RF-Scanner: Shelf Scanning with Robot-assisted RFID Systems

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***Abstract*—Shelf scanning is one of the most important processes for inventory management in a library. It helps the librarians and library users discover the miss-shelved books and pinpoint where they are, improving the quality of service. By traditional means, however, manually checking each bookshelf suffers from extremely intensive labor and long scanning delay. Although some existing RFID-enabled approaches have been proposed, they suffer from either high-cost infrastructure or complicated system deployment, forming a great barrier to commercial adoption. In light of this, we in this paper propose a smart system called RF-Scanner that can perform the shelf scanning automatically by combining the robot technology and the RFID technology. The former is used for replacing the librarians and liberating them from intensively manual labor. The later is installed on the robot and moves with the robot to scan the on-the-shelf books. We formulate two important issues concerned by librarians, the book localization and the lying-down book detection, and give the sophisticated solutions to them. Besides, we implement RF-Scanner and put it into practical use in our school library. Long-term experiments and studies show that RF-Scanner provides fine-grained book localization with a mean error of just 1.3 cm and accurate detection accuracy of lying-down books with a mean error of 6%.**

I. Introduction

Tracking each book on bookshelves is one of the most important processes for inventory management in a library. Consider an arbitrary library that easily comprises hundreds of thousands of books to be frequently borrowed and returned. These books are placed in a specific shelf and sorted in sequence according to the call numbers. If a book is miss-shelved, the library users can search it out via the library management systems but cannot pinpoint where it is, lowering the quality of service. According to statistics [1], the shelving accuracy of some school libraries in US is no more than 90%; this accuracy will appear much lower in public libraries. In other words, more than one tenth of library users cannot find their wanted books even though these books reside in the library indeed. Hence, a miss-shelved book is a lost book and accurately locating each book (including miss-shelved book) is critical to providing good service to the public.

To pinpoint the real position of each book, the librarians need to execute shelf scanning over all bookshelves in the library. By traditional means, the library staff first conduct shelf reading, i.e., manually checking each book by observing the call number attached to the book's spine. If a book is miss-shelved, they need to tip it out, search the position where it would be, and insert it into the correct location. This process is extremely labor intensive and time-consuming, which is almost infeasible for the large-scale library management.

In recent years, the use of Radio Frequency Identification (RFID) technology in libraries has grown as it is able to ease the shelf scanning by moving the portable handheld reader [2]–[5] or deploying smart bookshelves [6]–[9]. These RFID-enabled solutions greatly improve the scanning efficiency and reduce the manual labor. However, they are not perfect. For one, the librarians still need to manually move the handheld reader to pass through each book on the shelves, which suffers from long scanning delay as well as much manual labor. For another, the usage of smart bookshelves requires high-cost infrastructure and complicated system deployment, which is a great barrier to commercial adoption.

In this paper, we propose a smart system called RF-Scanner that can perform the shelf scanning automatically by combining the RFID technology and the robot vehicle. The design of RF-Scanner follows '$3A$' principles. (i) *Accuracy*: the system should pinpoint each book's position in a fine-grained (e.g., cm-level) way. (ii) *Automation*: the shelf scanning should be performed in a completely automated way, saving the labor resources as well as improving the scanning efficiency. (iii) *Availability*: the system is supposed to be cost-effective and easy-to-deploy without any modifications to the existing infrastructure, which makes it available to practical use.

Based on above design principles, we first present the system architecture of RF-Scanner that consists of two main components: robot and RFID. The former is used for replacing librarians and liberating them from intensively manual labor. The later is installed on the robot and moves with the robot to scan the books on the shelves. By integrating these two components together, RF-Scanner is able to achieve the shelf scanning automatically and efficiently. With the advanced mechanical manufacturing, we in this paper just borrow the off-the-shelf robot technique while concentrate more on the RFID-related functions for shelf scanning. Two key problems concerned by librarians are addressed by RF-Scanner.

The first is how to accurately locate miss-shelved books. Unlike existing localization work [10]–[12] that estimates the absolute 3D coordinate of a tag, the localization of RF-Scanner returns a triple (shelf #, tier #, order) that respectively indicates in which bookshelf, in which tier, and in which order a book is placed, facilitating the library users to find out the wanted books quickly. There are three key technical challenges in locating. The first one is to achieve high accuracy just through one-pass scanning for each tier of the bookshelf. Any pre-deployed infrastructures, including the readers and the reference tags, are neither practical nor allowed. The second challenge is the samples of physical-layer information for each tag are sparse, especially in the case of shelf scanning where the reader needs to simultaneously interrogate dozens of books under its coverage and each tag can get only a few chances to respond. This small number of data collections within the 'V-zone' makes the existing work STPP [13] hard to achieve high localization accuracy. The third challenge is when scanning a specific tier of the shelf, the books on the upper tier, lower tier, and even the backside of the shelf will participate in the response, making the system fail to determine which one is the ground truth. To address above challenges, RF-Scanner takes the RF phases of a tag as the vehicle to pinpoint the tag's position. It collects all RF phases of a tag, removes the periodic patterns, and combines the intermittent curves into a continuous super V-zone. By a series of formula transforms and taking full use of all RF phases rather than only the small V-zone in STPP [13], RF-Scanner theoretically models the super V-zone to a hyperbola, conduct the curve-fitting of hyperbola, and finally derive the tag position based on the coefficients of hyperbola.

The second problem is how to detect the lying-down books. As shown in Fig. 1, the books usually stand on the shelf with correct placement. However, in some specific cases, e.g., to catch up buses, the readers just hastily place the books that they have read above the stand-up books, rather than carefully insert them into the proper position. To correct these abnormal lying-down placement, the librarians need to check all bookshelves one by one, which is both time-consuming and labor intensive. By carefully observing the pose difference between lying-down books and stand-up books, we find three useful metrics, the reading period, the number of reads, and the curvature of RSSI $\wedge$-zone, which can be used to determine whether or not a book is lying-down. We combine these three metrics together and take them as the input of SVM with the KBF kernel to produce a binary classifier that distinguishes the lying-down books and the stand-up books.

