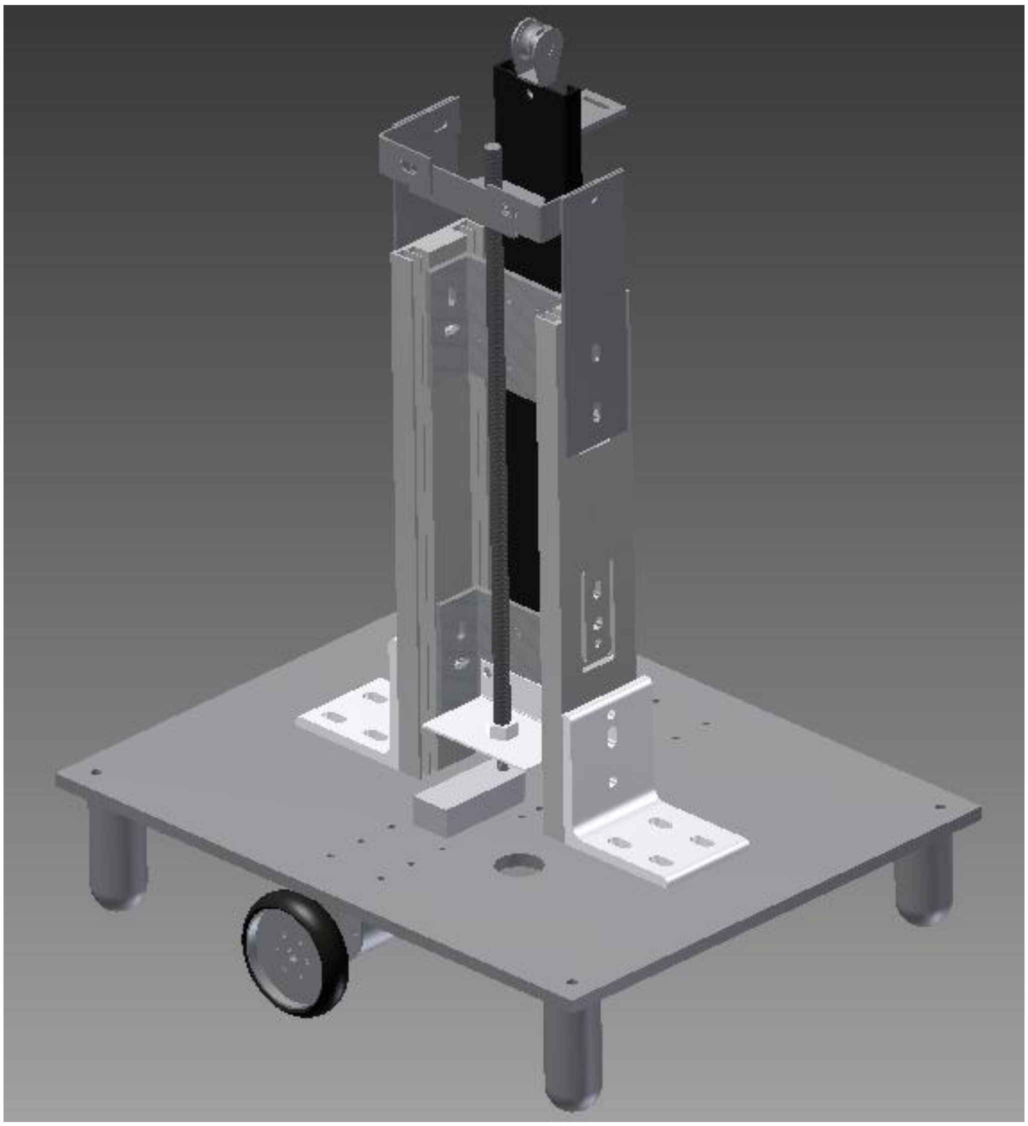
“The Librarian”
A Library Book Indexing Robot



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ENGR 340
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Executive Summary

The proposed senior design project is to design and build a proof of concept for a book indexing robot. Libraries use employees to shelf read, or check the order of the books on their shelves. The design team believes that this time consuming task could be performed at a great accuracy and reliability, and at a lower cost by a robot that autonomously navigates past each shelf in a library to scan and index the books. The library personnel would then be free to use their skills for other tasks. It uses a data acquisition system that utilizes a barcode scanner to identify each book and then compares the book's location, or its order on the shelf, to the library database. By moving past each shelf and adjusting to read the books on shelves of differing heights, the robot indexes all of the books in a simulated model library. It produces an output file of misplaced books and their locations for users. The full scale design will allow library employees to access the file from a library computer at the circulation desk. They will then be able to focus on the books that are out of order and move them to their proper locations, instead of checking every shelf visually, spending most of the time looking at books that are in their right locations.

This report summarizes the final design of a shelf reading robot proof of concept prototype. It covers the research, design, mechanical fabrication, programming, and electrical systems of the project. The full scale design would require more engineering and design work. This report details the prototype design and implementation, as well as detailing the requirements for both the prototype and full scale design robots. A business plan is included, with a full scale manufactured production price of $10,800 for the robot itself, plus additional labor costs for customizing the robot's programming for an individual library. While a number of automated retrieval and storage systems exist, preliminary research indicates that the robot is on the forefront of book indexing of existing library shelving environments, and the market for such a device would be hospitable to steady sales and revenue.

The team's prototype successfully navigates forwards and backwards along a bookshelf, scans barcodes on the spines of books, can scan books on shelves with different heights, and outputs the locations of the books that are out of order. It stops if an obstacle is placed in its path for safety concerns and to ensure that the robot is not damaged. A motor with a 90-degree shaft moves the barcode scanner up and down to adjust for the bottom and top shelves. The robot drives along the bookshelf using line sensor arrays that follow a black line on a white painted wooden surface. The robot can move forward along the bottom shelf, then backwards while raising the scanner to the appropriate height. It then moves forward to read the highest shelf, and outputs the locations of the books that need to be moved to their correct locations. Scanning accuracies range from 70% to 95%. The robot, called "the Librarian," successfully proves that with a larger budget, more time, and more engineers, a full scale production robot could be designed and built to function as a shelf reader in a library, replacing the hundreds of man-hours typically required in a library today using the standard manual shelf reading process.

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1 Introduction

1.1 Problem Definition

This project sought to solve the problem of misplaced books in libraries. Librarians are constantly frustrated by misplaced books due to library patrons placing them back incorrectly onto the shelves. For example, in the Hekman Library of Calvin College, which has over 1.7 million texts as stated in *The Chimes* 16 September 2011 issue[1], any book placed incorrectly is most likely lost until the next shelf reading session, potentially a year later. 'The Librarian' is a robot that is able to autonomously traverse the aisles of a simulated model library while scanning books to determine if they are in their expected locations. A report, in the form of a spreadsheet accessible to library employees at a circulation computer, is then be generated to communicate the results of the book indexing. The aim of the full scale robot is to save library employees the daunting task of shelf reading and therefore enable a better allocation of resources within the library.

1.2 Market Research

Research has shown that similar products have been designed and built, but there is no significant commercial market for such products. Robots have been designed to retrieve books from space-saving storage facilities[2,3,4] in a number of projects, both academic and commercial. There have also been some prototypes that automate the shelf reading process[5,6]. However, this project emphasizes the integration of such a robot with an existing library, using the library's current shelving system. Implementation of the full scale design would not require a complete reorganization of the physical setup of the library books, but would require adjusting the library's book labeling system. Furthermore, in an age when library funding is often at a premium, as evidenced by branch closings, employee reductions, and hour cutbacks[7], the investment in the full scale design would be a boon to libraries in many locations, especially those that would not have the budget to fully automate by drastically reconfiguring their book storage systems or building new ones. The niche for a product like the Librarian definitely exists.

1.3 Customer

The target customer for this project is the Hekman Library of Calvin College, the Grand Rapids Public Library, and other libraries with circulations of approximately 200,000 items per year[8]. The Hekman Library uses a Dewey-decimal process for book indexing and the Grand Rapids Public Library uses RFID for book indexing. However, for purposes of this project, we will be constructing a robot that uses barcodes as its data acquisition system. In the future, the data acquisition system would be adjusted to suit the particular customer requirements.

1.4 Project Team

The team consists of three seniors with mechanical concentrations in engineering (ME) and one with the electrical and computer concentration (ECE). All team members are graduating seniors in the Calvin College Engineering program. This project is the major focus for the capstone course of the Calvin Engineering program: a senior design course. In this report, the team members will collectively be referred to as 'The Bookkeepers'. Figure 1 below shows a picture of The Bookkeepers, who, from left to right are: Kobby Appiah-Berko (ECE), Andrew Dykhuis (ME), Nnamdi Maduagwu (ME) and Tyler Helmus (ME).

Kobby Appiah-Berko is a senior Electrical and Computer concentration student from Ghana. Kobby has had multiple internships over the past four years. Two major ones were with Johnson Controls in the summer of 2010 and most recently with Goldman Sachs in the summer of 2011. Kobby has previous programming experience in the C programming language, which has for that reason been chosen as the programming language for this project, and has also completed ENGR 304 (Digital Design) at Calvin. He has been assigned the tasks of interfacing with the library database and designing the book ordering algorithm.

Andrew Dykhuis has metal fabrication knowledge from his current and previous internships. He has experience with mills and metal forming, and used the associated skills and knowledge he has to help fabricate The Librarian's metal components for both the drive and the vertical systems. Andrew has worked on smaller mechanical projects previously. He worked with Tyler Helmus on the drive system and on the vertical movement system design required to move the data acquisition system, after which he fabricated most of the assembly. Andrew plans on earning his Ph.D. in the Department of Nuclear Science and Engineering from the Massachusetts Institute of Technology after graduating this May from Calvin College.

Nnamdi Maduagwu is a senior mechanical concentration student from Nigeria. For the past two summers, Nnamdi has been interning at Johnson Controls in Holland. Through the internship, he did feasibility analyses for 2012 instrument panel clusters as well as material selection and strain gage analysis for Ford Clusters. More recently, he is interning with Highlight Industries where he is performing mechanical risk assessment on most of their existing machines. Nnamdi was in charge of team communication with the adviser, coordinating group work on reports and proposals, and was in charge of data acquisition tests. After graduation, he plans on attending graduate school for an MBA after working a couple years in industry.

Tyler Helmus has completed ENGR 322 (Machine Design) at Calvin and has participated in multiple mechanical design competitions, including work in robotics and small mechanism design. He has also programmed in Java and his programming experience was utilized to program robot movement and vertical movement of the data acquisition system. Tyler helped lead the design of the vertical movement mechanism, and with Andrew Dykhuis' support, led the drive system design. Tyler will be working in new product development at Tennant, Inc. after graduating from Calvin College this May.

Figure 1: The Bookkeepers

1.5 Course Overview

Engineering 340 is the second and final part of a year-long capstone course that is required for graduation from the Calvin College Engineering program. Students were expected to work on a design similar to what will be expected of them in their future jobs and endeavors. The course placed a high emphasis on the overall design process. ENGR 340 focused on the completion of the project proposed in the Project Proposal Feasibility Study completed in the first half of the course, ENGR 339. This document can be found the team website (http://www.calvin.edu/academic/engineering/2011-12-team2/).

The remainder of the document gives an overview of the project. It outlines the project management, project requirements, the design norms that the team worked with, project design, project fabrication, and programming. The document then goes into further detail on the process of integration and testing of the system. Finally the report concludes with a business plan chapter where we show that the product will be marketable.

2 Project Management

The team was formed at the start of the academic year with a vague knowledge of the project's end result, although team members knew that the project would almost certainly evolve. However, we were comfortable with the prospect of working together as partners and were sure that we wanted to work on a project that was inter-disciplinary, bringing electrical and mechanical concentrations together. The team consists of three mechanical concentration engineers (ME) and one electrical and computer concentration engineer (ECE) and so might seem uneven in skill sets. However, Tyler (ME) has extensive knowledge working in the Java programming language and as such will be leading the programming portion of the project.

2.1 Team Organization

Since the decision to work on the current project, the team resolved to assign tasks to the individual with relatively higher experience in that particular area. For instance, Kobby, having prior knowledge on building websites, is the team website manager. The task lead is then supposed to pull in from the team any individuals that he needs to complete the assigned task.

The team reports to the team adviser, Professor VanderLeest of the Calvin College Engineering department. Professor VanderLeest provided feedback on various proposals, reports, and other documents throughout the project. Engineering Department assistant Michelle Krul, Lab Manager/Technician Bob DeKraker, Industrial Consultant Tim Theriault, Electronics Shop Technician Chuck Holwerda, and Metal & Wood Shop Supervisor Phil Jasperse provided valuable resources and advice throughout the project. They assisted in research, purchases, and the fabrication of the prototype. Chuck Holwerda provided the team with barcodes for data acquisition system component testing and for the simulated model library environment. Bob DeKraker has helped the team with purchasing by submitting the orders after Professor VanderLeest approved them.

The team reported to Professor VanderLeest on a weekly basis in the form of a memo. The memo was a status report that detailed hours spent working as individuals, hours spent working in total as a team both for that week and overall, accomplishments for the past week as well as future goals for the coming week, and finally any issues we may have had. The adviser then gave us feedback based on our write up.

The team was scheduled to meet from 1:30pm till 2:30pm on Mondays, Wednesdays and Fridays during the fall semester, and since the spring semester had a lot of work days instead of full class lectures for ENGR 340, the team used those days to meet as a group, in addition to whatever other group meetings were scheduled for that week. This time allowed us to communicate any new ideas and/or assign tasks to be done to individuals. Whenever any extra collaboration time is needed, time was scheduled based on the availability of the students in that given week and also the due date of the assignment. When the lecture periods of ENGR 340 were scheduled as group work days, the team met in the Calvin College Engineering Building to brainstorm new ideas, assign upcoming tasks, exchange feedback on work, collaborate on tasks that require the entire group, and fabricate and assemble the prototype.

2.2 Schedule

The team drafted a work break down schedule, shown as Table 1 below. A link to the work break down schedule may be found at http://www.calvin.edu/academic/engineering/2011-12-team2/DOWNLOADS.html. The intent was that the schedule should help us track our progress but also give us milestones and deadlines to work with. A list of the major tasks for this project may be seen in Table 1 below.

Table 1: Table showing major tasks for project completion

Task	Anticipated Duration [hours]	Actual Duration [hours]	Duration Estimation Error [%]	Expected Completion Date	Actual Completion Date	Status [%]
Market Survey	20	11.5	(43)	10/26/2011	1/27/2012	100
Research	15	29.5	97	12/9/2011	12/9/2011	100
Reports	88	308.5	251	5/11/2012	5/9/2012	100
Project Display	67	74.5	11	12/10/2012	4/19/2012	100
Project Management	30	70.5	135	11/11/2012	12/9/2012	100
General Testing and Debugging	40	224.5	461	5/11/2012	5/5/2012	100
Business Plan	78	13.5	(83)	12/9/2012	12/16/2012	100
Mechanical Systems	354	209	(41)	3/11/2012	4/30/2012	100
Electrical Systems	138	199.5	45	3/11/2012	5/5/2012	100
Combined Tasks	**830**	**1141**	**37**	**5/11/2012**	**5/9/2012**	**100**

Nnamdi Maduagwu (ME) was in charge of managing, updating and maintaining the schedule. The rating rubric employed to keep track of progress may be seen in Table 2 below. The intent for such a simplified format was consistency and to ensure that there are no incorrect estimations. It was therefore easy to glance at each task and get an overall feel for where it stood in terms of completion. It also reduced the time that was required to update the schedule, while still enabling the team to stay organized and on track for the major tasks.

Table 1 above estimated the duration for completion of the project to be about 1141 hours. As shown in the table above, all the tasks were either overestimated or underestimated. The most accurate estimation being that of the Project display where the error was only 11% above the actual duration. However, some notable overestimations are in the General Testing and Debugging, Project Management, and Reports categories. The above results are a testament to the fact that there is more that goes into a project than just the typical research, and build phases. Adequate documentation and project management is required to bring any project to completion. Ample time during and after phases of the project build is also required for testing and debugging the system.

Table 2: Table showing the rating rubric for the WBS

Percentage (%)	Status
0	Not Started
10	Started
100	Completed

Figure 2 below shows the time spent working on the project for the given months. The graph details the total hours logged by the team from September 23rd, 2011 to May 8th, 2012.

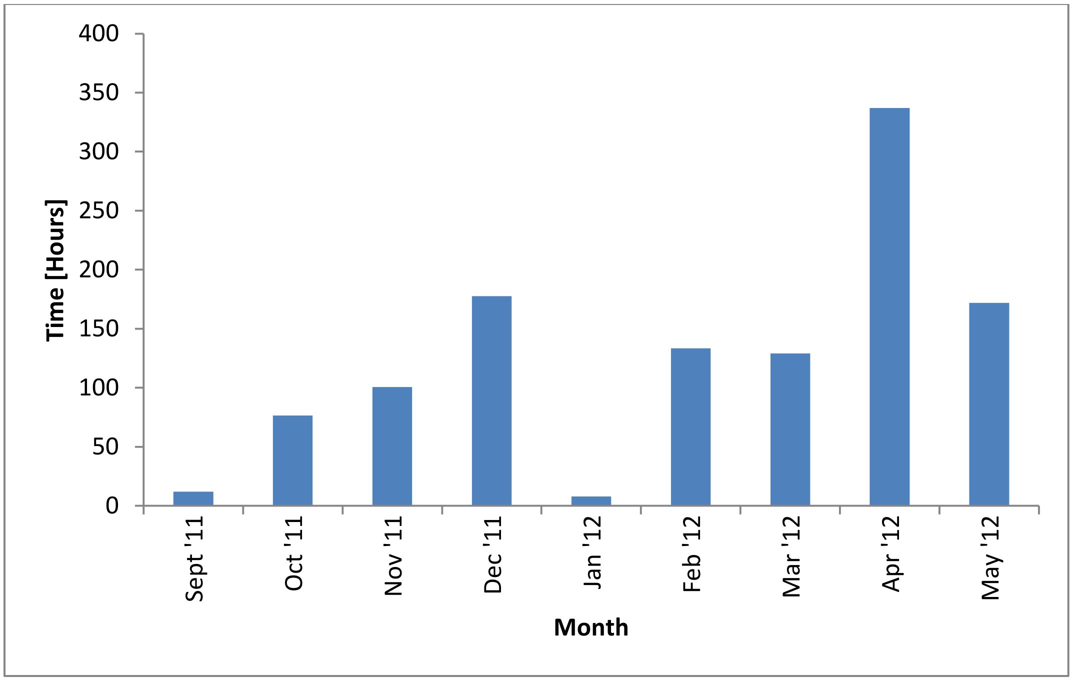

Figure 2: The Bookkeepers' Total Hours Spent on the Librarian

September did not have many hours, as the team was still being formed and the project defined. The sharp drop from the large amount of time spent in December to the smaller amount of time spent in January was due to the intensive Engineering Special Topics Elective courses that each of the team members were taking. The huge spikes in the months of April and May are accounting for the time spent constructing, and testing and debugging The Librarian.

2.3 Prototype Budget

The team submitted a budget of $1,650 for the completion of the prototype of the Librarian. A preliminary amount of $300 was released on 11 November 2011, and a full budget was approved in December. The final prototype budget breakdown for the group may be seen in Table 3 below. The numbers in red are accounting for donated items.

Andrew Dykhuis was in charge of budget management and kept track of our available funds with the aid of a spreadsheet. The spreadsheet detailed our approved budget, our purchases and the resulting available funds.

Table 3: Final Prototype Budget

Part	Unit cost	Quality	Total cost
Motors with encoders	$39.95	2	$79.90
Motor for vertical system	$50.00	1	$50.00
Arduino Processor	$50.00	3	$150.00
Mounting bracket	$7.95	1	$7.95
Tire set	$7.25	1	$7.25
Wheel hubs	$7.95	1	$7.95
Battery	$100.00	1	$100.00
RFID tags	$1.05	25	$26.25
RFID card reader	$39.99	1	$39.99
Infrared line finder	$6.50	2	$13.00
Barcode scanner	$29.99	1	$29.99
Barcodes	$0.00	20	$0.00
Web camera	$4.99	1	$4.99
Wiring and connectors	$50.00	1	$50.00
Bolts & screws	$10.00	1	$10.00
Motor control system	$90.00	1	$90.00
Black general purpose tape	$7.00	1	$7.00
IR LED & phototransistor sensor	$2.49	2	$4.98
Power regulators	$5.00	4	$20.00
Website template	$65.00	1	$65.00
Shipping	$50.00		$50.00
Cart (no wheels) 10" x 13" plate Donation	$60.00	1	$60.00
Cart (vertical support) Donation	$20.00	1	$20.00
Overhead			$100.00
Total			**$814.25**

Table 4 below breaks down the budget by category and also details how much was actually spent in the construction of the prototype. The final cost of the prototype as at May 5th 2012 amounts to approximately $622 out of the approved $814.25. The discrepancy is mostly due to the change in scope of the project as well as changes in design that occurred in the course of the semesters.

Table 4: Budget Breakdown by Category

Part	Budget	Purchased	Returns	Remaining
Motors	$150.00	$98.83	$0.00	$51.17
Electronic Components	$100.00	$166.32	$0.00	($66.32)
Vertical System	$50.00	$15.85	$0.00	$34.15
Structure	$40.00	$0.00	$0.00	$40.00
Wheels	$40.00	$40.11	$0.00	($0.11)
Battery	$50.00	$20.00	$0.00	$30.00
Sensors	$100.00	$101.70	$0.00	($1.70)
Vision system				
RFID	$80.00	$74.23	$0.00	$5.77
Barcode ID	$60.00	$63.96	$0.00	($3.96)
OCR	$25.00	$7.48	($7.48)	$25.00
Wiring	$25.00	$0.00	$0.00	$25.00
Bolts, screws, etc.	$20.00	$0.00	$0.00	$20.00
Misc	$75.00	$33.89	$0.00	$41.11
Total component cost	**$815.00**	**$622.37**	**($7.48)**	**$200.11**

2.4 Method of Approach

The team realized early in the fall semester that the project as a whole could be broken down into two major sections: the data acquisition system and the drive system. Both of which we thought could be potential independent senior design projects. This meant that we were not able to optimize both processes given our time and budget constraints. As a result, the team decided to focus its attention on developing the drive system while working with a basic data acquisition system. We understood however that there had to be a bridge between both systems and worked hard to seal any gaps, as seen in subsections below. The full system architecture can be found in the Design section of this document under the "System Architecture" heading.

2.4.1 Data Acquisition System

A barcode scanner, RFID scanner, and portable camera were purchased as of 11 November 2011. Testing was carried out on these data acquisition systems and the outcomes of the testing for each of the three systems were:

- Minimum acceptable book width for consistent reading.
- Maximum allowable distance away from book for consistent reading.
- Maximum drive-by speed allowable for consistent reading.

Consistent reading in this report was considered to be 95% and above accuracy, which translates to reading 19 out of 20 books. This percentage was our benchmark obtained from the estimated accuracy of Hekman library student employee shelf readers. Hekman Library Director Glenn Remelts estimated that they are accurate in shelf reading about 95% of the time.

The Bookkeepers used the test results to choose the best option for the data acquisition system. They integrated the electrical and physical aspects of the barcode scanner, RFID reader, or camera with the required mechanical and physical structures to mount it on the Librarian's base. The data collected is sent from the scanner, reader, or camera to a microcontroller to be processed and analyzed.

2.4.2 Drive System

The drive system provides the mobility required of the data acquisition system. The design of the drive system is addressed later in this document. The milestones for the drive system are as follows:

- Research drive system designs
- Research and purchase chosen drive system components
- Build working drive system
- Test drive system
- Integrate drive system with data acquisition system

Upon completion of the drive system, the team began building the data acquisition system's mechanical structure. The drive system is controlled by a microcontroller to maintain the Librarian's speed and proximity to the bookshelves.

3 Project Requirements

This section describes the requirements for the device. The goal is for The Librarian to be able to operate on each of the library floors in the case that more than one exists, which requires transportation between floors. Based on complexity, the team would enable the full scale design to use elevators.

