

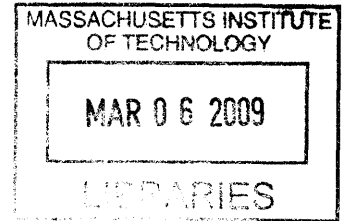
Enlightened Shelf Awareness

by

Isaac M. Ehrenberg

B.A., Physics (2005)

Yeshiva University



Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Master of Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 2009

© Massachusetts Institute of Technology 2009. All rights reserved.

Author
Department of Mechanical Engineering
January 15, 2009

Certified by
Sanjay Sarma
Associate Professor of Mechanical Engineering
Thesis Supervisor

Accepted by
David E. Hardt
Chairman, Graduate Committee

Enlightened Shelf Awareness

by

Isaac M. Ehrenberg

Submitted to the Department of Mechanical Engineering
on January 15, 2009, in partial fulfillment of the
requirements for the degree of
Master of Science

Abstract

The use of RFID technology in libraries has increased to the point where it is now the centerpiece of emerging automated self-checkout, return, and theft detection systems. With the external borders of the library secure, focus has shifted to improve the internal state of a library's collection, which is subjected daily to use and abuse by library patrons. In this thesis I present BookBot, a robot equipped with RFID readers, that automates the otherwise manual shelf-reading process and helps librarians keep their database in sync with the library's physical inventory. Experiments on single shelves and entire bookcases confirm that this robot-assisted approach to inventory management can not only detect misplaced books reliably, but accurately determine the order of the books on the shelves and even localize the coordinates of each book to within a few centimeters, enabling both the librarian and the user to reach a state of Enlightened Shelf Awareness.

Thesis Supervisor: Sanjay Sarma

Title: Associate Professor of Mechanical Engineering

Contents

1	Introduction	8
1.1	The State of RFID	8
1.2	Libraries and RFID	8
2	Motivation	11
2.1	Library Inventory Management	11
2.1.1	Handling Library Inventory	11
2.1.2	Shelf Reading	12
2.1.3	Shelf Reading Negatives	13
2.2	Shelf Reading Technology	13
2.2.1	Barcode Scanning	14
2.2.2	RFID Scanning	15
2.2.3	Smart Shelves	15
2.2.4	BookBot	16
3	Related Work	17
3.1	Robots and RFID	17
4	BookBot	20
4.1	BookBot 1.0	20
4.1.1	Tag Localization	22
4.1.2	Experimental Assessment	26
4.1.3	Tag Localization Accuracy	30

4.1.4	Alternatives to Bayesian Localization	33
4.2	BookBot 2.0	33
4.2.1	Results	34
4.3	BookBot 3.0	37
4.3.1	Plymouth Library	37
4.3.2	System Design	38
4.3.3	Software	43
4.3.4	Experimental Setup in the Library	44
4.3.5	Results	45
4.3.6	Discussion and Future Work	48
5	Conclusion	50

List of Figures

1-1	9
4-1	21
4-2	23
4-3	25
4-4	27
4-5	28
4-6	28
4-7	29
4-8	30
4-9	31
4-10	32
4-11	34
4-12	35
4-13	36
4-14	37
4-15	38
4-16	39
4-17	41
4-18	41
4-19	42
4-20	42
4-21	43

4-22	44
4-23	45
4-24	46
4-25	47

List of Tables

- 2.1 Library Shelf-Reading Statistics From the Literature [7, 31] 13
- 4.1 Evolution of the BookBot shelf reading system. 20
- 4.2 Average Error in the Single Shelf Experiments. 27
- 4.3 Dimensional Errors. 31
- 4.4 Percentage of the books detected and correctness of book order. 45
- 4.5 Average error in position for Library experiments. 47

Chapter 1

Introduction

1.1 The State of RFID

Conceived originally for military purposes during World War II, the concept of a wireless identification system has evolved to the point where the estimated number of RFID tags sold worldwide in 2008 was expected to reach 2 billion, the entire RFID sector was expected to generate roughly \$5 billion [12], and the governance of the industry's standards body is shared by some of the most powerful players in the global economy. The world over, RFID is being used to track merchandise through the supply chain, to collect tolls on highways and to help maintain security and ensure secure personnel access at businesses and universities. The keys to that success has been the inherent simplicity and low cost of RFID systems, which in turn has opened the doors to an even larger variety of smaller, application specific solutions to everyday problems, one of which will be the primary focus of this work.

1.2 Libraries and RFID

This thesis will touch upon the use of RFID in Public Libraries, an application of RFID which has seen only limited deployment due to the usual monetary constraints placed on public education facilities, but is expected to gain more popularity as prices fall and the economic benefits are better understood. In the few libraries where they have already been

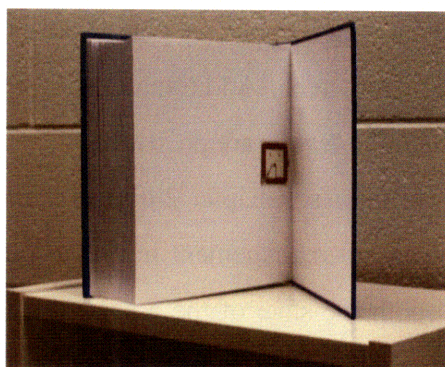


Figure 1-1: HF RFID Tag Embedded in a Book.

installed, RFID has helped improve several aspects of library operation and the experience of all those involved. Once past the laborious stage of embedding an RFID tag in the cover of every book (Figure 1-1), CD, or other media format in the collection, libraries have implemented automated book systems that handle the flow of materials out of the library and facilitate their speedy placement back on the shelves. While users previously had to see library staff in order to checkout any books, all it takes now is a visit to the self-checkout station where the RFID tags embedded in the books are identified by an RFID reader automatically updating the user account. Enhanced security precautions are also possible when using RFID, as readers at all entrances and exits can monitor for the unauthorized borrowing of library material. RFID means a more organized library, resulting in happier librarians, and more satisfied customers.

In addition to the innovations mentioned above, commercial RFID solutions have also proposed the use of hand-held RFID readers which can be used to scan the library inventory while on the shelves and detect discrepancies between the virtual and physical inventory. To do this, library employees need to guide the hand-held devices past each book on every shelf so the RFID tags inside the books can be identified and recorded. While definitely an improvement over conventional inventory methods based on visual inspections, this process is still a manual and time-consuming task as each of the hundreds, if not thousands of shelves in large libraries need to be scanned. In this thesis, I investigated the use of a mobile robot equipped with an RFID reader to automate the task of shelf reading. The initial results show that the RFID enabled robot, in well controlled circumstances, can

correctly determine the order in which books are placed on a shelf and localize the books with an error of only a few centimeters. Additional testing in an actual RFID equipped library was also conducted, and the results are presented.

The thesis will proceed as follows: Chapter 2 discusses the motivation for this work, the ongoing challenge of inventory management in public libraries. Chapter 3 presents related work with regard to both the state of the art in shelf reading technology and the usage of RFID thus far in robotics circles. Chapter 4 describes the BookBot system design, evolution, and experiments with discussion of future work before Chapter 5, which presents the conclusion.

Chapter 2

Motivation

2.1 Library Inventory Management

While the role of the library continues to evolve with the advancement of the Internet and other information technologies, the fact remains that the library is still the premier warehouse for the written word. An estimated 800 million printed books make up the backbone of the United States' Public Library system [11], and that number is only going to grow as time progresses.

2.1.1 Handling Library Inventory

With the average library collection reaching somewhere between 10 thousand and 100 thousand printed books [11], inventory management is no simple task and is almost universally reliant on computer databases, barcode systems, and lately RFID systems to handle the dynamic transfer of materials leaving and re-entering the library system. It is inside the library where the situation can get a little disorganized. In a library, unlike an average warehouse, the public is invited daily to peruse and use the collection, to find and remove what they want from the shelves [13]. This potentially high degree of abuse would put any organizational system to the test [33], and libraries themselves are especially sensitive. While one primary function of a library, to allow the localization of information in the minimal amount of time, requires a high level of organization, allowing the masses the

freedom to remove, and replace, books on every whim, also essential to library freedom, creates the inevitability of widespread disorganization. Books can be removed from a shelf in one section of the library and reshelved accidentally on the next shelf, or in the next section entirely, without any record of this transition being made [4]. Over a long enough time one would expect a perfectly organized library to eventually reach an almost unusable state, which is why many libraries practice inventory reorganization procedures, commonly know as shelf reading.

2.1.2 Shelf Reading

Shelf reading, both adored and abhorred by library administrators and employees worldwide, is the process of manually cataloging whether an information resource is in its proper location within the library [33]. On the one hand it is known to be a vital component of a library's upkeep regimen, while at the same time it stands accused of being an onerous and tedious activity. It takes a great deal of time [31], manpower [10], money [30] and patience to reorganize and relocate the few hundred or thousand misplaced books in the standard American library (cf. Table 2.1), but to not do so has the potential to upset the user. "Shelf Failure", a term for when books fail to be found in their proper places, is one of the more common complaints raised by library patrons [8] [23] [33]. Shelf reading regularly limits shelf failure by ensuring that library books are returned to their proper places and organized in the appropriate manner.

Aside from catching library blunders like Tolstoy's *War & Peace* in the childrens section or encyclopedia yearbooks out of chronological order, shelf reading can catch other library fumbles as well [33]. These include books that appear in the inventory database as checked out or missing but are actually on the shelves. Some of these out of touch library books would be virtually lost without shelf reading, causing libraries to needlessly waste money and replace them [6] [5] [33].

Volumes	Total Misshelved	Error Rate in %	Badly Misshelved	Hours Shelf Reading	Volumes Read per hour	Source
N/A	N/A	9	N/A	N/A	N/A	Bennet <i>et al.</i>
89,684	3,376	3.8	N/A	67	1,229	Pedersen et al
92,889	3,164	3.4	225	73	1,272	Pedersen et al
94,877	3,020	3.2	220	81	1,171	Pedersen et al

Table 2.1: Library Shelf-Reading Statistics From the Literature [7, 31] .

2.1.3 Shelf Reading Negatives

While shelf reading prevents wasteful spending on replacement books and increases access to information at the basic level, critics of shelf reading argue that it simply is not worth it. The cost in man hours of manually shelf reading a library is tremendous, possibly more than the cost of replacing all lost, misplaced and mangled books combined. [30] While those specifics may vary on a case by case basis [33], all agree that shelf reading takes a long time. Studies have shown shelf reading rates that reach only between 800 to 1200 books per hour per person (cf. Table 2.1). That adds up to 70 hours of work in a library of 100,000 books or 700 hours for a million books. While not hard labor in the usual sense, shelf reading has been referred to as a “tedious manual task” with a high burnout rate [5], which can, ironically, raise the probability of human error corrupting the shelf reading process [28]. In addition to being hard on the library employees, some libraries have the practice of closing their doors to the public and requiring all borrowed materials to be returned for the shelf reading period, which can last from days to weeks depending on collection and staff sizes, in order to make the process as error free as possible. This large inconvenience to patrons has to be balanced against the previously mentioned positives when evaluating the viability of conducting a shelf reading exercise [30].

2.2 Shelf Reading Technology

In recent years technology in the form of hand-held barcode and hand-held RFID scanners has come to the aid of shelf reading librarians with properly equipped collections. Previously, shelf reading consisted of a librarian meticulously cataloging and evaluating the order of the books on each and every shelf. Typically, that would mean confirming the shelf’s contents with a shelf list that was kept nearby [10], and checking that all books

were in numerical order under the Dewey Decimal Classification system, or any other library ordering scheme. Books slightly out of order would be reinserted on the same shelf, while others suffering from a greater displacement would be pulled off the shelf for later reshelving.