We implement RF-Scanner by integrating a self-designed robot vehicle and a commercial off-the-shelf (COTS) RFID reader (Impinj R420 [14]) equipped with two antennas. The robot vehicle is able to walk along the bookshelves via magnetic navigation and provides the RFID reader with continuous and steady mobile-scanning. We put RF-Scanner into practical use in our school library. It works at night and achieves a complete shelf scanning of 80,000 books within several hours. Long-term studies and experiments in the library show that RF-Scanner has great performance: the localization error of miss-shelved books is low as 1.3 cm, and the detection accuracy of lying-down books reaches up to 94%.

The contributions of this paper are summarized as follows:

- We propose a comprehensive system architecture of RF-Scanner to serve the shelf scanning automatically by combining the RFID technology and robot technology.
- We formulate two important problems concerned by librarians and propose the effective solutions to them.
- We implement RF-Scanner and put it into practical use in our school library. The long-term experiments and studies show that RF-Scanner is able to achieve cm-level localization accuracy of miss-shelved books and high detection accuracy of lying-down books.

Fig. 1: Lying-down books on the bookshelf.

The rest of the paper is organized as follows. Section II presents the system architecture of RF-Scanner. Section III locates the miss-shelved books. Section IV detects the lying-down books. Section V implements RF-Scanner and evaluates the system performance. Section VI introduces the related work. Finally, Section VII concludes this paper.

II. System Architecture of RF-Scanner

In this section, we first give an overview of our system architecture and then detail the scanning procedure of RF-Scanner. RF-Scanner generally consists of two components: robot and RFID. The robot is a mobile vehicle that is used for replacing the librarians and liberating them from intensively manual labor. The most two basic modules of the robot are: *(i) navigation* that enables the robot to move along the bookshelves as required, and *(ii) self-charging* that ensures the robot automatically commutes between the scanning shelves and the home base for recharging. With the advanced mechanical manufacturing, we in this paper just borrow the off-the-shelf robot technique while concentrate more on the RFID-related functions for shelf scanning.

The RFID component is deployed on the robot and comprised by an RFID reader and several antennas. A single reader can provide four or more antenna connections and uniformly schedule connected antennas at different time slots in a round-robin way. The antenna is fixed on the robot arm and is able to move up-and-down for scanning each tier of the shelf. To sense all books by the reader, each book carries an RFID tag that exclusively indicates the book itself. High Frequency (HF), working at 13.56 MHz, is one of the first RFID technologies to be successfully commercialized for numerous applications, including contactless payment, access control, and even library inventory. However, HF has the well-known drawbacks of the low data ratio and short communication range, which may lead to unreliable reading (e.g., miss-reading) when dealing with many tags concurrently. In RF-Scanner, we choose the Ultra-high Frequency (UHF) RFID system that operates in the frequency band of 860-960 MHz as the vehicle for shelf scanning. There are two reasons. First, the high read rate (more than 25Kbps) of UHF enables the parallel processing of books in the mobile environment. Second, the long read distance (up to 30 feet) of UHF benefits the reliable reading and theft detection. Hence, the UHF tag is a viable alternative to both bar code and EM security strip that are used for exclusively labeling a book and guarding against theft in the traditional library system, as shown in Fig. 2.

With above two components, the scanning procedure of RF-Scanner can be described as follows. The robot first navigates to an appointed starting point that is closed to the first bookshelf. After that, the RFID component is activated

Fig. 2: The difference between the traditional library and the UHF RFID-enabled library. One UHF tag is a viable alternative to one bar code and one EM security strip.

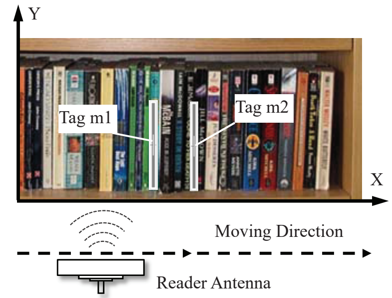


Fig. 3: Scanning process of RF-Scanner.

and starts to scan books on the shelf. Each scanning from one end of the shelf to the other is referred to as one *pass/scan*, which may involve scanning a single tier or multiple tiers of books. In each pass, each antenna moves to the right height to deal with each tier, as shown in Fig. 3. After the scanning of this shelf is done, the RFID reader goes to sleep and the robot navigates to the next bookshelf. This process repeats until all shelves are scanned. The data collections by each pass are recorded with shelf # and tier #, which are taken as the input of the following data processing. The objective of RF-Scanner in this paper is to pinpoint each book's position as well as figure out the lying-down books based on these data collections.

III. Localization of Miss-shelved Books

Locating miss-shelved books is one of the main concerns of the librarians. In this section, we detail how to accurately pinpoint each book's position. As aforementioned, instead of returning the 3D coordinate of each book, the localization result of RF-Scanner is a triple (shelf #, tier #, order) that respectively indicates in which bookshelf, in which tier, and in which order a book is placed. Below, we first introduce how to get the order of each book and later detail the localization of shelf # and tier #.

