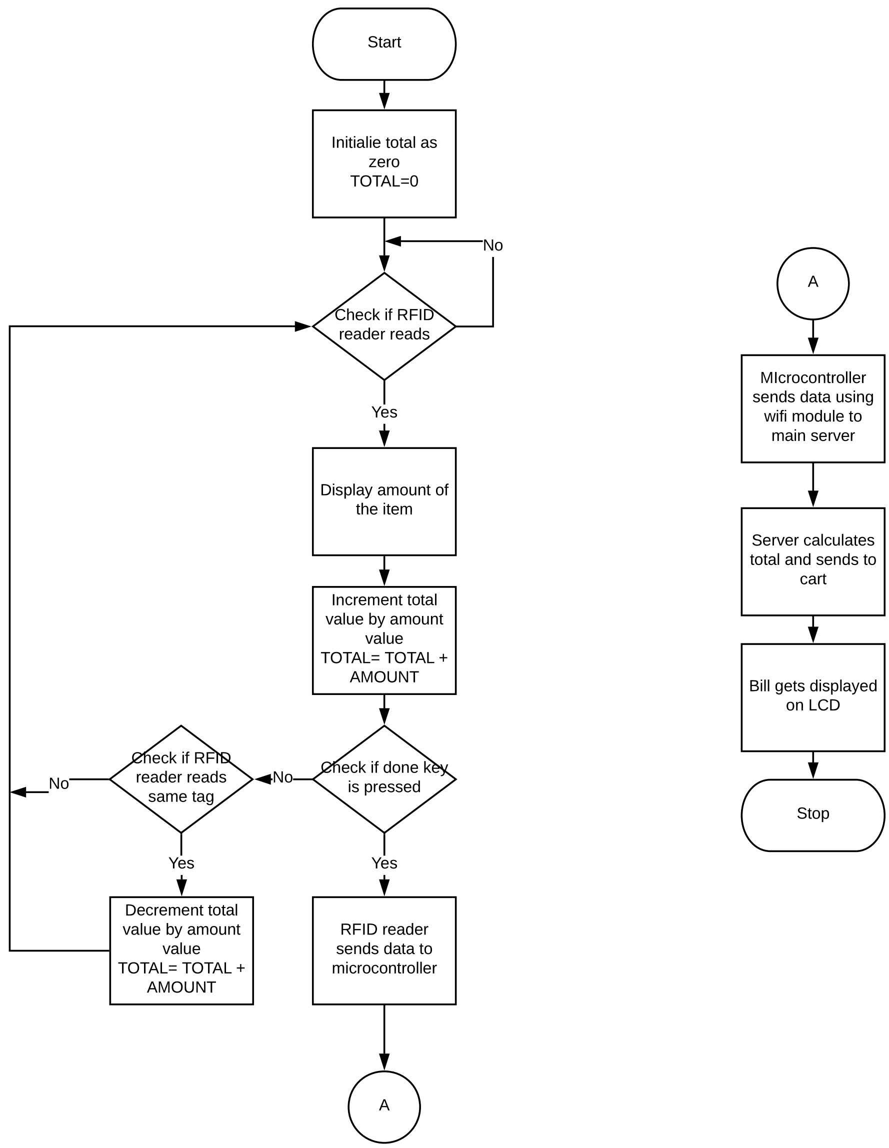

Figure 3.27: Automated billing program flow

4 Results and Discussion

This chapter entails an overview of the achieved design and the data collected during the testing and optimization phase of the smart shopping cart.

4.1 Final design of the smart shopping cart

The figure below 4.1 illustrates the design that was set out to be achieved.