The Librarian is expected to move from rest position to the designated area, index the books, and then return back to rest position. The Librarian is expected to be autonomous in carrying out its functions. The Librarian shall output a file indicating books that are out of place in the form of a Microsoft Excel spreadsheet. The order of the books shall be defined by the libraries database.

3.1 Product Weight

The Librarian shall not exceed 150 lbs. The chosen target weight is to ensure maneuverability if being handled by someone weighing 150 lbs. with a mechanical advantage of 1. Our weight choice is within the suggested rated capacities of elevators in office buildings: 3,500 pounds.[9]

3.2 Size

The size of The Librarian shall be compatible with the Library's environment. This includes being able to pass through a standard doorway that is no more than 32" wide as well as fit in an elevator.[10]

Our size choice is within the suggested inside dimensions of elevators in office buildings: 80" wide x 65" deep. The size requirement will be dominated by the lesser dimension of the two constraints.

3.3 Material

The materials used to construct The Librarian must not endanger exposed persons' health.[11]

3.4 Lighting

The Librarian shall be able to function at night.

3.5 Starting

The Librarian must be started only by an intentional control action taken by the operator.

It must be possible for The Librarian functioning in automatic mode to be restarted easily after a stoppage once the safety conditions have been fulfilled.

3.6 Transportation

The Librarian shall be capable of both autonomous and manual movement within the library.

3.7 Noise

The Librarian shall be quiet enough so that it does not disturb library patrons while it is operating, taking into account the technical progress and the availability of means of reducing noise.

3.8 Maintenance

Robot components which have to be changed frequently must be capable of being removed and replaced easily and in safety.

3.9 Manual

A user manual for the Librarian shall be provided, containing operation, maintenance, and safety information. For the proof of concept prototype, no manual will be provided.

3.10 Functionality

The Librarian is expected to be able to read no less than 95% of book labels correctly. This would translate to the prototype being accurate for 19 out of 20 books. The suggested accuracy for employees reading book labels is about 95% according to Glen Remelts of the Hekman Library, and this design enables the robot to meet the current standards at the very least, hence being a competitive option in terms of functionality.

3.11 Battery

The battery shall not leak any fluids in daily operation or in the case of a rollover.

The Librarian must be so designed and constructed that the battery can be disconnected with the aid of an easily accessible device provided for that purpose.[12]

3.12 Safety

The Librarian shall be able to stop at least 1 inch before an object in its path. The object shall be defined as anything that is at least 2 inches in height in the path of the robot.

3.13 Implementation

The robot is to be easily implemented into the current Library system, meaning that minimal modifications to the existing library need to be made. Minimal modifications means that the books are still stored on the bookshelves, and the library floor and shelves are not modified or altered during installation or use of the robot's navigation system beyond a customer-specified aesthetic and physical amount (ex. Changing the entire floor material of the library). One of our potential customers, Grand Rapids Public Library said, "We simply can't reshape our historic building to efficiently install something with a greater sort."

3.14 Speed

The Librarian shall index books at a rate that allows for complete indexing of a library with 250,000 books in one year, with minimal interference with day to day library operation, such as shelf reading only at night. A calculation of the actual time required to index Hekman Library can be found in the Integration, Test, Debug section of this report.

4 Design Norms

4.1 Background

Design norms are a key part of the design process. They function as moral guidelines.[13] Engineering design requires the use of some set of ethical guidelines. Normative design forces the designer to not just consider the technical aspects but also the ethical effects and trade-offs of the design. Many designs contain ethical constraints and requirements, and using design norms helps to categorize and prioritize these design norms. Not every design project will require consideration of all of the design norms, as certain norms do not apply. The team sought to consider the following three design norms especially in all of its design work for ENGR 339 and 340. The design norms were not simply overarching themes to be considered in a broad sense, but could be applied to the components, subsystems, and individual part design of this project, and therefore needed to be considered in all phases and scopes of design.

4.2 Transparency

Transparency means that there is open communication about the design. The customer clearly understands the decisions and results of the designers. The design is understandable. There are no hazy aspects of the design. A transparent design is characterized by consistency, reliability, and predictability. The Librarian exists to index books. It moves through the library and scans the books, comparing them to the database and allowing users to review the output file and streamline their reorganization of the bookshelves. Since The Librarian will often function when no humans are present, the design needed to make clear what it will be doing while it is running at night, or when the library is closed.

4.3 Integrity

Integrity is connected closely with completeness. A design with integrity has harmony of form and function. It is pleasing and intuitive to use. There are no superfluous additions that complicate the use of the design. Users understand it and its use simply makes sense. The design promotes human values and relationships. For this project, the above design norm applied because of the end result of our production model. By using The Librarian, human employees' talents and abilities can be better utilized in other areas in a library. The Librarian needs to be able to do its duties and only its duties. It has a job, and cannot be inadvertently tampering with library property, such as book damage, while it operates at night.

4.4 Trust

A design should be trustworthy. This means that it is dependable and reliable. The design performs its function not just once or twice, but over and over again. Users can depend on the design to fulfill its function repeatedly. For this project, the users must be able to trust that The Librarian will do its job, since The Librarian will be running when no employees are present. It needs to be trusted to not damage the library books, shelves, carpeting, desks, tables, or any other physical property of the library.

5 Design

5.1 Decision Methods

We used decision matrices for the majority of our decisions in both ENGR 339 and 340. In this report, when decision matrices are presented, the leftmost column contains the design criteria for that given design choice. The second column from the left contains the weight of each criterion. The weights were assigned based on relative importance compared to the other criteria. For example, if only two factors were considered and they were equally important, then they would both be weighted at 50%. The weights sum to 100% and each design alternative is given a score for each criterion on a scale of 1 to 10. Each score is multiplied by the applicable criterion's weight, and the weighted scores are summed. The highest total indicates that that particular design alternative best fits the team's priorities for the given criteria.

It is important to note that decision matrices do not give the absolute best choice necessarily. There is subjectivity in setting the weights of each design criterion and which criteria the decision matrix contains. However, the team thoroughly and carefully decided on design criteria for each choice and on the relative weights. It is important to note that the highest score is low on the 1 to 10 scale the matrix can still indicate the best design choice: that matrix then illustrates that all of the design options do not satisfy the design criteria exceptionally well. The color scheme in the decision methods is used in this report to help visually illustrate the top design options. The colors, descending from the highest score are:

Highest	Second highest	Third highest	Fourth highest

5.2 System Architecture

Figure 3 below is the system architecture for the project. The system was separated into two systems. The first is the locomotive system comprising of the distance sensors, line sensors, tachometer, drive motors, drive drivers and the vertical systems and the second the data acquisition system comprising of the barcode scanner integrated with the SD card. The two part system was adopted to prevent interrupt conflicts and also to allow for simultaneous functionality development and debugging.

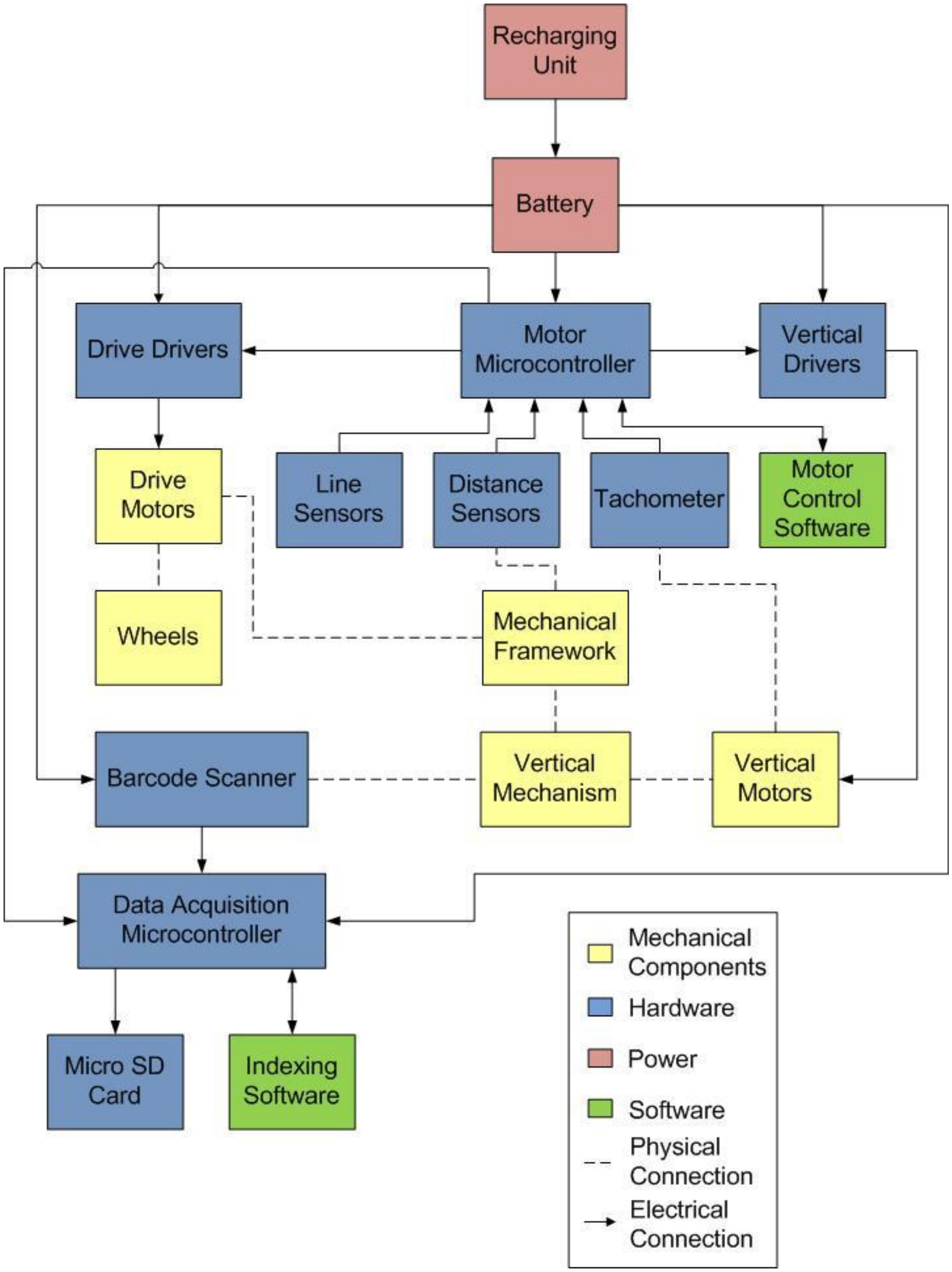

Figure 3: System Architecture

5.3 Drive Motor

5.3.1 Criteria

The choices of motors for the system were influenced mostly by availability on major motor retailer websites that had gear motors with the relative ranges for which we were interested in. We only investigate the websites with sufficient data to perform an analysis of the motor options. The choices were then compared on categories of: best speed and torque match to estimated loads, mounting ease, and speed control. The price was considered as well though the aforementioned criteria were held far above this as the motor prices were well within the stated budget. Operating speed and force to maintain the operating speed were estimated to be 1 foot/second and 1 pound force, respectively. Based on the wheels chosen, the wheel diameter was input to be 58 millimeters. Because minimizing the effects of the Librarian's operation on the library in which it functioned is important in the robot's design, the team chose to specify the wheels before the motors, since the wheels will directly contact the library floor surface. The motors could turn the wheels in such a way that the floor surface is damaged, either by their speed or by the robot's turning motion, but these effects can be eliminated through careful programming.

5.3.2 Alternatives

The suppliers chosen were Anaheim Automation and Pololu. The team looked into many different suppliers before choosing these two. The possible options were excluded based on three main areas: price, motor sizes, and availability of motor and gearing data. The motor types from Anaheim Automations which best fit our size, speed, and torque estimates were the BDPG-24-30 and BDPG-28-38 Series with ranges from 5.2-1297 RPM and 1.39-69.44 ounce-inch at peak efficiency. From Pololu, the 37D mm gear motors were closest to our design estimations. These gear motors result in speed and torque ranges of 63-397 RPM and 19.1-56.9 ounce-inch at peak efficiency. A total of thirty-three different motors were analyzed all of which can be found at http://www.calvin.edu/academic/engineering/2011-12-team2/DOWNLOADS.html#.

5.3.3 Decision

A spreadsheet was created to choose the best motor given the criteria. The spreadsheet was designed to contain the desired nominal speed of the cart (in meters/second, feet/second, miles per hour, or inch/second), the nominal force needed to move the cart (in pounds force, ounce, or milliNewton), and the diameter of the wheels (in meters, millimeters, inches, or feet). From this information, motor RPM and torque can be calculated using Equation 1 and Equation 2.

Equation 1

$$Angular\ Velocity = \frac{Translational\ Velocity}{\pi * Diameter}$$

Equation 2

$$Torque = Radius \times Force$$

All units were converted to the motor data units of RPM and ounce-inches so as to be calculated accurately. This spreadsheet also allowed the user to adjust which criteria are more important, the applied torque; the speed of the cart, or the build ease and this weighting is applied to the decision process. The decision was made by calculating the error for each motor from the user defined parameters using Equation 3 with other build parameters taken into account as well. Equation 4 was used to determine this decision number, the minimum of which is the best case given all the inputs and their weights. In this equation, T is torque, V is angular velocity, B is Build, E is presence of a mounted encoder, M is ease of mounting, and A is availability before the end of the semester. Variables A and E were rated on a pass fail basis of 0 or 1.

Equation 3

$$Error = \left|\frac{Actual - Desired}{Desired}\right|$$

Equation 4

$$Decision\,\# = (T_{error})(T_{weight}) + (V_{error})(V_{weight}) + \frac{B_{weight}}{E + M + A}$$

The spreadsheet also highlighted the three best combinations of speed and torque to be taken into consideration before making the purchase. These as well as the optimal case motor data and decision data can be seen in **Table 5**. The user defined data was a team decision based on estimates of the necessary speed to collect data efficiently at a constant rate and the resultant force to move the cart at that speed. The spreadsheet can be found at http://www.calvin.edu/academic/engineering/2011-12-team2/DOWNLOADS.html#

Table 5: Motor Decision Spreadsheet Top 7 Motors Only[14]

Operating Speed	1	ft/s				**Weights (0-1)**				
Wheel diameter	58	mm								
Force to move Cart	1	lbf				1	Build			
DESIRED RPM	100.4	rev/min				1	RPM			
DESIRED Motor Torque	9.134	oz-in				0.1	Torque			
			Build			**Peak Efficiency**		**Decision Data**		
Motor	**Gear Ratio**	**Price**	**E**	**M**	**A**	**Torque [oz-in]**	**RPM**	**Torque Error**	**RPM error**	**Total**
BDPG-24-30-12V-6000-R19	19	31	0	0.5	0	7	253	0.2336	1.5208	3.5441
BDPG-24-30-12V-6000-R27	27	31	0	0.5	0	10	178	0.0948	0.7735	2.783
BDPG-24-30-12V-6000-R51	51	31	0	0.5	0	18	94	0.9707	0.0634	2.1605
BDPG-28-38-12V-4000-R14	14	39	0	0.5	1	12	214	0.3138	1.1322	1.8302
BDPG-28-38-12V-4000-R27	27	39	0	0.5	1	24	111	1.6276	0.1059	0.9354
1445	67	39.95	1	1	1	45.5	119.3	3.9799	0.1885	0.9199
1446	100	39.95	1	1	1	50.0	79.5	4.4779	0.2076	0.9888

5.4 Wheels

5.4.1 Criteria

The wheels on the cart must support the weight of the cart, and should be designed for two years of operating time when considering failure analysis. They need to provide enough traction to allow for the cart's starting, stopping, and reversing movements without slipping and possibly damaging the carpet. Furthermore, since the cart functions to precisely move the data acquisition system along each bookshelf, the movements of the cart must be precise as well. No slipping of the wheels will be allowed. The cart needs to be able to move in small, precise motions, such as forward the width of a book, at a slow speed, so the wheels need to support this requirement with good grip. The motors were chosen with the design specification that the wheels did not slip. In sizing the wheels, they must not be too large, which would occur if they are chosen with too high of a design or safety factor. If the wheel diameter is too big, the wheels would cause excessive cart height above the floor, which would create issues and complications related to the data acquisition system accurate reading of the lowest shelves. The data acquisition system must be able to read or scan books with a label that is three inches above the floor, as determined by library visits by team members to Grand Rapids Public Library and the Hekman Library at Calvin College. Larger wheels would also require larger torque because of their larger diameters, and would therefore require larger, more expensive motors. Equation 2 shows the relationship between required torque, radius, and force. For a given force required to move the robot forward, larger diameter wheels require a greater torque.

For a constant force, increasing the radius of the wheel means that the torque must increase as well. The wheels must also not be too small, as this would mean that the wheels would need to rotate at much higher speed in order to provide the same horizontal speed for the robot. Smaller wheels would rotate too quickly for a medium torque. The data acquisition system's accuracy and ability to read the books depends on the cart moving at the proper speed. Smaller wheels (on the order of 1 inch in diameter) could cause the speed and motor programming to increase in complexity to accommodate the smaller wheels and their higher rotational speeds. The diameter of these small wheels was based on manufacturer motor speed data and a simple conversion to linear velocity for a 1 inch diameter wheel. The wheels must not also be overly expensive. They must not damage the carpet or be harmful to the environment due to toxicity or allergens, since they will be used on a robot that functions in a space used by a number of people on a daily basis. It was a preference that the wheels would fit the output shaft of the motors, in order to simplify fabrication of the robot. If the wheel hub did not exactly match the shaft, then additional labor and fabrication would be required. The team wanted to minimize the added time and complexity of doing so.

Since the wheel size and the compatibility with the motors are the most important factors, these two criteria were weighted at 20% and 25%, respectively. Cost, tread texture, and width of tread were the next most important factors, and were therefore all weighted at 15%. Material and safety were the remaining two criteria and 5% of the weight was allocated to each of those criteria.

5.4.2 Alternatives

Given the team's drive system design choices, there are no workable alternatives to wheels. Using a rotating track system would increase the potential for carpet damage, as well as decrease maneuverability by being overly sized. Tracks require more surface area, and require a longer distance to be in contact with the floor at any given time. Wheels are required to provide proper turning and movement capabilities to the cart. Other drive systems might utilize tracks or a greater number of wheels, but the team's design requires just two wheels and two casters. The number of wheels and casters is determined by the drive system design decision, and the size of the casters is determined by the cart's height, and will be chosen based on wheel choice. They are required to provide stability and ensure the cart's accurate turning and therefore accurate navigation through the shelves of a library. The wheel surface could be rubber or plastic. Smooth plastic or smooth rubber would not provide enough traction on the carpet of the library. There is a variety of textured surfaces on rubber wheels that therefore provide varying amounts of traction for the given carpet surface.

5.4.3 Decision

The best choice for the cart was a medium sized wheel, approximately two inches in diameter. This size ensured that the motors would be able to rotate the wheels at a proper speed, but also ensured that more torque on the motors was required. The wheel surface is a textured rubber. The wheels do not have a great deal of tread in order to minimize the friction when the robot is turning and pivoting on one wheel. The amount of texture is therefore in between very smooth and very textured rubber with large tread. The cart will primarily be used on a thin carpet surface which minimizes slipping. Table 6 shows the decision matrix containing the 6 wheel options that were determined to be possible options using research.

Table 6: Wheel decision matrix[15]

		Tamiya 70145 Narrow Tire Set $3.63 per wheel	4" Plastic Robot Wheel $0.50 per wheel	Waxman 6 inch diameter $7.25 per wheel	Solarbotics GM10 1" $2.35 per wheel	Tamiy Truck Tire Set $1.03 per wheel	Tamiya Sports Tire Set $3.25 per wheel
Cost	15%	6	10	2	4	9	5
Tread texture	15%	7	2	4	7	4	6
Width of tread	15%	9	2	3	3	9	7
Diameter	20%	8	6	1	4	5	8
Material	5%	7	7	7	7	7	7
Safety	5%	9	7	10	8	9	10
Motor compatibility	25%	8	1	1	4	5	8
TOTAL	10.0	7.7	4.3	2.7	4.7	6.4	7.2

5.5 Drive System

5.5.1 Criteria

Based on the location in a library setting, and the required navigation around tight corners and in between shelves, several criteria were compiled to rate and evaluate the drive systems. These criteria were then weighted based on importance to the overall function by the team:

- Maneuverability – defined as the ease with which the robot can make tight turns or changing direction. This was given a weight of 24% as libraries have many shelves that create many areas where acute orientation adjustments are necessary.
- Agility or traction – how well a specific command will be correctly output due to slip. This was weighted a 14%. Though this is a very important attribute for the speed and agility of the robot, it was rated a 14% and not higher because much of this can be corrected with a feedback control system and acceleration profiles for the motor to reduce the amount of slip.

- Construction simplicity – defined as how easily the design can be physically implemented: the simpler the better. This was rated a 17% because we as a team believe that simplicity leads to greater robustness in field operation. Quite simply, the fewer components there are, the less components can malfunction. With this in mind, we also didn't want to limit ourselves by only simple ideas.
- Programming simplicity – defined as how easy it will be to control with a program. If it is easy to control the robots movements because each input has a specific and predictable output, then it is likely that the programming will be simpler and will have less bugs or coordination errors. It was still rated a 12% because adding a few lines of code to compensate for any complexities would take time, but little else and the issue would be null.
- Price – mainly attributed to the number of motors needed but other construction techniques and materials are included as well. Rated a 12% because we did not want price to drive our design decisions even though it does need to be taken into account.
- Damage – defined as the likelihood this design will physically alter anything within the library, specifically damaging carpet due to tire turning or twisting. It is very important to customers that no damage will be done to any part of their library and thus this was given a weight of 21%.

5.5.2 Alternatives

Five different drive systems options were determined for consideration. The first was a parallel wheel system. In this, steering would be managed by one motor connected to all the wheels. This would rotate the wheels to a desired direction and individual motors would power each wheel (see Figure 4). This would allow for point to point movement without orientation change which would be very advantageous when aligning with a bookshelf or a specified path.

Secondly, the team considered a dual drive wheel system with the drive wheels located in the middle of the robot and casters added for stability on the front and back (see Figure 5). This allows for easy orientation change without total robot location change. Also, this is a symmetric system which would allow for easy direction changes (from forward to backward) and the same coding for driving backward and forward. This system will have a harder time staying on a straight course as minor fluctuations of one motor will lead to direction changes because the motors are lined up on the center of gravity of the robot and thus the moment needed to change direction will be less than that of a system with offset motors.

Third, the team considered a dual drive wheel system with the drive wheels located in the front of the robot (see Figure 6). This is very similar to the previous system with the only difference being that this system results in more stable forward movement as there is a greater moment required to change the direction of the robot. This results in less exact orientation changes and a trailing end that must be compensated for. This design is much less susceptible to errant motor glitches.

Fourth, the team considered a fixed, four wheel system. The most basic of the drive systems, this uses four motors linked in pairs (see Figure 7). It has a similar drive profile to that of the dual drive, middle placement system. It has simpler construction because there are four motors to mount and there is no need to worry about casters and balancing. Turning with this system necessitates dragging spinning wheels across the carpeting, causing carpet damage.

The fifth drive system has four casters at each corner and two drive motors set at 90 degrees from each other (see Figure 8). When the robot needs to go forward, the forward motion orientated motor lowers the wheel down and powers the forward movement with a similar action for the side to side movement. This allows for similar movement to that of the parallel wheel system with less complexity, though it will have trouble changing the orientation of the robot. Additionally, this motor configuration will cause some wheel drag when moving diagonally.

