Abstract—Nowadays, 3D reconstruction has been introduced in monitoring the package placement in logistic industry-related applications. Existing 3D reconstruction methods are mainly based on computer vision or sensor-based approaches, which are limited by the line-of-sight or battery life constraint. In this paper, we propose RF-3DScan to perform 3D reconstruction on tagged packages via passive RFID, by attaching multiple reference tags onto the surface of the packages. The basic idea is that by moving the antenna along straight lines within a constrained 2-dimensional space, the antenna obtains the RF-signals of the reference tags attached on the packages. By extracting the phase differences to build the angle profile for each tag, RF-3DScan can compare the angle profiles of the different reference tags and derive their relative positions, then further determine the package orientation and stacking for 3D reconstruction. We implement RF-3Dscan and evaluate its performance in real settings. The experiment results show that the average identification accuracy of the bottom face is about 92.5%, and the average estimation error of the rotation angle is about 4.08°.

I. INTRODUCTION

Nowadays, the traditional logistic industry-related applications, such as warehouse management and logistic transportation, are emerging with brand new requirements. For example, during the process of warehouse management or logistic transportation, the packages are usually required to be placed according to some specified regulations. In particular, in regard to a single package, if it contains orientation-sensitive goods, such as chemical reagents or precision instruments, then it is prohibited from being rollover or upside down; in regard to multiple packages, they are also required to be precisely arranged in some specified order, e.g., heavy objects are placed on the bottom, whereas light objects are placed on the top, to ensure safety in the transportation. To deal with the above requirements, the technology of 3-dimensional (3D) reconstruction has been introduced to tackle these issues in monitoring the package placement. 3D reconstruction is a process of capturing the shape and appearance of a single or multiple real objects. In principle, there are two key aspects to realize 3D reconstruction for packaged objects: 1) Package orientation for a single object, it refers to determining the relative orientation for each package, i.e., figuring out the bottom/top face, as well as the angles of the other vertical sides for the specified object in the specified coordinate system. 2) Package stacking for multiple objects, it refers to determining the relative stacking situation for multiple packages, i.e., performing the relative localization of multiple objects.
straight lines within a constrained 2-dimensional space. As the antenna is moving, by extracting the phase differences from the specified tags at different time points, we build the angle profiles to depict the geometry angles between the antenna-tag pairs. By comparing the angle profiles of different reference tags, we are able to derive the relative positions of these tags on the specified package, and further figure out the package orientation and package stacking for multiple packages.

There are three key challenges to realize 3D reconstruction via RFID systems. The first challenge is to determine the package orientation according to the RF-signals from the reference tags attached to a specified package. To tackle this challenge, we extract angle profiles from the phases of the RF-signals, then we build an angle-profile-based model to transform the RF-signals into the indicators for the relative localization among the reference tags. Thus, after performing 1-dimensional mobile scanning along a straight line, we can determine the relative positions of the reference tag pairs on the package, and use this information to further derive the package orientation. The second challenge is to determine the stacking situation among multiple packages, according to the RF-signals from the reference tags attached to multiple packages. To tackle this challenge, we further perform a 2-dimensional mobile scanning to scan the packages along the orthogonal direction of the previous scanning direction, such that the relative 3D positions of the reference tags from different packages can be determined. In this way, we can estimate the centers of packages according to the reference tags, and derive the relative locations of different packages in the 3D space. The third challenge is to select effective reference tag pairs for accurately deriving the package orientation and stacking situation. To tackle this challenge, we filter out those reference tags with unstable phases, which are located outside the field of major antenna beam during scanning, by referring to the received signal strength (RSS). Further, as our empirical study shows that the absolute phase of the RF-signal varies with different orientations of the reference tag, thus we measure the phase differences to extract the angle profiles from the reference tags during the mobile scanning.