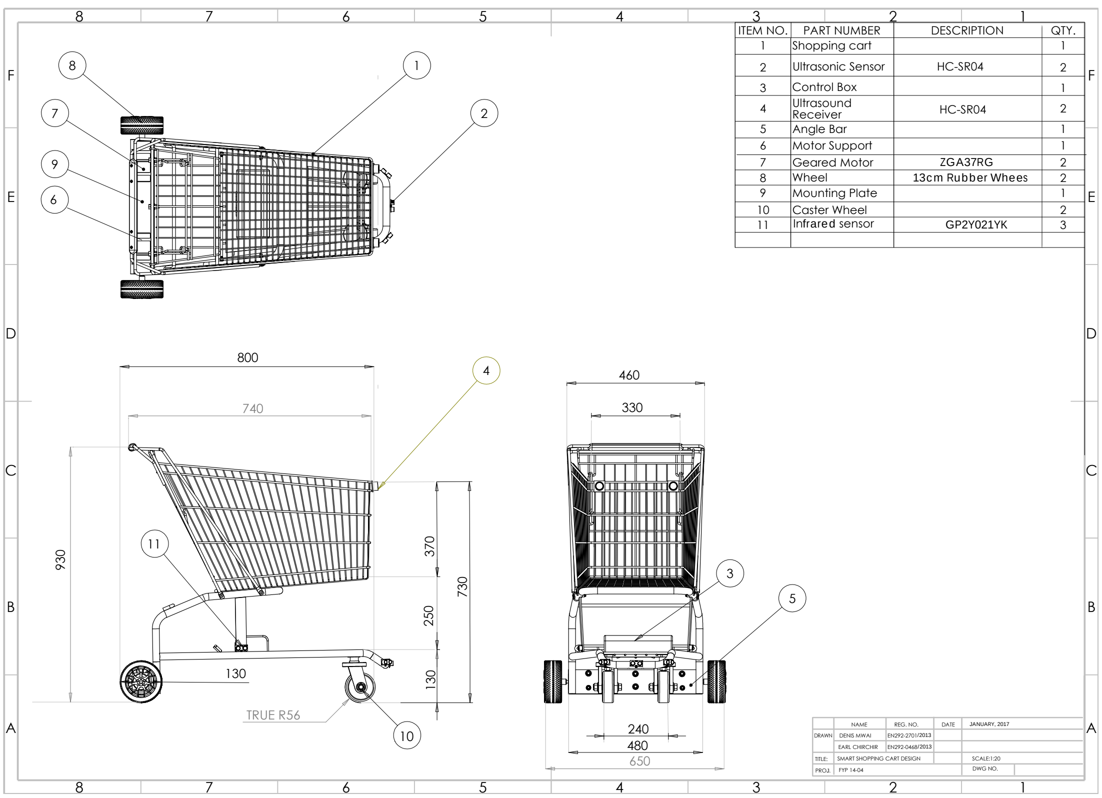

Figure 4.1: Shopping cart design

4.2 Fabricated and modified mechanisms

4.2.1 Actuation mechanisms

The figure 4.2 shows the modification done to the shopping cart's wheel assembly that enabled electrical actuation.

The wheels were mounted to the motor shaft using the 3D printed motor hubs shown in the figure 4.3. The motor hubs had bolting slots where a bolt and nut would be used to hold the wheels and hubs firmly together.

4.2.2 Fabricated control box

The figure 4.4 illustrates the control box where the micro controller and electronic components were housed.

Trunking was done from the control box to the respective sensors. The trunking consisted of wiring to the ultrasonic receivers, RFID readers to be used for billing and the infra-red proximity sensors used for obstacle avoidance.