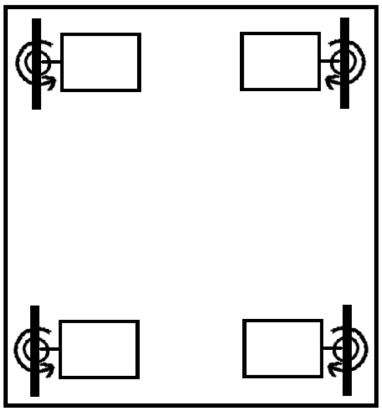

Figure 4: Parallel Wheel

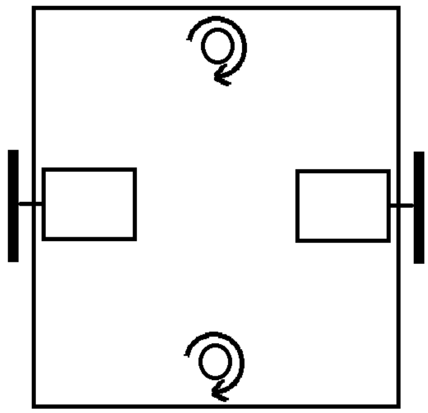

Figure 5: Dual Wheel, Middle

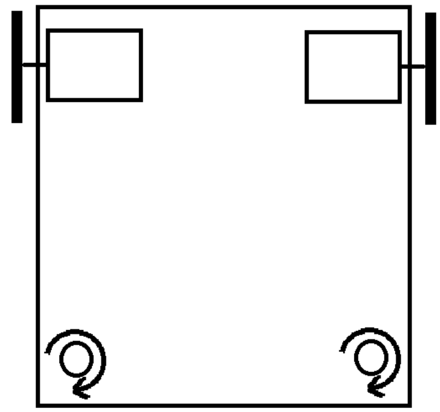

Figure 6: Dual Wheel, Front

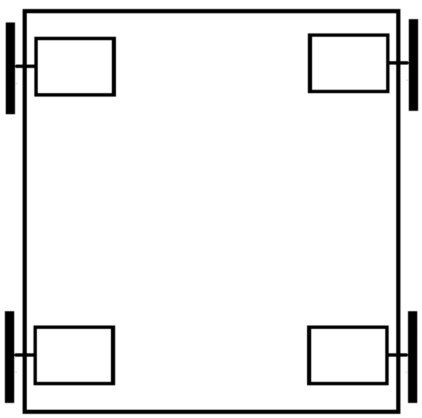

Figure 7: Four, Fixed Wheel

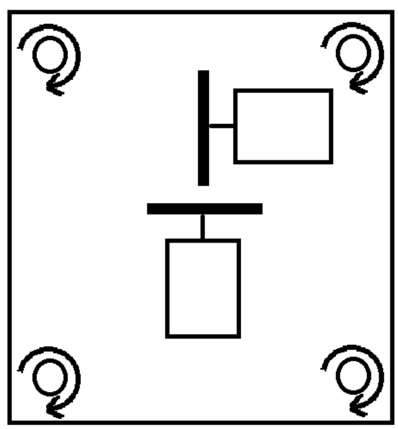

Figure 8: Four Caster, Bi-Directional Motors

5.5.3 Decision

Based on the characteristics of these drive systems, the criteria, and weights for each criteria, the team created a decision matrix to determine the best system for the project. This decision matrix is shown below in Table 7.

Table 7: Decision Matrix for Drive System

		Parallel Wheel	Dual Drive, Middle	Dual Drive, Front	Fixed Four Wheel	Coasters, Bi-Directional
Maneuverability	24%	10	9	7	8	4
Agility/Traction	14%	7	10	7	7	3
Construction Simplicity	17%	1	6	9	9	3
Programming Simplicity	12%	1	8	8	7	2
Price (number of motors)	12%	1	8	8	3	8
Damage	21%	3	8	7	1	4
Total	10.0	4.4	8.2	7.6	5.8	3.9

5.5.4 Design Iteration

After further analysis of the system, the team determined that additional casters were needed for the selected design. The casters would help with balancing the system better while reducing the load on the wheels to enhance performance. The casters would also enable the robot to effectively travel forward and backwards relatively easier, because the team was planning to mount line sensors in the central axis of the base where the wheels would have been in the initial design. Figure 9 below shows the modified base design for The Librarian.

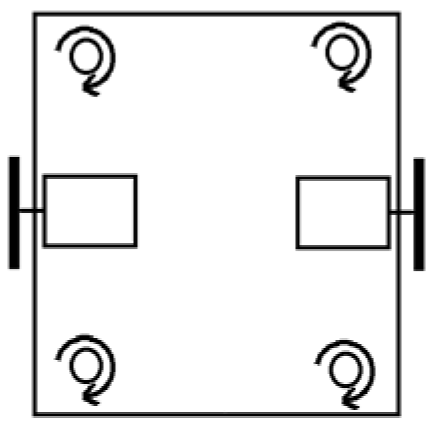

Figure 9: Four Casters, Dual Wheel, Middle

5.6 Navigation System

5.6.1 Criteria

The navigation system for the Librarian controls its movement around the library. The Librarian must move past each shelf at least once, making multiple passes for more than one shelf height. It must maintain the proper driving speed to ensure that the data acquisition system can properly read each book's label or scan its barcode. The navigation system must also make sure that the robot maintains the proper distance from the bookshelves and books. It makes sure the bookshelf does not hit, scrape, or do other damage to the side of the robot, and maintains the proper position for the data acquisition system to function accurately. Although multiple scanners could be used to eliminate multiple passes of the bookshelf with each scanner at a different height, the scope of this project along with the technical ability of the team members dictated that only one scanner be used. The team also wanted to demonstrate the ability to change shelf heights to prove that it was possible in order to show that the Librarian's full scale design would be able to avoid lower ceiling and doorways. Moving multiple scanners up and down would have been well outside the scope of this project, both in terms of cost and complexity.

Not only does the navigation system affect the accuracy of the robot's movement, but also its reliability. The Librarian must move in an overall straight line, but it must not stray too far from the required path because that could affect the accuracy of the data acquisition system. The navigation system must be reliable. The customer must be able to trust that the Librarian will function after everyone has left and the lights are most likely turned off. If the Librarian deviates from its courses to the point where it can no longer fulfill its function properly, accurately, or safely, then the navigation system has failed.

The Librarian's navigation system must have minimal impact on the library environment with which it interacts. Some systems, such as the position mapping system, require placing sensors on the shelves or floor for reference points. Other systems, such as the laser line and tape line sensing systems, require installing lasers in the library or putting a taped path on the floor surface. Both of these systems map out the required path for the Librarian. The floor should not be damaged, nor the library employees' and visitors' experience altered by any equipment or distractions that detract from the library's purpose and their experience. Patrons and employees must not be at any safety risk. The cart must be able to serve its purpose without going off course and becoming a tripping or other sort of hazard.

The ease of implementing and using the navigation also needed to be considered. Increased complexity of design and required work and time to get the system built, installed, and functional would increase the difficulty of the design choice. The customers should be able to understand the navigation system with one or two hours of training when the product is delivered, and using the instruction manual that would be included with the Librarian. For this project, the team focused on the ease of design from the designers' point of view, the ease of use from the customers' point of view, cost, accuracy, environmental impact, safety, and reliability. Based on the relative importance of each of the criteria, the weights in the decision matrix were determined.

5.6.2 Alternatives

The team considered laser line sensing, tape line sensing, and position mapping.

Laser line sensing utilizes lasers as the guides for line sensors mounted on the robot. The programming of the navigation system would ensure that the Librarian would stay on the path prescribed by the lasers. The lasers must be mounted in the library, and would be costly to implement in a library of even average size, due to the large numbers of shelves and rows that the Librarian would need to drive by.

Tape line sensing uses the same feedback and control as laser line sensing, but uses tape on the floor as guides instead of lasers. The tape must be placed properly on the floor, but it allows for the simplification of the programming required for the Librarian's movement, since turns and other non-straight paths can be added to avoid objects or add new sections of the library that need to be checked. Tape line sensing might have limited reliability because of foot traffic from patrons and employees. It also has an aesthetic impact because there is a line on the floor running along each shelf.

Position mapping would use a rolling ball to track the actual movement of the robot. There would be a "home" or reference point located at a chosen location in the library that serves as the universal reference point for the robot's positioning calculations. The robot would move according to a preprogrammed layout of the library and its shelves based on the feedback from the tracking ball. The system is complicated to implement since it requires the creation of a two dimension map of the library in the robot's programmed code so that the robot proceeds past each shelf and throughout the library in the proper sequence and at the proper speed.

5.6.3 Decision

The team decided that a tape line system would be the best for this project. The decision matrix used to help make the decision is show in Table 8. Especially pertaining to the scope of this project, the tape line system could be implemented and tested simply due to its removable nature, and was less expensive. Due to the time scale of the project, being able to quickly set up and change the path for the Librarian enabled the Bookkeepers to test more easily and frequently than a more costly, time intensive endeavor like position mapping or laser line system.

Table 8: Decision Matrix for Navigation System

		Laser line sensing	Tape line sensing	Position Mapping
Ease				
Designers	20%	7	9	1
Customers	20%	6	8	4
Cost	20%	2	5	3
Accuracy	20%	7	8	6
Environment Impact	5%	5	2	9
Safety	5%	9	9	6
Reliability	10%	8	6	5
Total	10.0	5.9	7.2	4.1

5.7 Line Sensors

5.7.1 Criteria

The line sensors must interface easily with the programming aspect of the navigation system. They must be not too expensive, since the Librarian will require an estimated four line sensors. Some line sensors come in arrays, in which only one unit must be purchased to get the benefit of multiple line sensors. The total cost required to equip the Librarian with all of its line sensors is considered in the decision matrix as the cost criterion. The Librarian will use the minimum number of line sensors, determined by the fact that there is enough feedback to adequately move the robot in a straight line so that the data acquisition system accurately collects data. The line sensors are a critical part of the robot's movement, so the more easily the line sensors can be mounted and integrated into the robot's controls and programming.

The size of the line sensors is also important, since the prototype to be delivered in May has limited clearance below the base and above the floor. The line sensors need enough room to be securely mounted and read the tape path on the floor accurately. The number of sensors needed may change as the team continues the navigation system design, so it may need to purchase more line sensors after testing the navigation system. Therefore, the higher the accuracy of the initial purchase of line sensors, the fewer additional dollars and time need to be allocated to future line sensor purchases. At the current time, the team will judge the accuracy by the minimum number of line sensors required to read a line, with smaller numbers being more desirable. The decision matrix will give lower numbers of required sensors for accuracy higher numbers in the matrix. Based on the relative importance of each of the criteria, the weights in the decision matrix were determined.

5.7.2 Alternatives

Individual line sensors can be purchased, in which each sensor functions as a node. Line sensor arrays have multiple nodes on one array, so one single line sensor array functions similarly to a number of individual line sensors.

5.7.3 Decision

The team decided to buy the line sensor that met all of the criteria best among the options researched. The decision matrix used to make the decision is shown below in Table 9.

Table 9: Decision Matrix for Line Sensors

		Line Sensor Array for NXT	Assembled Trekker Line Following Kit	QTR-8RC Reflectance Sensor Array	Electronic Brick - IR Line Finder
	Price	$44.95 + S&H	$35.95 + S&H	$14.95 + S&H	$6.50 + S&H
Cost	50%	3	4	6	9
Ease of integration	20%	4	4	8	8
Sensors required for accuracy	30%	2	4	2	8
Total	10.0	2.9	4.0	5.2	8.5

5.8 Distance Sensors

5.8.1 Criteria

The distance sensors need to be able to read distances accurately from a distance of 2 cm to 20 cm; these values were chosen based on the distances the robot would be operating from the bookshelf. Preference was given to those that were Arduino compatible and could implement pre-existing libraries to be able to more effectively use the sensors and avoid unnecessary coding.

5.8.2 Alternatives

The PING Ultrasonic, Sharp IR, and HC-SR04 Ultrasonic Distance Sensor Modules were considered for this sensor choice. Cost was less for the HC-SR04 because it was available through Amazon and thus the team could get free two day shipping. As shipping was a significant cost in this purchase and shipment could be made within 2 days, the HC-SR04 had a distinct advantage. Also, the HC-SR04 had easy accessible libraries in the Arduino forums.

5.8.3 Decision

The decision matrix for the distance sensor can be found in Table 10. Based on the importance of the libraries and cost, the HC-SR04 distance sensor was chosen.

Table 10: Distance Sensor Decision Matrix

		PING))) Ultrasonic Distance Sensor	Sharp IR Distance Sensor	Ultrasonic Module HC-SR04 Distance Sensor For Arduino
Cost	30%	3	5	8
Libraries	50%	0	0	10
Range	20%	10	3	8
TOTAL	10	2.9	2.1	9

5.9 Casters

5.9.1 Criteria

The casters serve to support the robot at the edges of the base, away from the support provided by the wheels. They must be mounted at precisely the proper height to ensure that the motors can effectively move the cart. The casters must be as close to 0.5 inches as possible to ensure that they can be mounted in an adjustable manner so each caster can be adjusted as needed. If they not the same height, the base of the Librarian will be slanted forward or backward, affecting the effectiveness of the data acquisition because the base would not be level. The base must be level so that the robot can accurately shelf read and move in a consistent, repeatable manner. The casters precise mounting is therefore critical to the robot's effectiveness, and the cost of this precision is necessary. The casters need to hold the base of the robot level as the robot is stationary and as it is moving forward, backward, or turning. This means that two casters, one in the front and one in the back, or four casters on each corner of the base may be required to maintain stability depending on the weight distribution of the cart. This also means that the need to be able to move in any direction equally well. They must not damage the carpet with excessive friction, and for cleaning considerations, must not have material that might get scrapped off on the carpet either. Since the Librarian is a smaller proof of concept prototype, to maneuver the robot, the required power will be less than the production model, and the required precision will be greater than the production model.

Since height is the main criterion, it was weighted at 50% in the decision matrix. Cost and mountability both received 25% since maintaining a strict budget was important to the team and the casters needed to be mounted quickly so that drive system testing, including line following, could begin as soon as possible.

5.9.2 Alternatives

For our chosen drive system, there are not alternatives to casters, but there are alternatives among the different types of casters. Based on the size requirements for the base and the distance between the bottom of the base and the floor, many casters that are available are too large. Further alternatives are eliminated by the fact that the caster needs to be able to turn in any direction with the same amount of very low torque. There are casters that are able to move in any direction, and the team will evaluate their cost as a part of the design decision. The team might also mount a smooth, low-friction plastic piece on the bottom of a metal bracket in order to have the ability to precisely determine the height of the caster, as well as utilize materials from the Engineering Shop that would not be an expense to the Bookkeepers.

5.9.3 Decision

The team used a decision matrix to make a design decision for the casters. It is shown in Table 11 below.

Table 11: Decision Matrix for Casters[16]

		0.5" from Pololu	0.4" from Robotshop	1" from Lattice Instruments
Cost	25%	6	8	3
Height	50%	9	6	4
Mountability	25%	7	4	3
TOTAL	10	7.8	6	3.5

5.10 Vertical Lift System

5.10.1 Criteria

The vertical lift system must be able to deliver the data acquisition system to heights of 3 inches and 7.5 feet. In order to accommodate doorways or any path that has a height of less than 7.5 feet, the vertical drive system must have an extension part that can facilitate these possible areas of the library. For our prototype, we are assuming that if the system can reach 2 shelves, it can then be easily expanded to reach any shelves in a 7.5 feet window when brought to full scale.

Other criteria that influenced the decision of the vertical lift system were the complexity of the coding required to make the system function properly, the complexity of the fabrication, the weight of the system, the systems stability and the timing required to purchase and complete the sub components of the system. The timing criteria was meant to be a determining factor as to which system would be picked for the prototype phase assuming more than one alternative came out on top from the decision matrix.

The weights used in the decision matrix are shown in Table 12 below. The choices of the assigned weights are further explained below.

5.10.1.1 Cost

The assigned budget for the vertical drive system for the prototype is $112. For purposes of the prototype, this meant that whatever design we chose should cost below the allotted budget. Looking at all of our options, we observed that we could afford all the components for all the systems, with some being cheaper than others. Hence, the cost weight is assigned only 10% of the total importance factor. The choice for the different scaling across the table helps us estimate which system might allow us to invest a portion of our budget elsewhere if necessary.

5.10.1.2 Height Factor

The height factor is a measure of how height the vertical system has to stand while still meeting the requirement of getting as high up as 7.5 feet. Since all the systems meet the height requirement, to make this criterion more meaningful, a common dividing factor of the base height was used to divide the range. For purposes of interpretation, a lower base height is indicated with a higher score. A weight of only 5% was used because all the systems fundamentally meet the height requirement.

5.10.1.3 Complexity (Fabrication)

The complexity of fabrication was one of the major players in the decision matrix; hence it was assigned a weight of 30%. This is because, considering the scope of our project, a system that is able to function with minimal effort in putting together is better for the progress of the prototype because it allows us to spend more time in more needed areas.

5.10.1.4 Complexity (Programming)

The complexity of programming held a weight of 15%. This indicates average importance in implementation with the system. This is because all of the systems basically require the same amount of coding, even though they might require different forms of coding. This criterion however, helps the team evaluate the practicality of each of the options.

5.10.1.5 Weight

The weight of the system selected is very important for the progress of the prototype. The score of 20% reflects the importance of designing a system that meets the weight requirement of 150lbs for the final product.

5.10.1.6 Stability

It is necessary for whichever system selected to be stable, because that affects the performance of the motors. Where two systems have the same weight, the more stable one is the better option. Both the weight and stability criteria are supposed to work hand in hand. And so with a score of 20% and a combined score of 40%, that makes the weight and stability of the system the most important deciding criteria.

5.10.1.7 Timing

As stated earlier, the timing criteria was intended to be the deciding factor for any systems that might prove equal over the decision matrix. The system that could be built earlier would be the choice for the prototype. In this decision matrix however, we did not necessarily have to make use of this criterion because there was one clear winner.

Table 12: Decision Matrix for Vertical Drive System

	Weight	Platform	Swinging Arm	Dual Slide Dual Motor	Drawer Slides
Cost	10%	6	5	3	9
Height Factor	5%	3	3	2	2
Complexity (Fabrication)	30%	1	6	9	9
Complexity (Programming)	15%	4	1	8	8
Weight	20%	2	6	4	8
Stability	20%	9	6	4	2
Timing	15%	1	1	4	4
Total (Production)	10.0	2.5	2.7	3	3.8
Total (Prototype)	11.5	2.6	2.8	3.4	4.2

5.10.2 Alternatives

The alternatives came as a result of a team wide brainstorming activity. Several options were considered, and the requirement that the base height of the vertical drive system has to be low enough to easily maneuver through doorways, elevators and the like was the most important criterion. The alternatives are discussed below.

5.10.2.1 Platform

The platform system functions with the same principle behind a scissors lift shown in Figure 10 below. This option would most likely require a pneumatic cylinder for implementation. The system would be required to fold down when not in use and be able to achieve a range of 7.5 feet. However, implementation of this system might require a wide base and a powerful energy source.

Figure 10: Platform model for Vertical Drive System

5.10.2.2 Swinging Arm

The swinging arm system employs the same principles used in lifts or drilling devices. This would require the arm to be able to pivot about a center arm and with the aid of bar linkages in order to keep the orientation of the barcode constant the whole time.

For future production, such a system could also be telescoping, and be controlled with control systems. Such a system might permit the implementation of a lower base height.

5.10.2.3 Dual Slide Dual Motor
The dual slide dual motor functions as a telescoping device. The base device allows the indexing device to be mounted to an inner shaft capable of going the range of 4 feet. The shaft would also be connected to another shaft that can also go a range of 4 feet. Therefore, the full range of 8 feet would be achieved.

5.10.2.4 Drawer Slides
The drawer slides implements the same principle with the dual slide dual motor design. However, the system is simpler because it can function with only one motor. A self-locking motor would be used; this would ensure that the slides do not drop down when stopped.

5.10.3 Decision
After computing the numbers in the decision matrix, the “Drawer Slides” option was rated the highest. It has the advantages of timing and the relative simplicity of fabrication and programming. The system was also expected to be lighter than the other systems even though we speculated it might be relatively less stable. Fabrication and testing has shown that this is not a concern, however.

5.11 Major Vertical Lift System Components
Once the vertical lift system design was chosen, the team began to research and order components. The major purchases included the motor with a 90-degree shaft, hereafter referred to as a “90-degree motor,” and the drawer slides. The rest of the vertical lift system was to be fabricated in the Calvin College machine shop to create the custom components to fit the specific dimensional requirements of the design.

5.11.1 Drawer Slides

5.11.1.1 Criteria
The barcode scanner moves on a secondary track that is raised by the screw shaft carriage mounted to the drawer slides. The drawer slides need to capably move the screw shaft carriage up and down, allowing the scanner to move vertically with two degrees of freedom – one due to the screw shaft carriage, and one due to its sliding on a track mounted on the screw shaft carriage. The drawer slides need to have enough travel to move half of the distance of the total vertical distance that the barcode scanner needs to cover. With the chosen drawer slide vertical system design, the barcode scanner moves up and down relative to the base, as well as to the screw shaft carriage. The two extreme barcode scanner positions are shown along with a representative intermediate position in Figure 11. Based on the relative importance of each of the criteria, the weights in the decision matrix were determined.

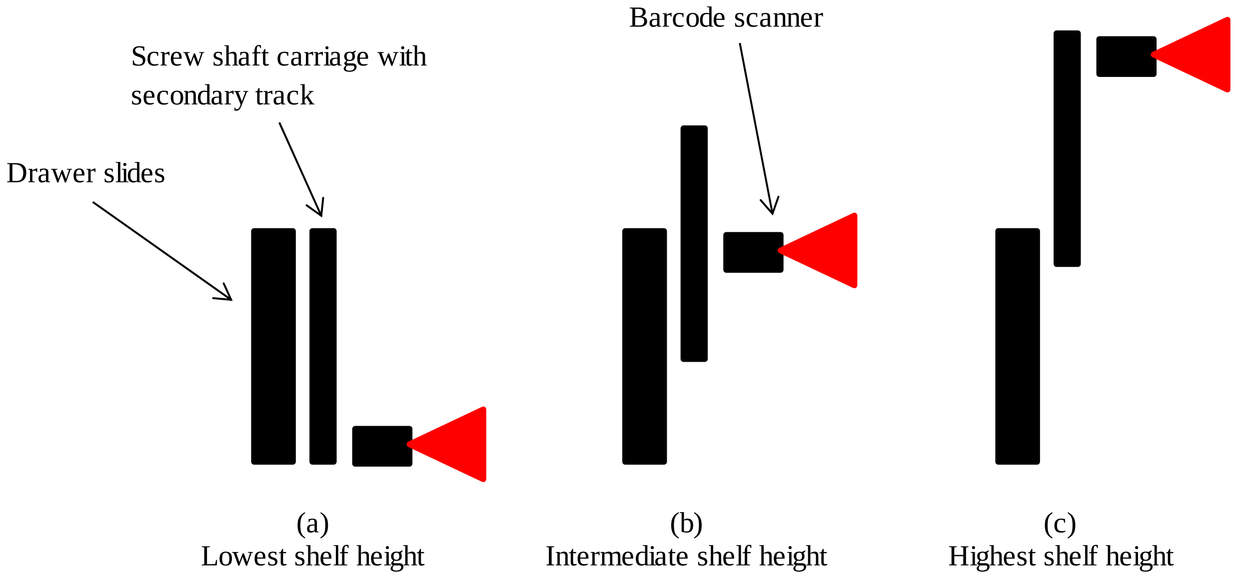

Figure 11: Possible vertical system positions

5.11.1.1.1 Travel

Based on measurements of bookshelves at Calvin College in various locations, including the Hekman Library and the Engineering Reading Room, the team concluded that if the scanner could read from three inches above the floor all the way up to twenty inches above the floor, then two standard bookshelves could be indexed in the proof of concept demonstration using a simulated model library. Therefore, he drawer slides needed to be able to provide ten inches of travel for the screw shaft carriage. Because of this critical requirement, the weight for this criterion was set to be 30%. The maximum height would scale with the size of the library shelves. If a library had six shelves, the maximum height would be around eight feet, depending on the exact shelving units being used. The minimum height would remain the same, and as the wheel size was scaled up to accommodate the increased size of the robot base, the vertical system could simply be moved either forward or backward from the centerline of the base so that the wheel would not interfere with the data acquisition system.

