A Wearable Wireless RFID System for Accessible Shopping Environments

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ABSTRACT
Present day shopping environments are centered around the needs of the consumer, and they aim to facilitate convenient access to different product lines varying from groceries to books to everyday electronics. Supermarkets and hypermarkets are examples of trends that have evolved providing a rich shopping experience. Unfortunately, such systems have been envisioned to cater to sighted customers and inadequately address the necessities of a person who is blind or visually impaired. In this work, we present a new system design that leverages the potential of emerging technologies like Electronic Product Code (EPC) and Radio Frequency Identification (RFID) to provide a wearable wireless device capable of delivering product information at real-time in order to enhance the shopping experience of customers who are visually impaired or blind. Various technologies have been proposed by earlier researchers to address the accessible shopping problem. In this paper, we have discussed each of these approaches, and analyzed their benefits and limitations, eliciting the motivation for a new design. Detailed descriptions of the various components of the proposed system are presented. An implementation of our system is illustrated with results from calibrated tests with wearable RFID readers and tags installed on various products. Studies of crucial design parameters like the variation of RFID reader sensitivity with orientation, range and material, along with system response time, are discussed to highlight the choice of technology elements in the design.

Categories and Subject Descriptors
J.7 [**Computer in Other Systems**]: *Consumer products, Real time.*

General Terms
Design, Experimentation, Human Factors, Performance.

Keywords
Accessible shopping environment, Radio Frequency Identification (RFID), Bluetooth, Database Systems, Human computer interface, Electronic Product Code (EPC), Wearable computing.

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1. INTRODUCTION
The 1.3 million people who are legally blind and the 11.4 million people who have a visual impairment in the United States alone continue to face the lack of independent access to retail stores including malls, department stores, gift shops (found in airports, hotels and hospitals), discount stores, pharmacies, and grocery stores.

Individuals, who are blind, generally navigate using a white cane, a guide dog, or a sighted person acting as a guide. While walking through an environment, they rely extensively on navigational cues that are derived from sounds, smells, surface textures, touch, and memory-of-path integration [1]. However, such cue-based techniques and conventional aids such as white canes and guide dogs cannot provide access to the text on store signs for each department, aisle signs, shelf tags, size and color of a garment, contents of a product, sale tags, and prices. For complete access to such shopping environments, an individual who is blind must rely on sighted assistance. This means they have no privacy in making their shopping decisions, nor can they shop on their own time, because they must schedule their shopping at times that are convenient to others not necessarily to themselves.

The vast amount of accessible information in a retail space stretches the goals of moving through a retail space beyond simple navigation. Rather, the consumer needs to be able to explore the objects/items located on shelves, hanging racks, baskets, and promotional displays that are strategically placed for customers to see. This means that there is a multitude of information presented to an individual at any given point in time and space. While an accessible shopping environment should have the capability of providing information about the products located on the shelves, irrespective of their type, it should not impede the user's movements. It is also important to design the system such that it goes beyond just leveling the proverbial playing field for people with visual impairments, including those who are totally blind, to a system that can be of immense value to all shoppers. This approach towards a design of an interactive shopping environment not only enhances access from the perspectives of assistive technology, but also increases the likelihood for such a system to be accepted and adopted in the mainstream market.

As a part of the initial requirement study for this project, we conducted focus group studies that included people with visual impairments and blindness. The focus group included high school kids (from Arizona school for the deaf and blind), college students (from Arizona State University) and working professionals with visual impairments. In this work, we present a system design that takes into account the necessities that were identified from this focus group and builds towards a tool that makes shopping environments not only accessible but also convenient. A Radio Frequency Identification (RFID) wireless reader solution is proposed within a portable computing system framework that allows the user to access data unparalleled by any existing system or design.

The rest of the paper is presented as follows: Section 2 covers past work done in the area of assistive shopping environments while highlighting the benefits and limitations of these technologies. Section 3 introduces some of the emerging technologies that the proposed system relies upon while Section 4 and Section 5 introduce the system architecture and data flow model respectively. The system evaluation, results and their discussion are covered in Section 6, 7 and 8. Conclusion on our design and our plans for future work are presented in Section 9, followed by references.

2. RELATED WORK

Accessible shopping environments centered on helping people who are blind have recently attracted a lot of attention in the research community. A recent research project at Utah State University's Department of Computer Science and Center for Persons with Disabilities is the *Robotic Guide* [2], which is a robot that employs multiple sensors to provide navigational assistance to users who are blind. The user interacts with the robot through speech, a wearable keyboard, and audio icons. Although the multimodality approach offers significant advantages, feedback from the participants who are blind and who used the robotic guide, published by the research group, indicated that the robot moved too slowly. Additionally, the navigation system for the robot was based on SONAR, which caused jerky movements, and sometimes provided unreliable results, due to specular reflections and cross talk. The feedback from the focus group of users with visual impairments also indicated that a major portion of decision-making was unnecessarily being off-loaded to the robot thereby restricting their freedom, which was viewed as an undesirable feature. This solution approached the problem from a navigational view point rather than as an accessibility issue. This is an important limitation because people who are blind can navigate independently through an environment using traditional methods, but they cannot read the printed signs, shelf tags, or package labels, nor can they determine the size, color, or pattern in a fabric of clothing in a retail shop.

