Location-Aware RFID Mobile Device System for Museum Applications

William Coon
University of Colorado at Boulder, coondoggie82@gmail.com

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Location-Aware RFID Mobile Device System for Museum Applications

by

William Coon

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Location-Aware RFID Mobile Device System for Museum Applications
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has been approved for the Department of Computer Science

Prof. Clayton Lewis
Advisor

Prof. Dirk Grunwald
Committee Member

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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.
Coon, William (M.S., Computer Science)

Location Aware RFID-Mobile Device System for Museum Applications

Thesis directed by Prof. Clayton Lewis

Abstract

The present capabilities of smartphone devices provide users with novel ways to interact with the world around them and retrieve information about it. This thesis explores how these capabilities may be extended in order to enhance the experience of museum visitors and simultaneously provide museums with valuable data about their visitors. Outlined in this thesis are the overall design and constraints of a system that pairs radio frequency technology with smartphone devices. The author created a proof of concept prototype which provides a foundation from which to develop the full-scale system.
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Chapter 1

Introduction

Over the last few years there has been an explosion of smartphones in society and applications that users download and use in their everyday life. Applications have a vast range of functionality and serve purposes for entertainment, health, education, travel and more. In January of 2011 the Apple App Store alone reached its 10 billionth application download [14]. It is safe to assume that the popularity and use of smartphones and smartphone applications will only continue to grow. With over 350,000 applications available for the iPhone platform alone, it is not surprising that users expect to find an application for just about anything they can think of [15].

The extensive capabilities of smartphones can be utilized in revolutionary ways especially by pushing the boundaries of how they are typically used. With the addition of technology that determines your precise location within a space, the smartphone can be transformed into an intelligent guide that is aware of your surroundings. Imagine walking through a museum while your phone comes to life to instantly tell you extensive information about any exhibit you happen to be looking at. Not only would you be able to enjoy the physical displays of the exhibits, but this handheld tour guide will show you videos, play audio clips, and give you an expansive amount of information that would otherwise be unavailable on the physical exhibit label. The system outlined in this paper is designed to perform exactly these functions, and even more.

The drive for museums to adopt this location-aware smartphone technology would not only be based on enriching the experience for their visitors, it would also provide an invaluable service to the museum itself. Museums have an obligation to perform evaluations in order to
assess the effectiveness and value of specific exhibitions and the overall experience they provide for their visitors. An important form of evaluation focuses on timing and tracking visitors' movements. This evaluation involves collecting data about the amount of time visitors spend at specific exhibits and locations throughout the museum as well as determining the common paths that visitors take while navigating the museum [12]. This data allows museums to distinguish between high and low areas of interest and assess how visitors navigate through the physical space. The current method typically used for collecting this sort of data involves a human evaluator observing visitors in a museum while using a stopwatch, pen, and paper to record data [11]. This methodology presents challenges related to the amount of time and money required to collect the data, as well as limitations related to the accuracy and volume that any human observer is capable of recording in this type of environment.

The location-aware smartphone would be an ideal solution to these issues. While visitors are enjoying the museum, the smartphone will display information about exhibits to the user while simultaneously sending timing and tracking information to a server within the museum. This will allow accurate data to be collected at all times for every visitor using the smartphone application. Vast amounts of aggregated data will be stored on the server and museum staff would have instantaneous access to it with the ability to visualize, analyze, sort, and export valuable information for evaluation.

The central focus of this paper outlines the design of a system that fulfills all of these revolutionary functions. Discussed in this paper are descriptions of all of the necessary components and implementation considerations required to accomplish these goals. In addition, a prototype that performs the basic functions of this system has been built and is described in detail.
2.1 General Description

The basic flow of information for typical use will include 3 major components in the system: (1) Radio Frequency Identification (RFID) tags, (2) a mobile device with attached RFID reader apparatus, and (3) a local server that stores information (images, text, video, or audio) about the museum exhibits. RFID tags will be placed on or near exhibits in the museum, as well as on pathways. When a mobile device is within range of an RFID tag, the tag will transmit its unique identification number to the reader, which will relay this information to the mobile device. The mobile device will then transmit this identification number along with other relevant information to the server via WiFi. The server will respond accordingly by transmitting media and location information that will be displayed to the user. The server will also store timing and tracking information about the user for evaluation purposes so that museums will be able to understand how visitors are moving through the museum and spending their time. With these three components in place, a museum visitor may easily navigate the space while seamlessly receiving information about nearby exhibits, and the server will automatically collect and store valuable data about the museum visitors. The basic flow of information for typical use is shown in Figure 2.1.
2.2 Radio Frequency Identification