5.11.1.1.2 Sliding friction

The drawer slides needed to be able to slide smoothly to facilitate smooth motion of the barcode scanner and reduce the power required by the vertical lift system motor. The less friction there is as the drawer slides function, the quieter the barcode scanner movement will be. Because of the criticality of a smoothly sliding vertical system, the weight for this criterion was set to be 40%.

5.11.1.1.3 Removability

Since many of the parts of the vertical system are connected directly to the drawer slides or are connected very close to it, for ease of fabrication, assembly, and disassembly, if the drawer slides can be taken apart, they will be easier to work with and will also help facilitate the efficient fabrication of the vertical lift system. The weight for this criterion was chosen to be 20% in order to help ensure that the fabrication of the vertical system proceeded efficiently and that the system could be assemble and disassembled without significant labor time.

5.11.1.1.4 Cost

The drawer slides could not be more than half of the allocated vertical system budget, even though they are one of the major components of the vertical lift system, since the budget for the vertical lift system was $50.00, and the motor, screw shaft, and other components were also possible purchases. This cost also includes labor cost in assembling, modifying, and/or building the drawer slides. Purchased drawer slides have far less labor required by the team involved in their fabrication, but the in-house drawer slides might require less time for modification. Because of the team's efficient use of the budget and desire to maintain fiscal responsibility, the team allocated 10% of the weight to this criterion.

5.11.1.2 Alternatives

Drawer slides can be purchased in a wide variety of lengths, amounts of travel, and strengths. A sliding track system could have been designed and built by the team in-house to increase customizability. In-house fabrication would be more time consuming and the team expected the final product would be of lower quality and precision than a purchased component from a drawer slide manufacturer.

5.11.1.3 Decision

The team's decision is shown in the decision matrix below, in Table 13. Purchasing drawer slides proved to be a good decision based on the fulfillment of the performance expectations with regards to the design criteria in actual use.

Table 13: Decision Matrix for the Drawer Slides[17]

		Fulterer FR5000 Full Extension Slide 10"	In-house fabricated drawer slide
Travel	40%	4	4
Friction	30%	2.7	1.2
Removability	20%	1.2	1
Cost	10%	0.7	0.6
TOTAL	10	8.6	4.9

5.11.2 Vertical Lift System Motor

5.11.2.1 Criteria

The motor for the vertical lift system needs to be a 90-degree motor so that it can rest on the base of the Librarian and drive the screw shaft to raise and lower the screw shaft carriage, thereby moving the barcode scanner up and down as required. A 90-degree motor is also self-locking, and the barcode scanner is not allowed to fall down when the motor is not running, which helps fulfill the design norms the Bookkeepers focused on (integrity).

5.11.2.1.1 Speed

The motor needs to turn at a speed so that the screw shaft carriage does not move at such a slow speed that the barcode scanner movement is a significant delay in the shelf reading operation of the Librarian. The team wanted to maximize the speed of the barcode scanner, which meant that the rotational speed of the motor was to be maximized. Using the threads per inch of the screw shaft and the speed of the motor, the speed of the barcode scanner in the vertical direction could be calculated. The team weighted this criterion significantly, at 50%.

5.11.2.1.2 Fabrication

Mounting the motor needed to be able to be completed in no more than two days to ensure that mounting it and coupling it to the screw shaft was not a bottleneck in the critical path of the prototype fabrication completion. Motors that come with mounting brackets, or had partially flat shafts or key ways are generally easier to mount and can be mounted in a shorter length of time when compared with those that do not. The team looked at these possibilities when evaluating motors. The team weighted this criterion at 25% of the total.

5.11.2.1.3 Cost

The team could not afford to go over budget for any of the purchased components, so avoiding the purchase of an overly costly motor was paramount. The team weighted this criterion at 25% of the total.

5.11.2.1.4 Torque

The motor simply needs enough torque to be able to raise and lower the screw shaft carriage, so since all motors considered had enough torque, the amount of torque was not a differentiating factor, and therefore was not included in the decision matrix, and received no weight in the decision.

5.11.2.2 Alternatives

The 90-degree motors that the team found through research varied in torque and speed. Research also showed that the number of motor options was fairly limited; although there are lots of 90-degree motors available for purchase, the size requirement of this project severely reduced the number of motors that could be used for the Librarian, as the vast majority of 90-degree motors were far too large for this project.

5.11.2.3 Decision

Supporting data for this design decision is shown in Table 14 and Table 15 below. Table 14 shows the target range of the vertical speeds of the data acquisition system. The range of motor speeds highlighted in green shows the target range, which was chosen because preliminary research had shown the range of speeds on motors that were small enough to mount on the Librarian’s base. From this preliminary research, further research provided the data for Table 15. The chosen motor is shown in the decision matrix below in Table 16.

Table 14: Motor data for possible 90-degree motors

Motor RPM	Scanner speed (in/s)	Screw Shaft Speed (rev/s)	Screw shaft (threads/in)	Half of scanner speed (in/s)
60	0.25	1.0	8	0.125
80	0.33	1.3	8	0.167
100	0.42	1.7	8	0.208
120	0.50	2.0	8	0.250
180	0.75	3.0	8	0.375
240	1.00	4.0	8	0.500
300	1.25	5.0	8	0.625
360	1.50	6.0	8	0.750
420	1.75	7.0	8	0.875
480	2.00	8.0	8	1.000
540	2.25	9.0	8	1.125

Table 15: Specific 90-degree Motor Data

Voltage (V)	90-degree Motor	Unloaded RPM	60%	75%
6.0	143:1 from Solarbotics	78	46.8	58.5
6.0	216:1 from Robot MarketPlace	84	50.4	63
6.0	224:1 from Trossen (GM3)	43	25.8	32.25
6.0	224:1 from The Robot MarketPlace	43	25.8	32.25
4.5	120:1 from Pololu	120	72	90
6.0	120:1 from Pololu (with scaled up specifications)	160	96	120

Table 16: Decision Matrix for the 90-degree Motor[18]

		143:1 from Solarbotics	216:1 from Robot MarketPlace	224:1 from Trossen (GM3)	224:1 from The Robot Marketplace	120:1 from Pololu
Speed	50%	5	4	4	4	8
Fabrication	25%	5	2	5	5	7
Cost	25%	6	3	8	6	8
TOTAL	10	5.3	3.3	5.3	4.8	7.8

5.11.3 Screw Shaft

The screw shaft transmits the rotational power of the 90-degree motor into vertical motion of the screw shaft carriage. It is the method used to move the barcode scanner up and down so that the Librarian can read different shelf heights.

5.11.3.1 Criteria

The screw shaft must be long enough to provide adequate vertical travel of the screw shaft carriage in order to raise the barcode scanner to the proper height. It must be able to support the weight of the screw shaft carriage by holding the nut of the screw shaft carriage connection. It must have a large enough diameter to facilitate effective coupling to the 90-degree motor. The screw shaft cannot slip on the motor, or else the barcode scanner's vertical motion will not be consistent and reliable, meaning the Librarian would not be able to carry out the task it was created for.

5.11.3.2 Alternatives

Instead of a screw shaft, a ball screw could be used. Ball screws have threaded shafts where ball bearings act as a precision screw. They can handle high thrust loads, and possess very little internal friction[19]. Lead screws can have square threading, which is the most efficient threading and has the least amount of friction when compared to Acme threads (29 degree angle), V-threads, and Buttress threads, which are triangular in shape[20]. Lead screw systems have high internal friction. They are less efficient that ball screws, but also typically cost less.

5.11.3.3 Decision

Based on the budget of the project, ball screws presented an unnecessary additional cost. For the thrust loads of this project, a V-thread lead screw is adequate. Although the friction is higher with a lead screw, which will be referred to as a "screw shaft" for the rest of this document, the cost is much lower. Additionally, this application does not require high precision movement since the barcode scanner has a broad scanning width. The diameter of the screw shaft was large enough (5/16 inch) so that the 90-degree motor could be coupled to the screw shaft, and the threading is 18 threads per inch. Since this diameter and threading combination is common, finding a nut to link the screw shaft carriage connection to the screw shaft proved simple, and this fabrication simplicity was considered in the design choice.

5.12 Microcontroller

We are currently using two microcontrollers. The first is the Arduino Mega 2560 to handle the locomotion of the robot and the operation of the vertical lift system. The second microcontroller is the Arduino duemilanove to handle the triggering of the barcode scanner, the collection of the data and procedure for storing it onto an SD card. We used two microcontrollers to afford us the luxury of simultaneous code development and debugging. The second microcontroller, i.e. the Arduino duelmilanove, did not come to us at an extra cost. It was owned by a team member who offered it for the purpose of being able to overcome our time constraint. Using a second microcontroller did not add substantial complexity. The data acquisition system of the robot is a standalone portion of the robot functionality and doesn't require heavy interaction with the locomotive system of the robot. The overlap in functionality between the locomotive system and the data acquisition system occurs when the robot is in reverse. In that situation the locomotive function sends a signal to the data acquisition system to pause scanning when the robot is in reverse. For our production model, all the functions will be run by one microcontroller thereby reducing the cost of purchasing an extra microcontroller and avoiding the complexity of interaction between the two microcontrollers.

5.12.1 Criteria

The microcontroller must have substantial supporting libraries as well as community support. It must be easy to use and well supported. It is very important that the microcontroller has a lot of documentation readily available such as open source code, videos and failure stories to aid expedite our design phase.

It is also crucial that our microcontroller has hardware to handle pulse-width modulation as well as communication protocol support for human interface devices such as barcode scanners. Pulse-width modulation is a necessity for speed control to improve battery life during extended runtimes. The microcontroller should be programmed in C or be compatible with a C-based language. The microcontroller should be rich in features to be able to accommodate several analog and digital pins. The microcontroller must have an integrated voltage regulator and ample flash memory to handle our code.

5.12.2 Alternatives

We considered a number of different microcontroller families suited for robotics. Other alternatives to the Arduino family are Parallax microcontrollers, ZX-24a, and Pololu microcontrollers. Alternatives such as the ZX-24 and Pololu microcontrollers did not offer us a large enough support community. The documentation for these microcontrollers and the available examples were not up to what we required in terms of specifications and performance data.

5.12.3 Decision

Our conclusion after considering our various criteria was to proceed with the Arduino Mega and Arduino duemilanove. These microcontrollers offered a combination of a large support community as well as well detailed documentation. They also had all the features necessary for us to carry out our project. Also, the Arduino microcontrollers provide a platform to be able to mount shields which allow USB and SD card capability which allow us to interface with our barcode scanner as well as our SD card. The decision matrix for this choice is shown in Table 17.

Table 17: Decision Matrix for Microcontrollers

		Arduino Duemilanove	Arduino Mega2560	Arduino Uno	ZX-24a	Orangutan SVP-1284	Arduino Pro
Cost	10%	4	2	4	4	2	6
Power	5%	4	4	4	5	4	8
USB Capability	10%	5	5	5	0	5	0
Flash memory	35%	2	6	3	2	4	1
Number of ins & outs	40%	5	10	5	3	8	5
TOTAL	10	20	27	21	14	23	20

5.13 Motor Drivers

5.13.1 Criteria

There were many factors which went into the decision for the motor drivers. There are many features that help to improve the longevity, functionality, and performance of the robot. Though many of these features were examined, for this prototype, it was determined that these would not be the deciding factors in this decision.

5.13.1.1 Cost

The team was working on a budget, and needed to buy motor drivers that both fit the budget and the criteria.

5.13.1.2 Assembly

With limited time and soldering abilities, it was preferable though not necessary to have a board that came preassembled. This would ensure that the connections were well made and would reduce the risk of damaging the board during installation.

5.13.1.3 Pulse-width Modulation (PWM)

Pulse-width modulation was a very important consideration because, from the research, it was learned that this can drastically reduce power consumption. For a robot that will be running continually at low speeds which may need to be adjusted, this is a necessary consideration.

5.13.1.4 Voltage and Amperage

The voltage and amperage ranged for all of these allowed for the operation we were searching for but higher scores were given to those that allowed for adjustments higher and lower than the necessary range of the motors. The motors were tested for voltage and amperage requirements by attaching the barcode scanner and setting it to a speed where it read the barcodes consistently. The voltage was found to be 2 volts and the constant operating amperage was 0.55 amps. The drivers which more closely associated around these values got higher scores.

5.13.1.5 Regenerative braking

Regenerative braking is a feature that would also improve battery life but is much more useful when quick and often braking is necessary. As this is not the case here, it is given a lower priority.

5.13.1.6 Circuit Protection

Circuit protection is important for the longevity of the drivers. As this is a prototype, this is not as important as other considerations.

5.13.2 Alternatives

The alternatives for the drive motors were chosen based on functionality and price. A range of drivers were considered to determine the best choice. The drivers chosen all met the requirements for the system as stated before.

5.13.3 Decision

The decision was made to purchase the Pololu Dual Motor Driver because of its cost effectiveness and good fit with the required voltage and amperage ranges. Additionally, as other parts were being ordered from Pololu, an additional shipping reduction further aided the cost effectiveness. The decision matrix for the motor drivers is shown in Table 18.

Table 18: Decision Matrix for Motor Drivers

		DFRobot Arduino Compatible Motor Shield	Sabertooth dual 5A motor driver for R/C	Adafruit Motor Shield Kit for Arduino	Pololu TB6612FNG Dual Motor Driver Carrier
Cost	20%	4	1	4	9
Assembly	5%	8	8	2	8
PWM	40%	10	10	0	10
Voltage Range	10%	2	3	9	9
Amperage Range	10%	8	3	4	9
Regenerative Braking	5%	0	10	0	0
Circuit Protection	10%	0	10	5	5
TOTAL	10	6.2	6.7	2.7	8.5

5.14 Data Acquisition Components

5.14.1 Background

The team considered three options for the data acquisition system: RFID, a barcode scanner, or a web camera using image recognition software. In order to determine the best option for the final prototype, the team wanted to test each possibility. That required the purchase of each of the possible options.

5.14.1.1 RFID Reader

5.14.1.1.1 Criteria

The RFID reader must have USB output to better facilitate the data collection and the required programming to connect the collected book information with the library database. It must not be excessive in size so that it can be mounted on the base of the Librarian without too much difficulty and without significantly affecting the balance and weight distribution.

5.14.1.1.2 Alternatives

The RFID reader is one of the required components for the data acquisition testing phase of the project in order to inform the final data acquisition method decision.

5.14.1.1.3 Decision

The decision matrix shown in Table 19 was used to determine the best option among the possible purchases. Information on the testing of the RFID reader can be found in the Integration, Test, Debug section of this document.

Table 19: Decision Matrix for RFID Readers[21]

		Omnikey CARDMAN321RFID Smart Card Reader	Neewer Newer USB EM4100 Proximity Reader	Parallax RFID Card Reader (USB)
Cost	50%	2	4	6
USB Output	50%	10	10	10
TOTAL	10	6	7	8

5.14.1.2 RFID Tags

5.14.1.2.1 Criteria

The RFID tags need to be small enough to fit on the spine of a library book. The team needed to buy preprogrammed tags so that it did not have to purchase a RFID tag printer, which can cost potentially more than $300, which is equal to the guaranteed amount of funding that each senior design group will receive. The team also needed enough tags to make testing books possible. This number was selected by the team to be twenty tags, because it allows for approximate one foot of testing length, which is sufficient to determine how a larger section of an actual bookshelf would need to be scanned. RFID tags also are produced in different thicknesses, and for testing, they needed to be thin enough to not protrude excessively far off of the spine of the book so that they would be easier to get bumped or scraped off.

5.14.1.2.2 Alternatives

RFID tags come in a variety of sizes, and the team needed tags that were small enough to fit on the spine of books. Individual tags are available for purchase, but it is more cost effective to purchase a group of tags, which are widely available in groups of twenty.

5.14.1.2.3 Decision

The team purchased a group of twenty RFID tags that are ¾ inch in diameter and were under $3 (plus shipping and handling). They were only three millimeters thick and therefore best fit the design criteria.

5.14.1.3 Barcode Scanner

5.14.1.3.1 Criteria

The barcode scanner needs to have USB output for simplicity with interfacing the collected data and the microcontroller that will interact with the library database. USB better facilitates the programming of the database interface, since Excel provides a simple interface that can be used with the C programming language to perform simple operations, such as checking if a book has been scanned twice or is repeated. This additional scanner feature simplifies the programming complexity required for library database interfacing and the book ordering algorithm. It must have a reading distance of at least 3 inches so that it will be able to read the barcodes of books on a shelf while mounted on the Librarian located adjacent to the shelf. Minimizing cost was important, since there is a chance that the barcode scanner will only be tested, and will not be used on the final prototype. Programmability is also a consideration. Some barcode scanners are programmable so that scanned barcodes will start a Macro in Microsoft Excel, which would greatly help the data analysis aspect of the Librarian's function. Minimizing weight would be beneficial for helping maintain a balanced weight distribution on the Librarian. Cost was the main criterion for this decision, and therefore received a weight of 50%. Reading distance, USB output, and programmability were the next key criteria, and were weighted at 20%, 15%, and 10% respectively. The weight of the scanner, while a factor, was not as key as the other criteria, and only received a weight of 5%.

5.14.1.3.2 Alternatives

The barcode scanner is one of the required components for the data acquisition testing phase of the project in order to inform the final data acquisition method decision.

5.14.1.3.3 Decision

The barcode scanner in column two of the decision matrix shown in Table 20 was purchased first.

Table 20: Decision Matrix for Barcode Scanner[22]

		Symbol LS 2208 Scanner	Barcode Scanner SC1-C	Wired Handheld USB Automatic Laser Barcode Scanner	Unitech MS210 Bar Code Reader
Cost	50%	1	10	5	3
Weight	5%	7	4	9	9
USB Output	15%	10	10	10	10
Reading Distance	20%	10	2	8	4
Programmability	10%	5	0	7	5
TOTAL	10	4.85	7.1	6.75	4.75

5.14.1.3.4 Design Iteration

After receiving the chosen barcode scanner, the team performed a preliminary test of its functionality. The maximum reading distance for the SC1-C was determined to actually be only up to 20 mm (0.78 inches), and this would not be sufficient for its required function. The team needed at least 3 inches. The decision matrix from above was revised to reflect changes in the weighting of each of the criteria. The cost was determined to be a less critical factor, with reading distance and programmability increasing in importance. The second barcode scanner also has a continuous scanning mode, so there is no need to design and build or wire a system to tell the scanner to scan for each and every barcode. The scanner can be placed in continuous scanning mode and the Librarian can move around with a greater chance of reading each and every book barcode because the scanning never stops. The revised decision matrix is shown in Table 21.

Table 21: Modified Decision Matrix for Barcode Scanner

		Symbol LS 2208 Scanner	Barcode Scanner SC1-C	Wired Handheld USB Automatic Laser Barcode Scanner	Unitech MS210 Bar Code Reader
Cost	20%	1	10	5	3
Weight	5%	7	4	9	9
USB Output	20%	10	10	10	10
Reading Distance	35%	10	2	8	4
Programmability	20%	5	0	7	5
TOTAL	10	7.05	4.9	7.65	5.45

5.14.1.4 Web camera

5.14.1.4.1 Criteria

The web camera needs to have night vision, considered to be a night vision option on the camera or a light on the camera that can be used in the dark. Minimizing cost is important because the web camera may only be used in data acquisition testing, and not on the final prototype. The simplicity of mounting the camera is important because it increases the design and build time of the vertical lift system. The picture quality increases the image recognition capability of the data acquisition system, but increasing the picture quality inherently increased the cost of the component. The weights in the decision matrix were determined and assigned based on the relative important of each of the criteria.

5.14.1.4.2 Alternatives

The web camera is one of the required components for the data acquisition testing phase of the project in order to inform the final data acquisition method decision.

5.14.1.4.3 Decision

The decision matrix shown in Table 22 displays the design choice for the web camera.

Table 22: Decision Matrix for Web Camera[23]

		Round Webcam with LED for night vision	Logitech HD Webcam (1080p)	Microsoft LifeCam Cinema Web camera (720p)	Logitech C310 HD Webcam (720p)
Cost	50%	9	1	3	2
Night vision	30%	10	0	0	0
Picture Quality	10%	4	10	7	7
Simplicity of Mounting	10%	4	5	8	5
TOTAL	10	8.3	2	3	2.2

6 Fabrication and Design Implementation

Construction and fabrication were performed concurrently with receiving parts. As the project progressed, the team was able to make minor adjustments and more completely specify components and systems using the knowledge gained from the completion of more foundational tasks. After the design was finalized for the vertical lift system, fabrication began. This was an important step in the chronological progression of the project, since the programming and coding for the drive and vertical systems could at best only be preliminary until it could be run on the robot for testing and debugging. A three dimensional CAD model of the Librarian that shows the mechanical systems can be found in Figure 12 and Figure 13 below. More detailed CAD drawings can be found on the team website on the download page at http://www.calvin.edu/academic/engineering/2011-12-team2/DOWNLOADS.html.

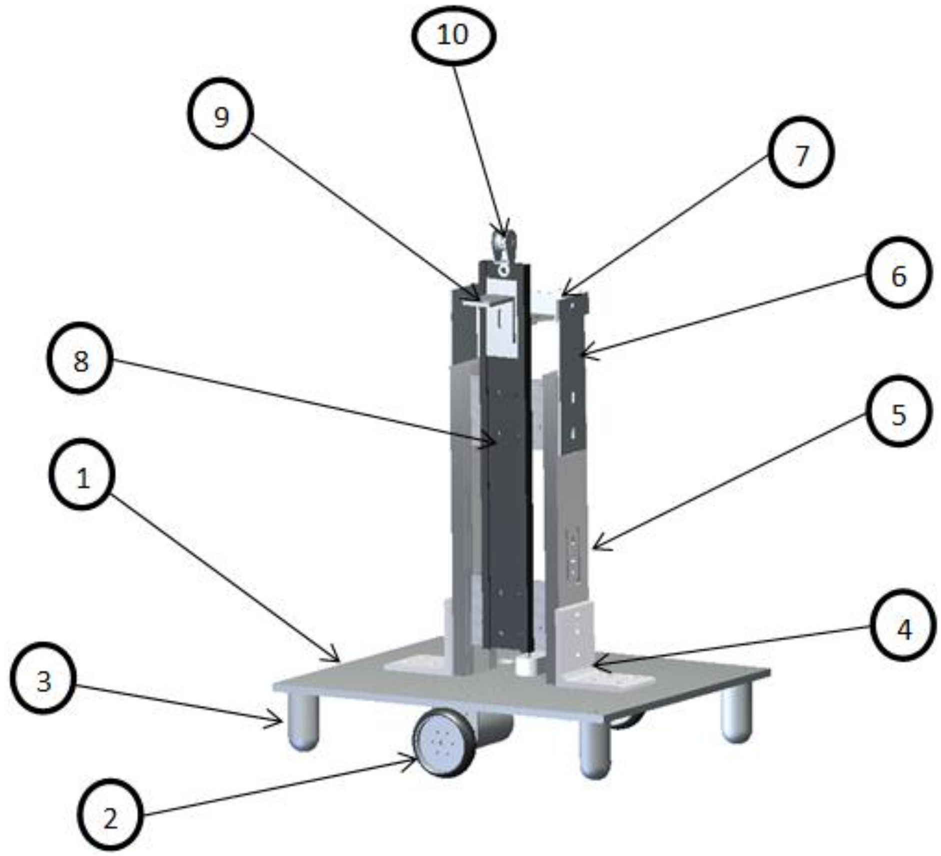

Figure 12: Front View of the Librarian

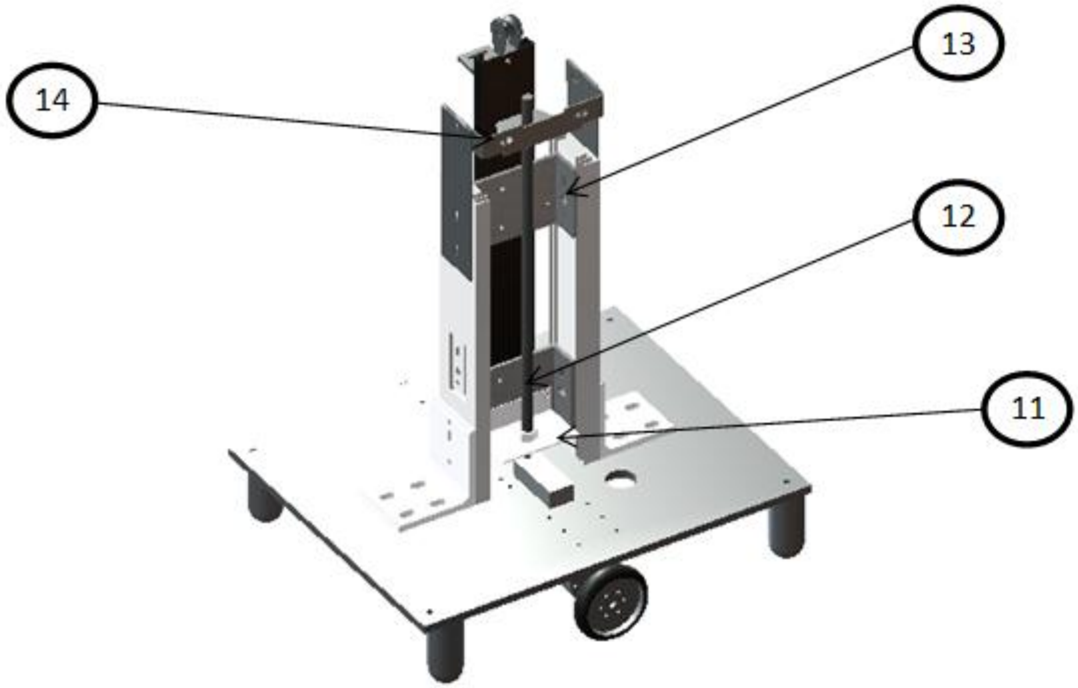

Figure 13: Rear View of the Librarian

The parts are labeled in Table 23 below.