2.2.1 Barcode Scanning

The shelf reading procedure remained pretty much the same after the incorporation of hand-held barcode scanners into the mix. However, instead of mentally discerning the order of the shelf content, books fitted with barcodes are processed by the hand held device [13] [15]. When loaded with the entire library database, the scanner relates the barcode or tag ID number of every book to its Dewey Decimal number. As the librarian goes from one book to the next to the next, the numbers of the books are compared. If the book in the middle does not fall between the other two in the grand scheme of the shelf, the librarian is alerted that this book is out of order [3] [34]. The scanner can also alert the librarian if a book that was supposedly checked out is actually on the shelf, or if a book that was thought to be missing turns out not to be so.

The use of a barcode scanner for shelf reading and inventory was evaluated by Miller *et al.* [28]. A bookshelf of 200 books was set up in order, and then randomly disordered. Four inexperienced shelf readers were given the task of doing inventory and finding the misshelved books. Given the small number of books and participants the results of the study have limited value, but several sources of error in shelf reading with and without barcodes were discussed in detail. Errors from manual shelf reading result from the librarian skipping books, failing to identify a misplaced book, or falsely identifying ordered books as out of order. The same errors were found while scanning barcodes. It is of course still possible to skip books, but the seemingly impossible mental mishaps of the librarian mentioned above, falsely identifying a book as misplaced, or not realizing that a book that was scanned in order was misplaced, can be simulated by scanning the books in the wrong order [14] [28].

2.2.2 RFID Scanning

While certainly an improvement over the old fashioned way, barcode scanning is far from the ideal solution to shelf reading. Rarely are barcodes placed on the outside of books to enable quick and easy scanning [1], and even if they are, many books are too thin for the barcode to be on the stem, requiring physical manipulation of most books to get the code in view of the scanner. That is where RFID enters the scene. As a contactless, wireless technology, the librarian simply has to wave the scanner and its antenna by the stem of the book, and the book is identified. Commercial handheld scanners are available on the market today, including 3M's Digital Library Assistant, and the Tagsys WiFi Inventory Reader.

Several case studies of the 3M Digital Library Assistant have been documented. At the Mary Riley Styles Public Library in Falls Church, Virginia, a library of approximately 100,000 volumes, shelf reading time decreased 43 percent and accuracy rose 23 percent. At the library in the University of Glasgow, 80,000 volumes in their short loan collection were fitted with RFID tags. Initial usage of the DLA revealed a 12 percent error rate among the collection, which dropped to 6 percent as regular shelf reading was implemented, excluding exam periods. The time required for shelf reading dropped as the librarians became more experienced with the technology, starting at around 400 volumes per hour per person, finally rising to about 800 volumes per hour. Comparisons were done against the manual shelf reading rate, which was only 452 volumes per hour per person.

2.2.3 Smart Shelves

The introduction of RFID into the library mix has opened up the possibility for using smart shelves as an alternative to shelf reading [22]. Smart shelves are exactly like normal shelves but with multiple antennas built in to every shelf. The antennas are spaced appropriately so the read ranges do not overlap, meaning any tag detected by a specific antenna is definitely in close proximity to it. A library equipped with smart shelves would be able to tell the general location of every book on every shelf, alerting librarians to books being in the wrong location. While this solution means instant inventory, it does not ensure that the books are in any type of order, and can get rather expensive. Considering that RFID systems

already break the bank for all but the most well to do libraries, smart shelves will likely remain cost prohibitive.

2.2.4 BookBot

With smart shelves off the table, the full potential of RFID applied to library inventory management has yet to be realized. RFID handheld readers have made a librarians task of shelf reading less back breaking and mind numbing, but the shelf reading process remains a tedious and time intensive manual task since hundreds, if not thousands, of library shelves need to be scanned manually. To eliminate that problem, this thesis introduces BookBot, the automated RFID library inventory and shelf reading solution. By combining robots and their sensors with the RFID systems used in libraries, BookBot can drive by a shelf of RFID tagged books and not only determine whether the books are present, but where the books actually are in the coordinate system of the library, and the order of the books on every shelf in the library. While not a real time location system, BookBot can be wholly autonomous, requiring little or no human input to carry out its mission, and has advantages over smart shelves including a more accurate localization of books and a lower system cost.

Chapter 3

Related Work

3.1 Robots and RFID

Though RFID is at its core an identification technology, a tag is more than just a fancy barcode. Barcodes, which in essence operate via a one dimensional binary color image recognition system, are limited in their application by the fact that they require line of sight for the barcode number to be decoded. RFID systems have no such constraint, as the radio signal transmitted between reader and tag can pass relatively unobstructed through a wide range of nonmetal objects. This property broadens the scope of applications where RFID can act as a sensor, beyond those of binary image recognition schemes, especially in the growing field of robotics.

Over the last decade, RFID systems have been used by the robotics community as a sensor to improve the mapping and localization accuracy of mobile robots. Kantor and Singh [24] conducted an experiment where an autonomous vehicle fitted with an RFID reader system was left to map out an area containing ten RFID tags. The positions of nine were known a priori, while the position of the tenth was unknown. Using the concept of time of flight, the time differential between when the radio signal from the reader was sent and when a response was received, the distances between RFID landmarks and the ATV were calculated. The distance information was used to give an initial estimate for the tenth tag's position, and then plugged into a Kalman Filter based SLAM algorithm to update the tag position and ATV trajectory. Bearing information was not discernible for individual

landmarks as the RFID system benefited from a 360 degree coverage pattern. Knowing the ATV was approximately a given distance from a tag meant it could be anywhere on the surrounding annulus. However, combining information from three separate tags resulted in a probability distribution with only one peak, which was used for both distance and bearing information.

The use of RFID tags for localization was taken to the next level by Hähnel *et al.* [19], where the identification of UHF tags with previously unknown locations was used to enhance the SLAM capabilities of a mobile robot equipped with a laser range finder. First, a highly accurate map of the environment was built using a laser range finder and the Fast-SLAM 2.0 algorithm, which recognizes environmental features as landmarks, and uses them to correct the trajectory of the robot. While building a map the robot recorded RFID tag IDs, and the position and orientation of the robot when the tags were read. After the final map was completed, Bayesian reasoning was used to localize the tags, given an assumed UHF tag sensor model, which gave the probability of reading a tag from a certain distance and bearing. Monte Carlo methods were employed to analyze the posterior distribution of each tag. As each tag was identified, a set number of points in the surrounding area were chosen and the probabilities for each were calculated. The one with the highest probability at the end of the run was the presumed position of the tag. Once the tags were localized and their posterior distributions calculated, it was shown the RFID tags could be used to localize a moving object, similar to Kantor and Singh's methods.

There have also been a number of publications that show applications benefiting from RFID-based robot localization. Kulyukin *et al.* [25] [26] used RFID in multiple situations to aid blind people in the navigation of indoor environments. Bohn *et al.* [9] presented a location-aware autonomous vacuum cleaner equipped with a mobile RFID reader and antenna which reacted to tags embedded in the floor space at any particular location. The RFID tags warned the robot to avoid areas that were marked as off-limits and to stay within an area surrounded by a virtual barrier.

The use of a mobile robot for asset tracking in an enclosed environment was discussed by Patil *et al.* [2]. A Roomba vacuum with a UHF RFID reader was let loose in a room with RFID tags spaced at one meter intervals. The location of the Roomba was determined

by a WiFi system. Tag locations were determined by either averaging the locations from where the tag was observed, or drawing confidence circles around the observation points, and finding their intersection. The accuracies of those methods were found to be 3.5 and 1.5 meters, respectively.

Similar to [2], this thesis combines mobile robots and RFID technology to provide a cost effective way to localize objects in the robot's environment, in this particular case books on library shelves. The RFID tags are thus not deployed in the environment to improve the accuracy of the localization of a mobile robot, rather the robot is interested in finding and localizing the tags without any known landmarks present. The probabilistic approach used here to localize the RFID tags given the uncertainty about their true position relies on recursive Bayesian updating, roughly the same approach used by [19] for the tag mapping. However, instead of choosing a finite set of points to represent the entire posterior distribution, a local search algorithm utilizing gradient ascent was found to be a much faster way of finding the most likely positions of the RFID tags.

Chapter 4

BookBot

The mobile shelf reading system presented in this thesis, known as BookBot, consists of two functionalities combined into one useful tool; the ability to move and track movement fulfilled by a mobile robot platform, and the ability to sense RFID library books using an RFID reader. Combining the information obtained from both of these modules makes it possible to localize RFID tags and the books they identify. Though the system as a whole went through several evolutionary stages (Table 4.2) as the project shifted from bench level experiment to on-site testing, this cooperation between robot and reader remained constant throughout the project.

4.1 BookBot 1.0

The goal of the bench level experiment phase of this project was to mount an RFID reader on a robot, and simply guide it down a row of RFID tagged books. Odometry and tag response data were collected and processed to see if the order of the books could be reconstructed afterward. The initial system design consisted of a *Feig* Midrange Reader ID ISC.MR101-A operating at 13.56 MHz mounted on an *iRobot Create* mobile robot

BookBot Version	RFID System	No. of Antennae	Robot Platform
1.0	Feig MR101	1	Create
2.0	Tagsys LR200	1-4	Create
3.0	Feig MR101	6	Custom

Table 4.1: Evolution of the BookBot shelf reading system.

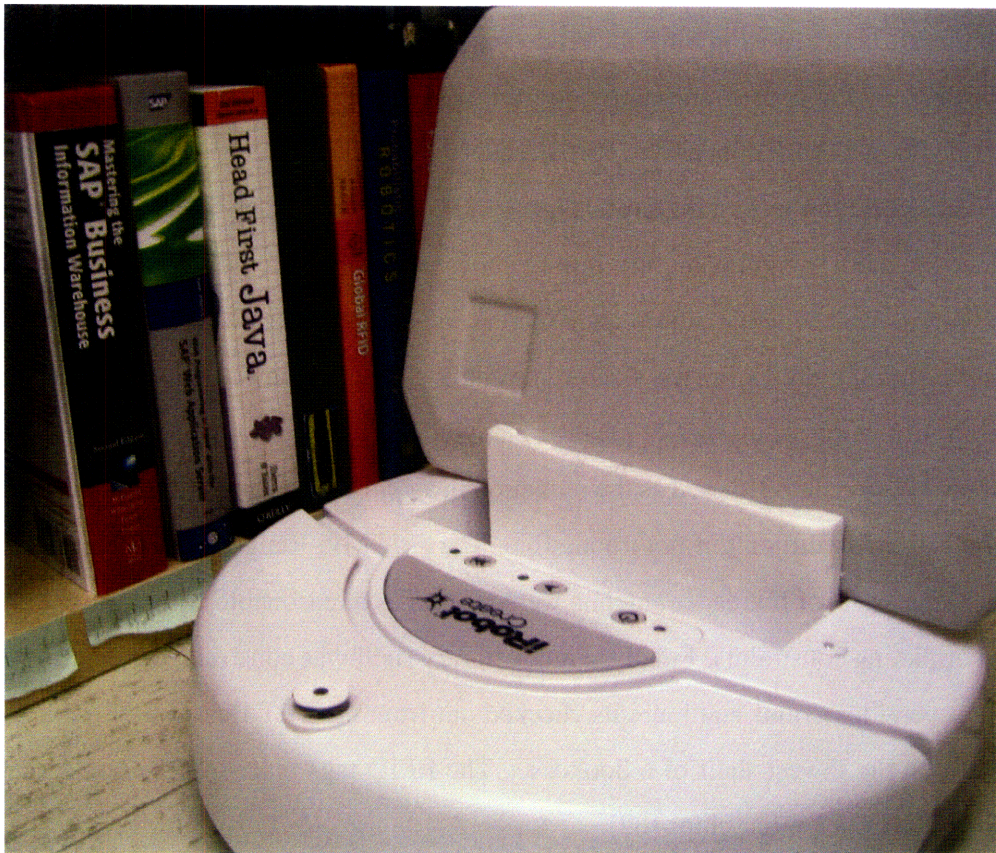


Figure 4-1: Robot with mounted RFID antenna in front of a book shelf.

platform [21]. A single *Feig* Pad Antenna (ISC.ANT340/240) of 34 by 24 cm, was also mounted on the robot in the orientation shown in Figure 4-1. Fortuitously, the robot's diameter was also about 34 cm. Both the reader and the robot were controlled via a laptop PC using open source Fostrack and RoomBacomm software packages [27].