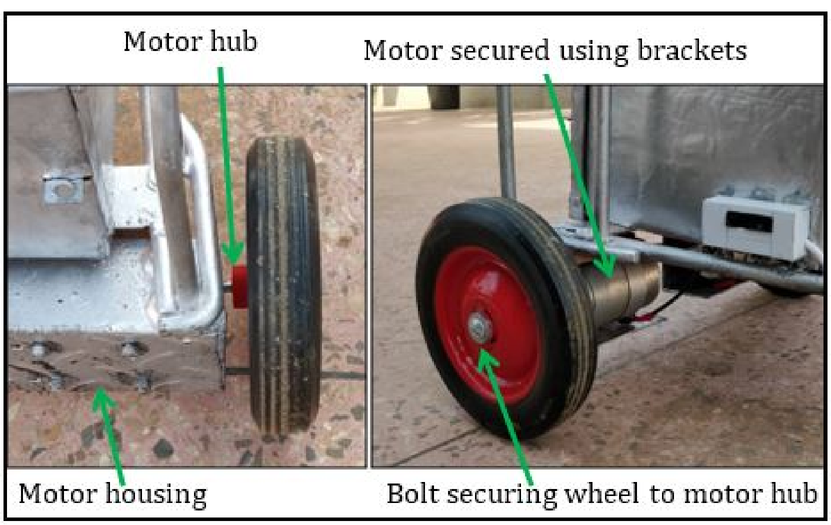

Figure 4.2: The motor and wheel assembly and fixture

Figure 4.3: 3D printed motor hubs

4.2.3 Fabricated circuit board

The figure 4.5 shows the printed circuit board through which power was supplied to the smart shopping cart's circuitry. The micro-controller was mounted directly onto the PCB as shown and the components used for the shopping cart's operation connected to the

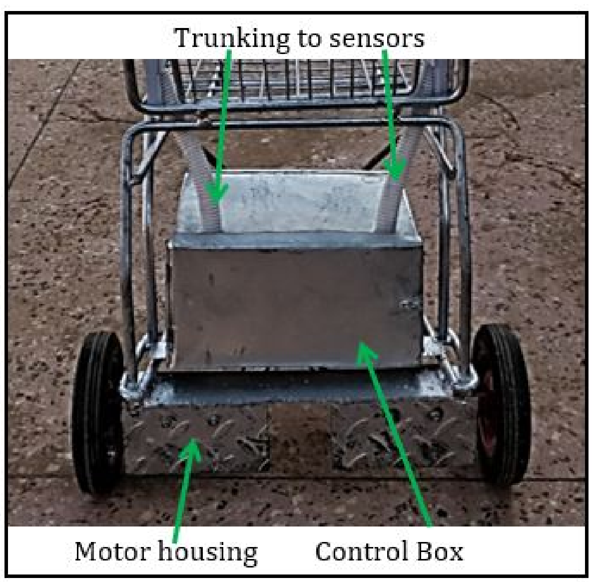

Figure 4.4: The control box

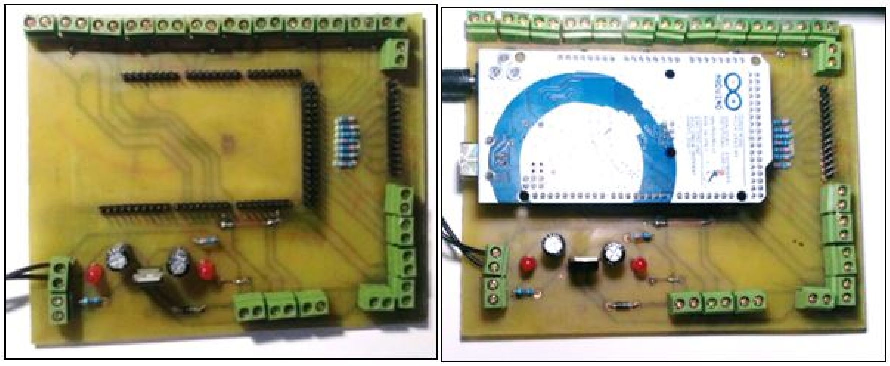

Figure 4.5: The motor controller PCB

PCB through wiring from terminal blocks as it ensured secure connections. The monster moto controller also had its PCB fabricated to enable connection to the micro-controller through wiring done via terminal blocks as shown in figure 4.6.