To the best of our knowledge, this paper presents the first study of using RFID for 3D reconstruction on tagged packages. We make three contributions as follows. 1) For 3D first study of using RFID for 3D reconstruction on tagged packages. We make three contributions as follows. 1) For 3D reconstruction on the specified objects, usually multiple depth cameras are deployed at different positions to perform multi-view reconstruction for their 3D models [1], or a moving depth camera is used to build the 3D models in a mobile approach [2]. In a word, these approaches suffer from the line-of-sight (LOS) constraint in 3D perception, and they are vulnerable to the limitation of the light intensity. Sensor-based solutions [3, 4] mainly attach the battery-powered sensors (such as inertial sensors or GPS modules) to the surface of the objects, and continuously monitor the 3D placement of the specified objects, so as to track the orientation variation [3], or the stacking situation among multiple objects.

B. RFID-based Approach

Orientation tracking: By attaching multiple RFID tags onto the specified object, it is possible to track the orientation variation of the object according to the variation of the corresponding RF-signals [5, 6]. Tagball [5] is proposed as a 3D human-computer interaction system, where multiple passive tags are attached to a controlling ball, such that the motions of the ball rotation from users can be detected from the phase changes of multiple tags. Tagyro [6] attaches an array of passive RFID tags as orientation sensors on the objects, by transforming the runtime phase offsets between tags into the orientation angle. Compared with our RF-3DScan system, these approaches track the orientation variation of the dynamically moving objects, whereas our approach aims to determine the orientation of statically placed packages.

Localization: RFID localization generally falls into two categories: absolute localization [7–10] and relative localization [11–15]. By attaching multiple tags and pinpointing each tag’s 3D coordinates, the absolute localization can be tailored to our problem for 3D reconstruction. However, this approach suffers from complicated system deployment and collaboration. For example, the state-of-the-art absolute localization schemes PinIt [7] and Tagoram [10] are able to achieve cm-level localization accuracy, however, they either need to deploy many reference tags or require sophisticated calibration of multiple readers. Rather than absolute localization, recent RFID researches start to focus on the relative localization of multiple objects without any pre-deployment of reference nodes. Relative localization investigates the relative locations of a set of objects as oppose to their absolute coordinates. STPP [13] is the first work to tackle 2D relative localization. It investigates the spatial-temporal dynamics in the phase profiles. However, this approach leverages large-range scanning to detect the V-zone from the phase sequences, as it requires the antenna to cross the perpendicular point during the scanning to collect enough phases. Compared with STPP, our approach performs 3D relative localization by leveraging the angle profiles from rather small-range scanning.
III. ANGLE-PROFILE-BASED MODELING

A. Limitations of Phase-based Measurement

The RF phase is a widely used attribute of the wireless signal, ranging from 0 to $2\pi$. Due to the ultra-high working frequency (indicating short wave-length) in RFIDs and fine-grained measure resolution of phase value by COTS readers, the phase is very sensitive to the tag-antenna distance, which gives us the potential chance to achieve accurate 3D reconstruction. Suppose $dis$ is the distance between the antenna and the tag. Since the backscatter communication of RFID is round-trip, the signal totally traverses a distance of $2dis$ in each communication. Besides the distance, some hardware characteristics will also distort the phase value. Hence, the phase $\theta$ reported by the reader can be expressed as:

$$\theta = \left(\frac{2\pi}{\lambda} \times 2\text{dis} + \eta\right) \mod 2\pi$$

where $\lambda$ is the wavelength, $\eta$ represents the phase offset caused by the hardware characteristics. Although the phase accurately reflects the distance, we face three challenges before putting into use: 1) The distort factor $\eta$ is unknown; 2) The phase value repeats periodically, it is not feasible to use it directly; 3) In addition to $dis$ and $\eta$, our extensive experiments show that the tag orientation influences the phase value $\theta$. Fig. 2 plots the phase change as a tag rotates along the $Z$ axis, as the phase varies continuously over the rotation. Next, we discuss how to use the angle-of-arrival approach to overcome above three challenges, and benefit our system design in the sequel.

B. Angle Profile

Angle-of-Arrival (AoA) is one of the most popular RF-based localization measurements using phase difference. The basic idea of our approach is that by moving the antenna to scan the tags, we extract the phase differences from the specified tags at different time points, then we derive the geometry angles between the tag-antenna pairs at different positions, which is called angle profile.