A. RF Phase Profile

The RF phase is a basic attribute of electromagnetic wave that reflects the offset degree between the received signal and the sent signal, ranging from 0 to 2π (360°). Let d be the distance between the reader antenna and the tag. Since the backscatter communication of RFID is a round-trip, the signal traverses a total distance of $2d$ in each communication. In addition to the phase shift over the distance d, the reader's transmission circuit, the tag's reflection coefficient, and the reader's receiver circuits will also introduce extra phase distortion, which are denoted as θ_{TX}, θ_{TAG}, and θ_{RX}, respectively. The phase output θ measured by the reader is:

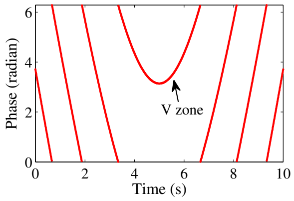
$$\begin{cases} \theta = (2\pi \times \frac{2d}{\lambda} + \mu) \mod 2\pi \\ \mu = \theta_{TX} + \theta_{RX} + \theta_{TAG}, \end{cases} \tag{1}$$

where λ is the wavelength. The term μ is called diversity term that is a constant and determined by hardware characteristics. Most COTS RFID readers (e.g., Impinj R420 [14]), are able to measure and report θ as the phase difference between the emitted signal and the received signal. With the ultra-high working frequency and fine-grained measure resolution of phase value by COTS readers, it is potential for RF-Scanner to achieve high localization accuracy [12].

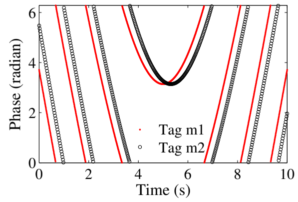
The basic idea of RF-Scanner is to continuously scan a set of tags and for each tag, the reader interrogates many times to obtain a sequence of RF phase values together with the corresponding timestamps, which form a *phase profile* of the tag, denoted by $\{(\hat{\theta}_1, t_1), ..., (\hat{\theta}_n, t_n)\}$. The core is to use each tag's phase profile to locate it on X-axis. Consider the tag m_1 in Fig. 3. When the reader moves (with the mobile robot) along the X dimension, the distance d between the reader and the tag m_1 first decreases, so does the phase value according to (1). Since the phase θ periodically repeats over d, when it drops to 0, it will suddenly jump to 2π in the next measure. This process repeats until the reader antenna reaches the point that is closest to the tag (the line connecting the tag and the reader is perpendicular to X-axis), where the phase value stops decreasing and starts to increase, periodically repeating from 0 to 2π.

Fig. 4(a) shows the theoretical phase profile of a tag when the reader moves along X-axis, which follows two patterns: 1) there is a 'V-zone' where its bottom happens when the line connecting the tag and the reader is perpendicular to X-axis; 2) multiple curves outside 'V-zone' increase or decrease monotonously, within the range of [0,2π); each curve corresponds to a period of the phase profile. It is easy to find that by observing the order of the bottom of 'V-zone' we can determine the order of tags along X-axis. Fig. 4(b) plots the phase profiles of two tags m_1 and m_2 5cm apart in Fig. 3. As expected, the tag m_1 reaches the bottom of its V-zone earlier than m_2, which is consistent with the real order of these two tags along X-axis.

Although V-zone is a good vehicle for ordering, directly adopting it like in STPP [13] has three drawbacks. 1) The samples of phase values for each tag are likely to be sparse, especially in the case of shelf scanning where the reader needs to simultaneously interrogate dozens of books under its coverage and each tag can get only a few chances to respond. This sparse sampling makes V-zone contain only a small number of phase values, thereby lowering the localization accuracy. 2) Even worse, the robot might not be reachable to some tags located at the end of the bookshelf that is next to the wall, which makes the reader just collect the phase curves outside V-zone rather than V-zone itself. 3) It is a waste to abandon many useful data outside V-zone that would-be helpful to locate tags.



(a) V-zone.



(b) Tag order along X-axis.

Fig. 4: Theoretical phase profile along X-axis.

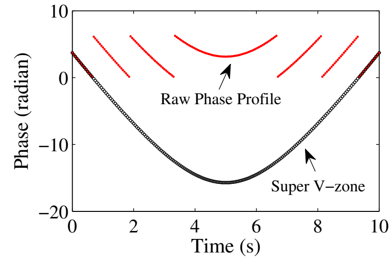


Fig. 5: Removing the periodical patterns of the phase profile to form a super V-zone.

Therefore, besides V-zone, how to use the curves outside V-zone is the key to improve the localization accuracy. In RF-Scanner, we first try to merge the V-zone and all curves outside V-zone together to form a *super V-zone*, and later use the curve-fitting of hyperbola to fit this super V-zone and derive the real position of each tag.

B. Removing Periodicity

The sudden jump between adjacent curves is the major barrier to using the whole phase profile. In light of this, we need to remove the periodicity of the phase profile and merge all curves (including V-zone) into a non-jump one before locating. According to (1), the periodic patterns are due to the modulo operation of 2π. To get rid of it, we need to execute the period compensation when a jump occurs. More specifically, we first sort all phase values based the corresponding timestamps and then compare each pair of neighbor phases in turn, from the first one to the last. Consider any two neighbor phases $\hat{\theta}_i$ and $\hat{\theta}_{i+1}$. If there is a jump from near 0 to near 2π, i.e., $\hat{\theta}_{i+1} - \hat{\theta}_i \approx 2\pi$, all follow-up phases $\hat{\theta}_j, j > i$ minus 2π. On the contrary, if the jump is from near 2π to near 0, i.e., $\hat{\theta}_i - \hat{\theta}_{i+1} \approx 2\pi$, all follow-up phases $\hat{\theta}_j, j > i$ plus 2π. This process repeats until the last two neighbors. After this period compensation, all curves in the previous phase profile connect together and form a super V-zone, denoted by $\{(\hat{\theta}'_1, t_1), ..., (\hat{\theta}'_n, t_n)\}$.

Take Fig. 5 for example. The upper half of this figure shows the raw phase profile of tag m_1 in Fig. 4(a). From the first curve to the second, the phase profile sees a phase jump from 0 to 2π. Hence, all curves (phase values residing these curves) minus 2π expect the first one. Similarly, the third curve and the raw V-zone (the fourth curve) drop by $2 \times 2\pi$ and $3 \times 2\pi$ as two and three 0-to-2π jumps happen, respectively. After that, the jump turns out to be 2π-to-0. Once a jump occurs, all following phases plus 2π. The final result is that we obtain a super V-zone as shown in the lower half of Fig. 5.