4.2.4 Tracking system

The implemented tracking system entailed the use of three modified HR-S04 ultrasonic sensors such that one, which was to be used on the tracker, consisted of the ultrasonic transmitter only and the other two which were mounted onto the cart, consisted of only the receivers. Mounting of the receivers onto the shopping cart is illustrated in the figure

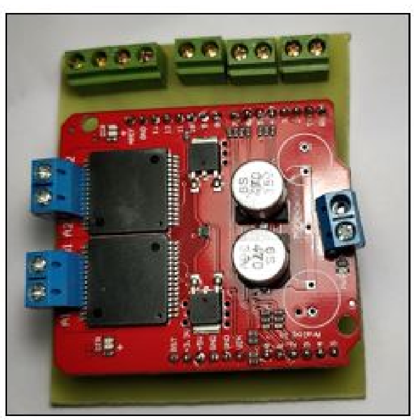

Figure 4.6: The motor controller PCB

4.7.

A 3D printed design was used for housing of the tracker's components, that is, the Xbee module to be used as a radio signal receiver, the ultrasonic transmitter, a battery and a power conversion circuit to step down voltage to the rated voltage of the individual components. The housing and tracker assembly is shown in the figure 4.8 .

4.2.5 Obstacle avoidance sub-system

The figure 4.9 illustrates the placement of the obstacle avoidance sensors. The IR sensors were mounted on either side of the control box and one at the front.

Figure 4.7: Tracker housing

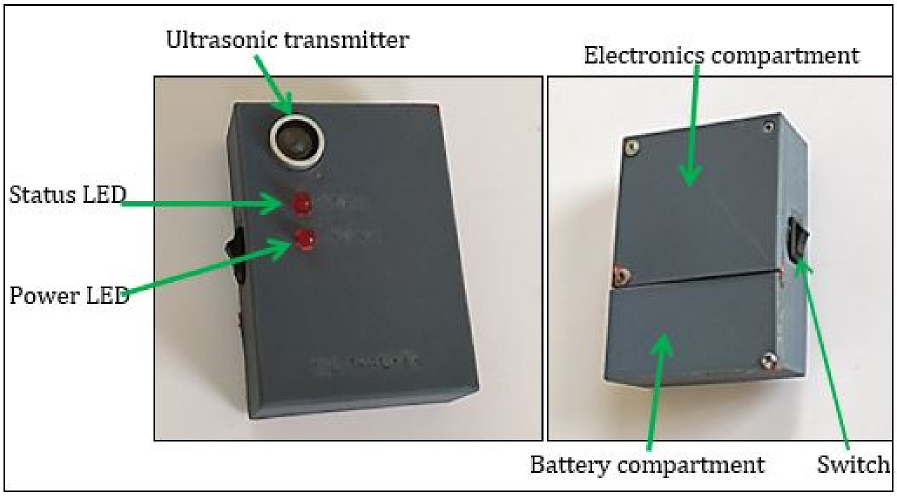

Figure 4.8: Tracker housing

Figure 4.9: Right and front IR obstacle detection sensors

4.2.6 Billing sub-system

The figure 4.10 illustrates the billing sub-system set-up.

4.2.7 Overall smart shopping cart implementation

The figure 4.11 shows the overall results of the implemented shopping cart.

4.3 Performance Tests

4.3.1 Mobility and manoeuvrability

Weight

The shopping cart weighed a total of 12.45 kgs and could carry an additional weight of up to 4 kgs. Due to its heavy weight, the additional load the cart could push was limited

Figure 4.10: Placement of the RFID readers

Figure 4.11: Overall smart shopping cart design implementation

due to the amount of torque the motors could supply. This limited the weight of items that could be added into the cart for demonstration of billing.

Turning and speed

The cart was able to turn through differential drive. By supplying more voltage to one motor, the motor would rotate faster than the opposite motor and would effectively turn the cart towards the opposite direction.

In forward direction, the cart moved at a speed ranging between 0.4-1.2 m/s (varied by supplying the motor voltage between 8-15V), and was programmed to move at a speed range of between 1 m/s-1.2 m/s depending on how far the shopper was from it.