1) Angle in Static Scanning: As shown in Fig. 3, a tag is set at $T$, $A_1$ and $A_2$ are two antennas separated by $d$, $M$ is the middle point of $A_1A_2$, $V$ is the projected point of $T$ on the tag pair line $A_1A_2$, the perpendicular distance is $h$. The included angle between line $TM$ and line $MV$ is the AoA for tag $T$, denoted as $\alpha$. Let $d_{T,A_1}$ and $d_{T,A_2}$ represent the distances between $T$ and the antennas, the antennas collect the phases as $\theta_{A_1}$ and $\theta_{A_2}$ respectively. $\theta_{A_1}, \theta_{A_2} \in [0, 2\pi)$.

2) Angle in Mobile Scanning: With respect to multiple antennas, the phase offsets related to their own hardware characteristics are different, so it is hard to determine $\theta_\eta$. Hence, we prefer a mobile antenna to multiple static antennas, in which case the $\theta_\eta$ can be canceled.

For a mobile antenna, the angle-of-arrival is a little different. Without the loss of generality, we redefine the AoA in a mobile case, as shown in Fig. 4. Similarly, $T$ is the tag position and $V$ is its projected point on the antenna moving line, its perpendicular distance is $h$. Let the mobile antenna be at position $A$, then the included angle of line $TA$ and the antenna moving direction is just the angle-of-arrival ($\alpha$) for the tag when the antenna is at position $A$.

To estimate the angle at position $A$, we only need the phases collected at the two nearby positions ($P_1$ and $P_2$), centered on the antenna ($P_1A = AP_2$). Thus, the phase difference at position $P_1$ and $P_2$ can be used to estimate $\alpha$ with Eq. 2. By combining the angles at different antenna positions, we can derive an angle profile for a specified tag.

C. Metrics of Angle Profile

Suppose there are two tags and one antenna in the same plane (Fig. 5). The antenna moves linearly from $O$ to $A$, so it passes through $T_1$ first, followed by $T_2$. When the antenna passes through the tag (corresponding to point $V$ in Fig. 4), the angle-of-arrival ($\alpha$) of that tag reaches $\pi/2$, naming this point as the perpendicular point. Similarly, we call the distance from the tag to the perpendicular point perpendicular distance, the direction perpendicular to the antenna moving direction as perpendicular direction. As $T_1$ is on the left along the antenna moving direction, its perpendicular point shows earlier than $T_2$. Hence, the perpendicular point is the key metric for the tags’ relative positions along the moving direction.

Besides the perpendicular point, there is the other special point: equal angle point. The equal angle point is where the
antenna and the two tags are in the same line, so \(T_1\) and \(T_2\) share the same angle. Before equal point, the angle of \(T_1\) is smaller than the angle of \(T_2\). On the contrary, the angle of \(T_1\) changes to be bigger than that of \(T_2\) after the equal angle point. No matter for \(T_1\) or \(T_2\), its angle increases continuously during the antenna moving process, so it is obvious that the angle of \(T_1\) changes faster than that of \(T_2\). Such phenomenon is due to the smaller perpendicular distance of \(T_1\). Thus, according to the angle change rate, we can determine the tags’ relative positions along the perpendicular direction.

**D. Model of Angle Profile**

To depict the angle-profile-based measurement metrics in mathematics, we build a linear model to derive the metrics from the angle profile automatically. Considering Fig. 4, the angle-of-arrival can be expressed as:

\[
cot \alpha = \frac{y_V - y_A}{h}
\]

where \(\cot\) means the cotangent function, \(h\) is the perpendicular distance between the tag and the antenna moving trace. \(y_A\) and \(y_V\) represent the coordinates of point \(A\) and \(V\) along the antenna moving direction. Assume there is an antenna start point \(S\), the distance from \(S\) to \(V\) is \(l_0\), the antenna moved distance be \(l\). Thus, \((l_0 - l)\) represents the distance from the antenna to the perpendicular point (same as \((y_V - y_A)\)), the angle can be rewritten as:

\[
cot \alpha = kl + b, \quad k = -\frac{1}{h}, \quad b = \frac{l_0}{h}
\]

where the scope \(k\) is related to the minus reciprocal of \(h\), the intercept \(b\) depends on the ratio of \(l_0\) and \(h\).