RFID technology has been in existence since the 1950s and has been gaining in popularity ever since in a wide range of applications [1]. RFID solutions have been used for many purposes, including key-card access, highway tolls, industrial applications, inventory management, and more. For example, Wal-Mart has been striving to use RFID tags that would allow easy tracking of items from the point of manufacture all the way to the shelf [2]. The basic
Premise for RFID involves 2 major components [3]:

- **The transponder** is the component that is placed on the object or location that will be identified. The most basic transponders simply transmit a unique identification number when prompted. More complex transponders have the ability to store and transmit larger amounts of data, and also may be written to. For the purposes of this project, the transponder is only required to transmit an identification number. The transponder will be referred to as an RFID tag, or simply tag throughout this paper.

- **The reader** transmits and receives RF signals in order to read and/or write to the RFID tags. The reader typically includes middleware which allows it to filter, format, and transmit data to a computer application [1]. In this project, the reader is only responsible for reading the identification number from tags and relaying this information to the mobile device.

### 2.2.1 RFID Transponders

The transponder, or tag, is the component that is used to identify objects in the RFID system. Tags may come in many different sizes, shapes, and varieties depending on the application. There are three basic components included in a typical transponder: (1) an antenna, (2) an integrated circuit, and (3) a substrate on which the other components are mounted [1]. The antenna serves to receive and transmit RF waves, and in the case of passive tags it also acts as an energy converter to power the integrated circuit. In the most basic applications, the integrated circuit stores and broadcasts the tag's identification number. The substrate can vary depending on the application and may be designed to suit the environment in which the tags are used. For example, a thin flexible plastic substrate may be used to attach a tag to the pages of a library.
book, while a robust plastic housing may be used for a tag that would be attached to a keychain. For the purposes of this project, the ideal tag would be one that is easy to attach on or around an exhibit in a way that is invisible to the visitor.

There are three classifications of RFID tags that must be considered for the desired application as well [4]:

- **Passive tags** do not require onboard power; these tags rely on the electromagnetic radiation emanating from the reader in order to power their transmission and integrated circuit. The lifetime and number of reads capable of passive tags is potentially unlimited. Read ranges are limited since they rely on the reader's power for transmission.
- **Active tags** have an onboard battery and do not need to harvest energy from the reader in order to function. Due to this, they have the ability to transmit to a reader several hundred feet away. Since they require an external source of power, they have a limited lifetime and eventually need to be replaced.
- **Semi-passive tags** have an onboard battery and use both the reader's electromagnetic field as well as battery power. These tags have characteristics of both passive and active tags.

The selection of tags relies heavily on the environment in which they are to be used and their placement within that environment. Within the scope of this project, there are many factors that must be considered depending on the domain in which the system will operate. These factors may not be consistent depending on the specific location. Ideally, passive tags would be preferred over active tags for any large space that would require numerous exhibits to be tagged. The cost and time required to replace thousands of tags every few years may not justify the use of active tags. Harsh environments such as outdoor spaces like botanical gardens may require
robust casings for tags to protect them from the elements. There are also environmental factors such as metal and water which can decrease the read range of transponders that must be assessed for proper functioning of the system [6]. In spaces that are heavily affected by these types of factors, such as aquariums with large amounts of water, active tags may be necessary to overcome the limits imposed by the surroundings.