C. Localization via Curve-fitting of Hyperbola

In this subsection, we discuss how to locate the tag based on the super V-zone. According to the procedure of removing periodicity, the bottom of the super V-zone and the raw V-zone has the same X coordinate as we just move the curves along the dimension perpendicular to X-axis. In other words, the order of the super V-zone is consistent with that of the raw one; scanning the super V-zone and searching the minimum can directly infer the tag order. In practice, however, there is more to this. For one, instead of the continuous curve, the real samples are discrete, which makes it possible that the super V-zone does not cover the minimum as we expected. This probability will be much higher in the case of spare samples mentioned above. For another, the reported phase values by the reader contain some noise that generally follows Gaussian distribution with a standard deviation of 0.1 radians [12]; using only one sample of the super V-zone to locate the tag is crude.

Therefore, to take full use of all data, we first fit the discrete phase values with a like-V-zone-curve and then use the fitting curve to infer the tag's position. Let us take a closer look at the super V-zone. Removing the periodical pattern of the phase profile is equivalent to taking away the modulo operation of 2π from (1). Hence, the phase output θ can be re-written:

$$\begin{cases} \theta = 2\pi \times \frac{2d}{\lambda} + \mu = \frac{4\pi}{\lambda} d + \mu \\ \mu = \theta_{TX} + \theta_{RX} + \theta_{TAG}. \end{cases} \tag{2}$$

Now we consider how the distance d changes over the time t. As shown in Fig. 6, we assume the reader antenna initially stays at the origin and a tag (book) is located at the position (a, b), where a is the distance between the tag and the origin in X dimension and b is the distance of the tag to the X-axis. As the reader moves along the X-axis at a constant speed of v, it is located at (vt, 0) at the time t. Hence, we have the distance d at the time t.

$$d = \sqrt{(a - vt)^2 + b^2}. \tag{3}$$

Substituting (3) for the distance d in (2), we have the phase value with respect to t:

$$\theta = \frac{4\pi}{\lambda} \sqrt{(a - vt)^2 + b^2} + \mu. \tag{4}$$

In (4), we know the constants λ and v a priori but not the other three constants a, b, and μ. Amongst them, a and b are our concern. That is because, for one, the term a indicates the book order on the shelf. The smaller a is, the more left the tag is placed on the shelf. For another, the term b tells us whether or not the book is located at the current tier and the current shelf that the reader is scanning. If so, b is supposed to be small enough, e.g., less than 20 cm. Otherwise, b tends to be larger when it resides in other tiers or shelves. By a series of formula transforms from (4), we have

$$\frac{(\theta - \mu)^2}{(\frac{4\pi}{\lambda})^2 b^2} - \frac{(t - \frac{a}{v})^2}{\frac{b^2}{v^2}} = 1, \tag{5}$$

where θ and t are variables and others are constants. The equation indicates that the super V-zone is actually the above half of the north-south opening hyperbola. We can borrow

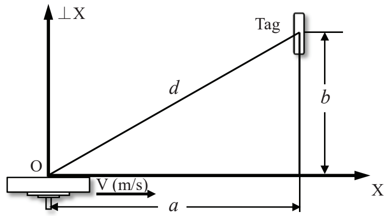


Fig. 6: The distance between the reader antenna and the tag with respect to the move of the antenna.

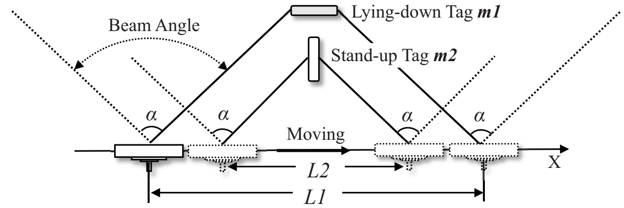


Fig. 7: The difference between the lying-down tag and the stand-up tag: the former has more chances to be read as the reader antenna moves along X-axis.

one of existing curve-fitting algorithms of hyperbola [15]–[18] to get the estimates of a, b, and μ, and then determine the tag's position based on a and b. Additionally, we can also perform the simple quadratic fitting as the alternative and approximate way on the super V-zone to locate the tags. Assume the quadratic function is $a'(t-b')^2+c'$. The value of b' determines the order of tags along the X-axis: the smaller b' is, the more left the tag is. The value of a' reflects the tier # and shelf #. If a tag is located at the tier and the shelf that the reader is currently scanning, the value of a' is supposed to be bigger than those in other tiers and shelves.

IV. Detection of Lying-down Books

In this section, we discuss the other problem of RF-Scanner: the detection of lying-down books, as shown in Fig. 1. One may concern why not use the video cameras to detect these abnormal book placement. There are two reasons for this. First, the drawback of using video involves lighting issues. As RF-Scanner works at night, the low light level adds much noise to the images, and even though the infrared cameras are used the images still suffer from non-uniformity and artifacts. Second, using video camera introduces extra hardware overhead, increasing the system complexity and the system cost. In light of this, we aim to achieve the detection goal with only RFIDs. The details are given below.

A. Lying-down Tag vs. Stand-up Tag

In order to pick out the lying-down tags from the stand-up ones, we need to figure out what the difference is between them. Below, we first observe the pose differences, in terms of the tag's location and the tag's orientation, and then discuss the beam angle of the directional antenna that has the potential impact on the lying-down book detection.