Table 23: Part Description, Material, and Process List

#	Part Description	Quantity	Material	Process
1	Base	1	Aluminum	Fabricated
2	Wheel	2	Rubber	Purchased
3	Caster	4	Aluminum	Purchased
4	Drawer Slide Mounting Bracket	2	Aluminum	Fabricated
5	Drawer Slide	2	Zinc	Purchased
6	Bearing Support Plate	2	Aluminum	Fabricated
7	Screw Shaft Support Bearing	1	Steel	Fabricated
8	Secondary Drawer Slide	1	Steel	Fabricated
9	Barcode Scanner Mounting Bracket	1	Aluminum	Fabricated
10	Pulley	1	Steel	Purchased
11	Screw Shaft Carriage Connection	1	Steel	Fabricated
12	Screw Shaft	1	Steel	Purchased
13	Secondary Drawer Slide Mounting Bracket	1	Steel	Fabricated
14	Screw Shaft Alignment Bracket	2	Steel	Fabricated

6.1 Mechanical Fabrication Process

6.1.1 Method and Purpose

The motors were mounted on the base during ENGR 339 which allowed for basic testing during that course. For more information on that testing, refer to the Integration, Test, Debug section of this report. During the spring semester, the vertical system was constructed and integrated with the electrical aspects of the project. The team understood that ensuring correct functionality at each step of the process was critical to a workable assembly, and ultimately the prototype. The parts listed in Table 23 above were designed with the goals of simple assembly and disassembly in mind. No welding was used in the construction of the Librarian. This was done to allow for adjustability in the alignment of the various components to correct for problems encountered during initial testing, such as the alignment of the screw shaft. By using nuts, bolts, and tapped holes, if one particular section of the mechanical system needed to be removed or adjusted in order to work on an area that is difficult to get to, or a particular part needed to be modified in some way because of mechanical interference or aesthetic purposes, it was possible to partially disassemble the Librarian, perform the necessary work, and then reassemble the Librarian so that it was put together in the same way as before.

6.1.2 Dimensional Aspects

The team made sure to use given dimensions of purchased components to more accurately fabricate other related components. By design, the mechanical systems were fabricated to have larger tolerances, adjustability, and also to be able to be disassembled/reassembled.

6.1.2.1 Slots

CAD models for the components of the Librarian can be found in on the team website on the downloads page. In many of the parts, care was taken to use slots instead of holes in as many locations as was possible. This was done to increase the adjustability of the vertical lift system's mechanical components. Machining slots instead of drilling holes also allowed for faster fabrication, since the slot gives each part a greater tolerance when tightening bolts and screws.

6.1.2.2 90-degree Motor

Technical specifications were used for dimensions on the 90-degree motor. These can be found in the appendix of this report. Because of the small dimensions of both the motor shaft and the screw shaft, the accuracy of the manufacturer's dimensional specifications allowed for a coupling that was also removable, which enabled the team to couple and uncouple the motor and shaft to better facilitate other work, such as assembling the entire vertical system and building a tachometer directly on top of the 90-degree motor.

6.1.2.3 Drawer Slides

The drawer slides also had dimensional data from the manufacturer, which allowed for precise machining of the motor mounting brackets, the secondary drawer slide mounting bracket, the bearing support plates, and the screw shaft carriage connection. Being provided these dimensions also allowed for repeatability when fabricating parts. The symmetry of two drawer slides gave the team the opportunity to use a program on a mill to produce multiple identical parts, which helped ensure that when the vertical system was assembled, it was not only symmetrical but also precise.

6.1.2.4 Motor Mounting Brackets

These brackets were formed and then machined with two slots. Since two screws get tightened into threaded holes in the base, the brackets themselves can be adjusted to apply the desired amount of clamping force on the 90-degree motor. Although the screw shaft alignment bracket ensures that the screw shaft is vertical, any vibrations get transmitted to the motor, since the rest of the vertical system is fixed to the base. By adjusting the location of the motor mounting brackets, there is less stress on the motor since it has some clearance to take the play in the screw shaft's rotation. This clearance was designed into the system to reduce stress on the motor, since it is made of plastic and its durability is much lower than a motor with metal gears, as would be used in the full scale production design.

6.1.3 Line Sensor Array

The line sensor array was originally located in the middle of the underside of the base, centered between the motors. As more fully explained in the Integration, Test, Debug section, after initial testing, which showed the line following control system to be unstable, the line sensor was moved to the front of the base. An additional line sensor array was mounted on the rear of the base in order to enable the Librarian to accurately and effectively travel backwards past the shelf to begin its second pass to read the highest shelf. The line sensor arrays were mounted to a precise height in order to provide the best feedback for the motor control system. The arrays were mounted at the optimal height, as specified by the manufacturer. In order to facilitate the testing and debugging phase of the project, the mounting allows the line sensor array to have its height adjusted, so that if the simulated model library line following environment's variables changed the performance of the line sensor array so that its optimal height above the floor was different, the array could be moved until the optimal height was reached.

6.2 Electrical Design Implementation

The design of both the hardware and software electrical systems brought many unique challenges to the team. Circuit diagrams for the vertical motor, tachometer, and distance sensors are shown in Figure 14 and Figure 15.

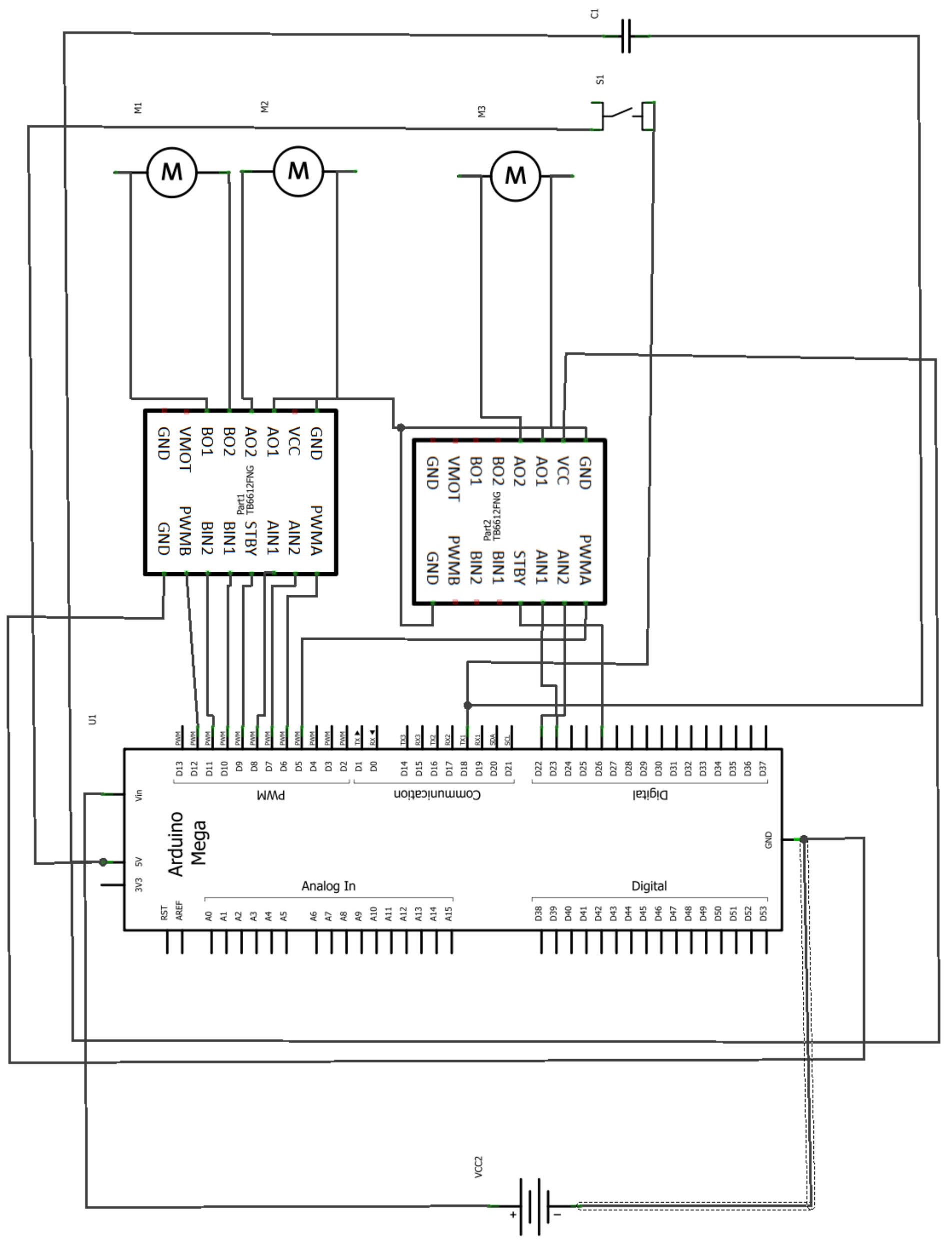

Figure 14. Circuit diagram for the motors and vertical tachometer

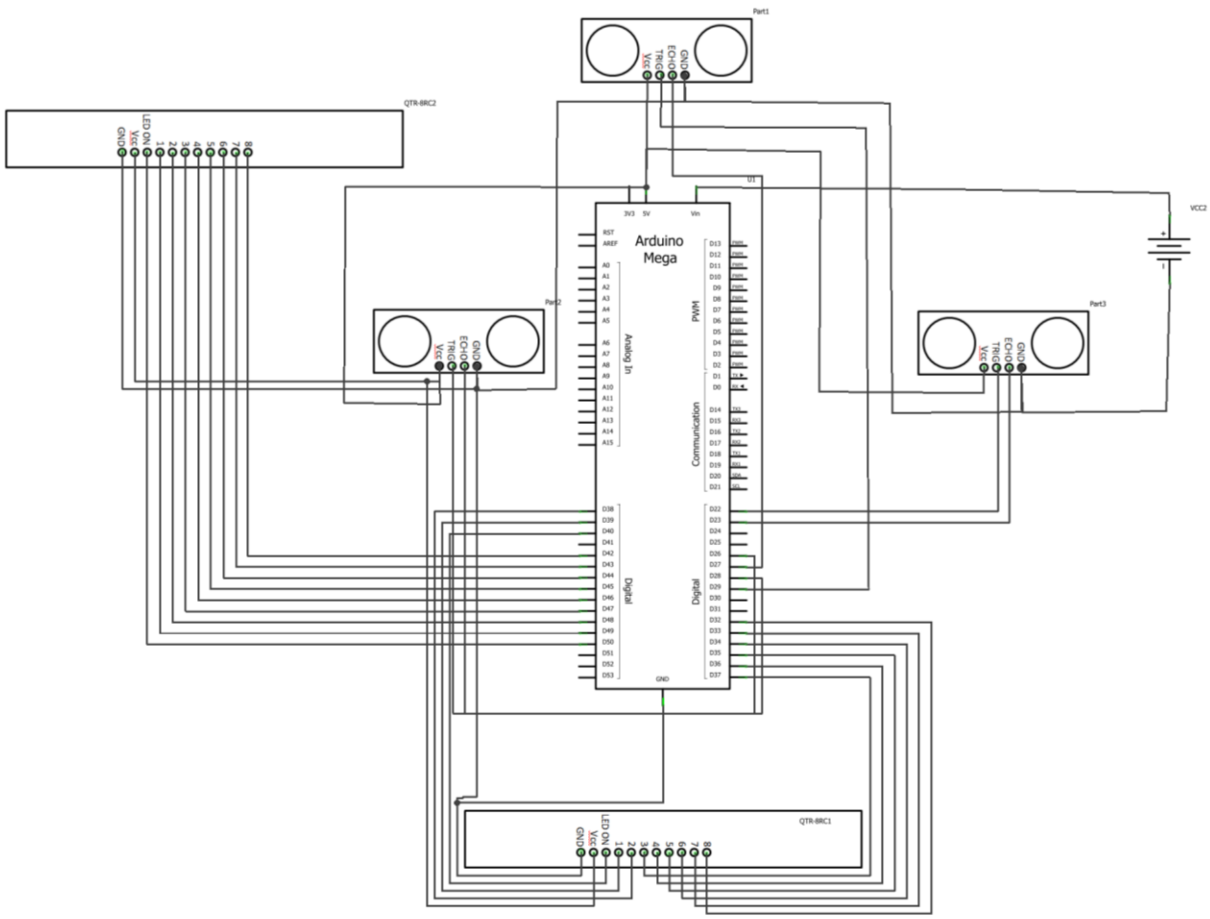

Figure 15. Circuit Diagram for sensors

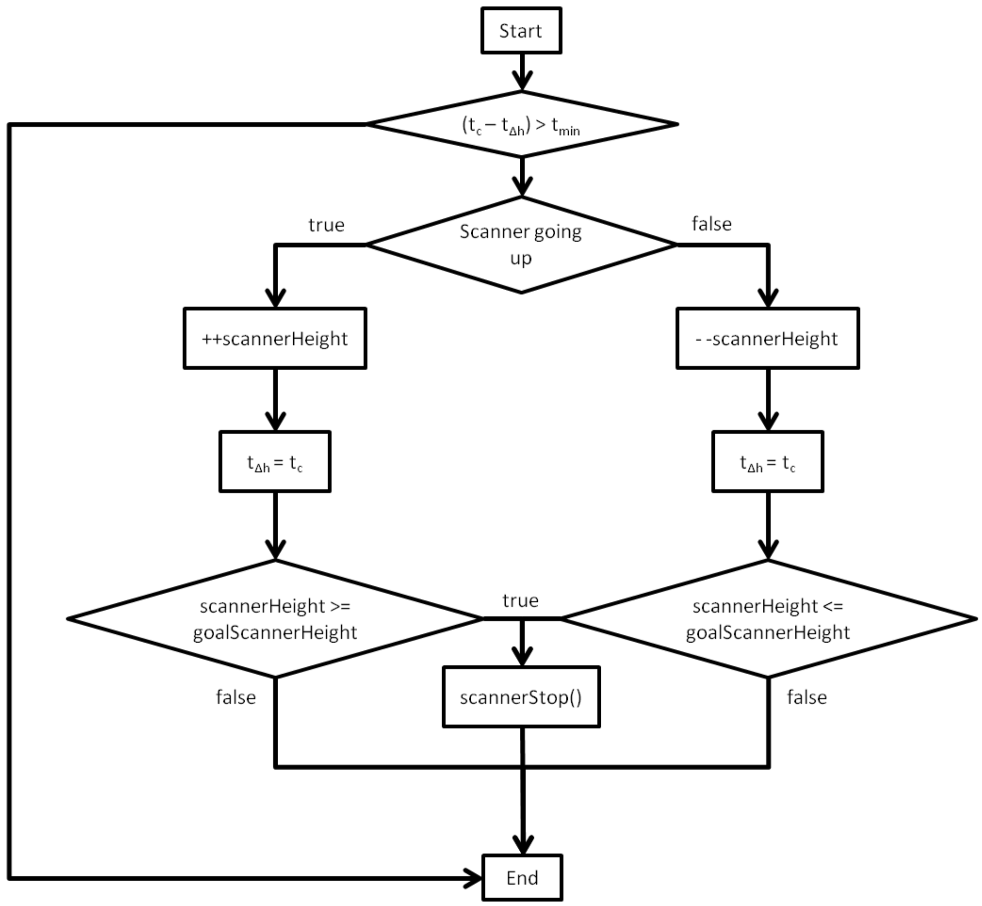

Figure 16. Vertical tachometer code with debouncing

The vertical tachometer is used to determine the height of the barcode scanner as it moves to different shelf heights. The sensor for this is a simple single throw switch which is engaged every rotation of the vertical motor. This triggers an interrupt in the code. There was significant bounce on this circuit so the sensor had to debounced both with software as seen in Figure 16 in the decision block after Start and with the hardware as seen in **Figure 14** with the 350 nanofarad capacitor. This size capacitor was chosen after consulting with another engineering student who suggested starting with a 100 nanofarad capacitor and increasing capacitance till the signal received was consistent at one trigger per button event. Capacitors values up to 500 nanofarads were tested with no improvement in signal integrity from the 350 nanofarad capacitor. Though the capacitors greatly improved the signal, debouncing was still required in the software. In the software, the signal is debounced by comparing the current time (t_c) and the time when the scanner last changed height ($t_{\Delta h}$). If this difference is less than the minimum trigger time (t_{min}) the signal will not be counted as a change in shelf height. The minimum trigger time is 200ms which was determined by the free running speed of the motor. If the difference is greater than the minimum trigger, the direction of the motor is checked to see if it is moving the scanner up or down. If the scanner is moving up, scannerHeight is increased by one and if it is moving down, scannerHeight is decreased by one. At this point $t_{\Delta h}$ is set to t_c. This method also terminates scanner motion if the goal height is reached. The goal height is a global variable which is set in other methods. Less-than-or-equal-to/greater-than-or-equal-to was used for this decision because only using equal to resulted in overshoot which caused the scanner to oscillate up and down as the precision of the motor control was not great enough to zero in on the exact value. Because the scanner has a wide beam compared to the barcode length (barcode length = 1.5 inches) and each turn constitutes a vertical movement of only one sixteenth of an inch it is not important to be exactly at the shelf height while still reading with the same accuracy.

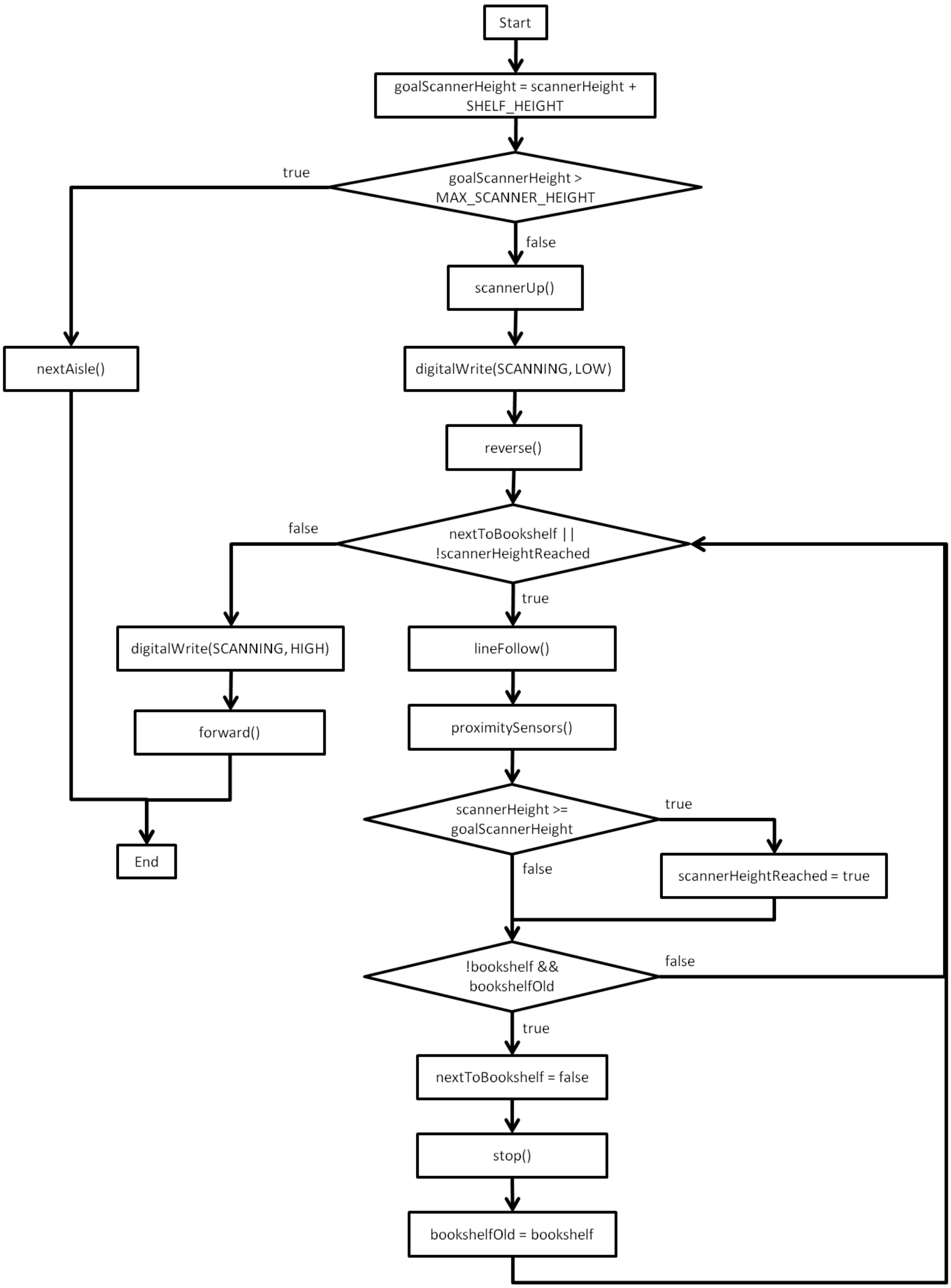

Figure 17. Method called nextShelf to scan the next highest shelf after finishing a lower shelf

The method nextShelf seen in Figure 17 is triggered by a falling edge from the proximity sensor (it was next to the bookshelf and now it is not) and starts by setting the new goal height for the scanner which is equal to the current shelf height plus the distance to the next shelf. If the goal height is greater than the vertical system's maximum range, the method nextAisle will be called and nextShelf will be exited. If the goal height is less than the vertical system's maximum range, the scanner will be sent to that height, the scanner will be turned off to prevent unintentional scanning, and the drive motors are put into reverse. At this point a while loop is entered depending on the variables nextToBookshelf and scannerHeightReached. If the robot encounters a falling edge from the proximity sensor the boolean nextToBookshelf is set to false, the drive system will stop the robot's horizontal motion, and the while loop will end if the boolean scannerHeightReached is set to true. To set scannerHeightReached to true, the scanner height must be greater-than or equal-to the goalScannerHeight. This method ensures that once the scanner reaches the end of the shelf, it will reverse the horizontal motion to reset the robot to the beginning of the shelf, bring the scanner to the correct height for the next shelf, and wait for both of these to be in the correct positions before scanning the next shelf.