Tracking

The tracking system could detect the tracker's signal from a maximum distance of 6.5 m, enabling the shopping cart to move towards it.

The angular range of transmission and detection of ultrasonic signals was however quite narrow as the transmitter and receivers were housed in caps which limited their angular range to 15 degrees, since the original purpose of the sensors was to measure distance. This limited the angular range of tracking, enabling determination of the tracker's position only when the tracker was positioned infront of the receivers at a distance of at least 40 cm.

The transmitter and receivers were therefore further modified so as to increase the angular range of transmission and receival of ultrasonic signals. This entailed minimizing the length of the caps within which the ultrasonic transmitter and receivers were housed as shown in the image below 4.12 .

This effectively increased the angle of transmission of the transmitter to 80 degrees and the angle of receival to 60 degrees.

The test on angle of transmission and receival entailed placement of the sensors on a plain sheet of paper, making the relevant connections to the micro-controller and using the serial monitor of a computer to monitor receival of the pings. The transmitter was

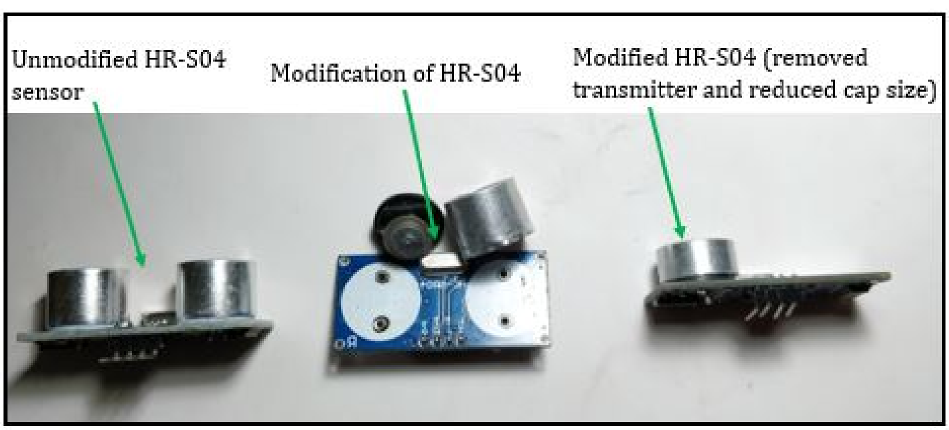

Figure 4.12: Modification of the ultrasonic sensors

moved from infront of the receivers across the sheet until the receivers no longer recorded receival of pings. The point at which the receivers stopped receiving pings was marked and the angle measured.

To enable a wider tracking range, the smart shopping cart's micro-controller was programmed in such a way that if only one of the sensors received ultrasonic pings, the cart would turn towards the direction of the sensor receiving the pings so as to better align itself with the tracker.

4.3.2 Obstacle avoidance

The shopping cart was expected to stop whenever the tracker unit was within a pre-set range (1 m) from the cart or whenever there was an obstacle detected within a pre-set range (1 m) infront of it. This function was achieved by programming the motor controller to supply the motors with a brief reverse signal (by reversing the voltage).
If the cart detected an obstacle infront of the cart within a range of 1 m while in motion, it engaged braking. If not in motion, motion would not be initiated.
After moving at full speed, the braking distance was measured to be 0.5 m, whereas if moving slowly (whenever the distance between the individual carrying the tracker and the shopping cart was consistently maintained close to the pre-set range), the cart was able to stop immediately.

If the sensors on the sides detected obstacles within a range of 0.6 m from the shopping cart, the wheels towards the side of detection were rotated relatively faster than the opposite motor, causing the cart to turn away from the obstacle.

4.3.3 Billing and transmission of data

Billing test

Testing of the billing subsystem entailed determining the effective range of detection of the

RFID readers. This involved a comparison between two different RFID reader modules that is the 125 kHz reader proposed in section 3.5 and the EM-18 readers discussed on the same section.