Another project involves researchers at University of San Diego's Department of Computer Science and Engineering [3], who are trying to find a computer vision solution to the problem of accessible shopping environment. A customer who is blind is required to prepare a shopping list before entering the shopping space by using a specially designed program that looks for images of products online. These images are loaded onto a mobile computing device that is attached with a camera. Once the shopper arrives at the store, the goal is to identify the products on the user's shopping list by matching the stored images on the device with images that are captured real-time from the shelves in the shopping environment. Though this team seems to have approached the problem with a priority towards accessibility than navigation, the idea of using cameras to achieve product recognition is a tough approach. The area of object recognition has been an active area of research for the past two decades and solutions offered in these areas are barely perform in highly controlled environments. Escalating such simple solutions to images coming from a camera that is being moved arbitrarily through the environment will be a tough problem to solve. Further, this approach does not provide the customers the benefit of browsing for products beyond their search list. No information beyond what was put in the list is accessible to the user. Additionally, holding a camera in the hand impedes the freedom of arm movements of the individual and would cause fatigue in their arm and shoulder.

The third project, Trinetra, at CMU [4] intends to provide accessible information to customers who are blind by providing them with a Bluetooth enabled barcode reader, and a mobile phone with a speech software. The customer, who is blind, picks up a product off the shelf and scans the item for its UPC code. The data is then transferred to the phone which accesses internet to pull information on the product from the public UPC database website (www.upcdatabase.com). Among the above mentioned competing solutions to the accessible shopping problem, Trinetra comes closest to allowing data access similar to what a sighted user would retrieve. Unfortunately, the system relies on the user to scan the product for the barcode information. Scanning numerous products from the shelves is tiring and mentally strenuous for a customer, considering that the barcode can be printed anywhere on the product. Since the system provides no information about the aisle, section or shelf, the shopper, who is blind or visually impaired, is left to guess where items of interest are located and would most likely still have to depend on sighted assistance to finish their shopping in a timely manner.

An assistive device that truly promotes independent shopping should provide a highly interactive accessible human interface that allows a user to access any information deemed appropriate to the situation. This allows decision making to remain with the user. The work presented here derives its ideology from considering shopping in an everyday setting, with the goal of providing the ability to browse for products and thereby, the underlying freedom of choice in shopping. The design incorporates all of the limitations that have been identified in the previous efforts and incorporates them. To this end, important aspects like comfort of use, uninterrupted access to large databases of product information, freedom of browsing and the accessibility of the provided interface are all accounted for in this design.

3. EMERGING TRENDS IN SHOPPING ENVIRONMENTS

Shopping environments of recent years have been managed using the familiar combination of barcode and UPC (Universal Product Code). However, the advent of RFID technology has led to EPC (Electronic Product Code), which is soon expected to revolutionize inventory management in shopping environments [5]. We briefly discuss the EPC-RFID combination, which is the underlying assumption of the system presented in this work.

UPC in the form of barcodes has been the choice among manufacturers for tagging almost all the products. However, with the emergence of inexpensive RFID tags, manufactures are shifting to this new technology to overcome constraints associated with barcodes. Barcodes need perfect visibility under the laser scanners for an accurate reading and are meant only one use, product check out at the end of shopping. Compared to barcodes, RFIDs are wireless systems that do not need contact with the reader. These systems can work wirelessly at distances that make not only product check out easier, but also allow for innovation in inventory management, theft detection and shipment tracking which are all associated with unique product identification.

Having identified the potential of RFIDs in shopping environments, manufacturers and standardization groups have adapted RFIDs to append/replace barcodes. The UPC equivalent of barcode is the newly introduced EPC (Electronic Product Code). EPC piggybacks on the RFID technology to provide contactless data reception from the products. Technology is progressing in the field of EPC tags to help manufacturers in adopting EPC in all their products with the same ease of printing registered UPC on their product boxes. Already products are appearing on the shelves that carry EPC along with UPC for product identification.

By adapting this emerging technology into our design, we believe that our novel system would be complete and geared up by the time EPC is absorbed fully into the shopping environments. The following section highlights how RFID technology will be put to use in building a wearable wireless product data access system. Although we are aware of the differences between EPC and RFID, for the sake of convenience, in the rest of the paper, the two terms are used synonymously.