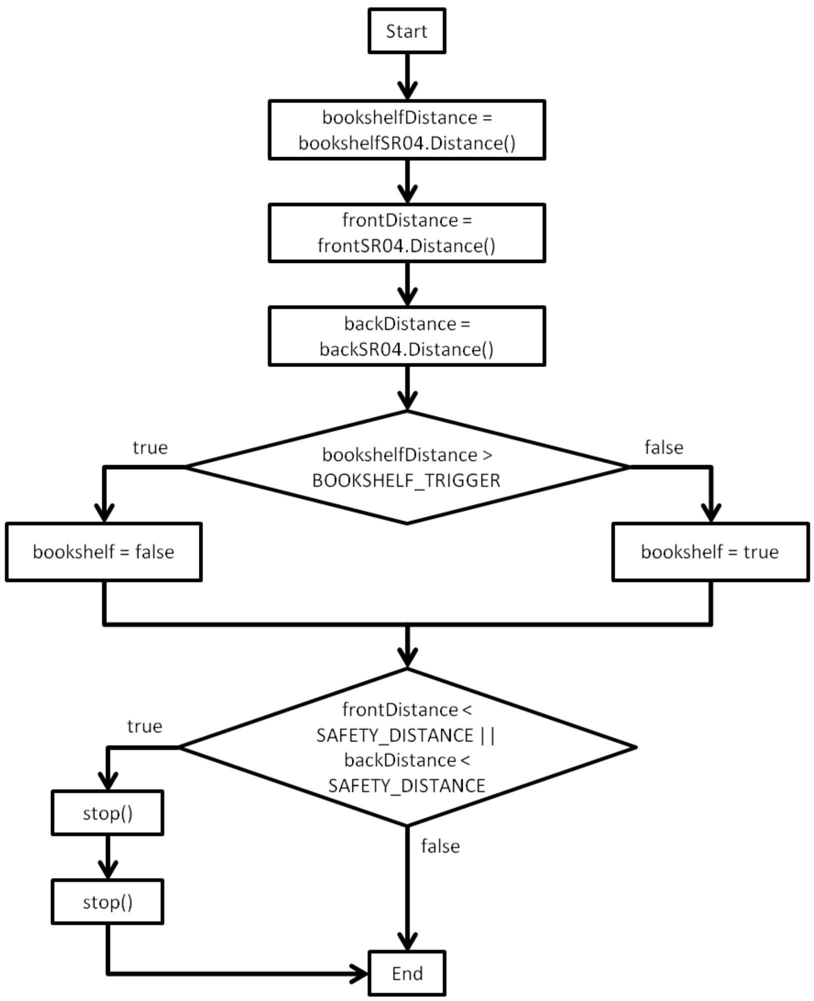

Figure 18: Proximity sensor and safety code

This method, shown in Figure 18, was called to check the robot's position along the shelf (whether it is by the shelf or not) and to make sure there is no obstructions in the robot's path. It implements the library for the SR04 distance sensor used to determine the distances of objects from each sensor. These distances are then converted to Boolean values depending on their respective trigger distances. If the front and back safety sensors are tripped, the robot will stop and go into standby mode until a library employee removes the obstruction and releases it from standby mode.

7 Integration, Test, Debug

In order to ensure optimum performance of The Librarian, testing and debugging of potential issues had to take place. A test order was established to ensure a good flow of the design process. The proposed order may be seen below:

I. Data Acquisition System
II. Motors
III. Drive system (in between shelves)
   a. Robot motion
   b. Proximity sensing
IV. Vertical system (up a row of shelves)
V. Combined system performance

7.1 Simulated Model Library Environment

This section will explain the setup of our model library. It will detail how and why we set it up, why it is the size it is, what we decided to do for barcodes, our model for the library database, etc. TBD. The setup of the simulated model library environment was determined by the different aspects of the full scale design that our proof of concept robot, the Librarian, was designed to demonstrate to viability of. To prove autonomous operation, we used a line of black electrical tape on a smooth piece of wood that was painted white. This contrast helps the line sensor arrays function accurately. To prove the shelf-reading of different shelf heights, the team purchases a bookshelf with three possible shelf heights, and filled the bottom two with books. To prove interaction with a library database, the Bookkeepers created a database of the books on the shelves, which were labeled with barcodes. To demonstrate data acquisition capability, the barcodes were located on the spine of the books at a consistent height from the bottom of the book. To prove the turning capabilities of the Librarian, the team added a semicircle of black electrical tape so the robot had a curve to follow and turn 180 degrees.

7.2 Data Acquisition System

7.2.1 Background

The team's design depended largely on the results of the testing of the data acquisition system possibilities. The team had decided that Radio Frequency Identification (RFID), a barcode scanner, and a camera with image recognition software were the three preliminary candidates for the data acquisition system. In order to better inform the ultimate design, the team purchased items to test each system. Sections 5.14.1.1 to 5.14.1.4 detail these decisions. Chuck Holwerda created the barcodes required for both testing and the final prototype demonstration.

7.2.2 Barcode Scanner

We obtained 20 barcodes from Chuck Holwerda of the Calvin College Engineering department. The barcodes were labeled BOOK 1 through BOOK 20. A table of barcode labels and their corresponding sizes may be seen in Table 24 below.

The barcodes were taped edge to edge on a white piece of paper as seen in Figure 19: Barcode Test Setup below. All the barcodes were aligned parallel to each other in order to simulate best case scenario for reading of the books on shelves. The test was performed under ambient lighting of the Engineering building. Videos and test results may be seen on the team website.

Table 24: Barcode Widths

Barcode Label	Width (inch)	Color
BOOK 1 – BOOK 7	¼	White
BOOK 8 – BOOK 14	¾	White
BOOK 15 – BOOK 20	½	Yellow

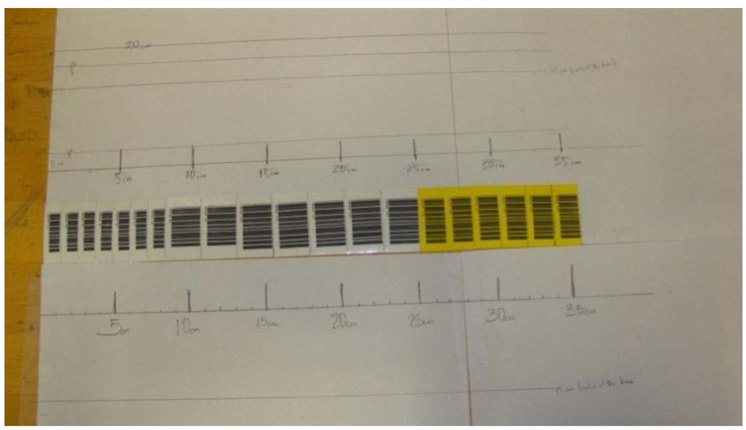

Figure 19: Barcode Test Setup

7.2.2.1 Test setup and procedure

The height was judged based on the bottom of the scanner, so there was some error depending on how much the scanner was angled, since this changed the actual distance from the reader to the barcodes. The barcode scanner's rays were used to maintain height through the reading process as seen in Figure 20 below. This was done to ensure repeatability of the test process since the barcode produced a fixed line for a given height above the table top. Lines were drawn in as guides for the person scanning to follow through the test process.

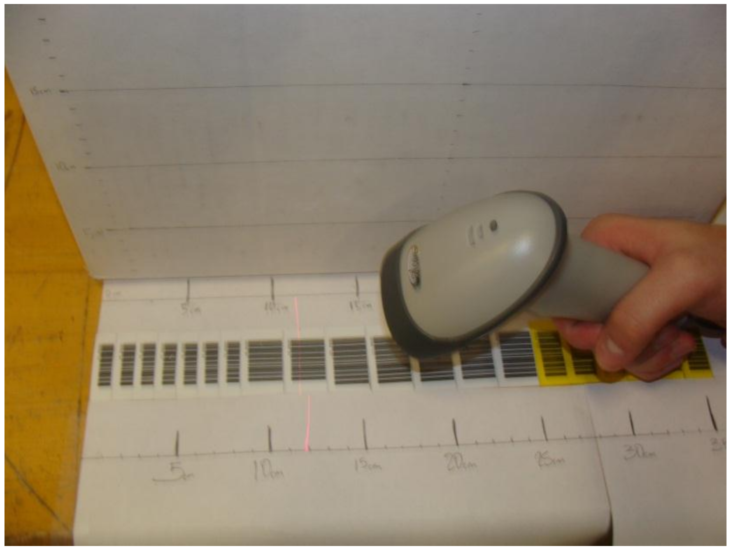

Figure 20: Barcode Testing

The test setup was geared towards calculating the speed of the scanning process. A team member would move the scanner as close to the desired speed as he could, and the team could verify the speed using the timer in the video on the bench and the timestamp of the video itself, using the scale on the bench to get the distance traveled.

However, after two runs of the test, this procedure seemed difficult and ineffective and as such was adjusted appropriately. The person scanning was no longer required to keep track of his location and the scale versus the timer in order to determine speed. Rather, the person was to scan the barcodes as consistently as possible down the rows and a time taken to do this was determined from the time stamp of the video. Both the distance travelled and the observed time were then used to calculate the average speed of the scanning process. This procedure worked a lot better, as seen in the consistency of results. For faster speeds, the person scanning moved faster and vice versa.

7.2.3 RFID Testing

The team used an RFID reader and RFID tags to more fully evaluate the potential benefits of using RFID to shelf read books instead of a barcode scanner. Testing was done on 13 February 2012. Three RFID tags were placed spaced 1.25 inches apart center to center, and the RFID reader was plugged into a desktop computer via USB so that the reader would output into Microsoft Excel. The reader was slowly passed over the tags a number of times to see how it would read the tags when they were as close together as they would be on a typical bookshelf. The reader would not read the RFID tag in the middle of the three unless they were spaced out even more that initially setup, however, and this setup would not have worked on a bookshelf because the tags were farther apart than they would be on a bookshelf. Furthermore, the reader would not read a second tag until it no longer picked up the radio field from the first tag that it read, which meant that the middle tag was missed at least seven times out of ten. In order to solve this issue, the team looked into RFID shielding[24,25.] Aluminum foil was placed over the RFID reader as shown in Figure 21. This greatly reduced the area of the RFID reader that could read RFID tags. The shielding did solve the issue of not being able to read tags that were placed closed together. The drawback to the shielded RFID reader was that it needed to be ¼ inch away from the tags, which is very close. On an actual bookshelf, the book itself would most likely be at least 1 inch from the edge of the shelf, which would mean that the RFID reader would not be able to get close enough to a book to read its tag.

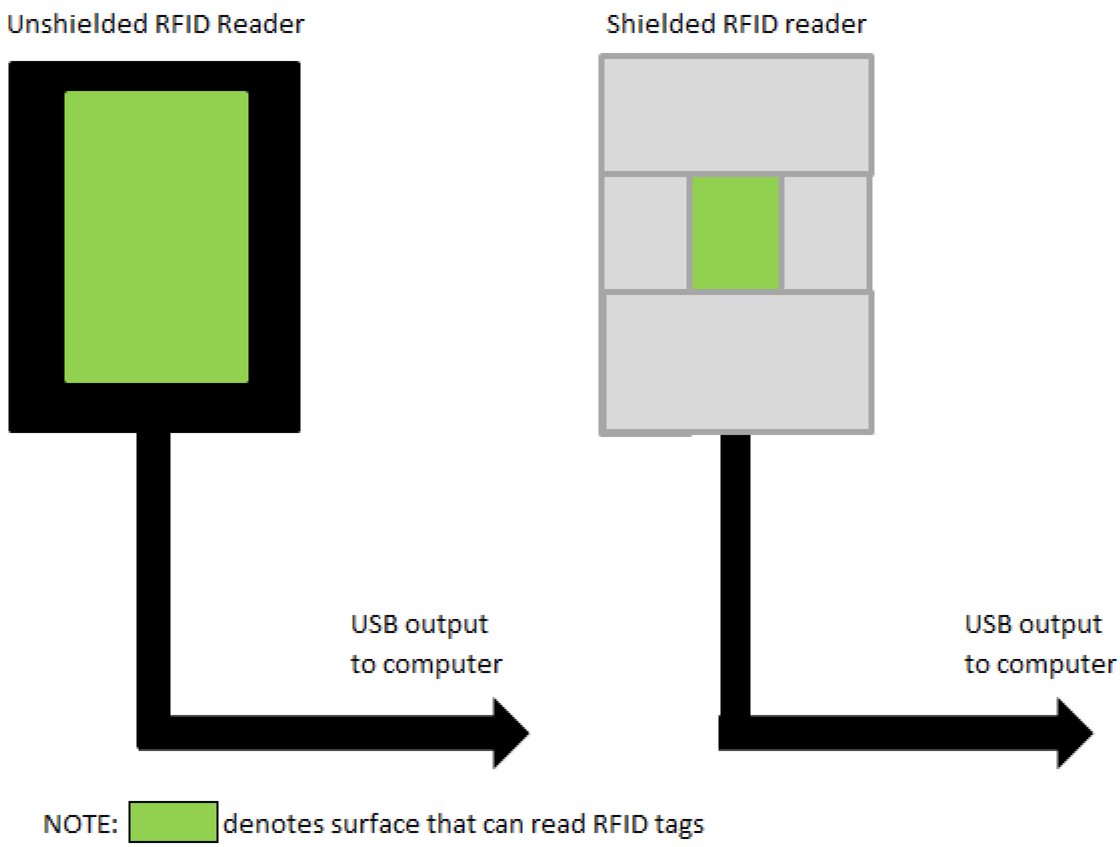

Figure 21: Unshielded and shielded RFID readers

The shielded RFID reader would also double-read RFID tags quite often. This issue would have to be addressed in the software/database processing aspect of this project.

By altering the shielded RFID reader, the performance improved. The altered reader is shown in Figure 22. Having a slit foil covering increased the reading distance to 1 inch and the reader did not double read as much since the reader was further away. However, the team decided that the RFID reader was not as viable of an option as the barcode scanner since the accuracy was far less consistent, and the reading distance was only 2.5 centimeters, compared with 10 to 15 centimeters for the barcode scanner.

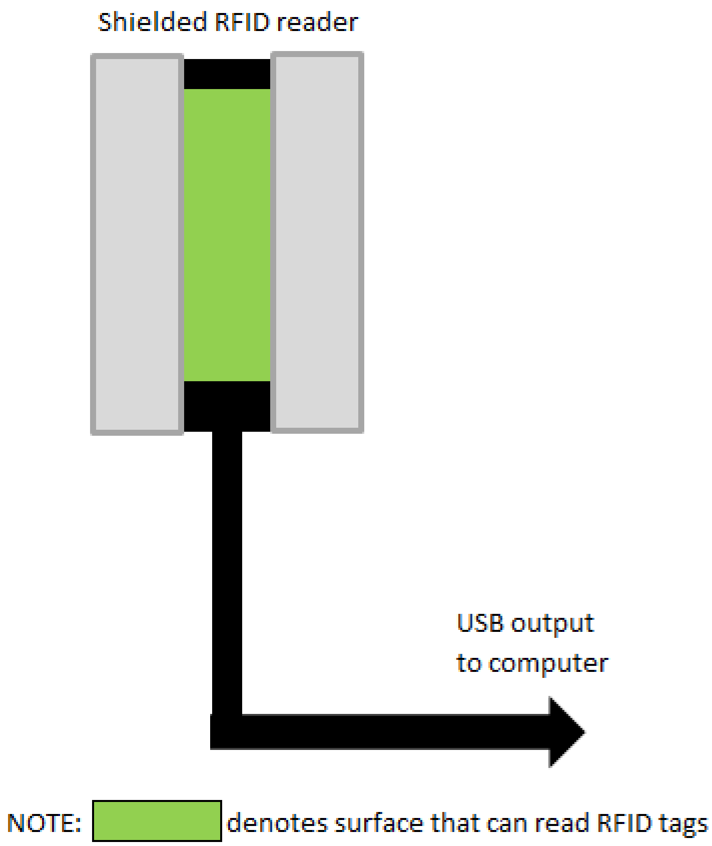

Figure 22: Second shielded RFID reader setup

7.2.4 Camera

The team also purchased a web camera with a light so that it could operate at night, when the Librarian was designed to function. After consulting with Team 1, another Calvin College Engineering Senior Design team for the 2011-2012 academic year, the Bookkeepers decided to forego actual testing of the camera. This decision was based on work and feedback from Team 1 informing the Bookkeepers that they had not had consistent accuracy using optical character recognition (OCR), and were not going to use it for their book sorting system. Based on this feedback and the time and effort that Team 1 had put into testing OCR, the Bookkeepers eliminated the camera option from the possible choices for the key component of the data acquisition system.

7.2.5 Barcode Integration with Microcontroller

The data acquisition system is comprised of a barcode scanner, SD card and an SD card reader integrated by an Arduino duemilanove microcontroller. The barcode scanner has three main functional parts: the illumination system, or laser, the convertor or sensor, and the decoder. After the laser from the barcode scanner hits the barcode label, the light gets reflected. The reflected light is detected by the sensor from the illumination system. From the reflection, an analog signal with varying voltages signifying varying intensities. The convertor then changes the analog signals to digital signals which are then interpreted by the decoder. After the integrity of the barcode is determined by the barcode scanner, it converts it to ASCII text. Our microcontroller is constantly listening for data from the output terminal of the barcode scanner, which in our case is the USB port. When the barcode is scanned, our code receives the ASCII text and recognizes each character sent and puts it into a string. A CSV file is created on the SD card and the data from the scanned barcode is printed to the CSV file. This sequence is looped until all the barcodes are read (when the robot gets done scanning the highest shelf in the simulated model library environment). The SD card is then taken out and put into a portable card reader and downloaded into our simulated model library database which imports the data from the SD card and makes all the relevant references comparing and producing a report of the books which are out of order.

7.2.5.1 Test Results

The results for the tests may be seen in Figure 23 below. Detailed results for each test run may be seen on the team website. From these, we were able to determine the following:

- Maximum allowable distance away from book for consistent reading – approximately 15 cm above the flat surface.
- Maximum drive-by speed allowable for consistent reading – approximately 5 cm/s for accuracy above 95%.

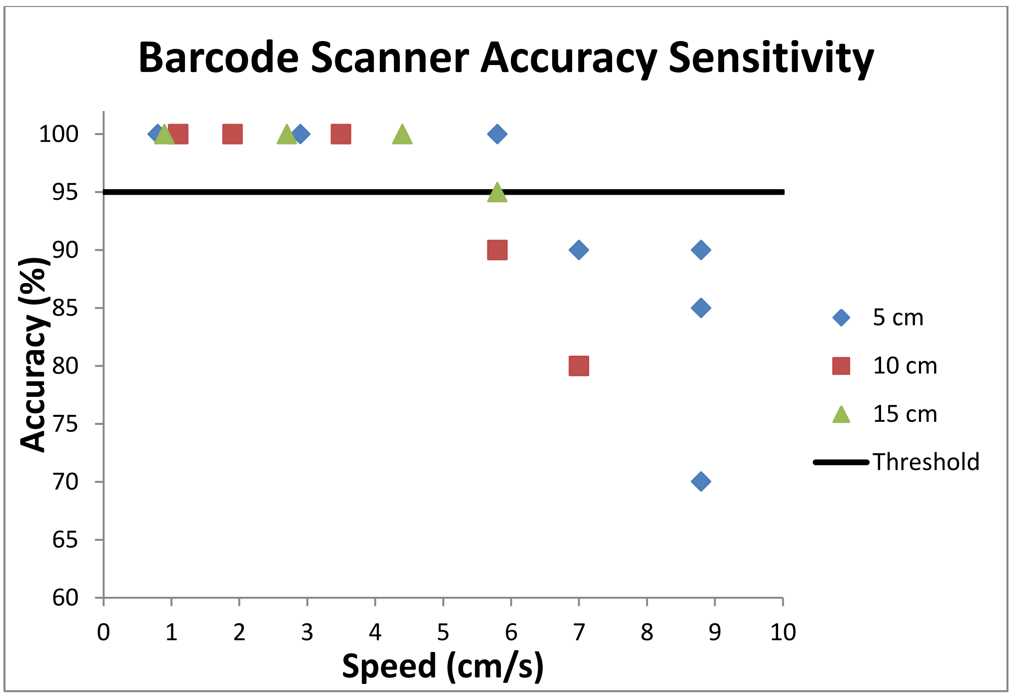

Figure 23: Barcode Scanner Test Results

7.3 Motors

The motors were to be purchased depending on the desired torque to move the robot at a speed such that the accuracy requirement was met. The motors were mounted to the base of the robot in the chosen drive system configuration and then tested to ensure that the robot moved with correct speed and provided sufficient maneuverability to the robot in the different driving states of forward, reverse, point turns, etc. The testing involved constructing a simple manual controller from switches and a variable voltage source. This shows that the motors will be adequate for the functionality required of them, such as turning and straight line driving ability. The motors were mounted on the bottom of the base since the team had not purchased casters at that time, and could use a small piece of foam to balance the robot for this particular round of testing. The motor functionality results are not affected by this mounting configuration. A picture of the setup used can be seen in Figure 24.

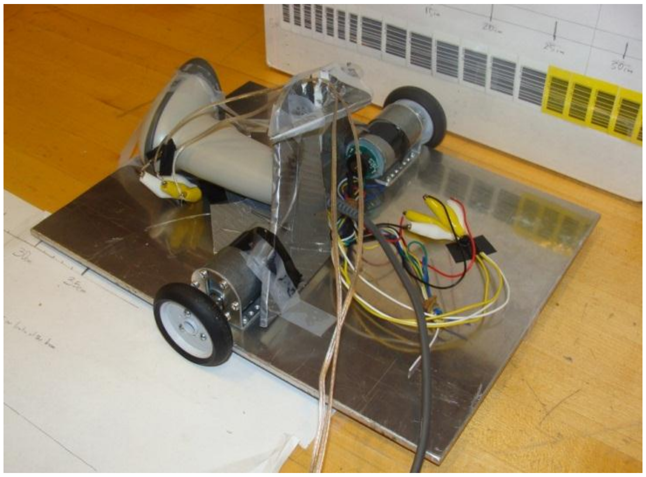

Figure 24: Initial Drive System and Data Acquisition Integration Test

7.4 Drive System

The drive system, which is comprised of the wheels, motors and base, was assembled together and then tested as a unit. This is a two phase testing process that was completed during the spring semester. Both tests were designed to test the robot motion and proximity sensing functionalities.

7.4.1 Robot Motion

The robot motion test ensured that the whole cart moved as expected. This was completed late in the fall semester. The robot could effectively turn and move in forward and reverse directions using manual controls.

7.4.2 Proximity Sensing

The proximity sensing test will ensure that the drive system is able to move at specified distances away from objects. This would be achieved with the aim of proximity sensors. Two line sensor arrays have been purchased for use in directed the robot.

7.5 Vertical System

Testing to ensure that a command can be given for an extension of the drive system to move up and down columns of the shelf was performed. Before that could occur, however, the system needed to be tested as the system was fabricated and the components were combined. First, after coupling of the screw shaft and 90-degree motor, the motor was connected to a variable power supply and held so that the shaft could rotate. This test successfully proved the coupling of the shaft to the motor. Secondly, the integration of the drawer slides with the secondary drawer slide track was tested manually. This proved that the secondary drawer slide track, on which the barcode scanner travels, could move up and down as constrained by the drawer slides. Third, the screw shaft carriage connection was put on the screw shaft. The 90-degree motor and the screw shaft carriage connection were held in such a way so that when the motor was connected to the variable power supply, the screw shaft carriage connection moved up and down the screw shaft. The next test was to mount the screw shaft carriage connection to the drawer slide assembly. The drawer slides were simply held in a vertical orientation and the 90-degree motor was run in both directions to move the screw shaft carriage connection and therefore the secondary drawer slide track up and down. The entire assembly was then mounted to the base of the Librarian, and the test we performed again. Because of the slight oscillation on the 90-degree motor, the motor mounting brackets were designed and fabricated to not only secure the motor in place, but also allow for some of the oscillation to reduce stresses on the motor and its connection screw shaft.