The HF RFID system was chosen since the majority of commercial RFID library solutions that tag books to automate the check-out process also use HF RFID tags due to their appealing form factor and read range characteristics. The choice of antenna was made as a trade off between extending the read range with more power, to ensure that all tags will be seen by the reader, and narrowing the read range, to lessen the uncertainty about a tag's position. The output of the RFID reader is binary in that it will only respond if it detects an RFID tag in its range (cf. Figure 4-2). No distance or bearing information is provided, so there is significant uncertainty about the true position of a detected RFID tag. One could make the identification range increasingly small to reduce the uncertainty about the true position by reducing the size or current of the reader antenna, but this also means that BookBot would likely fail to localize many books. The read range might be so small that some tags would be missed as the reduction in signal-to-noise ratio could render identification extremely difficult, if not impossible. The *Feig* Mid-Range Reader ISC.MR101-A and the letter-size RFID reader antenna were chosen as a reasonable compromise between these conflicting constraints. Finally, a mock library shelf was constructed by putting RFID tags in several textbooks and journals checked out from the MIT Barker Library and placing them on the lowest shelf of a bookcase. The RFID tags placed in the books featured *Philips* HF I-Code1 microchips [32].

4.1.1 Tag Localization

Bayesian Updating

To deal with the limited location accuracy of the HF RFID system and the resulting uncertainty about the true position of RFID tags after they are identified, a probabilistic approach based on recursive Bayesian updating was implemented. A Bayes Filter works by using probability to evaluate and update a belief, or a guess about something, in this case a belief

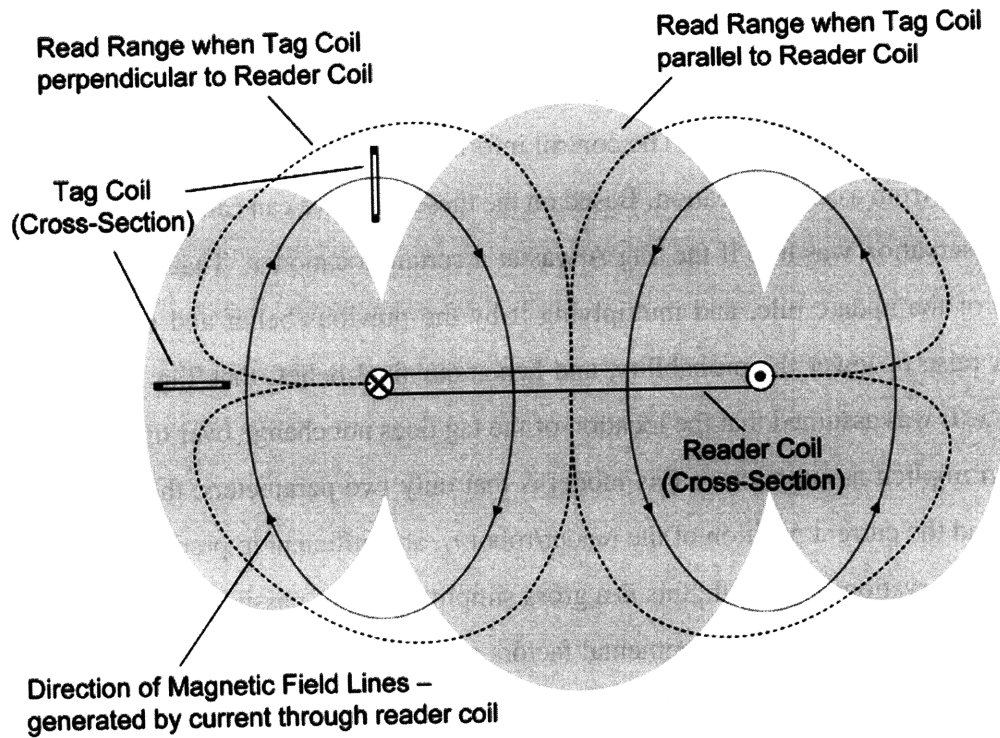


Figure 4-2: Read Range of a reader for a tag parallel and perpendicular to the reader coil [16].

about the true location of a RFID tag. The mathematical representation of a Bayes Filter is

$$P(x_t) = \alpha * P(z_t|x, u_t) * P(x_{t-1}) \quad (4.1)$$

where $P(x_t)$ is a current belief, $P(x_{t-1})$ is the past belief, and $P(z_t|x, u_t)$ is the "update rule". α is a normalization constant. The goal of the Bayes filter implemented here was to find the location x from the universe of all possible locations with the highest probability of being the true tag location. x in the above equation represents one such presumed tag location. $P(x_t)$, the current belief, is a measure at time t of the probability that the tag is truly at location x . $P(x_{t-1})$, the old belief, is the measure at time $t - 1$ that represents the probability the tag was at x . The update rule, $P(z_t|x, u_t)$, is what transforms the belief from one time to another, from old to new, and it involves the parameters z_t, x and u_t . z_t stands for a measurement at time t , which will be used to help update the past belief. If the reader looked for the tag at time t , z_t represents whether the reader saw the tag or not. u_t is control data, an example of which would be odometry data from a robot's sensors. With

all the definitions put together, $P(z_t|x, u_t)$ represents the probability that the outcome of the observation is correct given the control data and the assumed location x . For example: z_t observes that Tag A was seen. The control information says that this observation of Tag A was made from a certain location. Based on these facts, we can calculate the probability this observation was true if the Tag A was at a certain location x . That probability is the value of the update rule, and multiplying it by the previous belief and normalizing will either raise or lower the probability, and hence our final belief, that Tag A is actually at point x . It was assumed that the location of the tag does not change over time.

An implicit assumption of this model is that only two parameters, the location of the tag x and the current position of the reader/robot r_t , are sufficient to predict the probability of the observation z_t . In truth, this is a gross simplification of passive HF RFID, since past measurements and other environmental factors are not considered, but in practice they are very difficult to accurately model. The read range of near field RFID systems such as the RFID system used here is impacted by a number of environment factors that influence the read range:

- Ambient noise levels – A high ambient noise level resulting from intentional (other radios) or non-intentional (electric motors) transmitters lead to a reduction in read range because the weak tag replies can no longer be decoded in the presence of high noise levels.
- Proximity of other RFID tags – HF RFID labels typically feature a resonance circuit that is tuned to the operating frequency of the RFID reader. Other RFID tags in the vicinity introduce a parasitic capacitance that changes the resonance frequency of the RFID tags which leads to a reduced read range. The read range is also negatively affected by the mutual conductance represented by other RFID tags in close proximity [17].
- Proximity to metal objects – Just like other RFID tags, metal objects in the vicinity also detune the resonance circuit on the tag. In addition, metal objects also detune the resonance circuit in the reader antenna and the induced eddy currents in the metal significantly weaken the field created by the RFID reader and tag, all of which result

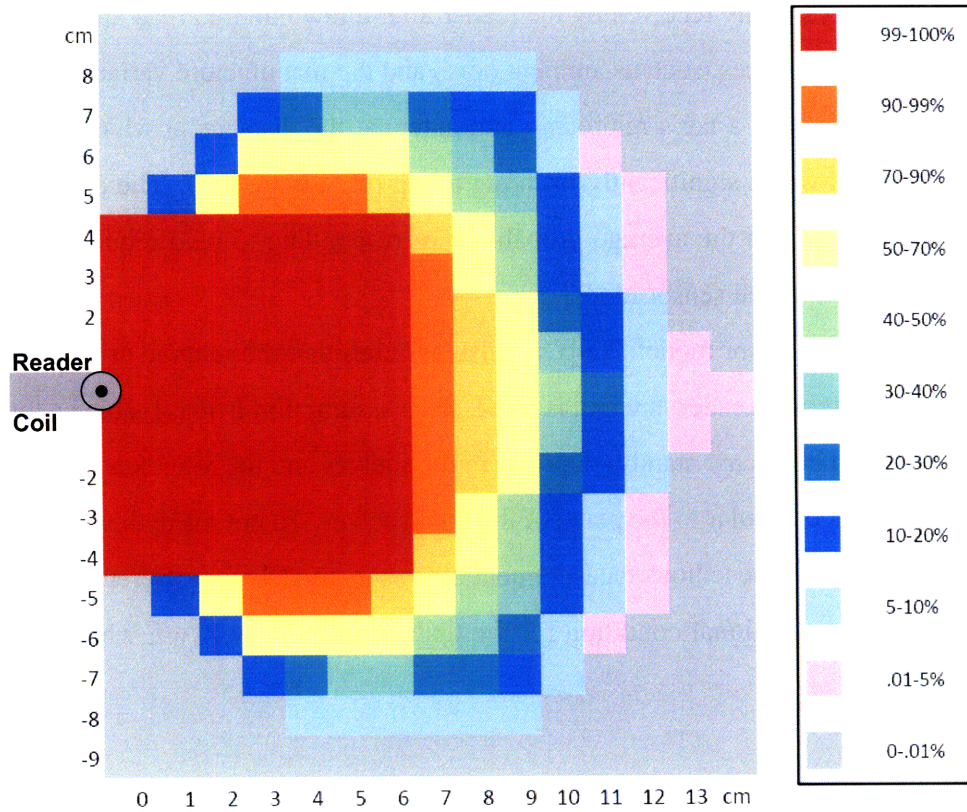


Figure 4-3: The sensor model used for Tag Localization, corresponding to the rightmost lobe of Figure 4-2.

in a reduction in read range [16].

Sensor Model

To determine numerical values for the probability distribution $P(z_t|x, r_t)$, a sensor model was built from experimental data relating tag read rates to distance from the tag to the reader in two dimensions (cf. Figure 4-3). While it is theoretically possible to develop a deterministic model to estimate read range as a function of the relative distance between the tag and reader based on the magnetic field strength generated by the reader antenna and the voltage changes in the reader antenna as a result of the load modulation, it is only feasible for simple geometries or with expensive software packages. Instead, we chose to generate the statistics through simple experiments. An RFID tag was placed at 2.5 mm intervals around the reader antenna with the coils parallel to one another while recording how often

the tag ID was successfully received by the reader after a few hundred read attempts. Due to environmental influences, such as ambient noise and tag manufacture variables, namely the connections between a tag's microchip and antenna, the distance at which the tag is no longer detected varies significantly from tag to tag (cf. Figure 4-3). The exercise was repeated for 20 tags, and the average probability of responding to read requests was the value chosen for the actual sensor model.

This antenna-tag sensor model $P(z_t|x, r_t)$ also assumes that the relative orientation between the RFID tag and reader antenna is fixed. This assumption is reasonable as long as all RFID-equipped books are standing upright in the shelves and the robot keeps the RFID reader antenna perpendicular to the plane of the bookshelves. To not make this assumption would require not only the tedious measurement of sensors models for different angles, but it would require an additional condition for the update rule, $P(z_t|x, r_t, w)$, where w is the orientation angle.