4. The System Architecture

The goal of the system is to have a wearable RFID reader and a portable computing element like PDA that a customer can use seamlessly to access information about products in a shopping environment. Towards this requirement we propose two-component architecture. The first component involves the wearable device on the customer which, a) collects the unique EPC code from products on the shelves, when the user approaches them, and b) delivers any product information, sent back to it, to the user via synthesized speech. The second component consists of a central server in the store that essentially is a relational database with information of all the products and performs the task of associating EPC sent by the wearable device to a unique product's information. The communication between the two components is enabled via a TCP/IP interface. Figure 1 shows the overview of the system architecture. The individual segments of the two components will be discussed in detail in the following subsections.

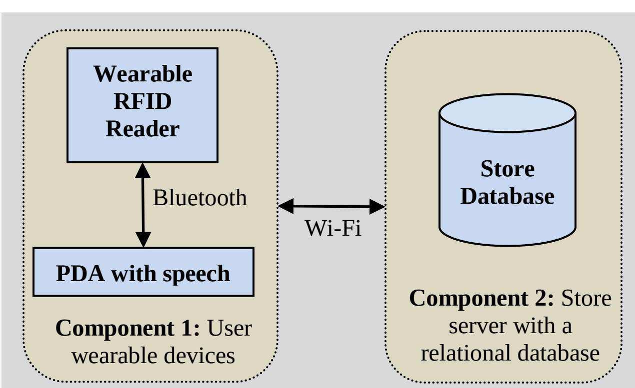


Figure 1: *Accessible caption:* This figure shows the two components of the proposed architecture as two boxes. The box to the left represents Component 1 (User wearable device) which has a bidirectional communication via Wi-Fi with Component 2, represented here by the right side box. Component 1 internally contains the wearable RFID reader that communicates using Bluetooth with a PDA. Component 2 shows a database server.

4.1 Component 1: Wearable device:

One of the important factors in our design criteria was to ensure that the wearable device be non-obtrusive to user movements to the possible extent. To this end, we choose a small form factor RFID reader and mounted it on a easy strap-on glove, and ensured wireless (Bluetooth) communication between the RFID reader and PDA. Figure 2 shows a typical application scenario where the customer is approaching a shelf wearing the RFID reader and the holding the PDA. The following subsections introduce the various elements that make up Component 1 of the architecture.

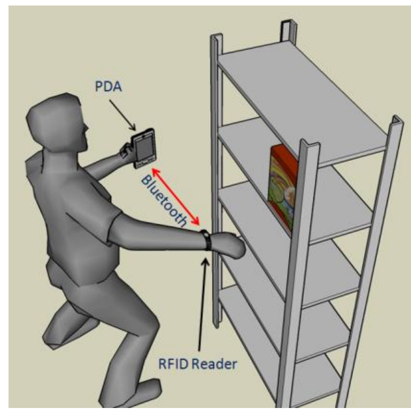


Figure 2: *Accessible caption:* Shows the typical application scenario where a user is approaching a product wearing the RFID reader close to his/her wrist. The reader communicates with a mobile computing element (PDA) via Bluetooth. This demonstrates an important design parameter of making the device less intrusive.

4.1.1 RFID Reader:

As briefly introduced in Section 3, RFID is a contactless identification technique that utilizes a RFID reader and a RFID tag in combination. A tag that understands the communication mode of a reader can uniquely identify itself using a series of digits called Tag ID. When a tag comes in the vicinity of a reader, the tag is activated from a state of dormancy and a communication link is established between the two.

The *modus operandi* of the RFID reader and the tag defines various standards that have been associated with RFID technology. For example, based on whether a RFID tag uses its own power source to communicate with the reader or it uses the radio waves from the reader to generate power onboard, the RFID systems are classified into active or passive respectively. Further, based on the frequency of the radio3 waves used by the RFID reader, the passive RFID systems are further divided into Low Frequency - LF (125 KHz), High Frequency – HF (13.56 MHz) or Ultra High Frequency – UHF (433 MHz, 865MHz, 900MHz) systems. The active RFIDs work at a much higher frequency range of around 2.45GHz. As a part of the developing standard, EPC has already been defined with UHF tags and HF tag standards are in the development pipeline. In all of the work presented here, we use passive tag, HF readers. The choice of this system was based on the form factor and power requirements as discussed below.

The proposed system uses a HF RFID reader manufactured by SkyeTek Inc. The HF M1 module marketed by SkyeTek offers the smallest form factor (1.5 in x 1.5 in x 1/8 in) in the industry with a low voltage (1.8V – 5.0V) and low power (500mW at 5V) requirement. This reader can work with many widely available accepted industries standard RFID tags [6] like ISO15693, ISO14443A and ECMA-319. This reader is complete in the sense that it has an onboard antenna that helps in transmitting both power and data to the RFID tags and does not need any external components other than a power source. The data is sent out of the module using standard RS-232 format which makes the communication convenient.