The 125 kHz readers required a maximum range of 2 cm to detect the RFID tags whereas the EM-18 readers recorded a maximum detection distance of 9 cm. The 125 kHz readers also presented a challenge of taking multiple reads when a tag was within range for a long period of time whereas the EM-18 readers did not. The EM-18 readers were therefore used as the sensors for detection of items.

Whenever an item with a tag was passed before an RFID reader, its identity was detected and LCD screen displayed the item's cost, total number of items and total cost of items within the cart. If the same item was removed from the cart (passing the item again within range of the RFID readers), the item's cost would be deducted from the total cost and the total number of items would reduce by one.

In order to ensure security, the number of items recorded aided ensure that an individual did not trick the system by not scanning an item. As a shopper checks out, the number of items would be cross checked with the indicated recorded number, and any discrepancies would be cross-checked.

Transmission test

As discussed in section 3.3.1, a combination of an ethernet shield and WiFi router set up as a WiFi repeater (which the remote computer connected to) were used to transmit data to a locally hosted web page. The web page was set to refresh at an interval of 2 seconds thus getting updated on the contents of the shopping cart close to real-time.

4.4 Challenges

Some of the challenges faced during the implementation of the smart shopping cart include:

1. In the tracking sub-system, voltage spikes occurred from the 3.3 V output voltage supply of the Arduino mega which powered the Xbee radio module responsible for initiating the ping cycle. The Xbee module has a maximum input voltage rating of 3.6 V, however it was realized that the voltage from the power supply spiked to 4 V which resulted to damage of the module necessitating replacement of the module which was quite costly (Kshs 3,600). The replaced Xbee module was powered through a dedicated shield (Xbee explorer shield) tailored to ensure the module received its rated voltage.

2. The motor controller purchased was not fully functional. One of the pins responsible for controlling the direction of rotation of one of the wheels was internally grounded. This limited the control of both wheels to rotate only in one direction (forward) and hampered effective braking, as only of the wheels could be reversed.

3. Of the three purchased EM-18 readers, one of the readers was defective thus limiting the readers used for billing to two, limiting the range of item detection within the shopping cart.

4. The ultrasonic sensors at times experienced noise from ultrasonic signals reflected against walls, whenever the tracker was pointed to a wall facing the ultrasonic receivers and there was no clear line of sight between the receivers and the tracker.

5. It was difficult to reduce costs without compromising on the functionality of the smart shopping cart.

5 Conclusion

The project goal was to design and implement an automated shopping cart capable of autonomously following a shopper while avoiding obstacles so as to minimize load and in addition, through automated billing, minimize the check out time that occurs during billing of items. The project was required to demonstrate that effective automation could be achieved by using available resources and technology.

The first phase of the project focused mainly on the design of the system. The following tasks were achieved:

1. Mechanical design which included the identification of a shopping cart and design of the modifications to be implemented.
2. Electrical component selection, testing and PCB designs. This also entailed research and familiarization with the use and operation of the selected components.
3. Development of the control algorithm for the system.

The second phase of the project focused on the realization of the design. The following tasks were completed so as to achieve this:

1. Assembly of the mechanical and electrical components.
2. Writing the code to control each subsystem and integration into one system.
3. Testing and optimizing of the system.
4. Improvement of the smart shopping cart's aesthetic appeal.

Based on the final results obtained, it is clear that the objectives of this project were met, therefore making the project implementation successful. Due to constraints such as costs and time available, the project still left some room for improvements. A few recommendations that would lead to improvement of this project include:

1. The use of an RGB-D camera instead of propagation time of a signal for the purposes of tracking which would allow the cart to differentiate between people, thus making tracking more reliable.

2. If propagation time of a signal is to be used as the tracking mechanism, the use of multiple ultrasonic receivers mounted around would enable a much wider angular tracking range.

3. By using more powerful motors, the smart shopping cart can be scaled up to enable support and pushing of heavier loads as well as increase manoeuvrability.

4. The use of a WiFi shield instead of a combination of an ethernet shield and router would allow for a simpler wireless data transmission process with less components.