1) Pose Differences: Recall Fig. 1. The pose of lying-down tags (books) differs from that of the stand-up tags, including the tag's orientation and the location. For one, the lying-down tag is parallel to X-axis whereas the stand-up is perpendicular to. For the other, the distance from lying-down tags to X-axis is a little further than that of stand-up tags. These pose-related differences provide valuable clues for the lying-down-book detection. Fig. 7 illustrates the different poses of the lying-down tag m_1 and the stand-up tag m_2.

2) Beam Angle: Before introducing the beam angle of an antenna, let us take a look at the directional antenna first. There are several different types of antennas in two general categories: the omni-directional and the directional. An omni-directional antenna propagates in all directions; a directional antenna or beam antenna preferentially radiates greater power in specific directions for increased performance. In RF-Scanner, the directional antenna is adopted as more power can be allocated to the shelf side for book scanning. The coverage area or radiation pattern of the directional antenna is measured in degrees, which is known as *beam angle*[1] or *beamwidth*, as shown in Fig. 7. There is almost no power outside of the beam. Therefore, only when the tag is located within the beam, it has the chance to be read.

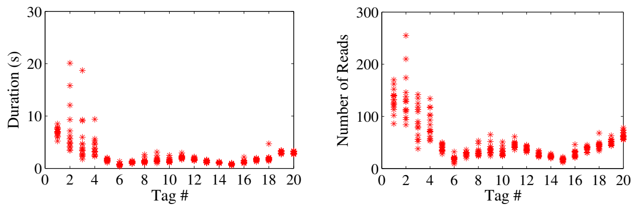
With above preliminaries of pose differences and beam angles, we find that, when the directional antenna moves along the X-axis, the lying-down tag m_1 in Fig. 7 not only reaches the antenna's beam zone earlier than the stand-up tag m_2, but also leaves the beam zone later than it. In other words, the lying-down tag m_1 has more chances (when the reader antenna is within the range of L_1) to be interrogated, compared with m_2 (when the antenna is within the range of L_2). With this observation, we get three useful metrics, i.e., reading period, number of reads, and curvature of RSSI $\wedge$-zone, to detect the abnormal lying-down placement.

B. Reading Period & Number of Reads

For each tag, the reading period P and the number N of reads respectively indicate the duration and the total number of the tag to be read when executing one-pass scanning over the X dimension. The former P is equal to the time of the last read minus the time of first read, and the latter N is initially set to 0 and increased by one once the tag is read. Since the reading range of the lying-down tag m_1 is larger than that of the stand-up tag m_2, both reading period P and the number N of reads of m_1 are supposed to be greater than those of m_2. Hence, by observing these two metrics after each shelf scanning, we can determine whether or not a book is correctly placed in theory.

To validate above inference, we perform a toy experiment with 20 tagged books which are labeled from #1 to #20. The first four books (#1 to #4) are lying-down books, and the left are correctly placed (stand-up books). In each scanning, the reader antenna moves along X-axis from one side (the most left) to the other side (the most right) at a constant speed of 0.2 m/s. After scanning, we record and plot the reading period and the number of reads for each tag. This process is repeated 20 times. Fig. 8(a) and Fig. 8(b) respectively show the reading period and number of reads for each tag during the 20 trials. As we can see, in most cases, the lying-down books (#1 to #4) have greater reading period and number of

[1]The beam angle of COTS RFID antenna is usually smaller than 90°.



(a) Reading period. (b) Number of reads.

Fig. 8: The reading period and the number of reads of lying-down books and stand-up books.

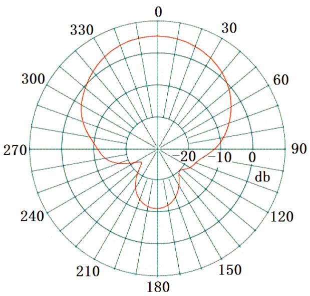


Fig. 9: Radiation pattern of ALR-8696-C antenna [20].

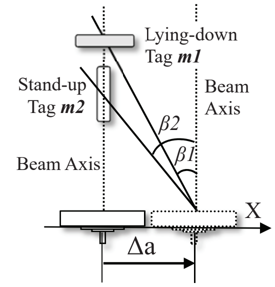


Fig. 10: Deviation angles from beam axis.

reads than stand-up books (#5 to #20). This is consistent with what we expected and basically validates the correctness of our previous inference.

However, there are some violations. For example, one sample of tag #18 is greater than some samples of tag #3, as shown in Fig. 8(a) and Fig. 8(b). There are two reasons for this. First, the effect of multipath. In wireless communications, multipath may cause signal interference including the constructive one and the destructive one. In other words, although $L_1 > L_2$ in Fig. 7 holds, the interval in L_1 but outside L_2 may have destructive interference, leading to the failure of reading m_1; the interval outside of L_2 may have constructive interference, resulting in more reads of m_2. Second, delay caused by identification protocol. As C1G2 standard [19] specifies, the frame-slotted ALOHA is the standard tag identification protocol, in which, each tag randomly selects a slot and only the slots chosen by exactly one tag can be used to collect tag ID and measure the physical-layer information (e.g., phase value). Since the identification may contain many frames, the lying-down tag is likely to reply in one of last few frames, leading to some delay from the time when the tag is the first time to get into the mobile reader's coverage. Hence, we say that the both metrics can basically reflect whether or not a book is lying-down, we however cannot purely rely on them for lying-down-book identification. This motivates us to explore the third metric: the curvature of RSSI $\wedge$-zone.

C. Curvature of RSSI $\wedge$-zone

Received Signal Strength Indication (RSSI) is a measurement of the power presented in a received radio signal, which is proportional to the quadratic gain G of the reader antenna and inverse fourth power of the distance d between the tag and the reader antenna, i.e.,

$$P_{RX} \propto \frac{G^2}{d^4}, \tag{6}$$

where P_{RX} is the power of received signal by the reader. According to (6), the power peaks at the maximum when the reader reaches the so-called *inflection point* that is closest to the tag. That is because, for one, d attains minimum at this moment. For the other, consider the radiation pattern of a directional antenna, such as Alien ALR-8696-C (RHCP) antenna [20] in Fig. 9. The gain along its preferred direction (0 degree) is larger than that of others. The further a point apart from preferred direction, the small the gain. We refer to this axis of maximum radiation as *beam axis*. At this moment when the antenna moves to the inflection point, the tag is just located at its beam axis. Hence, G attains maximum.