4.1.2 Bluetooth Communication:

The wireless communication between the RFID reader and the PDA is enabled by using a Bluetooth module. The module manufactured by Mitsumi (WML C40AH) has a form factor of 0.5in x 1in x 1/16in including an internal antenna and is capable of achieving 10m (33 ft) of reliable bidirectional communication link.

4.1.3 PDA with Speech software:

We used a Dell Axim X51V PDA based on Windows Mobile 5.0 OS. Although the system design is independent of the choice of the PDA or its operating system, our choice was guided by the fact that the selected device was supplied with a screen reader software (Mobile Speak). This speech software plays an important role of making the data on the PDA accessible to individuals who are visually impaired.

4.2 Component 2: Store Server:

While the RFID reader with the PDA provides a means of collecting the tag information from the product that the user might reach for, the information backbone is provided by using a centralized store server. The PDA and the store server establish communication over a Wi-Fi network. The server incorporates two important components.

1. A relational database with information about products, and corresponding aisles, sections and shelves.
2. An interface between the database and the wearable device.

4.2.1 The Relational Database:

The database (Microsoft SQL Server 2005 Express was used in our implementation) holds all the necessary information about various products and their locations within the store. In our implementation, each location is associated with an aisle, the corresponding section of an aisle, and the shelf in that section on which the product is placed. We believe that this design allows us to buffer all items from a particular shelf onto the PDA, and enable instant retrieval as the user "browses" through the shelf. Every product on the shopping floor is associated with all the manufacturers' information including but not restricted to price, nutrition value, ingredients, weight, brand name and product name (See Figure 3 for the listing of attributes). Each product is associated with a unique RFID. In addition to the product and RFID tables, there are tables that contain the aisle, section and shelf information. The triplet of aisle-section-shelf is associated with a unique location ID as the primary key. In each of these aisle/section/shelf tables, the respective neighboring aisles/sections/shelves on the left and right sides are also included. We believe that this database schema design provides for predictive retrieval of data, thereby reducing the response time of the system, and providing the user with the seamless shopping experience. The entity-relationship diagram of the database schema is shown in Figure 3.

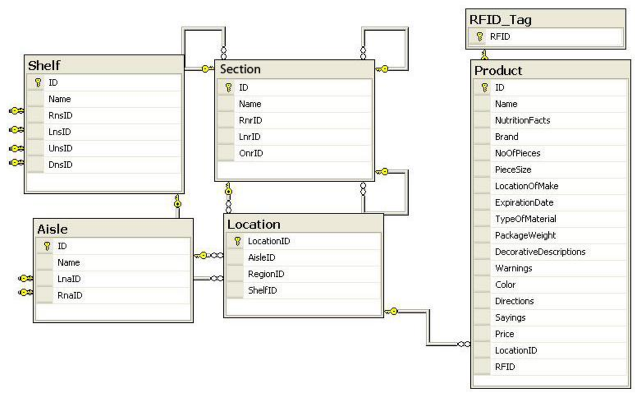


Figure 3: *Accessible Caption:* Shows the Entity Relationship (ER) diagram for the database used in the centralized server. The figure shows 5 table entries that correspond to Shelf, Aisle, Section, Location and Product information. RFID tag forms the primary key into these data.

4.2.2 The Interface

The interface between the database and the wearable device is implemented as a middleware layer. The middleware layer is equipped with the intelligence to not only retrieve the requested data, but also check related data (for example, neighboring shelf products) that need to be retrieved. Also, when multiple RFID tags associated with different items of the same product type are received, the middleware layer ensures that the product information is communicated only once to the client application on the PDA. Based on these criteria, this layer calls the required stored procedures and queries on the database. The functions of the middleware layer that are available to the client application are exposed as Web Services on Microsoft ASP .NET 2.0. The client application on the PDA calls the corresponding web methods, when the RFID tag information is received. The information thus received in the PDA is processed so that the speech software can deliver the appropriate data to the user.

5. The Data Flow Model

The complete data flow model is shown in Figure 4. The data originates at the user's end when he/she moves his/her hand close to a product on the shelf. The RFID tag on the product communicates with the RFID reader to transmit an ASCII tag ID associated uniquely with that product. This initiates a chain of events as listed below:

1. The RFID reader picks up the tag ID.
2. The tag ID is transmitted via RS-232 to the Bluetooth module.
3. The tag ID is transmitted wirelessly by the Bluetooth module to the PDA.
4. PDA initiates a web service call into the store server with the tag ID. The connection to the web service is enabled by the Wi-Fi connection into the Internet.

5. The web service on the middleware layer picks up the RFID tag, and interprets the tasks to be carried out. The middleware layer makes calls to appropriate stored procedures on the database.
6. The retrieved data is then transmitted to the PDA by the middleware layer through the web service call.
7. The program running on the PDA converts the data obtained from the server into an accessible list of information. The accessibility is in the fact that screen reading speech software reads highlighted text. The user can navigate to different menu items like product name, price, manufacturer and nutrition facts which are then read out to the user.