4.1.2 Experimental Assessment

To assess the feasibility of the early BookBot implementation, several possible scenarios were considered that would highlight potential issues with the system (cf. Figure 4-4 and 4-5). The first assessment was a computer simulation modeling a virtual RFID reader moving along a virtual RFID equipped library shelf. The sensor readings were generated according to the sensor model described earlier. As a simulation, it gauged performance without any of the human or robotic measurement errors that are inevitable in real world experiments. Second, the simulation was reenacted in reality with an RFID reader manually guided on a path along the length of a bookshelf holding RFID equipped books. The books on the shelf ranged in thickness from 2 to 4 centimeters and all the tags were placed in their respective books at approximately the same height. The reader antenna was kept within four centimeters of the bookshelf. The experiment was then repeated with the reader fastened to a mobile robot which carried the reader along the same path, using the robot's own sensors to determine its position. The robotic experiment was then repeated with a metal bookshelf to examine the effect of a metal environment on tag localization. This experiment

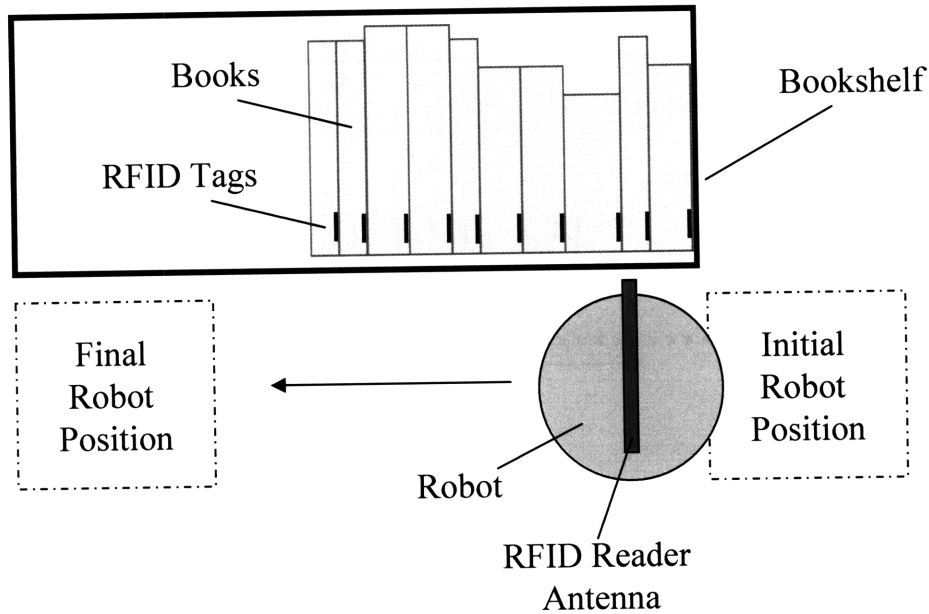


Figure 4-4: Top view of the measurement setup featuring a single bookshelf with tagged books, RFID-equipped robot, and robot trajectory.

Experiment	Avg Error(cm)	Std. Dev.(cm)	Max Error(cm)
Simulation	0.33	0.25	0.7
Manual	0.66	0.478	1.76
Robot (wooden shelf)	0.87	0.57	1.6
Robot (metal shelf)	1.3	0.44	1.7

Table 4.2: Average Error in the Single Shelf Experiments.

was repeated with a book shelf that only had a metal floor, but no metal sides. Then the robot was guided along a rectangular path passing two wooden bookshelves equipped with RFID books (cf. Figure 4-5). In this experiment the robot started from the origin oriented along the y-axis, and followed the perimeter of a 90 by 40 cm rectangle. The bookshelves stood facing each other 80 cm apart. Finally, to test the system on thin books, the robot was guided along a shelf with only books ranging in width from .5 to 1 cm. Each experiment was repeated ten times. The purpose of these tests was to evaluate the performance of the localization algorithm in conjunction with a sensor model and varying amounts of uncertainty introduced by human or robotic errors.

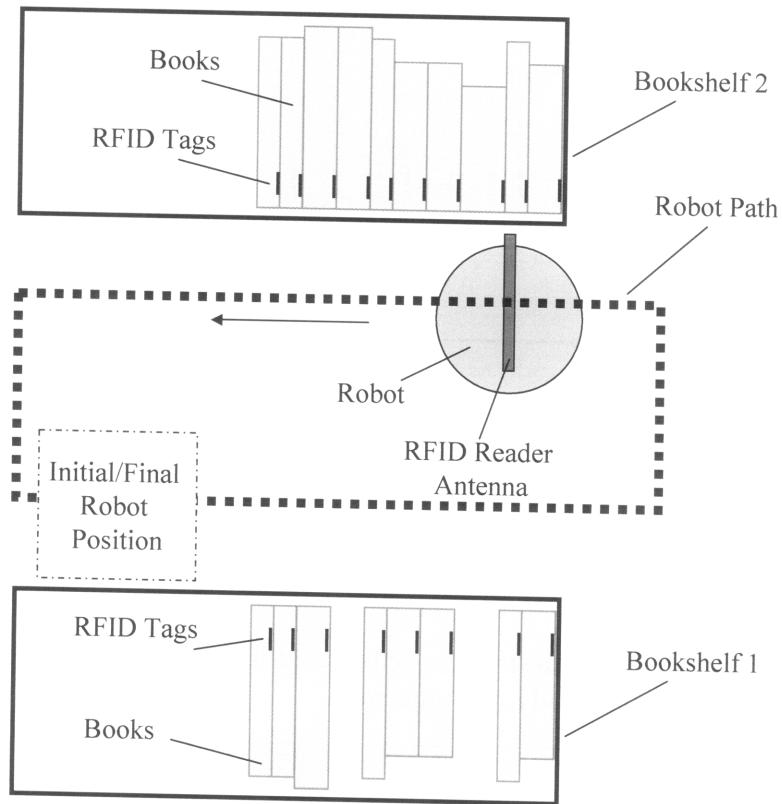


Figure 4-5: Top view of the measurement setup featuring two bookshelves.

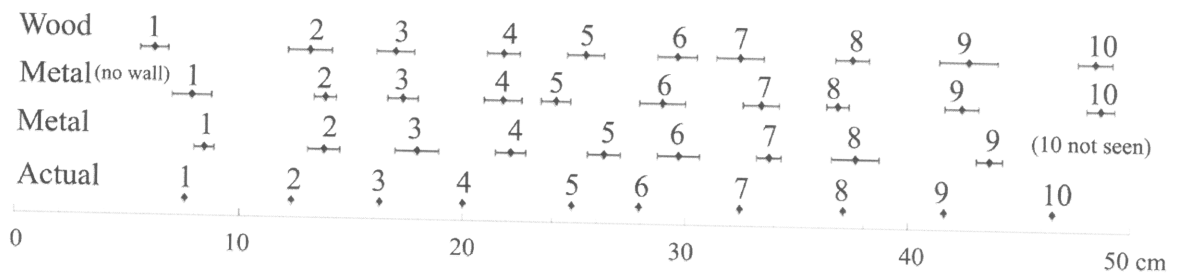


Figure 4-6: The actual and estimated tag position in the experiment with a single shelf. The figure shows the data from the experiment with the wooden and metal (with and without sides) shelf.

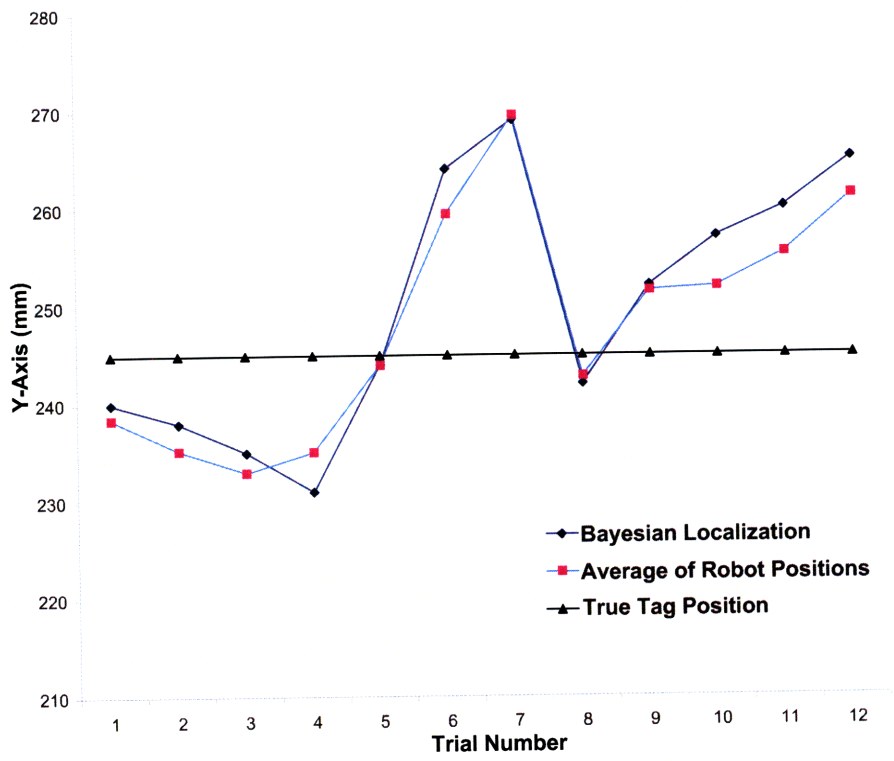


Figure 4-7: A comparison of two methods for estimating the location of a single tag on the axis of the bookshelf's length.

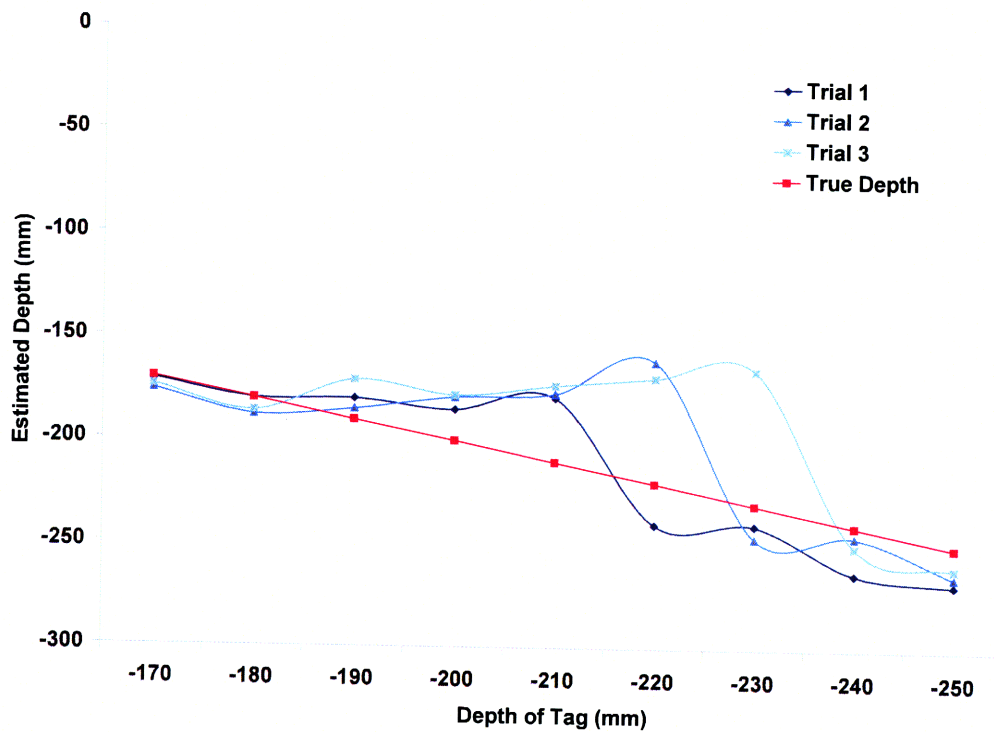


Figure 4-8: Actual and estimated depth of the tag using the Bayesian algorithm.