Successful commercialization and deployment of the smart shopping cart would greatly improve shoppers' experiences. It would make supermarkets and malls more accommodative of the elderly and disabled. It would however demand the use of more sophisticated sensors (such as RGB-D cameras) to enable it to differentiate between different individuals and be immune to noise.

The tracking sub-system would have multiple applications other than the supermarket environment. It can be applied in carrying of heavy loads in industries as well as carrying of personal luggage.

The billing sub-system would be effective in reducing the shopper's spend queuing at the check-out counter and would also improve on their convenience as it informs them of the running cost as they shop. It would however be quite expensive to implement in supermarkets since the bar code scanners and bar code stickers commonly used today are cheaper as compared to RFID readers of sufficient range (mounted in each shopping cart) and RFID tags.

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6 Appendices

Assembled smart shopping cart design schematics.

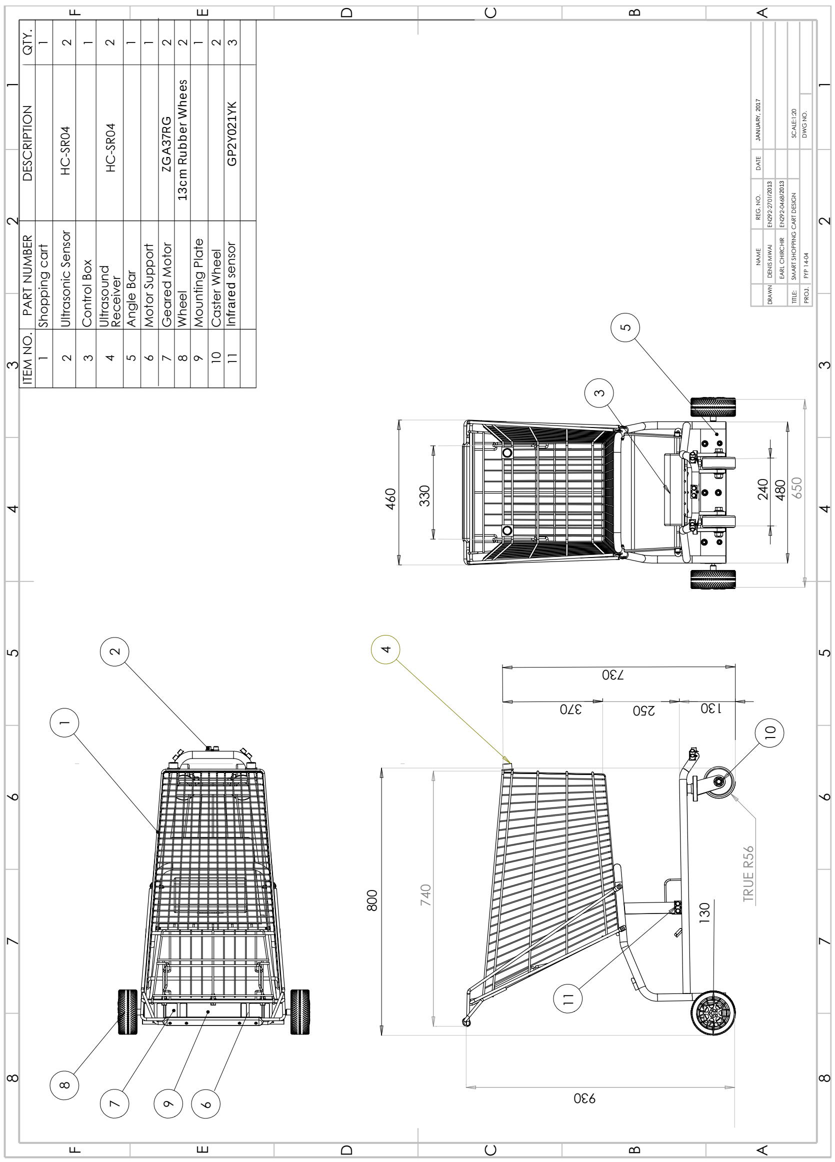

Figure 6.1: Draught Smart Shopping Design

Figure 6.2: Smart Shopping 3D Design

6.0.1 Cost analysis

Table 6.1: Smart Shopping Cart Cost Analysis

Components	**Description**	**No.**	**Price**	**Total**
Shopping Cart	Medium-size	1	1000	1000
Geared Motor	Zhenge ZGA37RG	2	1300	2600
Motor Controller	Monster Moto Shield	1	1500	1500
Wheels	13 cm Wheels	2	1600	3200
Ultrasonic sensors	HCR-SR04	4	200	800
Infrared sensors	GP2Y0A21YK	3	1000	3000
Xbee Module	Series 1	2	3600	7200
RF Reader	125KHz Module	3	500	1500
RFID Tags		4	100	400
WiFi Module	ESP8266	1	400	400
LCD Display	(20 x 4)	1	600	600
Buzzer	5 V active buzzer	1	20	20
Voltage regulators	7805, 7809, 7812	3	50	150
LED	Red	3	3	9
Microcontroller (Tracking)	Arduino Mega	1	1600	1600
Microcontroller (Billing)	Arduino Uno	1	800	800
Battery	LiPo (1500 mAh)	1	2800	2800
Total				27,579

6.1 Timeplan

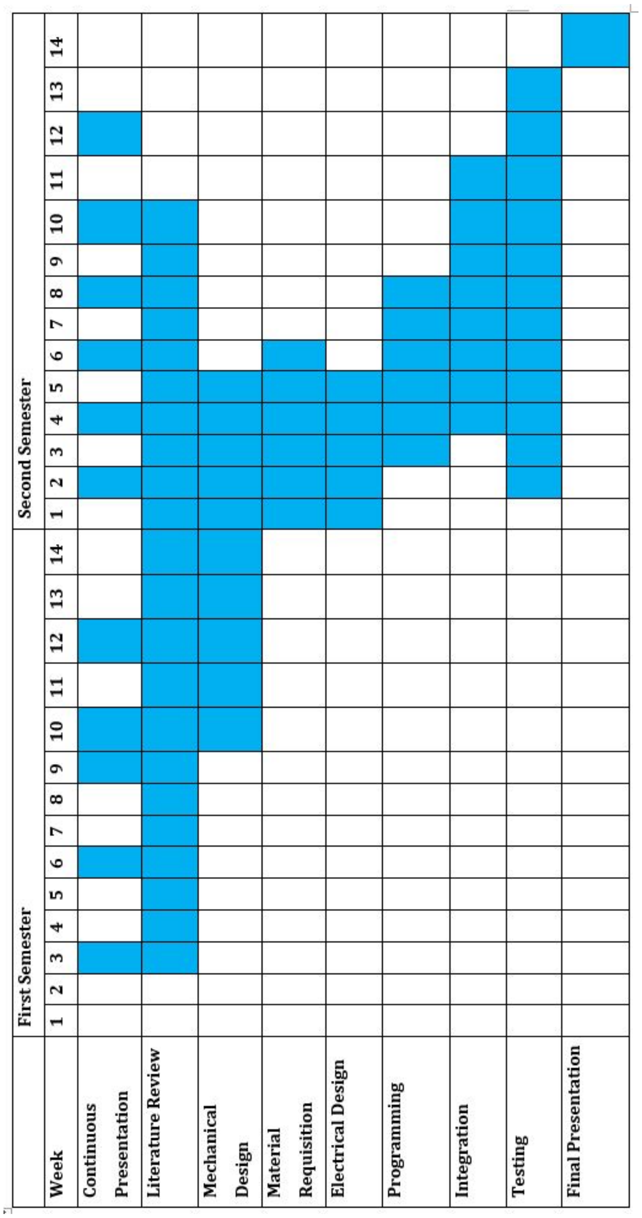

Figure 6.3: Project Timeline