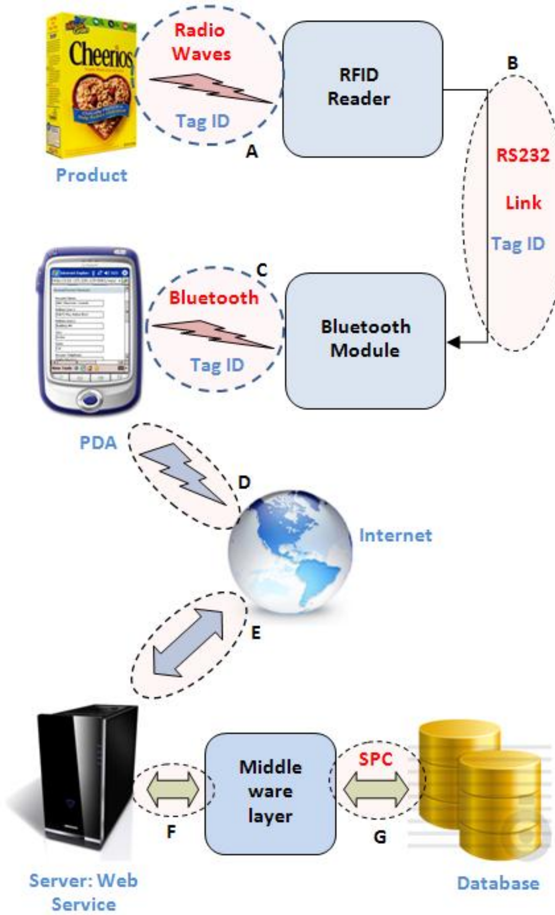


Figure 4: *Accessible caption:* The figure shows the complete data flow model for the proposed system. Product, RFID reader, Bluetooth module, PDA, store server and database are shown in a linear data flow model as explained in the Section 5.

6. SYSTEM EVALUATION:

Figure 4 shows the different data communication interconnects present in the system design. These include

A. Wireless-dedicated-unidirectional communication between RFID tag and reader
B. Wired-dedicated-bidirectional communication between RFID reader and Bluetooth module.
C. Wireless-dedicated-bidirectional communication between Bluetooth module and the PDA.
D. Wireless-shared-bidirectional communication between PDA and the Internet.
E. Wired-shared-bidirectional communication between server hosting web service and the internet.
F. Software-dedicated-bidirectional communication between the web service and middleware layer.
G. Software-shared-bidirectional communication between the middleware layer and the store database.

In the presence of different interconnects, measuring the performance of the device requires assuming stability and reliability of few of them. In the above list of interconnects, except for A, the connection between the RFID tag and reader, the rest of them have been used in many applications with acceptable levels of success. In the light of this, we decided evaluate two parameters towards testing the system performance.

1. Tag detection ability of the RFID reader under different conditions.
2. The overall system delay- $\mathbf{T_d}$, time taken by the device, from point of tag scan to the time when data is available for to the user on the PDA as a synthesized voice.

6.1 RFID tag-reader tests:

RFID tags and readers are generally affected by number of parameters like distance, orientation, power of the reader, the type/geometry of the tag (which limits the size of tags antenna), material on which the tag is installed (different materials absorb radiations to different extents), external antenna used with reader, power source for the tag and frequency of operation of the reader-tag combination. Wearability, being the goal of our system, we were restricted to RFID reader introduced in the Section 4.1.1. This fixed many of the above mentioned parameters. Thus, the parameters considered in the experiments that we conducted were

a. Distance from the tag to reader
b. Orientation of the tag with respect to the reader.
c. Material on which the tag is placed.
d. Type/Geometry of the tag.
e. Whether external antenna was used with reader.

In theory, all these measurements can be obtained by looking to the radiation patterns of the tag and the reader antennas. But this would require the use of specialized radiation measurement devices, which were not readily available. Thus, a calibrated experimental setup was built to measure the various parameters shown above.

6.1.1 Experimental Setup:

As shown in the Figure 5, the experimental setup consists of a circular disk of radius 1.5 feet that is marked with 1 inch radial distances at angular intervals of 20 degrees. The RFID reader is placed in the center such that the plane of the antenna is parallel to the 0 axis on the disk (Note that the reader carries an internal antenna etched on the PCB (printed circuit board) itself). The RFID tag is placed at different distances and orientations away from the reader to accurately measure the detection capability of the reader for that particular tag. In order to study the effect of product material on the reader performance, the tag was mounted on to different materials (like ceramic, cardboard, etc). Similar experiments were conducted by changing the tag itself.