The optimal placement of RFID tags will maximize the amount of space in which the reader will sense one tag and one tag only. In this way, overlapping interrogation zones will be minimized. A hypothetical layout of RFID tags and the areas they span is shown in Figure 2.2. This is a modified diagram of the University of Colorado Museum of Natural History's Modern Life Gallery used in observational studies [12]. The grayed circles depict the interrogation zones of five tags that would provide adequate coverage of the space, assuming a theoretical reading range of about 10 feet.
Figure 2.2: Optimal RFID Tag Placement

2.2.2 RFID Reader

The basic RFID reader has three major components: (1) an antenna, (2) a microprocessor, and (3) middleware. The antenna is responsible for transmitting and receiving RF waves used to communicate with and provide power to the transponder. The microprocessor is responsible for processing the information communicated with the tag, and may also use embedded algorithms to increase performance, such as anti-collision communication when more than one tag is within range of the reader [1]. The middleware is the software component that lies between the reader and the application software. The middleware's primary responsibility is to translate information received from the reader into data that may be transmitted to the data collection software.

Similar to RFID tags, there are many different factors that are considered for the design
of an RFID reader for a specific application. For the purposes of this application, several constraints are placed on the reader. Since this will be designed to be a handheld reader attached to a mobile device, the major constraints lie within the size and power consumption of the reader. The size of the reader must be appropriate for the size of a mobile device, and should not be cumbersome for the user to carry. The power for the reader should be drawn from the mobile device, and therefore the reader must have low power consumption. ThingMagic's M5e-Compact is an embedded UHF RFID reader module that is well-suited for this application [7]. The size of the reader is only 2.2 x 1.4 x 0.2 inches, which would be unobtrusive when attached to a mobile device. It is also rated to run off of a typical mobile device battery and consumes a relatively low amount of power.

### 2.2.3 Reading Ranges in RFID

RFID reading ranges depend on a number of factors including the operating frequency, environmental conditions, antenna size, gain on the reader's antenna, and whether the tags are passive or active. Theoretical ranges for different operation frequencies, including low frequency (LF), high frequency (HF), and ultra-high frequency (UHF) are shown in Table 1. These ranges are intended to give a general idea of the distances capable of each operating frequency [1, 7, 16]. Within each operating frequency, depending on the manufacturer and design, the ranges may exhibit extreme variation.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Tag Type</th>
<th>Theoretical Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>LF: 125-148KHz</td>
<td>Passive</td>
<td>&lt; 1'</td>
</tr>
<tr>
<td>HF: 13.56MHz</td>
<td>Passive</td>
<td>&lt; 3'</td>
</tr>
<tr>
<td>UHF: 680 – 900MHz</td>
<td>Passive</td>
<td>&lt; 20'</td>
</tr>
<tr>
<td>UHF: 680 – 900MHz</td>
<td>Active</td>
<td>&gt; 300'</td>
</tr>
</tbody>
</table>

Table 1: RFID Operating Frequencies and Read Ranges
The typical use in museum environments would require a reading range of around 10 feet in order to acquire the desired effect to instantly display information as a visitor approaches an exhibit. As mentioned in the previous sections, there are a large number of factors that determine the effective reading range. A passive UHF system that typically reads at a range of 10 feet might be reduced to inches in the presence of large quantities of water or physical obstructions [1]. For this reason, care is needed in designing each system to suit its environment. Under ideal conditions, the system that would be most desirable would be UHF with passive tags. As mentioned in the previous section, ThingMagic's M5e-Compact would be a suitable reader module paired with passive tags, with a reading range of around 12 feet [7].

### 2.3 Mobile Device

The mobile device will have several responsibilities in this system. It will be able to receive data from the attached RFID reader and communicate wirelessly with the server located in the museum. The device will be running an application designed to manage the content that is displayed to the user. When a new identification number is received from the RFID reader, the application will relay this data to the server over WiFi and wait for instructions on what actions to perform next. The mobile device will then receive media content and other relevant information such as locational data. The device itself will have no knowledge of what the identification numbers relate to until told by the server. In this way, the amount of storage space required by each device is minimized. Once new data is transferred to the device from the server, the device application will be responsible for displaying multimedia content and depicting the user's location on an interactive map. The application will also be responsible for responding to user actions and commands in order to allow visitors to navigate the user interface. Fortunately,
standard smartphones have the ability to perform all of these functions, and a large portion of society already owns these devices and uses them on a regular basis. For the portion of visitors who do not own a smartphone, museums may opt to loan out devices.