Now we observe the power change around the inflection point. Assume that the reader moves a distance of Δa along X-axis from the inflection point, as shown in Fig. 10. The lying-down tag deviates from the beam axis by β_1 and the stand-up tag deviates by β_2. Clearly, β_1 is smaller than β_2 due to the different poses of these two tags. That means the gain of m_1's position is larger than that of m_2's position, and thus the lying-down tag m_1 will get more power from the reader than m_2. From the long-run of Δa, we can infer that the power decline of m_1 is slower than that of m_2. This provides us with the key idea that uses the curvature of RSSIs (i.e., the rate of change of RSSI) to identify lying-down books.

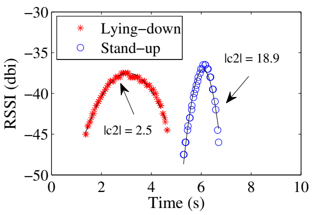
However, due to multi-path interference, the measured RSSIs usually contain noise and missing values, leading to some measure fluctuations and affecting the estimation accuracy of the curvature. Similar to phase profile, we refer to these RSSI mesurements together with the corresponding timestamps as *RSSI profile*, denoted by $\{(r_1, t_1), ..., (r_n, t_n)\}^2$. To alleviate the interference, for each tag, we first smooth its RSSI profile via moving average filter, and get the new RSSI profile $\{(r'_1, t_1), ..., (r'_n, t_n)\}$:

$$r'_k = \frac{\sum_{i=k-l}^{k+l} r_i}{2l+1}, \tag{7}$$

where l is the parameter that decides the extent to which the filter smoothes the raw curve. We repeat the experiment of 20 tagged books (#1 to #4 are lying-down and the left are stand-up) under the same experimental setting as in Section IV-B. Fig. 11 shows the smoothed RSSI profiles of two tags (#4 and # 16, for example) under the setting of $l = 4$. From this figure, we can see that the RSSI profile gives an appearance of "$\wedge$", which is called $\wedge$-zone. The curvature of the $\wedge$-zone is the key to determine the lying-down tags.

More specifically, we first use the least squares fit to get a quadratic fitting of the $\wedge$-zone, and then drive the curvature based on the fitting curve. In equation form, the quadratic function follows $y = \sum_{i=0}^{2} c_i x^i$, where c_i is the coefficient and x is the variable. The coefficient c_2 controls the degree of curvature of the quadratic function; a larger magnitude of $|c_2|$ gives the curve a more closed (sharply curved) appearance and thus a higher probability that the tag is stand-up (the curvature is bigger). Fig. 11 shows the quadratic fitting of the

[2] For each tag, the phase value, RSSI measurement, and the timestamp can be concurrently measured and reported by the reader when the tag is read; no more extra communication overhead is required here.



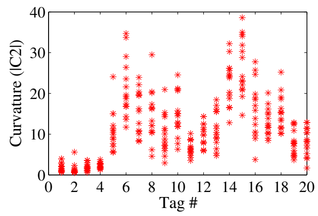


Fig. 11: Curvature of ∧-zone. Fig. 12: Curvatures of 20 tags.

∧-zone of tags #4 and #16. Clearly, the curvature ($|c_2| = 2.5$) of tag #4 is much smaller than that ($|c_2| = 18.9$) of #16, well distinguishing lying-down tag #4 and stand-up tag #16. Besides, we repeat the previous experiments 20 times and observe the curvatures ($|c_2|$) of 20 tags (#1 to #20). As shown in Fig. 12, the curvatures of lying-down books (#1 to #4) are smaller than others (#5 to #20) in most cases. This is consistent with our inference and indicates that the curvature of RSSI ∧-zone is a good vehicle to identify lying-down books. We can simply set a curvature threshold and the tag with smaller curvature is treated as the lying-down tag and the other is viewed as stand-up one. This works, however, similar to the reading period and the number of reads, there are a few of violations if we use only the single metric. For example, some curvatures of #9 are smaller than those of #1 to #4. Hence, we move one step further, combine the above three metrics together, and expect to obtain all benefits of them as well as improve the detection accuracy.

D. Putting Things Together

So far, we have discussed the individual impact of the reading period, the number of reads, and the curvature of RSSI ∧-zone, on the lying-down book detection. Instead of purely using one metric at a time, we now put all of them together and form a feature vector $< P, N, |c_2| >$ for each tag. The detection problem is reduced to a typical binary classification problem. For each tag, we compute the three metrics and obtain the feature vector, and take it as the input of a classification algorithm, such as SVM, to produce a classifier that is able to distinguish the lying-down books and the stand-up books. Since three metrics are taken into account, the detection accuracy is envisioned to be higher. In Section V-B2, we will detail the evaluation of lying-down book detection.

V. Implementation & Evaluation

In this section, we first present the implementation of RF-Scanner and then evaluate the system performance based on the real-world experiments in our school library.

A. Implementation

As aforementioned, RF-Scanner generally consists of two parts: robot and RFID.

Robot Component: The robot component of RF-Scanner is self-designed and implemented by using existing off-the-shelf robot-related technologies, which contains the navigation module and self-charging module. As shown in Fig. 13(a), Fig. 13(b) and Fig. 13(c), navigation module adopts the robust magnetic navigation system. By deploying a magnetic track along the bookshelves in advance, the robot vehicle can probe the magnetic signal and move along the track. The shelf-charging module helps the robot commute between the bookshelf and the home base in a automatic way, ensuring the reliable and continuous scanning.