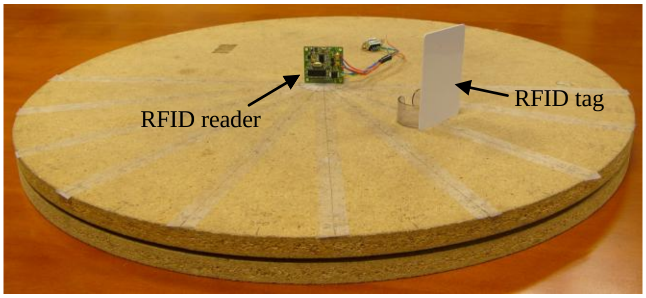


Figure 5: *Accessible Caption:* Shows the calibrated angular and radial marking table used to measure the distance and orientation of tag detection. The details of the device use are illustrated in the Section 6.1

Most RFID readers have the facility to use an external antenna to improve their read range. The reader used in this project could also be connected to a standard 50 ohm external antenna. The manufacturers of the reader provided an external antenna which was used in one experiment (with a chosen tag and material) to understand the benefits of using external antennas. The external antenna was never used in the project itself as the size of the antenna was restrictive for the application. Efforts are on the go to identify external antennas that have form factor suitable for this application.

6.1.2 Experiments:

Five different materials were chosen for the study along with four different types of RFID tags. Experiments were conducted to measure the Detection Distance-Orientation Maps (a map of how far and in what orientation would from the reader is a tag detected) for the twenty combinations of materials and tags. The tag that gave the best performance with the internal antenna was further used to evaluate the effect of coupling of the external antenna.

Tag #	Description	Material Number	Materials
1	Tag-It HF-I, Texas Instruments, 2.25in x 2.25in, ISO15693 compliant	1	Wood
2	Tag-It HF-I, Texas Instruments, 1.5in x 1in, ISO15693 compliant	2	Plastic
3	ICode SL1, Philips, 1 in diameter, Proprietary data format	3	Cardboard
4	ISO15693 compliant access-control card, 3.5in x 2 in	4	Glass
		5	Ceramic

Table 1: Shows the RFID tags and materials for which the twenty different Detection Distance-Orientation Maps were collected.

6.2 Overall system delay, T_d:

In order to measure the overall delay in the system, we measured the total time taken from the point of user reaching out for a product to the point when the data is read out to the user. This delay accounts for the data flow through the entire system.

The time T_d has two components to it.

1) $\mathbf{T_c}$: A constant delay of sending the data from the RFID reader to the PDA. This is calculated as follows. RFID tag ID is 20 ASCII characters in length. The Serial port was operated at 9600 bits/sec, 8 data bits, 1 start bit and 1 stop bit. This gives a constant delay of (20*(8+1+1))/9600 = 20.8 ms.

2) $\mathbf{T_t}$: Time from serial port scan to data being read to user. This was measured using a millisecond counter within the PDA. The counter was initialized when tag ID arrived at the serial port and was stopped by a user pressing a button on the PDA when he/she heard the synthesized voice from the text-to-speech converter software on the PDA. We measured this delay by nothing the time on the millisecond counter when tested with 5 users over 10 trails each.

The total system delay can be found as: $\mathbf{T_d = T_c + T_t}$

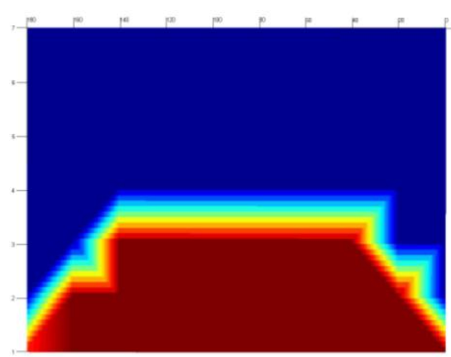
7. RESULTS

7.1 Results for RFID reader and tag tests:

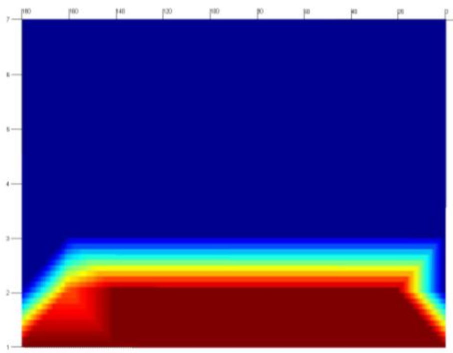
7.1.1 Results with Internal Antenna:

Figure 6 (a) to (d) (best viewed in color) shows the average Detection Distance-Orientation Maps for Material 1 with Tags 1 to 4 respectively. The average was taken over 3 trials of using the RFID reader to detect a particular type of tag at the same distance, orientation and on the same material. The X axis of these plots indicates the orientation of the RFID tag with respect to the reader, varying from 0° to 180°. The Y axis indicates distance of the RFID tag from the reader, varying from 1 inch to 7 inches. In these maps, the red region indicates distance-orientation combinations where detection is "certain" i.e. *p(detection)* = 1, while blue region indicates distance-orientation combination where tags are not detected i.e. *p(detection)* = 0. The regions in between red and blue correspond to distance-orientation combinations where intermittent success or failures were recorded during the 3 trails. For simplicity, the maps show a continuously interpolated region from sure detection to complete failure providing a measure of detection probability *p(detection)*.