2.4 Server

The server is the heart of this system. It will be loaded with all relevant information about the space being navigated, such as which identification numbers correspond to specific exhibits and locations throughout the museum. The server is responsible for receiving data from each visitor's smartphone. It must then transmit relevant media and information to the user that requests it. In addition to transmitting information to the user, it will also store data about each user such as the amount of time spent at each exhibit, an ordered list of locations that the user has visited, and any feedback the user has provided.

Beyond the real-time responsibilities of the server, the software would ideally provide an easy way for museum staff to work with content and collected evaluation data. This software would allow museum staff to edit and add new content (text, images, audio, and video) to existing exhibits, which would then be transmitted to visitors approaching those exhibits. Museum staff would also have the ability to add or remove RFID tags for different exhibits and modify the content accordingly. Museum staff would also be able to easily visualize, sort, analyze, and export the collected data for evaluation purposes.
Chapter 3
Technology Benefits

3.1 Visitor Experience

Since the explosion of smartphones in society, there has been a market for applications that provide services in nearly every aspect of life. Applications that provide services for travel, eating, social networking, game playing, and many other facets of everyday life are readily available and widely used by smartphone owners. Apple's trademark phrase “There's an App for That” succinctly demonstrates the general perception that for almost any reasonable activity that one would expect to be able to perform with their smartphone, somebody has more than likely developed an application that achieves it. Equally in the world of museums, visitors increasingly expect to find smartphone applications that will aid and enhance their experience in the museum.

There are many aspects of a museum experience that can be enhanced through the use of this system. The main points of benefit to users are:

- Visitors can easily navigate museums by using an interactive map included in the application that displays their location as well as directions to nearby restrooms, exhibits, kiosks, exits, and food.
- Visitors may immediately receive new information about exhibits in their physical proximity. This system will load exhibit-specific media information onto the users' phones without requiring any action to be performed by the user other than approaching the exhibit.
- Visitors can explore many layers of multimedia content such as text, images, audio, and video. This variety may appeal to users' different learning styles.
• Visitors may explore content in whatever depth they desire. They can investigate content that would otherwise be impossible to convey with physical museum displays.

For visitors that already own a smartphone, the application would be available as a free download. Museums may opt to loan smartphones to other guests that wish to use the application as well. The nature of this application requires a friendly and intuitive user-interface, especially for visitors that are unfamiliar with smartphone applications. During previous work for this project, a mock interface for this system was designed and tested on a group of potential users. This work was performed as part of the curriculum of CSCI 5839: User-Centered Design taught by Prof. Clayton Lewis in the Fall of 2010 at the University of Colorado. The users were given a series of tasks to perform with the simulated interface. They were timed and asked to provide feedback on problematic issues with the application. The simulated tasks included viewing video for a specific exhibit, finding directions to a restroom, sharing content on Facebook, and taking a tour. The majority of users were able to perform the tasks with only minor difficulties during their attempts. Example images of the mock interface are shown in Figure 3.1. [8]
As one would expect, there are many applications that have already been implemented for museums. The Museum of Modern Art has one such application that includes images, text, and audio for many of their exhibits. The MoMA iPhone application does not include any location awareness and requires users to navigate through multiple menus in order to find information about particular exhibits [9,10]. The American Museum of Natural History developed their Explorer iPhone Application which relies on WiFi triangulation in order to determine the visitor's location within the museum. Although this is a novel approach to determining visitor location, critic reviews suggest that the accuracy of location is limited to a room by room basis [10]. This may help with navigating the space of the museum, but users are still required to browse through several menu screens in order to find information about an exhibit. These examples are fairly representative of existing museum smartphone applications, and neither of them provide the ease of use and quality experience that is intended with this system. The demand for the services provided by this system are exemplified in Edward Rothstein's critique, “From Picassos to
Sarcophagi, Guided by Phone Apps”:

It is best to consider all these apps [from the American Museum of Natural History, the MoMA, and the Brooklyn Museum] flawed works in progress. So much more should be possible. Imagine standing in front of an object with an app that, sensing your location, is already displaying precisely the right information. It might offer historical background or direct you through links to other works that have some connection to the object. It might provide links to critical commentary. It might become, for each object, an exhibition in itself, ripe with alternate narratives and elaborate associations. [10]

3.2 Museum Evaluation

Museum evaluation consists of many different areas of research, including visitor feedback, timing and tracking information, and observations of visitor behavior. Regardless of the source of financing for museums whether it be private funding, government funding, or ticket sales, evaluation is an important endeavor for museums. Investors and grant awardees need to be shown some proof that their investments are being used effectively for their intended educational purposes. Museums that rely on ticket sales also need to be sure that they are providing the best possible experiences for visitors to ensure that people will keep attending the museum.