7.6 Combined System Performance

Combined system performance testing will entail a series of iterations to ensure that any future alterations do not affect predetermined conditions and parameters for operating the drive system. A video of a preliminary combined system operation may be seen at http://www.youtube.com/watch?v=-ReKzhD1hs8&feature=player_embedded. Once a concrete solution was achieved, further testing to simulate several working situations was performed. A list of testing videos can be found on the team website at http://www.calvin.edu/academic/engineering/2011-12-team2/project.html.

7.6.1 Forward and Reverse Line Following

Once the line sensor arrays were mounted on the bottom of the base in the front and the back, the Librarian was tested to see if it could accurately follow the black line on the floor in forwards and reverse. Testing quickly showed that the robot could line following accurately in the forward direction, but failed to follow the line when traveling in reverse. The robot was placed on two small pieces of angle aluminum so that none of the wheels or casters were in contact with the top of the workstation desktop. Tests were performed to test the line sensor arrays to ensure that they were functioning correctly and were not the cause of the driving error. Once they were confirmed to be functioning correctly, the motors were tested. They both turned forwards, but only one wheel would turn backwards. The wiring was double and triple checked, and the motor test was performed again. Then the motor driver for the wheel that would not turn in reverse was replaced with a spare, and the motors both functioned properly both forwards and backwards.

7.6.2 Line Following, Proximity Sensors, and Vertical System Test

Repeated testing and debugging showed that when the battery was used often and was never fully recharged in between tests so that it eventually ran out, the line following and proximity sensors did not function properly, causing the Librarian to veer off the black line on the floor of the simulated model library. After allowing the battery to charge without interruption or use for four hours, the tests were run again, and the drive control system, including the line sensor array and the proximity sensor, functioned properly again.

7.6.3 Line Following, Proximity Sensors, Vertical System Test, and Barcode Scanner Test

The Librarian was able to follow the line and maintain a constant distance from the shelf on both shelf heights. The barcode scanner scanned the barcodes on the spines of the books and input them directly into a team member’s laptop using the USB cord.

7.6.4 Overall Shelf Reading Speed

Based on completed prototype testing, the time required to scan two shelves with forty books on each shelf was recorded. The Hekman Library at Calvin College has 1.7 million texts. It takes one minute to scan a shelf with forty books. Since this speed was in a library environment where each shelf reading pass was only three feet in length, the time spent waiting at the beginning of the shelf after reversing will be eliminated on the full scale design. This is because in actual libraries, there are many bookshelves in a row, so the robot would be able to read a given shelf height for a much longer period of time. When the robot reverses along the shelf, the barcode scanner gets raised to the next highest shelf height, and with a much longer shelf, the scanner will be at the proper height before the robot reaches the beginning of the bookshelves and switches to driving forward again. Another option would have the barcode scanner raised at the end of one shelf with the robot waiting. It would then scan the next highest shelf going in reverse. The reverse scanning would in this case be accounted for and built into the programming. This would still mean that the majority of the time would be spent shelf reading books, which means that using the time it takes to scan a three foot long shelf provides adequate data to estimate the time it would take to scan an entire library. Since the Hekman Library has multiple floors, the robot would need to operate the elevator. Just like the time spent moving from one aisle to another, the time spent changing floors is small when compared to the time spent shelf reading, so it can be neglected when calculating the time required for a full library shelf reading operation.

Given the number of books in a library, Equation 5 can be used to calculate the number of years required to shelf read all of the books in the library.

Equation 5

$$\boldsymbol{time\ required = (number\ of\ books)\left(\frac{shelf}{40\ books}\right)\left(\frac{1\ minute}{shelf}\right)\left(\frac{1\ hour}{60\ minutes}\right)\left(\frac{session}{7\ hours}\right)\left(\frac{week}{5\ sessions}\right)\left(\frac{year}{50\ weeks}\right)}$$

It was assumed that the robot be used at night, and would scan for 7 hours. This length of time is based on the operating hours of the Hekman Library at Calvin College, the project’s primary customer. It was assumed that the robot would not be used if it meant a special trip to set it up, meaning that the only nights it would operate would be from a day that the library was open until the next day, when it was also open. Taking out time for holidays, it was estimated that there were the equivalent of 50 full weeks when the robot could function. This calculation functions as a general result that provides a conservative estimate of the time required to shelf read all of the books in a given library. Table 25 shows a comparison of the time taken to index a sampling of both public and academic libraries in the United States. The libraries are ordered from the smallest number of books to the largest number of books.

Table 25. The time required to index books in a sample of libraries.

Library	Books and other printed materials	Years per full indexing	Full indexes per year
Grace Bible College	42143	0.009	111
Grand Rapids Community College	71869	0.015	65
Aquinas College	91224	0.020	51.2
Hope College	368000	0.079	12.7
Kalamazoo Public Library	462000	0.099	10.1
Calvin College	1700000	0.364	2.7
Western Michigan University	2100000	0.450	2.2
Cleveland Public Library	4200000	0.90	1.1
Chicago Public Library	5500000	1.179	0.8
Detroit Public Library	7500000	1.607	0.6
UC Berkeley	11000000	2.357	0.4
Yale University	12300000	2.64	0.4
Harvard University	16300000	3.49	0.3

7.7 Issues Encountered

7.7.1 Sensor Damage

In an effort to improve the organization, mountability, and fit of the wiring system in the robot, the wiring system was redone from its initial testing and layout stage. In this process, the distance sensor were inadvertently powered directly from the battery power instead of the logic power. Over time, this damaged the sensors and caused them to fail. New sensors were purchased and the system was required to correct this error. No further issues were experienced due to mis-wiring.

7.7.2 Ambient Noise Interference

During the Senior Design Night presentation, the distance sensors appeared to be triggering at the wrong times. It was theorized and later corroborated by an engineer observing the project that high levels of ambient noise can cause the ultrasonic distance sensors to malfunction. As the expected uses for this robot is within a library setting (generally kept quiet) and for night operation, this should not be a problem if the robot was implemented. Furthermore, this phenomenon was not experienced while testing despite the team members talking during the test. For these reasons the team does not anticipate a problem with this when the robot is operated under intended conditions.

7.8 Barcode Scanner Accuracy

The barcode scanner proved to be the limiting factor in terms of the scanning accuracy that the Librarian could achieve. Fully integrated prototype testing resulted in accuracies ranging from 60% to 97%. The scanner sometimes had trouble scanner barcodes on curved book spines, smaller barcodes, larger barcodes, barcodes that were close together, and barcodes that were farther apart. By replacing the books that the scanner consistently did not read with books with flatter spines, making sure that the books' spines were flush with the edge of the bookshelf, that the spines were vertical, and the barcodes were as close to perpendicular to the barcode scanner's rays, the Bookkeepers were able to minimize the books that were missed when scanning. However, repeated testing showed that these measures only accomplished so much in increasing scanner accuracy. The team concluded that the barcode scanner was the main issue, and had controlled the other variables as much as was feasible. By replacing the books with wooden “books” with barcodes on the “spines,” the team expected that the scanning accuracy would be improved, but decided not to replace the books with wooden “books” because that would have reduced the accuracy of the simulated library model environment. By utilizing a superior barcode scanner that was a higher quality, the team fully expects that a full scale design could achieve the shelf reading accuracy goal of 95%.

8 Improvements

Looking into the future, the team has identified certain limitations that need to be overcome in order for The Librarian to become a practicable and useful product. Some of the major limitations are discussed below.

8.1 Locomotion

8.1.1 Issue

In many libraries, books are constantly being moved around to accommodate newer ones and since the shelves often are added, removed, and rearranged, a robust navigation system that can handle such complexities is necessary.

8.1.2 Possible Solution

As a result of the above stated issue, The Librarian would need some form of wireless interaction with the library environment. The team speculates that some possible solutions could include proximity sensors installed on all shelves, barcodes that function as signs to the robot, or a local global positioning system of such a library that would include coordinates of library, or magnetic sensors installed at certain strategic locations in the library and one on The Librarian so it can tell its position based on the magnitude of the magnetic field it experiences.

8.2 Books

8.2.1 Issue

During preliminary testing the team identified that books with flat spines were more easily picked up by the barcode scanner as opposed to books with curved spines. Thinner books were also harder to read than larger ones and therefore The Librarian might not be able to handle all book sizes. Right now, the threshold for which the team anticipates The Librarian to operate efficiently includes books from 0.25 inches and up. Finally, the Librarian might have problems with books that are not properly located on the shelf, that is either books having their spines slanted, as is usually the case with taller books required to fit on smaller shelves, or books placed in such a way that their spines are not revealed.

8.2.2 Possible Solution

A commitment from the library staff to ensure that books are located properly on the shelves would be necessary for optimum performance of The Librarian. The team believes that a system that would identify locations of shelves with books that are not scanned can be integrated into The Librarian to ensure that the Library staff can look over such locations.

To account for the curved nature of books, the team believes a more advanced barcode scanner such as an Omni-directional scanner might allow for better readability of barcodes along the aisles of any such libraries.

9 Business Plan

9.1 Executive Summary

The proposed senior design project was to design and build a proof of concept for a book indexing robot. Libraries use employees to shelf read, or check the order of the books on their shelves. The design team believes that this time consuming task could be performed at a lower cost by a robot that autonomously navigates past each shelf in a library to scan and index the books. It uses a data acquisition system that utilizes a barcode scanner to identify each book and then compares the book's location, or its order on the shelf, to the library database. By moving past each shelf and adjusting to read the books on shelves of differing heights, the robot would index all of the books in a library. It would produce an output file of misplaced books and their locations for the library employees, who will access the file from a library computer at the circulation desk. They will then be able to focus on the books that are out of order and move them to their proper locations, instead of checking every shelf visually, spending most of the time looking at books that are in their right locations.

9.1.1 Company Name

For purposes of this project, the Company would be referred to as 'The Librarian'. The name is supposed to reveal the intent of the project, being that the company intends to save any books that may be potentially lost from patrons placing them back incorrectly on the shelves.

9.1.2 Business Description

The business plan below details a manufactured production price of $11,329 for the robot itself, plus additional labor costs for customizing the robot's programming for an individual library. Research has shown that similar products have been designed and built, but there is no significant commercial market for such products which means that the market for such a device would be hospitable to steady sales and revenue.

9.1.3 Market Overview

The target market for this project will be middle to large sized libraries across the United States that have circulations of over 150,000 books per year. This was determined from a survey given to neighboring Grand Rapids libraries.

9.1.4 Managerial Team Overview

The management team consists of our advisor Professor VanderLeest, the four engineers consisting of Kobby Appiah-Berko of the Electrical & Computer engineering concentration, Nnamdi Maduagwu, Tyler Helmus and Andrew Dykhuis, all of the Mechanical engineering concentration.

9.2 Vision and Mission statement

9.2.1 Vision

'*To mitigate the frustration librarians experience in locating misplaced books and consequently free them from low skill, repetitive labor.*'

9.2.2 Mission Statement

The mission of The Bookkeepers is to create a robot that will efficiently and effectively index books thereby significantly reducing the time employees expend doing mindless tasks of locating misplaced books.

9.2.3 Values and Principles

The Bookkeepers value transparency, integrity and trust. The company values open communication about our product, staying consistent with user specifications resulting in the creation of a reliable, fully functional and trustworthy product.

9.3 Business strategy

9.3.1 Image and Market Position

The Bookkeepers will be the pioneers in creating automatic indexing solutions to libraries. We want to be the customer's first choice by creating a strong positive image through varying media platforms as well as the quality of our product. We want our product to be affordable and easy to operate.

9.3.2 Production Strategy

The operational strategy is to use a make to order or assemble to order manufacturing model. This means the product will only be made upon a customer's request. This will create a pull-type production in our supply chain management, where resources will only be used if there is a demand. The advantage of this model is that it allows each product to be highly customizable while decreasing the amount of inventory (product components) on stock. Having a highly customizable production strategy integrates nicely with the premium pricing strategy. This will also eliminate costs related to large storage space, surplus inventory, and labor associated with continuous assembly lines. Lastly the make to order model and pull production strategy is known to decrease customer lead time. The customizable aspect of our production strategy and shorter lead times will allow the customer to see the value in our product. With the customer understanding our value preposition they will be more inclined to oblige with our premium pricing strategy, thus ensuring our profits.

9.3.3 SWOT Analysis

9.3.3.1 Strengths

- Good quality product
- Customizable product
- Environmentally friendly product
- Highly skilled engineers and manufacturing team
- Strong marketing strategy and public relation
- Capturing new market in automatic book indexing in libraries

9.3.3.2 Weaknesses

- Inexperience
- Production cost

9.3.3.3 Opportunities

- Libraries want to cut down on the time spent manually indexing books
- Libraries want to increase the effectiveness and reduce the errors made in book placement when books are returned after they are taken out
- Automatic book indexing in libraries is an uncultivated market

9.3.3.4 Threats

- Libraries that are committed to conventional modes of indexing books
- Libraries with inexpensive operational budgets
- Small libraries that have limited inventory i.e. Books

9.3.4 Competitive strategy

Looking at automatic book indexing technology available today, there is no other product on the market that directly competes with the Bookkeepers' indexing robot in that the products currently available commercially focus on retrieval, not shelf reading; this in itself is a competitive advantage. Indirectly, The Bookkeepers' product is opposed by automatic indexing software, librarians providing labor to manual index the books, and even the technology of inventory tracking robots in other industries.

The Bookkeepers competitive advantage is that it automates the entire book indexing process by combining both the automatic indexing software and a mobile robot to eliminate the need of manual labor. The product will focus on large libraries with circulations of over 150,000 books per year. The Bookkeepers robot will be equipped with multiple indexing technologies. It will serve libraries with varying indexing conventions by being able to support bar-code, RFID and even hand written identification codes. Through the indexing software, the option for our product to interface with the libraries database will be provided. This interaction between the robot and the library's database will result in daily printable inventory accounts, adjustments and a list of all misplaced books. Lastly, the Bookkeepers indexing robot will take into consideration libraries with power requirements.

9.4 Market Strategy

9.4.1 Target market

9.4.1.1 Benefit/Product Value

The system of borrowing and returning books in the library poses some challenges with inventory tracking. After interviewing the director of the Calvin College Hekman Library it was discovered that some of the problems faced have to do with books that are missing or have not been returned, books being misplaced in the library, and books being damaged by borrowers or library patrons. Also while talking to librarians it was expressed that indexing the books, searching for misplaced ones, and investigating Our product is aimed to eliminate the issue of librarians spending endless hours going through aisles to scan books in order to locate books that are misplaced or missing.

9.4.1.2 Demographic profile

The target market for this project will be middle to large sized libraries across the United States that have circulations of over 150,000 books per year. This was determined from a survey given to neighboring Grand Rapids libraries. The results of the survey are displayed in Figure 25 below.

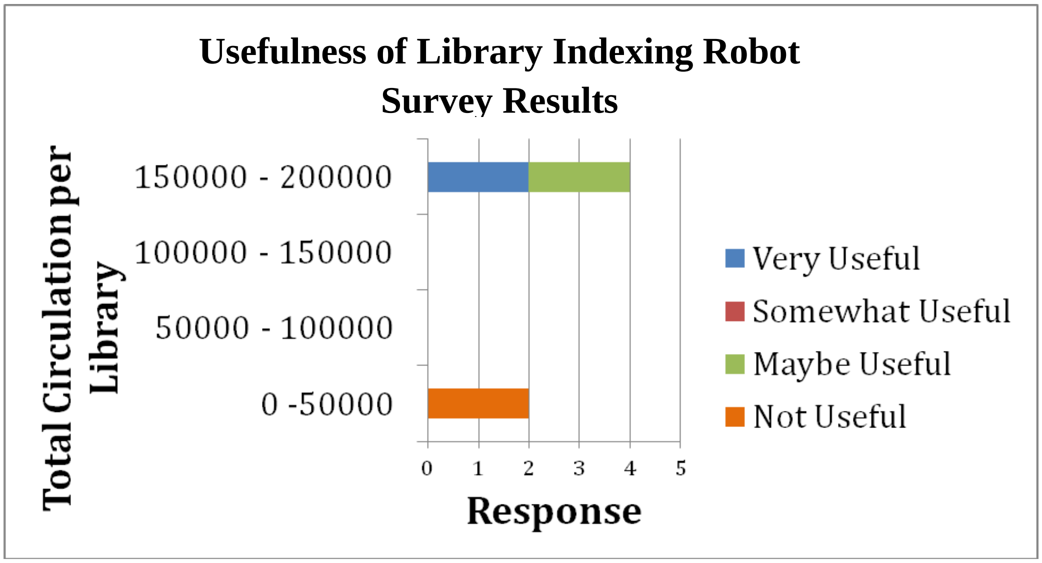

Figure 25: Library Survey Results

Initially the product will focus on libraries that hold between 150,000 and 200,000 books, and will gradually engage in the larger libraries (i.e. Grand Rapids Public). Table 26 shows the libraries consulted and their total circulation per year.

Table 26: Consulted Libraries' Circulation per Year[26]

Library	Total Circulation (books)
Hekman Library	~ 200, 000
Peter White Public Library	~250,000
Hackley Public Library	~192,000
Plymouth District Library	~1,000,000
Grand Rapids Public Library	~1,500,000

9.4.2 Advertising and Promotion

Our advertisement will be tailored towards large libraries that require significant man hours to do shelf-reading.

9.4.2.1 Message

The Bookkeepers indexing robot will reduce the amount of indexing errors, decrease the time spent in shelf-reading/re-shelving as well as reoccurring labor costs.

9.4.2.2 Media to be used:

9.4.2.2.1 Magazines

We plan to advertise our product in magazines that are targeted at libraries. An example of such a magazine is the American Libraries Magazine. Advertising in such a magazine directly addresses our customer and effectively creates an awareness of our product and the benefits it offers.

9.4.2.2.2 Company website

We will use our company website to showcase our product. We will showcase upgrades, promotions that we will be making.

9.4.2.3 Budget

For our advertising, we picked our top two scores from our decision matrix which are advertising in the American Libraries Magazine and the company web page. We believe our advertisement in the magazine and on our website will effectively capture the demographic we propose to sell our robot to We used a decision matrix. In our decision matrix, the score 5 represents very important and 0 represents no importance. The cost of advertising for a year came to $4,800. This was cost of putting an advertisement in the magazine at $400 per month on a single page. Below, Table 27 is the decision matrix we used in choosing the type of advertising that would be most prudent.

Table 27: Decision Matrix for Advertisement Choice

		Type of Advertisement			
		Newspaper	Magazines (American Libraries Magazine)	Webpage	Facebook, Google, and other digital ads
Cost	50%	4	5	4	2
Captures our demographic	50%	3	5	4	3
Total	5	3.5	5	4	2.5

9.4.2.3.1 Prototype design budget

The Bookkeepers will be designing a prototype robot to index books on shelves in a pseudo library rack that the team will build. Our miniature library of shelved books will serve as a proof of concept since the Hekman Library our initial customer has various challenges that cannot be met within the time and expertise constraints of the team. Table 28 shows the prototype design budget containing all the components that will be used in the development and assembly of the robot.

Table 28: Estimated Final Prototype Design Budget for The Librarian

Part	Unit cost	Quality	Total cost
Motors with encoders	$39.95	2	$79.90
Motor for vertical system	$50.00	1	$50.00
Arduino Processor	$50.00	3	$150.00
Mounting bracket	$7.95	1	$7.95
Tire set	$7.25	1	$7.25
Wheel hubs	$7.95	1	$7.95
Battery	$100.00	1	$100.00
RFID tags	$1.05	25	$26.25
RFID card reader	$39.99	1	$39.99
Infrared line finder	$6.50	2	$13.00
Barcode scanner	$29.99	1	$29.99
Barcodes	$0.00	20	$0.00
Web camera	$4.99	1	$4.99
Wiring and connectors	$50.00	1	$50.00
Bolts & screws	$10.00	1	$10.00
Motor control system	$90.00	1	$90.00
Black general purpose tape	$7.00	1	$7.00
IR LED & phototransistor sensor	$2.49	2	$4.98
Power regulators	$5.00	4	$20.00
Website template	$65.00	1	$65.00
Shipping	$50.00		$50.00
Cart (no wheels) 10” x 13” plate Donation	$60.00	1	$60.00
Cart (vertical support) Donation	$20.00	1	$20.00
Overhead			$100.00
Total			**$814.25**

9.4.2.3.2 Production design budget

The robot parts that will be used in the production design of the robot are priced at a volume discount for multiples of 50 parts. Some of the components purchased and used in the building of the prototype were less expensive due to vendors offering the team a discount on academic basis which we will not have for the production design. For our shipping, we estimated $500 based on a quotation from UPS. For 50 packages weighing 150lbs each for delivery within Grand Rapids, the cost total came to about $500. Table 29 shows the parts used in the final production of the robot together with the corresponding costs.

Table 29: Estimated final production design budget for The Librarian

Cost of Materials			
Part	Unit Cost	Quantity	Total Cost
Motors with encoders	$150.00	2	$300.00
Motor for vertical system	$150.00	1	$150.00
Arduino Processor	$89.95	3	$269.85
Mounting bracket	$7.95	1	$7.95
Tire set	$7.25	1	$7.25
Wheel hubs	$7.95	1	$7.95
Battery	$100.00	1	$100.00
RFID tags	$1.05	25	$26.25
RFID card reader	$39.99	1	$39.99
Line array sensor	$15.00	2	$30.00
Barcode scanner	$29.99	1	$29.99
Wiring and connectors	$50.00	1	$50.00
Bolts & screws	$10.00	1	$10.00
Motor control system	$90.00	1	$90.00
Battery recharging dock	$150.00	1	$150.00
Black general purpose tape	$7.00	1	$7.00
IR LED & phototransistor sensor	$2.49	2	$4.98
Power regulators	$5.00	4	$20.00
Website template	$65.00	1	$65.00
Packaging	$50.00	1	$50.00
Shipping	$250.00	1	$250.00
Cart (no wheels) 10” x 13” plate	$60.00	1	$60.00
Cart (vertical support)	$20.00	1	$20.00
Total			**$1,996.21**

9.4.2.3.3 Selling Price

The final cost of our product is based on our material cost and labor cost. Table 30 shows our total Assembly Costs with an assembly cost rate of $40/hr. A profit margin of 40% will be factored into the pricing of our product. Our selling price per robot is $10,839.

Table 30: Assembly Costs

Labor Cost			
Assembly Cost ($/hr)			40
Profit margin			40%
Assembly costs			
Activity	**Hours**	**Cost**	**Note**
Robot frame and arm	40	$ 1,600	Machining the arm of the data acquisition component as well as the base on which the locomotive components will be mounted
Mounting of mechanical components	10	$ 400	This is the time taken to install components such as the wheels, motors and pully for mechanical arm
Electronics assembly	10	$ 400	Installation of electronics components
Electronics installation	10	$ 400	
Packaging	1	$ 40	Time taken to package final product
Testing robot components	15	$ 600	Time for running all components to ensure that robot is fully functional
Assembly costs	**86**	**$ 3,440**	The total assembly costs is the time taken to put the components of the robot and ensure it is fully function.
Contingency		$ 344.0	Our contingency compensates for unexpected outcomes such as a blown component. It is 10% of our assembly costs.
Total Assembly cost		$ 3,784.0	
Material Cost		$ 1,716.21	From Table 4
Product Total		**$ 5,500**	
Profit Margin		$ 2,312.08	
Wholesale price		$ 8,092.00	
Selling Price		**$ 11,329**	

9.4.2.3.4 Fixed Costs

The Bookkeepers will rent a warehouse and machinery for the production of the robots. There will be four salaried employees comprising of the management and engineers. The Bookkeepers will invest in research and development as well as advertising each year with the goal of product improvement and product awareness to the general public. The main variable costs are due to labor and material cost. Table 31 shows the fixed costs attributed to production.