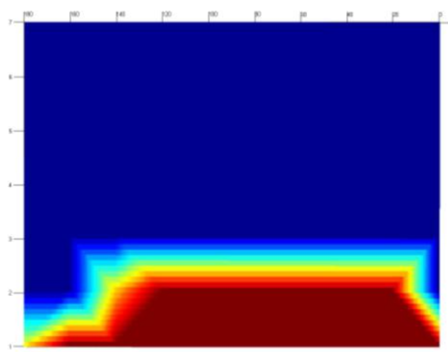
Figure 7 (a) to (e) (best viewed in color) shows the average Detection Distance-Orientation Maps for Tag 3 when used with Material 1 to 5 respectively.



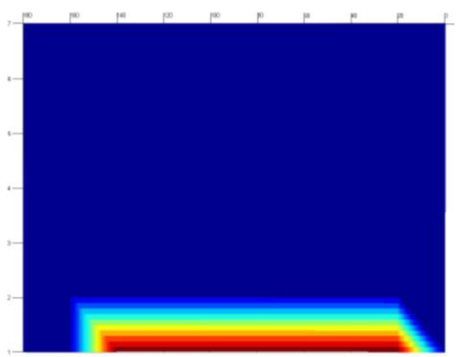
(a) Tag 1.



(b) Tag 2.

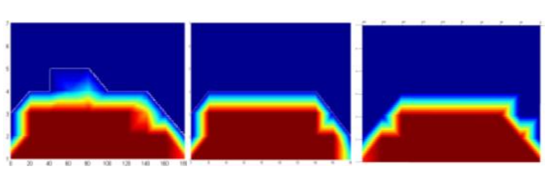


(c) Tag 3

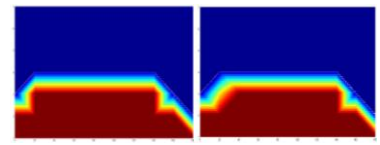


(d) Tag 4

Figure 6: *Accessible caption:* Figures show the average Detection Distance-Orientation Maps for Material 1 with (a) Tag1, (b) Tag 2 (c) Tag 3 and (d) Tag 4. The x-axis show angular change, while the y-axis show radial distances. The plots themselves have red regions that identify detection of RFID while blue identifies regions of failure. Between subfigures (a) to (d), the red region diminishes, thereby representing Tag 1 as the best RFID tag.



(a) (b) (c)



(d) (e)

Figure 7: *Accessible caption:* Shows the average Detection Distance-Orientation Maps for Tag 1 on Material 1 to 5 respectively. Red and blue regions are shown in this figure. The spread of two regions remain approximately the same between images concluding the material has no effect on RFID scan.

7.1.2 Results with External Antenna:

Figure 8 (best viewed in color) shows the average Detection Distance-Orientation Maps for Tag 3 when used with Material 1.

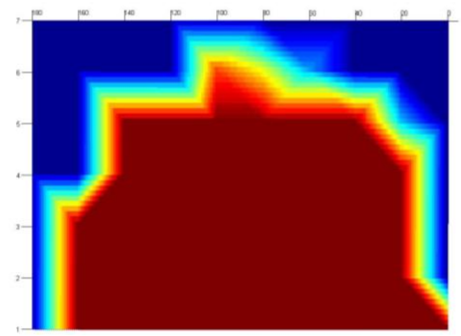


Figure 8: *Accessible caption:* Shows the average Detection Distance-Orientation Maps for Tag 1 on Material 1 using an external antenna. The red region in this figure is much larger than in the internal antenna case and extends outward up to 7 inches.

7.2 Results for the overall system delay test:

Having found $\mathbf{T_c}$, as shown in the section 6.2, delay $\mathbf{T_t}$, was found by taking 10 trials with 5 users while scanning the RFID tag with the reader and measuring the time taken until the text-to-speech reads the product information. Figure 9 shows the results obtained from the 5 users.

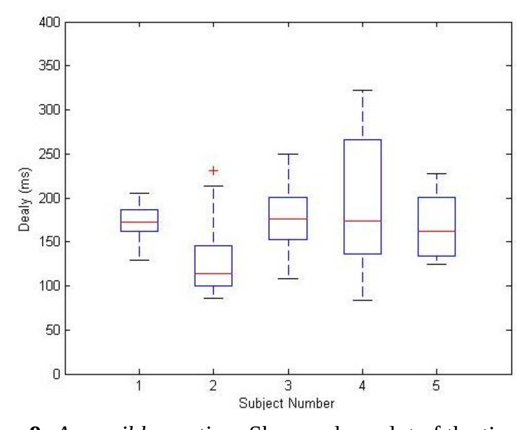


Figure 9: *Accessible caption:* Shows a box plot of the time delay $\mathbf{T_t}$ measured over 10 trials per user. The box shows the 50 percentile cutoff points of the individual user's recordings. The red line in the middle of the box shows the median. The min and max values per user are shown by the extreme edges of the individual graphs. Outliers, if any, are shown by '+' mark.