4.1.3 Tag Localization Accuracy

As can be seen from Figure 4-6 and Table 4.2, all the books on the single wooden shelf were identified and localized on average to within 0.9 cm of their actual position. While the maximum localization error over the course of the wooden shelf experiment did reach as high as 1.6 cm, in no single run was the ordering of two books on the shelf transposed. This suggests that in an RFID friendly library environment, this system has the potential to perform shelf reading functions and book localization with fairly high accuracy.

On the metallic shelf, all the identified books were localized to within 1.3 cm of their actual location on average. The largest single localization error on the metal shelf also reached about 1.7 cm, and again the shelf order was preserved. In addition to slightly higher localization errors, there were problems reading the two tags closest to the side of the metal shelf. The tag further from the wall was silent approximately twenty five percent of the time, while the tag directly up against the metal wall was not read once over all ten runs with the metal shelf. However, when the side of the shelf was removed all the tags were once again identified by the RFID reader. This implies that books standing on

Dimension	Avg Error(cm)	Std. Dev.(cm)	Max Error(cm)
x	6.2	2	9.6
y	.98	.59	3.0

Table 4.3: Dimensional Errors.

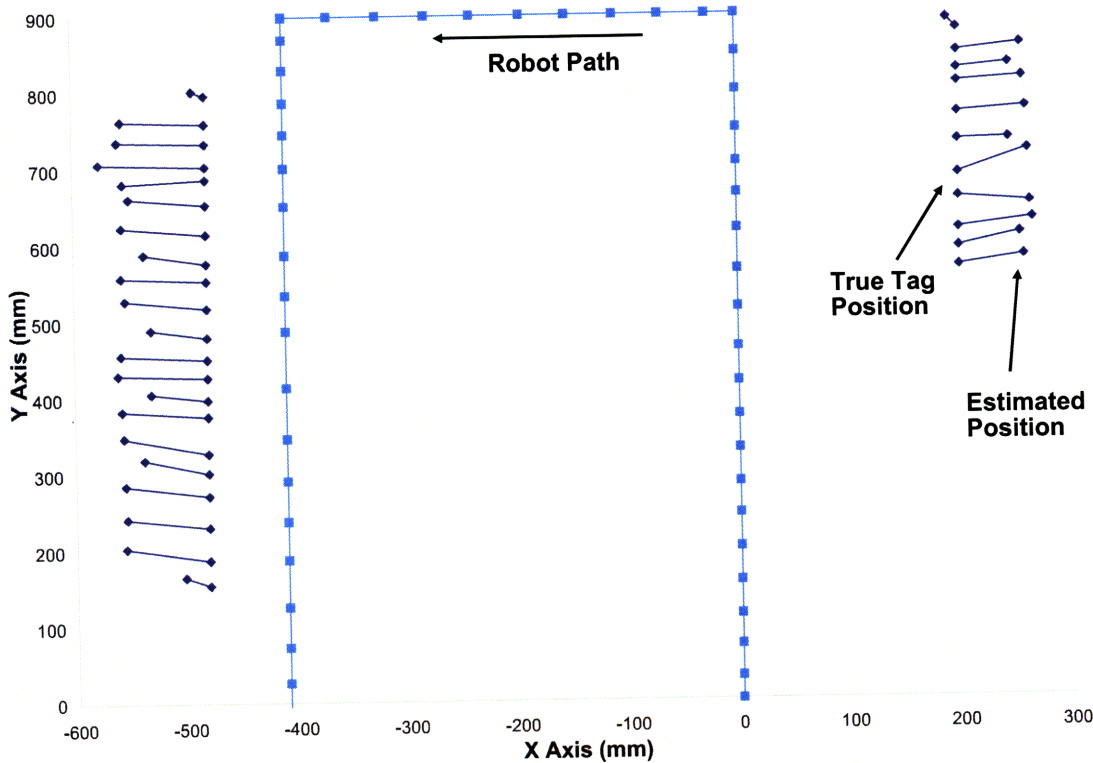


Figure 4-9: Actual and estimated tag positions (in 2D) from the mobile robot scanning the books on the two bookshelves.

metal shelves are not adversely affected by the metal underneath, which is intuitive given the assumed tag orientation and the magnetic field lines powering it. As a preventative measure, in order to maximize system performance, it would be ideal to use nonmetallic bookends to ensure some space between a metal shelf wall and any books.

While the single shelf experiments demonstrated how well BookBot could determine the order and location of books along a wooden or metal shelf, the two shelves experiment was meant to test BookBot's ability to localize library books in two dimensions. Looking from a bird's eye view at the results in Figure 4-9, the picture seems less accurate than the single shelf runs, mainly due to previously ignored errors in the x-direction (cf. Table 4.3). At times the algorithm would guess the tag to be on the opposite side of the robot, given that the sensor model used was perfectly symmetric and the route of the robot did not favor

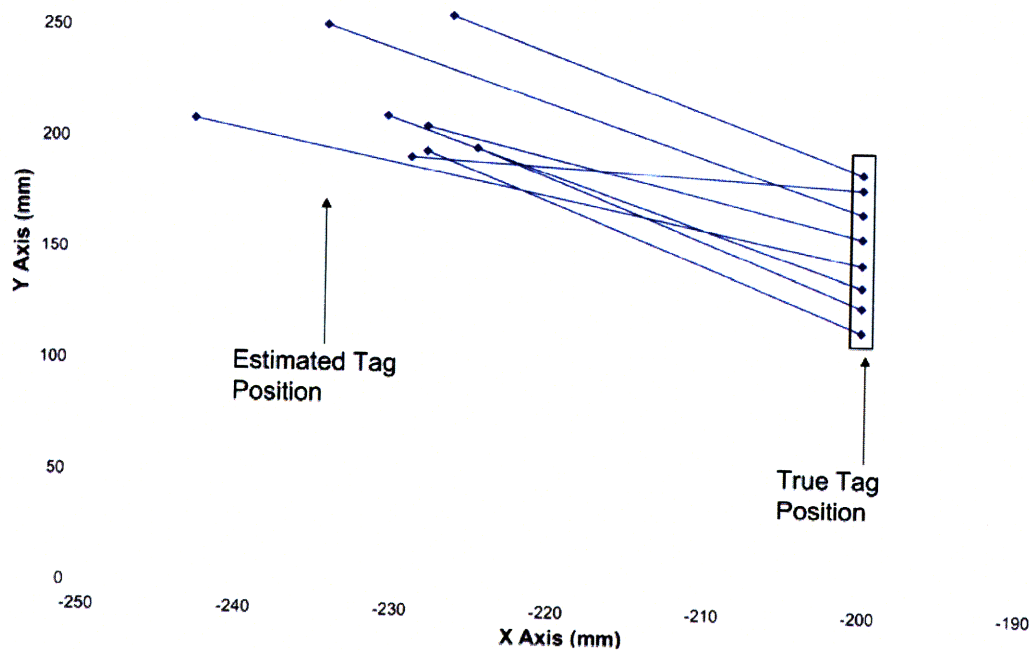


Figure 4-10: Actual and estimated (2D) tag positions of thin books.

one side over the other. Those anomalies were ignored when calculating the x-direction error. In the y-direction, however, the average error from the true position was only about 1 cm, though the maximum error was also high at 3 cm for one tag. Ordering of the books in the y-direction was still preserved in this case.

The situation of tagged thin books revealed several difficulties. At first, when all the tags were at the same height very few tags were read at all, even if the antenna passed within a few centimeters. A more powerful reader would be required to enable the detection of such tags in very thin books. To avoid detuning, the tags were repositioned at slightly different heights. This allowed all of the tags to be detected, but they were not localized very well. There was an average error of 6 cm along the y-axis, and it is clear from Figure 4-10 that the order of the tags was not well preserved.

4.1.4 Alternatives to Bayesian Localization

All of the results presented above were calculated based on the Bayesian approach described earlier. However, it was observed that simply averaging the positions of where a tag was detected fairly accurately predicted the location of that tag in the axis of the bookshelf, on par with the more complex localization algorithm which was used. To compare the two methods, the robot was directed past a single tagged book on a shelf twelve separate times. The position of the tag along the bookshelf's length was then estimated for each trial, and the results were nearly identical (cf. Fig. 4-7). This is a consequence of the symmetry inherent to the situation when the planes of the antenna and tag are parallel to one another. While there is some uncertainty associated with the read range of a randomly chosen tag, it is symmetric about the plane of the tags antenna. The Bayesian approach does have a definite advantage, since averaging does not offer any information about the depth of the tag on the shelf. Figure 4-8 shows the estimated depth of the tag after the robot was driven past one book nine times, while each time the book was placed deeper into the shelf. Averaging offers nothing in that direction, but in situations where an educated guess can be made, and the orientation of the antenna and tags can be controlled, using the average position from where tags are observed appears to be sufficient to determine book order.

4.2 BookBot 2.0

Once the system was shown to function fairly well on one shelf, though underperforming with regard to thin books, there was a move toward preparing the system for exposition in a real RFID library, and for this the *Feig* reader was swapped with the more advanced *Tagsys L200*. An HF reader with 4 antenna connections and various RF output power levels, the *L200* was chosen with an eye toward shelf reading an entire bookshelf at once with multiple antennas, and using higher power levels available to ensure all books would be identified, even hard to read children's books.

Similar experiments as before were conducted to gauge the system's ability to localize and order the books on the shelf. The reader and antenna were placed on the robot, which

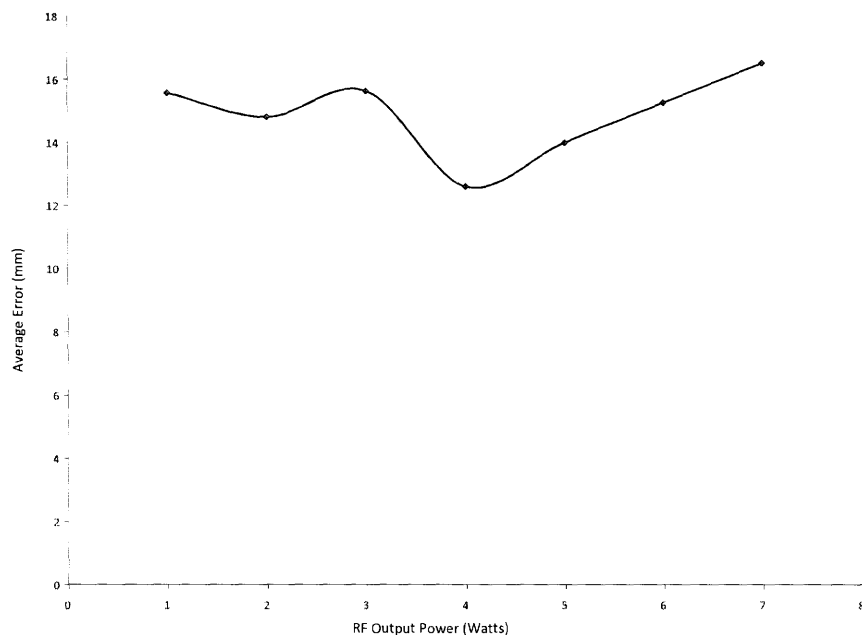


Figure 4-11: Average error for localizing books at different RF output power levels.

was guided by a row of 20 books. This time, a cluster of 4 thin books was placed within the row of larger books, and localization accuracy was measured for various reader power levels and robot speeds. Bayesian reasoning was not used to localize the tags for two reasons. First, the simple averaging technique was shown to provide nearly equivalent accuracy, and it would have taken a prohibitively long amount of time to manually build the sensor models for the 24 available power levels from 1 to 7 watts.