Current methods of evaluation typically involve either in house evaluators or third party evaluators who collect data through various methods. Visitors may either be asked to leave comments on cards, at kiosks, or directly to the evaluator through interviews. An evaluator may spend time observing visitors and taking notes on their behaviors and conversations while they engage in a particular exhibition space. Timing and tracking data involves collecting data about how much time individual visitors are spending at particular exhibits and the paths they choose to take throughout the space of the museum. This data is usually used to indicate areas of high and low use, where high-use areas indicate higher levels of engagement and potential learning [11]. Tracking data can illuminate issues of navigation and wayfinding; when museums undergo renovation projects, architects may request that museums conduct these studies to develop a better understanding of how visitors move through the entire museum space [12].
The standard method for collecting tracking and timing data involves an evaluator observing visitors in a museum (usually within a single gallery) while using a stopwatch, pen, and paper to record data [11]. In this situation, the evaluator typically observes only one visitor at a time. This is an extremely time consuming and tedious activity, especially when evaluating large areas, high-traffic areas, or areas where visitors stay for long periods of time. Depending on the scale of the museum, an evaluation may be done over the course of several months and may range in cost from tens to hundreds of thousands of dollars. Much of this cost is derived from the human-hours spent collecting, entering, and analyzing data.

Museums will be able to utilize this system in order to collect timing and tracking information, user demographics, and user feedback automatically and at all times. The collection of this data would be consistent for every visitor, unlike human collection methods which are inevitably variable from one evaluator to the next. The software system on the server would provide an easy way to visualize, sort, and display this data based on the particular needs of the museum.

Existing museum smartphone applications do not provide any type of timing and tracking data collection. The draw for these applications is based solely on the benefits to the visitor. In March 2011, the Museums and Mobile Online Conference II featured multiple speakers who addressed current trends and future directions of smartphone technology in the context of museums [17]. There was no mention of the potential for mobile devices to collect valuable timing and tracking data. The implementation of this system could prove to revolutionize the methodology of timing and tracking evaluation in terms of the volume and accuracy of collected data. This system could allow museums to harness a constant awareness of how visitors use their spaces and could prove to be an invaluable asset for a museum to utilize.
Chapter 4

Prototype Development

4.1 Overview

The prototype for this system was intended to be a proof of concept that this system is viable using technology that already exists. Although the prototype does not meet the ideal specifications for widespread use of this system, the purpose was to demonstrate that each component functions properly and that the system can be implemented in a small scale. For the system to function as described previously, three components must be interfaced: (1) an RFID reader, (2) a smartphone, and (3) a server. The prototype was designed using a jailbroken iPhone 3G, a low frequency RFID reader module, passive RFID tags, and a MacBook as the server. Communication between the iPhone and MacBook was through a WLAN. The RFID reader module was modified to communicate with the iPhone through the serial port based on a design outlined by Benjamin Blundell [13]. The RFID reader and tags operate at a frequency of 125 kHz and have a reading range of about one inch. Figure 4.1 depicts the flow of information in the prototype design.
In order to demonstrate the successful flow of information, each RFID Tag was assigned a reference number. Five tags were labeled 1-5, and the unique identification number of each tag along with the associated reference number were stored in the server software. As each tag is waved in close proximity to the RFID reader, the label written on that particular tag is displayed on the iPhone's screen after the information is processed according to Figure 4.1.

### 4.2 RFID Hardware

The central hardware component for the prototype was SparkFun's ID-12 RFID reader module. Additional components were required to make the ID-12 compatible with the iPhone, and these additions were based on recommendations from Benjamin Blundell [13]. The following hardware components were assembled to create the iPhone RFID reader:
• **RFID Reader ID-12 (125 kHz)** from SparkFun electronics. This is an easy to use simple module that performs all of the basic functions of an RFID Reader. Once it is powered and wired properly, it will read the identification number of any compatible 125 kHz tag in close proximity and transmits the data as a 9600 bps 8N1 TTL signal.