The graphs highlight the median time delay, the min and max time each user took and the 50 percentile regions of the time delay. These percentile regions indicate the deviation that each user might have in future trials.

8. DISCUSSION OF RESULTS

8.1 Discussion of results shown in section 7.1:

8.1.1 Discussion of results with internal antenna:

Figures 6 (a) to (d) show the average Detection Distance-Orientation Maps for different tags used on the same material (Material 1). It can seen from these images that

1. Tag 1 showed the best performance in terms of coverage on the Detection Distance-Orientation Map. This is very evident from amount of region shaded in red (that corresponds to certain detection) in the Detection Distance-Orientation Map. This can be related to the fact that the Tag 1 has a broader area (1.5 in x 1.5 in) in comparison to the other Tag 2 and Tag 3. The larger area accounts for bigger antennas inside the tag, which in turn helps in better distance and orientation of detection. Though Tag 4 had a larger area than Tag 1, the performance was poor, probably due to the lower number of antenna loops. The objective of this test, to determine the tag that can be detected for the maximum angular variation and radial distance, clearly picks Tag 1 for our implementation.
2. The maximum distance that any tag could cover was observed to be 3 inches when the tag was at an orientation of 90° with respect to the tag (that means that the tag was parallel to plane of the reader.). This was achieved by Tag 1. The 90° orientation can be described by the fact that the coupling of RF waves between the reader and the tag is maximum when the tag's antenna is normal to the field lines generated from the reader.
3. The detection probability gradually falls towards 0 as the orientation changes from 90° to either 0° or 180°. This can be explained by the fact that the tags antenna becomes parallel to the field lines generated by the reader and thus the net power transferred between the reader and the tag, in most cases, is reduced, if not zero.

Figure 7 (a) to (e) shows the average Detection Distance-Orientation Maps for Tag 1 when used with Material 1 to 5, respectively. It can be observed from the figures that all the maps look similar. Our experiments showed that the materials did not have any impact on the performance of the tag. Similar results were observed with other tags. Due to the lack of space, the results from the other experiments are not provided.

8.1.2 Discussion of results with external antenna:

We observed an increase the range of detection, when the reader was coupled with an external antenna. Comparing Figure 6(a) with Figure 8, it can be seen that the external antenna results in a significant gain in the performance of the RFID reader. The distance of detection increases drastically from 3 inches to 6 inches at 90° orientation. Further, the total spread of the detection region (red region) is much larger (quantitatively, the detection region is 2.5 times larger with an external antenna) leading to better detection capabilities when compared to the internal antenna case.

8.2 Discussion of results shown in section 7.2:

From the Figure 9 it can be seen that the median performance of time delay, $\mathbf{T_t}$, of 4 users out of 5 are similar. The average median performance of the 5 users was found to be 159.7ms. Combining this delay with $\mathbf{T_c}$, (from section 6.2), the total system delay, $\mathbf{T_d}$ can be found to be $\mathbf{T_d}$ = 20.8 + 159.7 = **180.5 ms**. All the users reported that this time delay did not introduce uncomfortable wait times between scanning the product and receiving the information. Further, from the Figure 9 it can also be seen that the 50 percentile spread (size of the box) are similar among 4 out of the 5 users. This shows that on an average, users tend to deviate very little from the delay $\mathbf{T_t}$ that was calculated above giving us more confidence in the users experience that the system was comfortably real-time.

9. CONCLUSION AND FUTURE WORK

In this paper we have identified important design constraints that have to be considered when designing a shopping assistant for helping individuals with visual impairment. Based on these constraints, we have proposed a wearable RFID system for identifying products placed on the shelves of retail stores. We have conducted experiments to study the range of detection (both angular and radial distances) of the RFID reader with respect to different tags and different materials. These experimental results lead us to identify the Tag-It HF-I (by Texas Instruments, ISO15693 compliant) to be the most suitable RFID tag for our application. The experiments showed that there was no effect of product materials on the performance of the RFID reader. Evaluation of the overall system delay showed 180ms time lag between scanning of a product and hearing the product data on the text-to-speech converter which was deemed insignificant by users.

The future work would involve identifying external antennas with appropriate form factor (to be used in wearable situation) to increase the read range of the reader to about 6 to 8 inches. We also plan to embed this system into an indoor navigational assistant to develop provide a holistic shopping aid that would meet the design requirements as identified by the focus group.

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