4.2.1 Results

Unfortunately, there was no appreciable gain in localization performance with the *L200* reader. It certainly had a larger read range, and was more reliable in terms of being able to detect tags in thin books, but the high power levels did not help, or hurt, localization accuracy in any significant way (Figure 4-11). Higher robot speeds were found to be detrimental to localization efforts (Figure 4-14), but neither speed nor wattage had a great effect on the estimated order the the books, as seen in Figure 4-13 and Figure 4-12. Book order

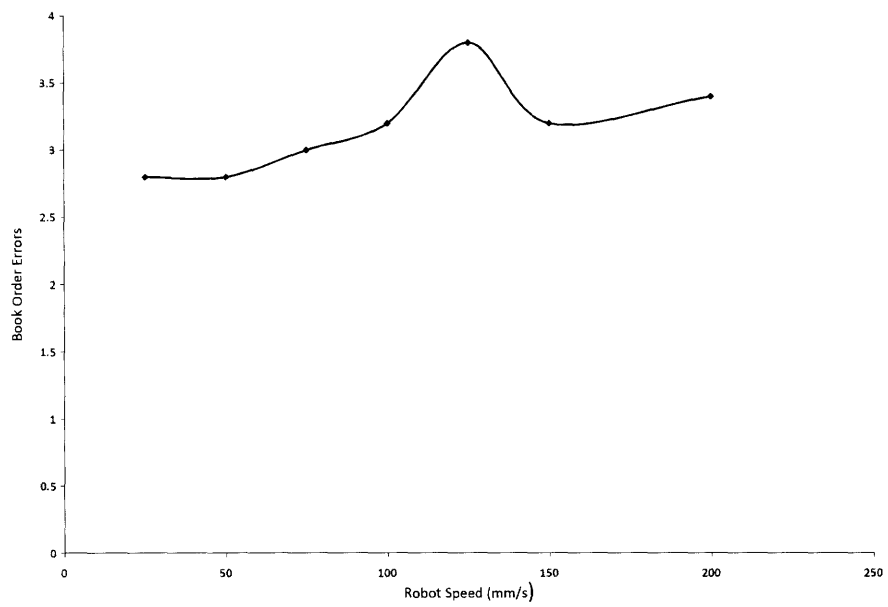


Figure 4-12: Average book order errors for different robot speeds.

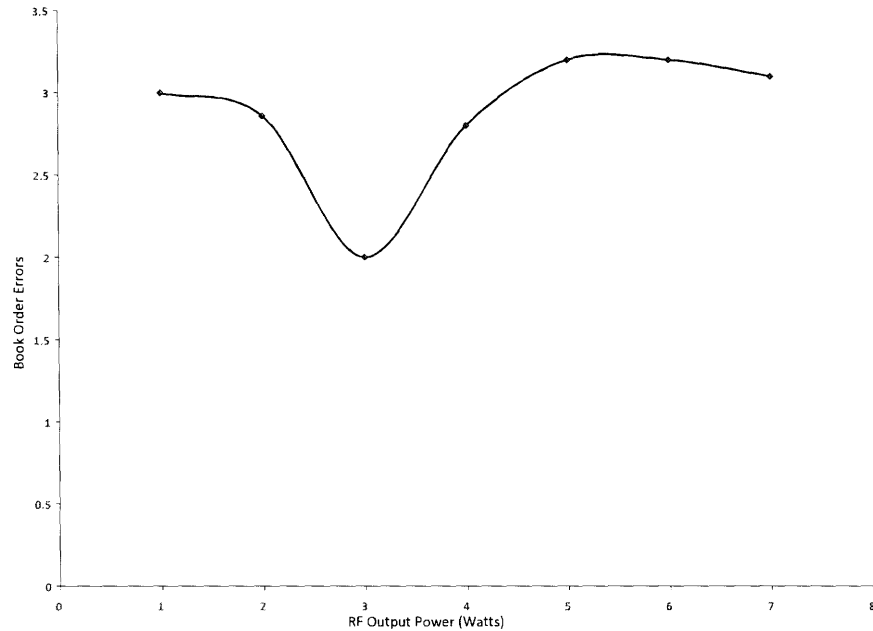


Figure 4-13: Average number of book order errors for different RF output power.

errors were counted as the number of books needed to be removed for the remaining books to be in their proper order. The overwhelming majority of books inadvertently claimed to be out of order were caused by the thin books. With the thin books removed, the number of book order errors nearly disappeared.

The results of the trials with varied robot speeds (Figure 4-14), however, does have important implications for the function of the entire system in general. By having the robot drive by the shelf at higher speeds, the amount of times the reader is able to identify a tag is reduced as the tag spends less time in the read range of the reader. This lack of data makes it less likely for a book to be localized properly. At slow speeds, even if the tag is read more times to its left than its right the errors on average will be low given enough data, but if the tag is only read two or three times, there is a greater chance for large errors. One way to counteract the effects of driving by the shelf faster would be to increase the rate at which the reader processes tag reads. In this case the *L200* reader was already set on the fastest mode available, but in any case these results imply that the sampling rate was crucial to

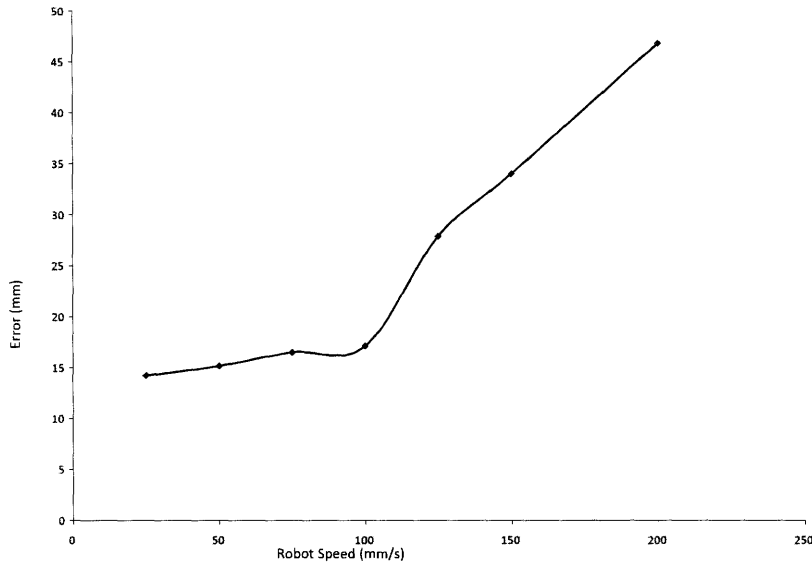


Figure 4-14: Average error for localizing books at different robot speeds.

system performance.

4.3 BookBot 3.0

The mission of the third and final phase of the project was to ready the system for deployment in an actual library, where it would semi-autonomously drive by entire bookshelves and report back the location and order of all the books on all the shelves.

4.3.1 Plymouth Library

The only library available for testing BookBot was the Public Library of Plymouth, Massachusetts. About 40 miles southeast of Boston, the Plymouth public library completed its incorporation of RFID in mid 2007 and it is estimated that over 95 percent of the book collection has been tagged. On the whole, RFID has been well received in the library, which features an RFID based security system, a bar-code and RFID self checkout machine, and



Figure 4-15: The public library in Plymouth, MA.

a 3M DLA for use by librarians. 4-15

Library materials have been divided amongst three sections: Non-Fiction, Fiction, and Children. Each section consists of several rows of collinear bookcases at regular intervals. The bookcases in the fiction and nonfiction sections were metal and had standard library dimension: six shelves, where the shelf itself is one inch thick and 14 inches between shelves. The lowest shelf is 3 inches from the floor. The children's section features wooden bookcases with only 4 shelves. 4-16

4.3.2 System Design

Several previously ignored factors were taken into account for the design of this phase. The first was the size and weight of the system to be carried by the robot base. Previously, BookBot was outfitted with only one RFID antenna, stood only a foot or two above the ground and carried a payload of at most 10 pounds. For a test at the Plymouth library, where bookshelves stand over 7 feet tall and six shelves must be scanned simultaneously, the



Figure 4-16: Typical view of the Fiction/Nonfiction.

bar had to be raised significantly.

RFID System

The first design decision was not to use the *L200* reader for the library experiment. While a powerful, multi-functional reader, it was only able to support the operation of 4 antennas at the same time. To reach the required 6 antennas to cover an entire bookshelf, two *L200* readers would have been required, but with each reader weighing over 10 pounds and demanding a large power supply, two of them would be challenging for a small mobile platform. Instead, six readers from the *Feig MidRange* family of readers were obtained, each weighing about 1.44 lbs with the pad antenna attached. The *Feig MidRange* readers included four *MR101s*, and one *MR100* and *MR200*. Despite being different versions, each reader had a similar range and featured a scan mode, which reports back any visible tag ID without a specific read request being sent.

Robot Platform

The second design issue was the robot platform itself. According to its manufacturer, the *iRobot Create* was designed to haul up to 5 pounds of payload. While *Create* was observed to function normally with a much more massive load, performance losses were observed after hauling 15 pounds for a significant amount of time, among them rapid battery depletion and motor failure. Instead, a custom built robot platform was constructed, featuring high torque *Pittman* motors and an *OrcBoard* robot control board.

Antenna Support

To support the reader antennas in a configuration so that each could scan one of the six library shelves, a seven foot high support was constructed from cardboard packing material. The material was chosen for its low cost and rigidity in the configuration show. The remaining wobbling was reduced by adding trusses, including the antennas themselves.

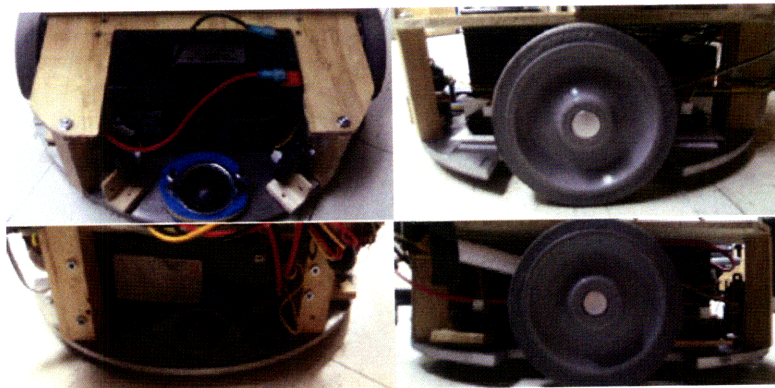


Figure 4-17: The robot platform.

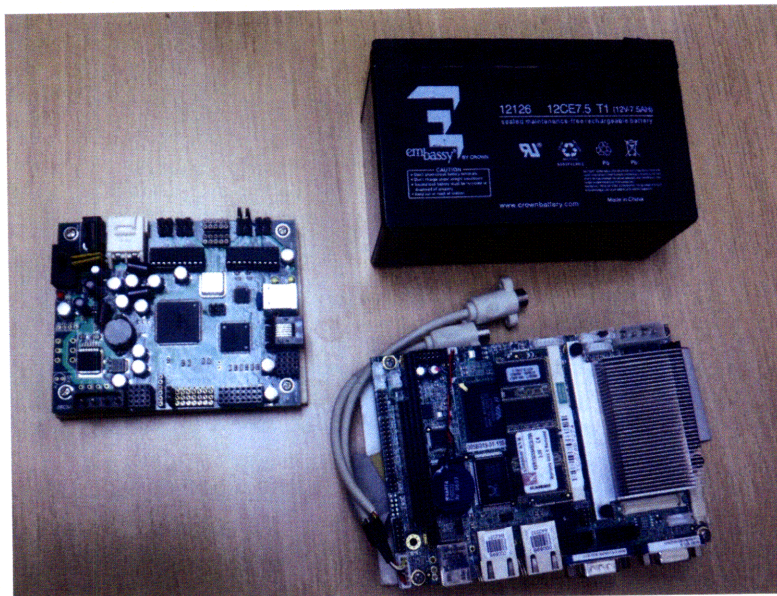


Figure 4-18: Orcboard, 12V battery, and small PC.