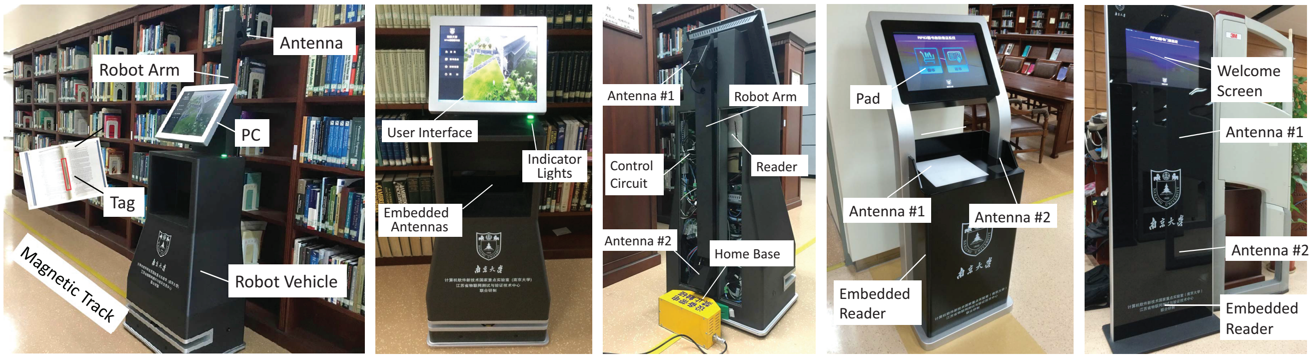
RFID Component: As shown in Fig. 13(c), the RFID component contains one RFID reader (Impinj R420 [14]) and two antennas. Each antenna is fixed on the robot arm that ensures the antenna moves to the correct height to scan each tier. Since a shelf has 6 tiers of books, three scans are needed for each side of a bookshelf. We label the 6 tiers from up to down as tier 1, tier 2, ..., and tier 6. The UHF tag embedded in the book is customized, with the same size of the existing EM security strip, as shown in Fig. 13(a).

Besides RF-Scanner, we also design and implement RFID-based self-checkout system and RFID-based electronic article surveillance (EAS), as shown in Fig. 13(d) and Fig. 13(e) respectively. These three subsystems constitute the entire library management system, which has been used to manage near 80,000 books in our school library.

B. Evaluation

In this subsection, we evaluate the performance of RF-Scanner based on above practical system deployment. In the experiment, we choose an arbitrary bookshelf with 500 tagged books in our library. The book on the shelf ranges in thickness from 1cm to 5cm. The performance is observed in six different cases, each corresponding to a different speed v of the robot vehicle, from 0.05 m/s to 0.30 m/s, at a step of 0.05. With these settings, we evaluate RF-Scanner from two aspects: the localization accuracy of miss-shelved books and the detection accuracy of lying-down books.

1) Localization Accuracy: As aforementioned, the localization of RF-Scanner returns a triple (shelf #, tier #, order) instead of the absolute 3D coordinate. Below, we first study the localization accuracy of (shelf #, tier #), as the both information are sufficient to help library users find miss-shelved books in a coarse-grained manner. For each localization of a book, if the predicted shelf # or tier # is not consistent with the ground truth, this localization is treated as a failure. The localization accuracy is the ratio of the number of successes to the total number of localizations. For ease of presentation, we compare the localization accuracy of books on tier 1, tier 2, tier 1 of backside shelf (B_1), and tier 2 of backside shelf (B_2), at the fixed speed of 0.1 m/s. As shown in Fig. 14, the confusion matrix implies the high localization accuracy of RF-Scanner: few tags are erroneously classified into the wrong shelf and only a few tier # of tags are mistaken. For example, the probability that a tag in the right side of shelf is mistakenly treated as the backside is about 2%; the probability that a tag in tier 1 is correctly classified into tier-1 reaches up to 91%. Although RF-Scanner cannot achieve a perfect classification, it still helps librarians or library users narrow down the large searching space to only the neighbor tiers or shelves of the real tag position. This great performance indicates that RF-Scanner is able to achieve an accurate book localization in terms of shelf # and tier #, which makes it possible for the users to find the miss-shelved books in tier-level.



(a) RF-Scanner (b) Font of RF-Scanner (c) Back of RF-Scanner (d) Self-checkout (e) RFID-based EAS

Fig. 13: RFID-enabled library management system, including RF-Scanner, self-checkout, and RFID-based EAS.

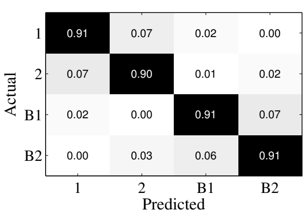


Fig. 14: Localization accuracy.

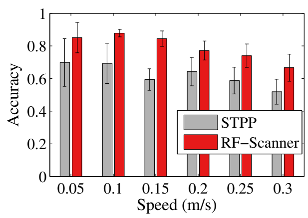


Fig. 15: Ordering accuracy.

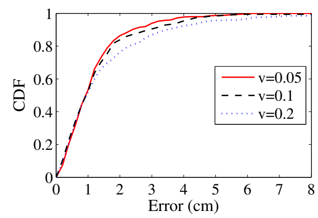


Fig. 16: CDF of Localization.

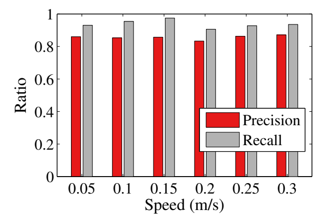


Fig. 17: Detection accuracy.