• **Logic Level Converter** from SparkFun electronics. This device steps down the 5V signal transmitted by the ID-12 to a 3.3V signal that is compatible with the iPhone.

• **PodBreakout** from SparkFun is a breakout board that allows easy wiring to the iPhone's dock.

• **2xAA Battery Pack with Vpack 5V DC to DC Step Up** from SparkFun electronics is the power source for the ID-12.

• **125 kHz RFID Tags** from Sparkfun Electronics are the passive tags that are read by the ID-12. They each store and transmit a unique 32-bit identification number.

With these components assembled and wired correctly, the reader simply plugs into the iPhone's dock and will output data to the serial port each time a card is read.

### 4.3 Mobile Device Software

The iPhone was selected as the mobile device to be used since it was representative of typical smartphones for the proof of concept design. The software for the iPhone was programmed in Objective-C and C++ and developed with Apple's iPhone SDK and Interface Builder. The software was not designed to mimic the mock user interface described previously, it was only intended to perform the basic functions that the mobile device is responsible for in this system. The following tasks are performed by the prototype software:
• **Receive identification number from the RFID reader.** This is accomplished by creating a thread that listens to the serial port for incoming data in the background. In order to access the serial port, it was necessary to load the application to a jailbroken iPhone. The other option would be to purchase a “Made for iPhone” license from Apple.

• **Transmit identification number to the server.** This is accomplished by creating a TCP connection to the server and sending the data via WiFi.

• **Receive relevant information from server.** Once the identification number is transmitted, the application waits on the same TCP connection for a response from the server. In the prototype design, each RFID tag was assigned an integer reference number for ease of recognition.

• **Display data to the user.** Once the transmit/receive process finishes, the application displays the integer reference number of the last tag read on the screen of the iPhone.

### 4.4 Server Software

The server software was developed in Objective-C and C++ and is designed to run on Mac OS X. The prototype was not intended to provide all of the functionality described in previous sections, but simply to perform the basic functions that the server is responsible for in this system. The following tasks are performed by the prototype server software:

• **Receive identification number from iPhone.** This is accomplished by establishing a TCP connection with the iPhone and waiting to receive data.

• **Process the identification number and retrieve relevant information.** The server software has a hard coded dictionary containing each of the RFID tag's unique identification numbers and their associated reference numbers. Upon receiving a new identification
number from the iPhone, the associated reference number is fetched from the dictionary.

- Transmit relevant information to the iPhone. The server then transmits the associated reference number back to the iPhone over the TCP connection.
Chapter 5

Conclusion

The prototype design described in this paper successfully demonstrates that RFID location-aware smartphone technology is viable. The prototype executes the flow of information depicted in Figure 4.1 which represents the essential components and communication necessary for the system. The prototype proof of concept is the fundamental starting point to develop the full scale functioning system.

In order to extend the prototype to fully exemplify the system described in Chapter 2 would require: (a) developing a UHF RFID reader compatible with smartphone devices, (b) building the user-interface described in Section 3.1 on top of the prototype smartphone software, and (c) extending the server software to perform all of the functionality described in Section 2.4.

RFID technology is an effective method for providing the precise location awareness needed for proper functioning of this system. Constraints and obstacles of unique physical spaces must be explored in order to successfully implement large scale versions of this system.

The major achievement of this system will be to take smartphones to the next level of location-aware pervasive computing. This will provide museum visitors with an enriched and highly enjoyable means to experience museums in a new way, and could potentially be extended to other spaces as well. This system will also be an invaluable asset for museums by providing a revolutionary method to collect large volumes of data about visitors' movement behaviors.

As smartphone technology continues to expand and become more pervasive, the potential uses and benefits reaped from this technology will expand as well. This system will potentially be positioned at the crest of this wave and impact high-precision location-aware applications as well as other technologies that strive to push the limits of smartphone capabilities.
Bibliography


May 2011.