Table 31: Fixed Costs

Component	Unit cost	Quantity	Cost	Note
Engineering of robot	$ 160	900	$144,000	This involves the design and engineering of robot
Salaries	$50,000	5	$250,000	1 CEO 1 EE 1 ME 1 Sales 1 Foreman
Benefits	$15,000	5	$ 75,000	This is 30% of the salary
Warehouse	$32,000	1	$ 32,000	8,000 sq ft ($4/ sq ft)
Utilities	$10,000	1	$ 10,000	
Machinery rental	$10,000	1	$ 10,000	Equipment for machining robot parts, packaging
Research and development	$ 7,200	1	$ 7,200	5% of engineering cost
Advertising	$ 400	1	$ 400	Adveriting in magazine for libraries ($400/page/month)
Prototype cost	$ 814	1	$ 814	Cost of building prototype
Intellectual Property Insurance	$ 8,000	1	$ 8,000	Patent infringement protection
First year total			**$537,414**	
Subsequent year total			**$392,600**	This cost is less the initial design and prototype

9.5 Description of management team

The management team consists of our advisor Professor VanderLeest, the four engineers consisting of one Electrical & Computer engineer, three Mechanical engineers. The design team members are graduating seniors in the Calvin College Engineering program. Figure 26 below shows a picture of The Bookkeepers, who, from left to right are: Kobby Appiah-Berko (ECE), Andrew Dykhuis (ME), Nnamdi Maduagwu (ME) and Tyler Helmus (ME).

9.5.1 Experience, skills and know-how they bring to the company

Kobby Appiah-Berko is a senior Electrical and Computer concentration student from Ghana. Kobby has had multiple internships over the past four years. Two major ones were with Johnson Controls in the summer of 2010 and most recently with Goldman Sachs in the summer of 2011. Kobby has previous programming experience in the C programming language, which has for that reason been chosen as the programming language for this project, and has also completed ENGR 304 (Digital Design) at Calvin. He has been assigned the tasks of programming robot movement, programming vertical movement of the data acquisition system, and interfacing with the library database and also with designing the book ordering algorithm. Kobby will be going off to work with Goldman Sachs after graduating. He plans to work with Goldman Sachs and pursue his MBA with a focus in banking and finance.

Andrew has metal fabrication knowledge from his current and previous internships. He has experience with mills and metal forming, and will use the associated skills and knowledge he has to help fabricate The Librarian's metal components for both the drive and the vertical systems. Andrew has worked on smaller mechanical projects previously. He is the lead designer of the drive system, and will work with Tyler on the vertical movement required to move the data acquisition system. Andrew plans on attending graduate school in nuclear engineering after graduating this May from Calvin College.

Nnamdi is a senior mechanical concentration student from Nigeria. For the past two summers, Nnamdi has been interning at Johnson Controls in Holland. Through the internship, he did feasibility analyses for 2012 instrument panel clusters as well as material selection and strain gage analyses for Ford Clusters. Most recently, he is interning with Highlight Industries where he is performing mechanical risk assessment on most of their existing machines. Nnamdi is in charge of team communication with the adviser, coordinating group work on reports and proposals, and would be in charge of data acquisition tests. Upon graduation, he plans on attending graduate school for an MBA after working a couple years in the industry.

Tyler has also participated in multiple mechanical design competitions, including work in robotics and small mechanism design. He has also programmed in Java, so he has programming experience that will supplement Kobby's work. Tyler has extensive experience with metal and woodworking. Tyler will lead the design of the vertical movement mechanism, and work with Kobby to aid the programming section of this project, and will work with Andrew on the drive system.

Figure 26: The Bookkeepers

9.5.2 Key Assumptions

These financial forecasts assume no change in accounts receivable, inventory or other current assets other than cash; accounts payable or other current liabilities other than notes payable; fixed assets other than equipment; or equity accounts other than retained earnings.

9.5.3 Financial statement

9.5.3.1 Income statement (Annual, 3 years)

	Year 1	Year 2	Year 3
Units sold	50	100	250
Sales revenue	257,335	514,669	1,286,674
Variable Cost of Goods Sold	97,350	194,700	486,750
Fixed Cost of Goods Sold	86,461	172,921	432,303
Depreciation	2,689	6,037	7,169
Gross Margin	70,836	141,012	360,452
Variable Operating Costs	5,000	10,000	25,000
Fixed Operating Costs	250,400	250,000	250,000
Operating Income	(184,564)	(118,988)	85,452
Interest Expense	11,250	18,750	7,500
Income Before Tax	(195,814)	(137,738)	77,952
Income tax (40%)	(78,326)	(55,095)	31,181
Net Income After Tax	(117,489)	(82,643)	46,771

9.5.3.2 Balance sheet (Annual, 3 years)

Interest Expense:	
Annual interest rate on debt	15%

	Year 1	Year 2	Year 3
Average debt balance	75,000	125,000	50,000
Interest expense	11,250	18,750	7,500

9.5.3.3 Cash Flow statement (Quarterly, 3 years)

	Year 1	Year 2	Year 3
Beginning Cash Balance	-	166,386	229,780
Net Income After Tax	(117,489)	(82,643)	46,771
Depreciation expense	2,689	6,037	7,169
Invested Capital (Equity)	150,000	200,000	500,000
Increase (decrease) in borrowed funds	150,000	(50,000)	(100,000)
Equipment Purchases	(18,814)	(10,000)	(10,000)
Ending Cash Balance	166,386	229,780	673,720

9.5.4 Break-even analysis

Based on the financial model adopted for The Bookkeepers, we expect to break even by the end of the 3rd year round. We are hoping to have investors that would fund the startup and consequent running of the company. For the first year, we expect to take a loan from the bank to help finance other operations and starting from the second year, pay back the loans in installments.

10 Acknowledgements

The Bookkeepers would like to thank several people that helped facilitate the success of this project this semester. Special thanks go out to the following:

- Calvin College for educating us and giving us the necessary skills to make such a project a success. We also thank Calvin College for funding the project.
- Professor VanderLeest, the team advisor, for offering the team necessary guidance and nudges throughout the semester.
- Professor Ned Nielsen, for suggesting the project be adjusted from putting books back on shelves to shelf reading books, which proved invaluable in picking a project with the proper scope for this course.
- Tim Theriault from GE Aviation, the team's industrial advisor, for offering the team wonderful advice and guidance.
- Chuck Holwerda from Calvin College Engineering department, for providing the team with barcodes used in testing the data acquisition system.
- Bob DeKraker from Calvin College Engineering department, for facilitating the purchase of the team's prototype parts.
- Phil Jasperse from Calvin College Engineering department, for giving the team access to the Metal and Wood shop as well as helping with the construction of the base for the prototype.
- Glen Remelts from Calvin College Library, for helping the team with research on similar technologies and also providing product requirements for the project.

11 Conclusions

The team successfully achieved its deliverables for the academic year. The deliverables were to build a prototype that could autonomously traverse the aisle of a simulated library, create a program in the library workstation to take data from the robot and then create a report, and a final design report. The program created was in the form of a Microsoft Excel spreadsheet that was able to compare the order of the books scanned and highlighted any books that were not in the right order. The team was able to consistently achieve a scanning accuracy of at least 78% which falls short of the expected 95% accuracy. Higher scanning accuracies were achieved, but not repeatedly. However, with further design iterations and system upgrades, the team believes the accuracy goal is still achievable. The Bookkeepers invested a total of approximately 1140 hours over the two semesters. The team is happy with the outcome. The Bookkeepers are looking forward to more successful collaborations as we delve into our various fields of work.

12 Appendix

12.1 Controlled Robot Testing Pictures

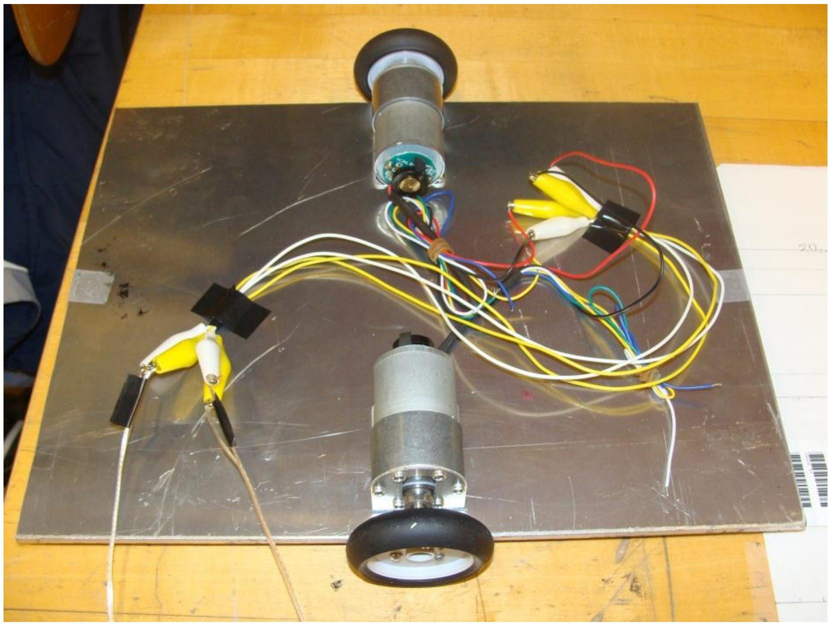

Figure 27: Underside of The Base

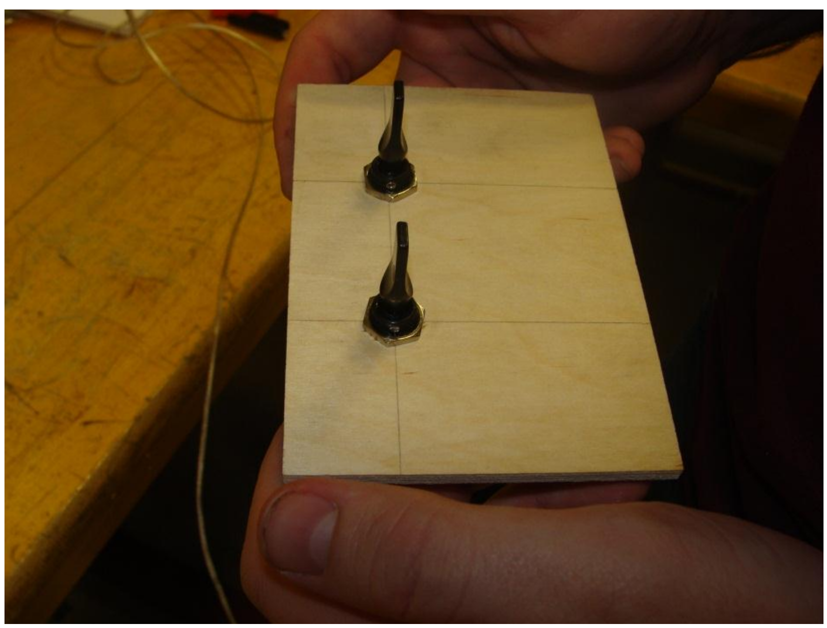

Figure 28: Manual Controller

12.2 Scanner Test Results

The results from the barcode scanning tests are shown in the following figures. Tests were performed for the barcode scanner extended 5 centimeters, 10 centimeters, and 15 centimeters from the barcodes.

Table 32: Barcode Scanning Results for 5 centimeters Displacement

	5 cm high, varying speeds								
Speed [cm/s]	N/A	N/A	0.8	2.9	5.8	8.8	8.8	8.8	7
Accuracy	TEST 1	TEST 2	TEST 3	TEST 4	TEST 5	TEST 6	TEST 7	TEST 8	TEST 9
5	BOOK 1	BOOK 1	BOOK 1	BOOK 1	BOOK 1	BOOK 1	BOOK 1	BOOK 1	BOOK 1
10	BOOK 2	BOOK 2	BOOK 2	BOOK 2	BOOK 2	BOOK 2	BOOK 2	BOOK 2	BOOK 2
15	BOOK 3	BOOK 3	BOOK 3	BOOK 3	BOOK 3	BOOK 4	BOOK 3	BOOK 4	BOOK 3
20	BOOK 4	BOOK 4	BOOK 4	BOOK 4	BOOK 4	BOOK 5	BOOK 4	BOOK 6	BOOK 4
25	BOOK 5	BOOK 5	BOOK 5	BOOK 5	BOOK 5	BOOK 7	BOOK 6	BOOK 7	BOOK 6
30	BOOK 6	BOOK 6	BOOK 6	BOOK 6	BOOK 6	BOOK 8	BOOK 7	BOOK 8	BOOK 8
35	BOOK 7	BOOK 7	BOOK 7	BOOK 7	BOOK 7	BOOK 9	BOOK 8	BOOK 9	BOOK 9
40	BOOK 8	BOOK 8	BOOK 8	BOOK 8	BOOK 8	BOOK 10	BOOK 9	BOOK 10	BOOK 10
45	BOOK 13	BOOK 9	BOOK 9	BOOK 9	BOOK 9	BOOK 11	BOOK 10	BOOK 11	BOOK 11
50	BOOK 14	BOOK 10	BOOK 10	BOOK 10	BOOK 10	BOOK 12	BOOK 11	BOOK 12	BOOK 12
55	BOOK 15	BOOK 19	BOOK 11	BOOK 11	BOOK 11	BOOK 14	BOOK 12	BOOK 13	BOOK 13
60	BOOK 16		BOOK 12	BOOK 12	BOOK 12	BOOK 16	BOOK 13	BOOK 14	BOOK 14
65	BOOK 17		BOOK 13	BOOK 13	BOOK 13	BOOK 17	BOOK 14	BOOK 15	BOOK 15
70	BOOK 18		BOOK 14	BOOK 14	BOOK 14	BOOK 19	BOOK 15	BOOK 16	BOOK 16
75	BOOK 19		BOOK 15	BOOK 15	BOOK 15		BOOK 16	BOOK 17	BOOK 17
80	BOOK 20		BOOK 16	BOOK 16	BOOK 16		BOOK 17	BOOK 18	BOOK 18
85			BOOK 17	BOOK 17	BOOK 17		BOOK 19	BOOK 20	BOOK 19
90			BOOK 18	BOOK 18	BOOK 18		BOOK 20		BOOK 20
95			BOOK 19	BOOK 19	BOOK 19				
100			BOOK 20	BOOK 20	BOOK 20				

Table 33: Barcode Scanning Results for 10 centimeters Displacement

	10 cm high				
Speed [cm/s]	1.1	5.8	1.9	3.5	7
Accuracy	TEST 10	TEST 11	TEST 12	TEST 13	TEST 14
5	BOOK 1	BOOK 1	BOOK 1	BOOK 1	BOOK 1
10	BOOK 2	BOOK 2	BOOK 2	BOOK 2	BOOK 2
15	BOOK 3	BOOK 3	BOOK 3	BOOK 3	BOOK 3
20	BOOK 4	BOOK 4	BOOK 4	BOOK 4	BOOK 5
25	BOOK 5	BOOK 5	BOOK 5	BOOK 5	BOOK 6
30	BOOK 6	BOOK 6	BOOK 6	BOOK 6	BOOK 8
35	BOOK 7	BOOK 7	BOOK 7	BOOK 7	BOOK 9
40	BOOK 8	BOOK 8	BOOK 8	BOOK 8	BOOK 10
45	BOOK 9	BOOK 9	BOOK 9	BOOK 9	BOOK 11
50	BOOK 10	BOOK 10	BOOK 10	BOOK 10	BOOK 12
55	BOOK 11	BOOK 11	BOOK 11	BOOK 11	BOOK 13
60	BOOK 12	BOOK 12	BOOK 12	BOOK 12	BOOK 14
65	BOOK 13	BOOK 13	BOOK 13	BOOK 13	BOOK 15
70	BOOK 14	BOOK 14	BOOK 14	BOOK 14	BOOK 16
75	BOOK 15	BOOK 15	BOOK 15	BOOK 15	BOOK 18
80	BOOK 16	BOOK 16	BOOK 16	BOOK 16	BOOK 19
85	BOOK 17	BOOK 17	BOOK 17	BOOK 17	
90	BOOK 18	BOOK 19	BOOK 18	BOOK 18	
95	BOOK 19		BOOK 19	BOOK 19	
100	BOOK 20		BOOK 20	BOOK 20	

Table 34: Barcode Scanning Results for 15 centimeters Displacement

	20 cm high	15 cm high				
Speed [cm/s]	N/A	1.8	0.9	2.7	4.4	5.8
Accuracy	TEST 15	TEST 16	TEST 17	TEST 18	TEST 19	TEST 20
5		BOOK 1	BOOK 1	BOOK 1	BOOK 1	BOOK 1
10		BOOK 2	BOOK 2	BOOK 2	BOOK 2	BOOK 2
15		BOOK 3	BOOK 3	BOOK 3	BOOK 3	BOOK 3
20		BOOK 4	BOOK 4	BOOK 4	BOOK 4	BOOK 4
25		BOOK 6	BOOK 5	BOOK 5	BOOK 5	BOOK 5
30		BOOK 8	BOOK 6	BOOK 6	BOOK 6	BOOK 6
35		BOOK 9	BOOK 7	BOOK 7	BOOK 7	BOOK 7
40		BOOK 10	BOOK 8	BOOK 8	BOOK 8	BOOK 8
45		BOOK 11	BOOK 9	BOOK 9	BOOK 9	BOOK 9
50		BOOK 12	BOOK 10	BOOK 10	BOOK 10	BOOK 10
55		BOOK 13	BOOK 11	BOOK 11	BOOK 11	BOOK 11
60		BOOK 14	BOOK 12	BOOK 12	BOOK 12	BOOK 12
65		BOOK 15	BOOK 13	BOOK 13	BOOK 13	BOOK 13
70		BOOK 16	BOOK 14	BOOK 14	BOOK 14	BOOK 14
75		BOOK 18	BOOK 15	BOOK 15	BOOK 15	BOOK 15
80		BOOK 19	BOOK 16	BOOK 16	BOOK 16	BOOK 16
85		BOOK 20	BOOK 17	BOOK 17	BOOK 17	BOOK 17
90			BOOK 17	BOOK 18	BOOK 18	BOOK 18
95			BOOK 18	BOOK 19	BOOK 19	BOOK 20
100			BOOK 19	BOOK 20	BOOK 20	
			BOOK 20			

12.3 Vertical System Build Plan

Operation	Instructions		Quantity
10	Design p/n 15 - coupler.		
20	Fabricate and mount p/n 15 - coupler.		
		Nut	1-2
		Bearing	1
		p/n 2 - screw shaft	1
		p/n 7 - 90-degree motor	1
		p/n 15 - coupler	1
30	Disassemble and modify Calvin supplied drawer slides.		
		Calvin supplied drawer slides	1-2
40	Mount track to drawer slides.		
		p/n 6 - top drawer slide track	2
		p/n 1 - 10 inch drawer slides	2
50	Design and fabricate p/n 8 - motor mounting bracket.		
60	Mount motor to base.		
		p/n 7 - 90-degree motor	1
		p/n 8 - motor mounting bracket	1
		base	
70	Design and fabricate the U bracket. Mount on the drawer slide tracks.		
		p/n 6 - top drawer slide track	2
		p/n 13 - U bracket	1
80	Design and fabricate the screw shaft carriage. Mount on the drawer		
	slide tracks, possibly using 'C' shaped parts.		
		p/n 3 - Screw shaft carriage	1
		p/n 6 - top drawer slide track	2
90	Design and fabricate the drawer slide mounting brackets (p/n 5)		

100	Design and fabricate the screw shaft bearing support plate.		
110	Support the screw shaft with the bearing (p/n 4) and plate.		
		p/n 4 - bearing for top of screw shaft	1
		p/n 1 - 10 inch drawer slides	2
		p/n 2 - screw shaft	1
		p/n 14 - screw shafter bearing support plate	1
120	Mount the drawer slides to the base. May need to run this operation		
	before op 110, or complete them concurrently.		
		p/n 1 - 10 inch drawer slides	2
		base	1
		p/n 5 - drawer slide mounting bracket	2
130	Mount barcode scanner on U bracket.		
		p/n 9 - barcode scanner	1
		p/n 13 - U bracket	1
140	Connect the string to the barcode scanner. Drill and tap a hole on the		
	base so that the string can be attached and the length adjusted.		
		p/n 11 - string	1

Figure 29: Build Plan for the Vertical System

12.4 CAD Models

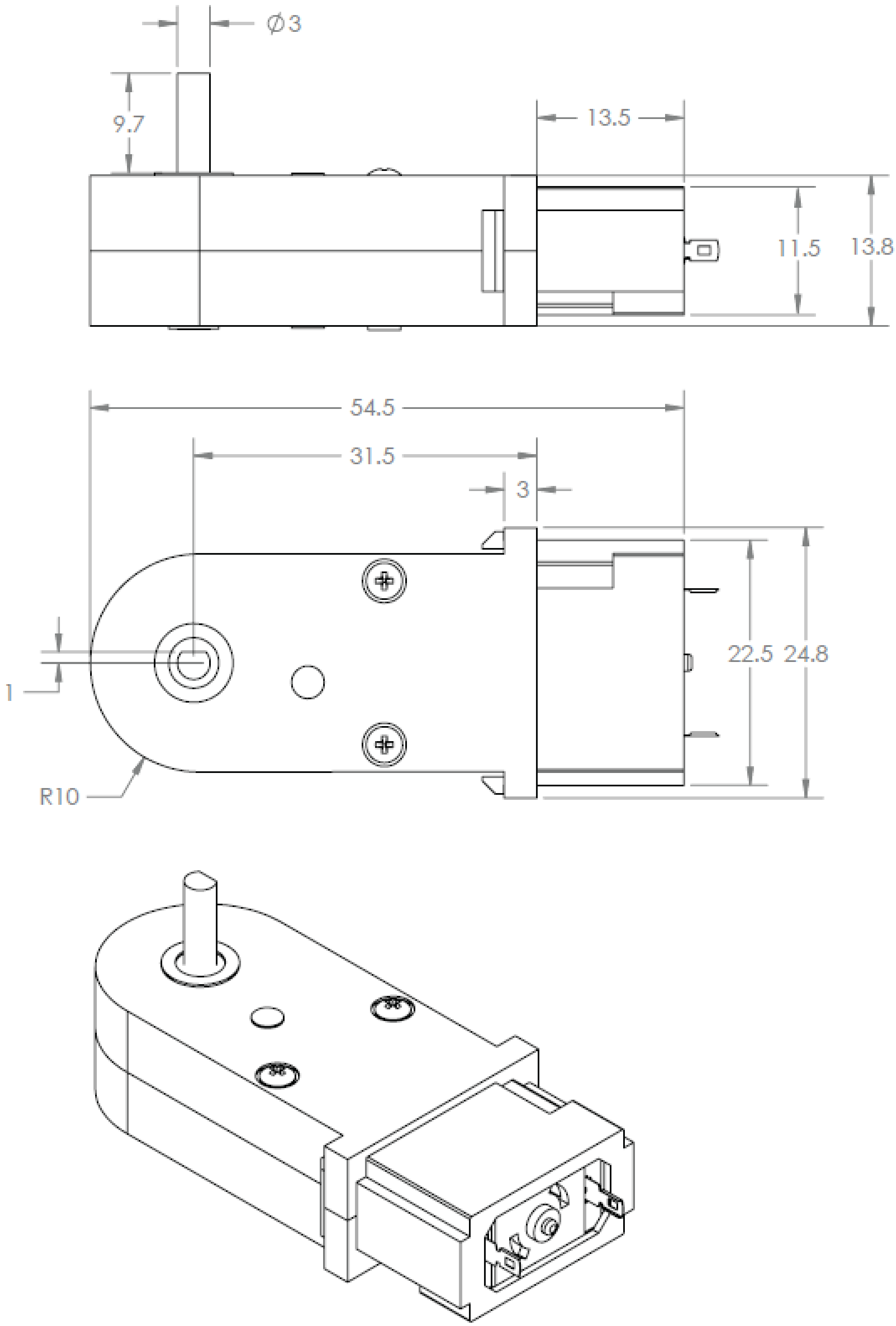

Figure 30: 90-degree Motor Cad Data

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http://lattice-instruments-inc.amazonwebstore.com/Ball-Caster-to-Mount-on-Mindstorms/M/B002JA514E.htm?traffic_src=froogle&utm_medium=CSE&utm_source=froogle
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