We now evaluate the ordering accuracy for more fine-grained localization. Consider n books on a tier of the shelf. We label these books in the correct order as 1 to n and this actual order is referred to as S. We run RF-Scanner and get an estimated order, denoted by $\hat{S}$. The ordering accuracy f is defined as the normalized Kendall tau distance [21], i.e., $f = \frac{K(S,\hat{S})}{\binom{n}{2}}$, where K is the Kendall tau function. Fig. 15 compares the ordering accuracy bewteen RF-Scanner and the state-of-the-art sorting algorithm STPP [13]. As we can see, the ordering accuracy of RF-Scanner is closed to 90% when the speed is slower than 0.1 m/s. With the increase of V, the accuracy sees a decline tread. This makes sense as the big V reduces the chance (duration) of the tags to be read, which in turn decreases the number of samples, thereby lowering the accuracy of curve-fitting. Besides, the figure shows that RF-Scanner is far superior to STPP in all cases. That is because, STPP uses only the V-zone of phase profile to locate tags, most useful information outside V-Zone (used in RF-Scanner) is abandoned by STPP.

In addition to the tag order, we also observe the absolute localization error along X-axis at the speed of 0.05 m/s, 0.1 m/s, and 0.2 m/s. As shown in Fig. 16, RF-Scanner is able to achieve cm-level localization along X dimension. For example, when the speed is fixed at 0.2 m/s, RF-Scanner achieves a mean error of 1.63 cm, with the standard variance 2.64 cm. With the decrease of the speed, the localization accuracy of RF-Scanner improves gradually. For example, when the robot vehicle speeds down to 0.1 m/s, the localization accuracy is further improved compared with 0.2 m/s. The mean error and the standard variance are 1.29 cm and 1.60 cm respectively, achieving the localization estimation in a high precision. This great performance improvement is essentially due to the full use of phase profile, the theoretical modeling of super V-zone, and the accurate curve-fitting of hyperbola in RF-Scanner.

2) Detection Accuracy of Lying-down books: Automatically detecting lying-down books is one of major concerns by the librarians. We now study the detection accuracy of lying-down books in RF-Scanner. In the experiments, we randomly lay down 100 books at different positions on different tiers of the shelf, and the left stand up by correct placement. The robot vehicle runs at different speeds, ranging from 0.05 m/s to 0.3 m/s. For a given speed, we repeat the experiments 20 times and 120 trials have been conducted in total. In each trial, we obtain all collections of a tag, compute its reading period, number of reads, and curvature of RSSI $\wedge$-zone, and use the standard SVM with the KBF kernel to train and classify the two types of books based on these three attributes. As shown in Fig. 17, we adopt the widely used *precision* and *recall* in a classification task to measure the detection accuracy of RF-Scanner. Precision is the number of true positives (correctly identified lying-down books) divided by the total number of elements labeled as lying-down books, and recall is defined as the number of true positives divided by the total number of elements that actually belong to the positive class (lying-down books). In other words, precision can be seen as a measure of exactness or quality, whereas recall is a measure of completeness or quantity. As we can see, the recall slightly fluctuates around about 94%, which indicates that RF-Scanner is able to achieve a complete (94%) identification of lying-down books. In contrast, the precision remains stable at 84% on average, which means that most lying-down books identified by RF-Scanner are consistent with the ground truth. Note that, unlike localization, the detection accuracy (including precision and recall) does not experience a sharp decline as the speed increases. This implies that the lying-down-book detection of RF-Scanner requires less samples for each tag, compared with the localization.

VI. Related Work

The use of RFID in library inventory has attracted increasingly attentions in recent years. The main purpose of using RFID technology is to change the library management from the manual mode to the fully-automated mode. Existing RFID-enabled solutions to shelf scanning of libraries generally fall into two categories: using portable handheld readers [2]–[5] and deploying smart bookshelves [6]–[9]. A hand-held inventory reader can be moved rapidly across a shelf of tagged books to read all of the unique identification information, which not only declines the cost of doing an inventory in the library, but also increases the odds of actually completing regular inventories. However, this is a semi-automated mode that still needs librarians to manually move the handheld reader tier by tier, which is time-consuming and labor-intensive. To address this problem, smart shelves appear. By deploying readers and antennas on the shelves, the smart shelves are able to interrogate the on-the-shelf books automatically and provide an accurate picture of the stock in real time. However, this design requires high infrastructure cost and complex deployment, which are a great barrier to commercial adoption.

The most related work on automated shelf scanning are LibBot [22] and AuRoSS [23]. LibBot is the first work that presents a mobile robot platform equipped with an RFID reader for the purpose of automating the manual shelf scanning and finding misplaced books autonomously. AuRoSS focuses on the key robotic enabling technology, i.e., surface tracking that allows RFID antennas to move parallel to the shelf with high accuracy. Although LibBot and AuRoSS achieve fully-automated scanning by combining RFID and robot, they choose the HF RFID systems as the vehicle, which have the well-known drawbacks of low data ratio and short communication range. These drawbacks not only lead to unreliable reading (e.g., missing-reading) when dealing with many tags simultaneously, but also make LibBot and AuRoSS fail to implement the RFID-based EAS. Unlike these work, RF-Scanner in this paper uses UHF RFID systems. We formulate the new problems under the new case and give the sophisticated solutions to them. The real-world experiments show high performance of our system.

VII. Conclusion

In this paper, we present RF-Scanner that automates shelf scanning in a library by combining the robot vehicle and RFID technology. We give an overview of the system architecture and formulate two important problems: localizing miss-shelved books and detecting lying-down books. For localization, we take full use of the phase profile and use the super V-zone to pinpoint the tag's position. For detection, we observe the pose differences of stand-up books and lying-down books, and put three metrics together to detect the abnormal placement. Based on the system design, we implement RF-Scanner and put it into practical use in our school library. Long-term experiments and studies show that RF-Scanner is able to achieve fine-grained localization of miss-shelved books as well as accurate detection of lying-down books.

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