Electronics

To control the readers and robot movement, a small 866 Mhz PC was mounted within the support structure. Power for the readers, the computer and additional sensors was provided by two 12V 7Ah lead acid batteries. It was estimated this would supply enough power for 1-2 hours of continuous operation, since the computer required upwards of 2A to function reliably, each RFID Reader pulled about .6A while in operation, and the motors demanded an additional Ampere, adding up to about 7.6 Amps total. The PC was fitted with a wireless ethernet card for remote control purposes.

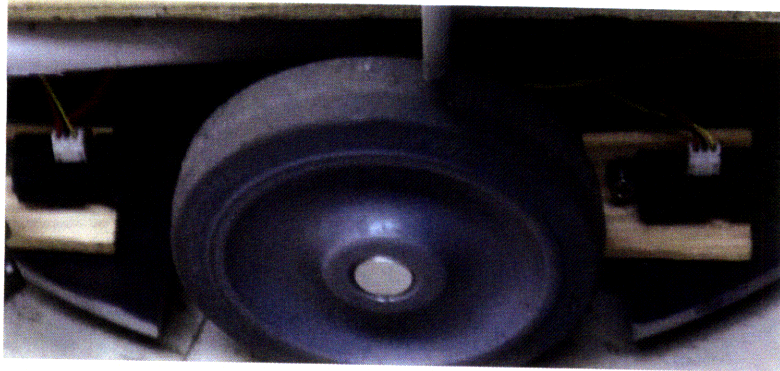


Figure 4-19: Sharp Infrared sensors mounted on BookBot.



Figure 4-20: Pittman Motors with embedded encoders.

Sensors

BookBot 3.0 carried two types of sensors: motor encoders and *Sharp* infrared range sensors. The encoders, embedded within each motor's casing, were used to collect accurate odometry data about the robot's movements. It has an accuracy of up to 1 degree. The infrared sensors, which measure distance by emitting infrared light and detecting the angle of its reflection, were mounted on the edges of the robot platform, and they were used to detect bookshelves and other obstructions. Eight sensors were placed along the front face of the robot, enabling it to detect objects both in front and on the left and right.

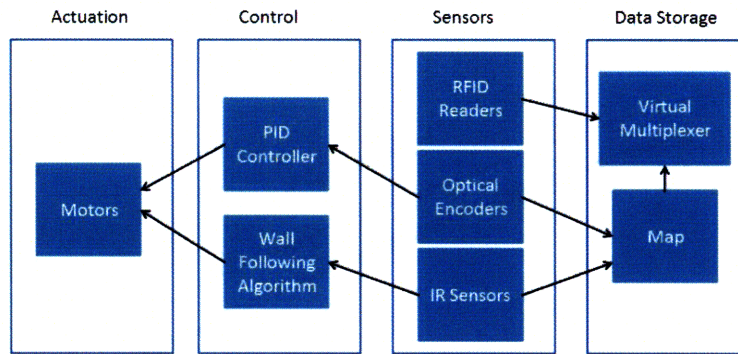


Figure 4-21: Representation of the different software and hardware components. Arrows represent the flow of data through the system.

4.3.3 Software

A multi-threaded approach was taken when programming this system, which combined six RFID readers, 2 DC motors, encoders and infrared sensors into a single system that navigated itself around bookshelves and IDed the RFID tags that were on them. Each part of the system was given its own thread, and information was passed between threads using the Observer Pattern [18]. If new odometry data became available from the motor encoders, it informed the map to update the robot’s position (red circle), and the PID controller to send feedback to the wheels and maintain a steady velocity. When IR sensor data came in, it was also sent to the map to update map features (green dots), and to the wall following thread to keep the robot on course. The map forwarded the robot position to the virtual multiplexer, which used that information to label all incoming tag reads.

Drive Modes

For the previous in-lab experiments, the robot was always lined up in front of the shelves and programmed with a specific path to follow, what amounted to a straight line and some well planned 90 degree turns. With an eye toward a fully autonomous BookBot in the future, wall following capabilities were added to the robot, enabling it to recognize, approach and follow walls. While doing so the antennas would be perfectly aligned for detecting RFID tagged books if the wall was actually a bookshelf. Navigation from one bookshelf to another autonomously is a more difficult problem having to do with mapping and artifi-

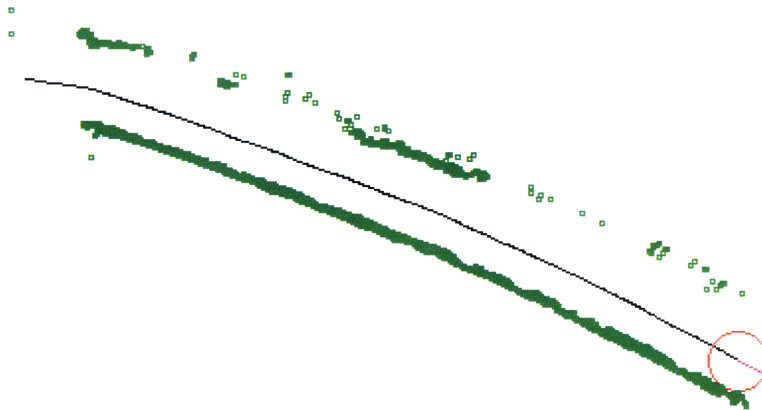


Figure 4-22: Map generated from odometry and infrared sensor data.

cial intelligence, and would be the final step of making this system fully autonomous, but it is beyond the scope of this work. Instead, the robot was configured so that it could be remotely guided from bookshelf to bookshelf by the user, where it could then perform the shelf reading on its own.

Wall following was achieved with the help of the infrared sensors. Once in wall following mode, if a wall was detected on either side, the robot would continue forward until it detected the wall was moving closer or away from the robot. Once the robot found itself in one of those two situations, the Wall Follow thread would tell the motors to speed up or slow down accordingly, so the robot would fall back into alignment. During in lab tests the robot was able to follow along the bookcase with a fair amount of accuracy.

4.3.4 Experimental Setup in the Library

Testing took place in a remote area of the nonfiction section in the Plymouth Library. While each of the Plymouth library's bookcases have 6 shelves in total, testing was done on a row of four bookcases that only utilized the four middle shelves. The total number of books on these shelves was 253 excluding untagged items such as VHS and cassette tapes. The robot was driven by the different sections while recording odometry data and tag reads. The robot's motors found it difficult to traverse the library's carpeted terrain, so human intervention was required to get across the entire row of bookcases. Inventory and shelf

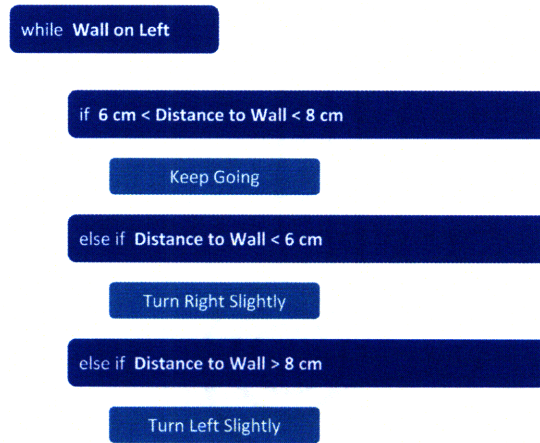


Figure 4-23: Simple Representation of the Wall Following algorithm.

reading functions of the robot were assessed at different speeds over all four bookcases as well as the position accuracy of the most of the tags on the first bookshelf. It should be noted that the books in this section were of considerable girth, ranging from 1 to 5 cm in thickness(cf. Fig 4-25), typical of most books in the adult section of the library.

4.3.5 Results

Due to the metal environment of the bookshelves, especially the sides of the shelves and bookends, it was expected that some tags would likely not be identified by readers very often, and some not at all, similar to results reported above. As mentioned, RFID tags do not perform well in close proximity to metal, and not at all when in contact with metal. Library staff confirmed that they were instructed by their RFID supplier to not use metal bookends or to keep the books away from them, but little attention was paid to this detail.

Trial	% Books Found	Exclude Close to Metal	% Order Correct	Speed
1	93	99	96	Slow
2	94	99	96	Slow
3	91	96	90	Fast
4	94	100	93	Fast
5	95	99	89	Fast

Table 4.4: Percentage of the books detected and correctness of book order.

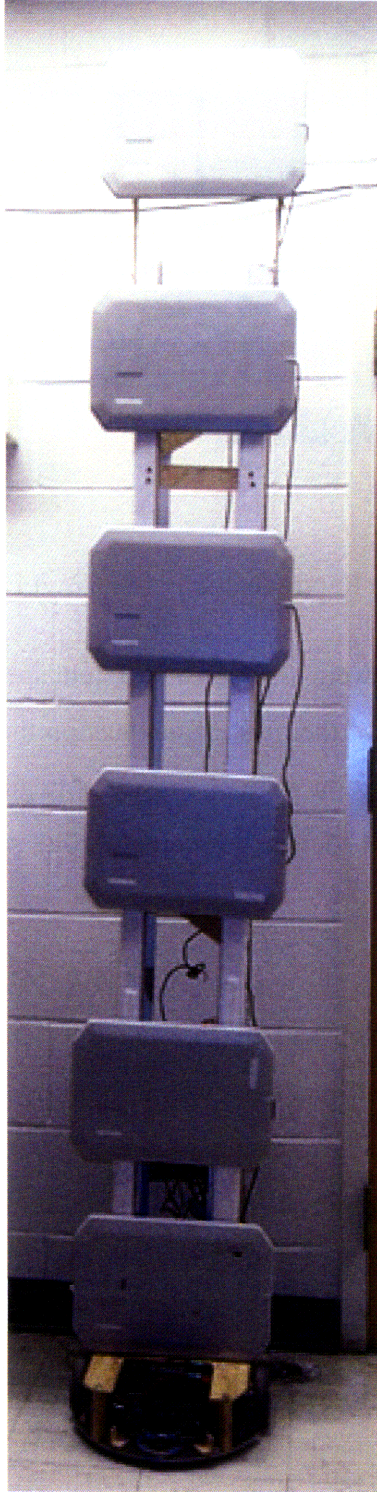


Figure 4-24: BookBot 3.0 at its full height.

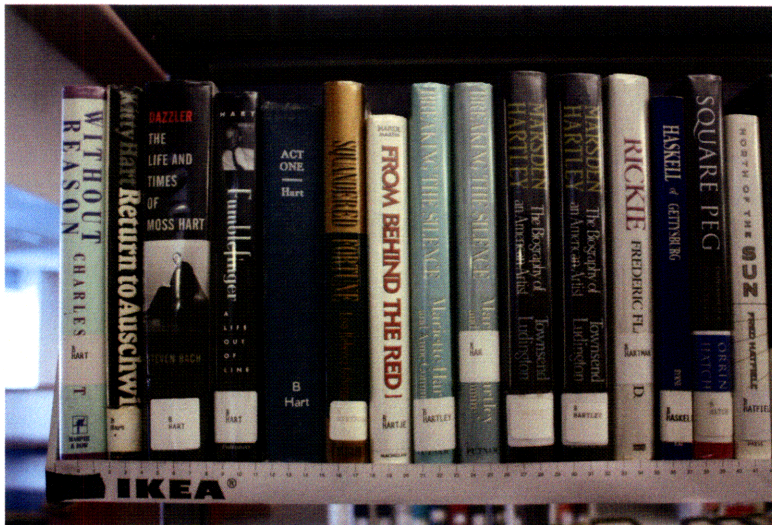


Figure 4-25: Test shelf in the library.

Shelf Number	Avg. Error (cm)
3	1.90
4	2.56
5	2.05

Table 4.5: Average error in position for Library experiments.

The results are summarized in Table 4.4. Aside from the books found close to the metal bookends, BookBot was able to inventory over 90% of the books in one pass, and nearly 100% if those close to metal were excluded. Books not close to metal were always detected by two or more of the 5 trials implying that some repetition supplementing proper procedure in a metal environment would raise the accuracy of the inventory operation close to perfect. Also in accordance with earlier results, the accuracy of the shelf reading operation was shown to depend on the speed at which the robot passed by the shelves.

The results in Table 4.5 show that the position estimation for BookBot 3.0 was much lower than that of its earlier versions, up from 1 cm to 2-3 cm, which is probably related to the environment being slightly less controlled and wheel slippage on the Library's carpet.

In one final note, during every run of the robot across the bookcases two ghost tags were detected; tag IDs that did not seem to belong to any known book on the shelf. One probable explanation for this peculiarity is the hour time difference between when the trials were conducted and when the order of tags on the shelves were manually recorded. Since the library was open to the public at the time when the experiment took place, it's possible a

library patron lifted the books from the shelf, highlighting the dynamism of this warehouse of words, even in a remote nonfiction section.

4.3.6 Discussion and Future Work

Looking back, BookBot's performance in the library was hampered by several remaining problems that once solved, will bring BookBot to the brink of commercialization as a key component in any deployment of a Library RFID system. These issues include precision design of the parts used to construct the robot base and antenna supports, fully autonomous behavior, and a further developed software package that can truly bring out the value in knowing the location of every book in a library. As far as the physical construction of BookBot was concerned, there lacked a well defined design process that went beyond the type of robot to be used, and the RFID systems available. Certainly, the system was able to achieve impressive results in its current prototype state, but the lack of precision in its construction placed upper limits on the ability of the system to perform its duties. For example, while remarkably stable and lightweight, the antenna support tower hacked together from cardboard packing material is not a long term solution. The L shaped pieces were not level, leaving the antennas leaning a few degrees forward and slightly to BookBot's left. While this had no effect on the RFID system directly, the implementation of wall following was made more difficult as antennas would come in contact with the bookcase and throw the robot off course. To compensate, the wall following was set to stay a few centimeters further away from the shelf, which is not ideal when trying to minimize the distance between antennas and tags to have optimal system performance. Several other design issues affected the robot's wall following and drive capabilities, including wheel misalignment and inadequate suspension and motor control systems. More robust systems would have meant the robot was better prepared to function properly on unfamiliar terrain, such as the library's carpeted floor.

A second place for improvement is in the realm of autonomous behavior. The semi-autonomous behavior described for BookBot 3.0 was a necessity given the robots inability to discern bookcases from a distance and the lack of any artificial intelligence enabling it to

move from one bookshelf to another, but full autonomy would be the ideal solution. Given the difficulty of actually mapping out a library from scratch, it would be more plausible to consider giving the robot a map of the library floor, or even a predefined path, the would enable it to perform inventory and shelf reading without any human intervention. However, even with a map there is little that can be done without more precise sensors so decisions can be made based on accurate information.

Finally, once BookBot has been fully redesigned and wall following perfected, an advanced software package would be required to help the robot take inventory and let librarians take full advantage of knowing the position of every book in the library. The robot can help itself by learning where difficult to read tags are located, so it can slow down or increase the power of the RF signal to raise the chances of the book's tag being seen and the accuracy of the position estimation. Additionally, a database of book dimensions would key the robot in to the presence of thin books, and make an actual representation of the books on the shelf possible. Interfacing with the library's existing database system and a 3D map of the library, book positions can be specified to the centimeter, speeding up the search for books by librarians and patrons alike, and inventory anomalies can be highlighted, such as severely misplaced books. The map of the library could also gather information on the usage of books inside the library, which could aid librarians in the design or evaluation of any layout or policy changes or experiments.

Chapter 5

Conclusion

As the proliferation of RFID penetrates deeper into the supply chain, more applications will be developed to take advantage of the technology on a level more personable than huge containers being loaded onto cargo vessels. RFID has found its way into diverse industries such as cattle ranching [29], transportation systems and security systems, but research into its potential for transforming the notion of a warehouse has only reached the tip of the iceberg [20].

This thesis dealt with the application of RFID in the library, a place where RFID has been present for several years, but has yet to achieve widespread implementation. Commercially available systems include features such as RFID security systems, self checkout stations, and handheld readers to conduct shelf reading and inventory operations. The focus of this thesis, in particular, was the concept of using RFID technology in concert with a mobile robotic system for the purposes of shelf reading and inventory, which has several advantages over the handheld versions. By combining the location information made available by the odometry from the robot's wheels, an accurate location of each individually tagged item in the library can be calculated. Implicit in that information is the status of an entire library's physical inventory and the order of books on its shelves, allowing for the discovery and quick return of misplaced books that would otherwise be lost in the stacks of history, mystery, or juvenile fiction.

The combination RFID reader and robot known as BookBot evolved from a foot high antenna with wheels to a 7 foot tall robotic librarian's assistant, capable of performing an

accurate shelf reading operation on over 200 books in no more than a minute. The system's efficacy was evaluated at different speeds and power settings, and in situations where RFID tags would be difficult to detect, such as thin books and in close proximity to metal. Overall, BookBot's performance in the lab and library has demonstrated that it is possible to use RFID systems in unexpected ways to achieve its potential and make our librarians less overworked, our libraries more organized, and their materials more accessible to patrons for the purposes of research, entertainment and relaxation.

Bibliography

- [1] SANTA CLARA COUNTY LIBRARY DISTRICT JOINT POWERS AUTHORITY RFID Analysis Committee Final Report, 2005.
- [2] David Wood Abhishek Patil, Johnathan Munson and Alan Cole. "bluebot: Asset tracking via robotic location crawling". *Computer Communications*, 31:1067–1077, 2008.
- [3] Virginia Allen. Automated library inventory using barcodes. In *International Association of Aquatic and Marine Science Libraries and Information Centers Conference Series*, 1997.
- [4] Josephine Andersen. Management of art library collections and extension of services. *Library Management*, 17(8), 1996.
- [5] Dawn R. Anderson. Method without madness: shelf-reading methods and project management. *College & Undergraduate Libraries*, 5(1):1–13, 1998.
- [6] Julie Banks. Shelf reading: A pilot study. *Collection Management*, 13:39–46, 1990.
- [7] MJ Bennett, DT Buxton, and E. Capriotti. Shelf reading in an open-stack library. *J Acad Libr 1979*, 5:4–8, 1979.
- [8] ROBERT J. BLIWISE. The book of answers. *Duke Magazine*, 2000.
- [9] Jürgen Bohn and Friedemann Mattern. Super-Distributed RFID Tag Infrastructures. In *Proceedings of the 2nd European Symposium on Ambient Intelligence (EAZI 2004)*, number 3295 in Lecture Notes in Computer Science (LNCS), pages 1–12, Eindhoven, The Netherlands, November 2004. Springer-Verlag.

- [10] A. S. Chandel and R. K. Walia. Computer-Assisted Stock-Verification System. *Libri*, 43:108–122, 1993.
- [11] Adrienne Chute, P. Elaine Kroe, Patricia OShea, Terri Craig, Michael Freeman, Laura Hardesty, Joanna Fane McLaughlin, and Cynthia Jo Ramsey. Public Libraries in the United States: Fiscal Year 2004 (NCES 2006349). U.S. Department of Education, 2006.
- [12] Raghu Das and Peter Harrop. Complete rfid analysis and forecasts 2008-2018. Technical report, IDTechEx, 2008.
- [13] Charles D. Emery. The use of portable barcode scanners in collections inventory. *Collection Management*, 13:1–17, 1990.
- [14] Jennifer L. Fabbi, Sidney D. Watson, and Kenneth E. Marks. Implementation of the 3m digital identification system at the unlv libraries. *Library Hi Tech*, 20:104–110, 2002.
- [15] Jennifer L. Fabbi, Sidney D. Watson, Kenneth E. Marks, and Zep Sylvis. UNLV Libraries and the digital identification frontier. *Library Hi Tech*, 23:313–322, 2005.
- [16] Klaus Finkenzerler. *RFID Handbook: Radio-Frequency Identification Fundamentals and Applications*. John Wiley & Sons, 2000.
- [17] Christian Floerkemeier and Matthias Lampe. Issues with RFID Usage in ubiquitous computing applications. In Alois Ferscha and Friedemann Mattern, editors, *Second International Conference, PERVASIVE 2004*, volume 3001 of *Lecture Notes in Computer Science (LNCS)*, pages 188–193, Linz/Vienna, Austria, April 2004. Springer-Verlag.
- [18] Eric Freeman and Elisabeth Freeman. *Head First Design Patterns*. O’Reilly, 2004.
- [19] Dirk Hähnel, Wolfram Burgard, Dieter Fox, Ken Fishkin, and Matthai Philipose. Mapping and Localization with RFID Technology. *IEEE International Conference on Robotics and Automation (ICRA)*, 2004.

- [20] Stephen Ho. *Intentional fragmentation for material storage*. PhD thesis, MIT, 2004.
- [21] iRobot Corporation. *iRobot Roomba Serial Command Interface Specification*, 2005.
- [22] D. Oh J. Choi and I. Song. R-LIM. An affordable library search system based on rfid. In *International Conference on Hybrid Technology*, 2006.
- [23] Deborah Jakubs and Robert Byrds. Critical choices: Perkins library system plan. 2000.
- [24] G. Kantor and S. Singh. Preliminary results in range-only localization and mapping. *Proceedings. ICRA '02. IEEE International Conference on Robotics and Automation*, Vol.2:1818– 1823, 2002.
- [25] V. Kulyukin, C. C. Gharpure, J. Nicholson, and S. Pavithran. RFID in robot-assisted indoor navigation for the visually impaired. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2004.
- [26] V. Kulyukin, C. Gharpure, and J. Nicholson. RoboCart: toward robot-assisted navigation of grocery stores by the visually impaired. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 2845–2850, 2005.
- [27] Tod E. Kurt. *Hacking Roomba*. Wiley, 2007.
- [28] Carissa Miller. An investigation of an automated shelf reading and inventory system for the clemson university cooper library.
- [29] P.H. Mun Leng Ng; Kin Seong Leong; Hall, D.M.; Cole. "a small passive uhf rfid tag for livestock identification,". *Microwave, Antenna, Propagation and EMC Technologies for Wireless Communication*, 2005.
- [30] L. O.Nwali. Academic Library Bookstock Management: The Case of Stocktaking in Abubakar Tafawa Balewa University Library, Bauchi, Nigeria. *Library Management*, 13(1):17–22, 1992.

- [31] Wayne A. Pederson. Statistical Measures for Shelf Reading in an Academic Health Sciences Center Library. *Bulletin of the Medical Library Association.*, 77:219–222, 1989.
- [32] Philips Semiconductor. I-CODE1 Label ICs Protocol Air Interface Datasheet, January 2005.
- [33] Ester Retief. The role of inventory control in service quality in south african academic library. Master's thesis, University of South Africa, 2005.
- [34] Donna R. Webb. Sidebar 3: Inventory. *Library Hi Tech*, 12:21–22, 1994.