Taking the tags in Fig. 5, the transformed angle expression using Eq. 4 should look like the lines shown in Fig. 6. As \(l\) increases continuously during the moving process, \(\alpha\) increases as well. When the antenna reaches the perpendicular point, \(\alpha\) is equal to \(\pi/2\), so \(\cot \alpha = 0\). The line of \(T_1\) reaches 0 earlier than \(T_2\). Thus, the order of such zero points are corresponding to the tags perpendicular points, and the spacing between two zero points just reflects the tags’ perpendicular points separation. In addition, the intersection of the two lines represents the position where the tags are projected on the same line with the antenna, corresponding to the equal angle point. Specially, the smaller \(h\) is, the larger \(\|k\|\) is, and the sharper the line is. As the \(h\) of \(T_1\) is smaller than \(T_2\), the \(\|k\|\) of \(T_1\) is larger, so the line of \(T_1\) decreases faster than \(T_2\).

For a certain tag, its angle profile records its angles at different positions. Note that, for analyzing the change of the angles, it is the separation between the positions and the corresponding change of \(\cot \alpha\) that matter, so the moved distance \(l\) does not necessarily the actual moved distance of the antenna. That is, we have no constrict to the coordinates of the positions, as long as they refer to the same basis. For example, let the antenna moves at a constant speed, and set a random time as the starting moving time. When the antenna collects phase during the moving process, it records the corresponding time as well, then that position can be estimated with the time interval and the constant moving speed. So, in Eq. 4, the angle \(\alpha\) and the moved distance \(l\) are known parameters, there’re two remaining unknown parameters: \(h\) and \(l_0\), which can be estimated by linear fitting with multiple angles during the moving process in the angle profile. Meanwhile, \(l_0\) depends on when the antenna passes through the tag. For different tags, the antenna start point should be the same one (as they share the same starting time), so the larger \(l_0\) is, the later that line reaches 0, and the tag is more ahead along the antenna moving direction. Thus, by leveraging these properties, we can determine the tags’ relative positions, as:

1) The value of \(\|k\|\) reflects the perpendicular distance from the tag to the antenna moving trace: the larger \(\|k\|\) is, the smaller the perpendicular distance is.

2) The value of \(l_0\) determines the projected position of the corresponding tag along the antenna moving direction. The difference of \(l_0\) between two tags indicates their interval in the antenna moving direction.

**IV. System Overview**

RF-3DScan is a 3D reconstruction system for tagged packages via RFID technology. For RF-3DScan, the geometry relationships of the tags attached on a single package is known as priori and the tag deployment obeys two important rules. Also, we make the following assumptions: 1) The antenna moves at a constant speed; 2) Each package is a standard cube, and they are fully on the ground or parallel to the ground (on the ground is the special case of parallel to the ground).

Fig. 7 illustrates the architecture of RF-3DScan. RF-3DScan takes the RF-signals from the tags as input, then outputs 3D profiles for multiple packages. The whole system consists...
of three components: 1) Preprocess: with the RF-signals of the tags, RF-3DScan builds the angle profiles by using the phase differences at different time points for each tag, and extracts the indicators in the angle profiles for the relative localization among the tags by linear fitting. 2) Determine package orientation for a single package: by comparing the relative positions of the tags on a specified package, RF-3DScan can determine which side of the package is on the ground, and then evaluates the angle of the vertical sides in a specified coordinate system. 3) Determine package stacking for multiple packages: after deriving the orientation of a single package, the centers of the packages are also determined along the scanning direction. By performing a 2-dimensional mobile scanning, RF-3DScan combines the results from the two orthogonal scanning, so the relative positions of these packages in the 3D space can be determined.

V. DATA PREPROCESS

With the raw RF-signals, we need to build angle profiles of different tags first. The preprocessing can be divided into three steps: angle computation, angle smoothing and linear fitting.

A. Angle Computation

As the antenna collects phases at different time points during its mobile scanning, we can extract the phase differences for a tag at different positions. Using these phase differences, we compute the angle-of-arrivals with Eq. 2. To get a deterministic angle, as mentioned above, the separation of the positions among two phases should be within \( \lambda/4 \).

B. Angle Smoothing

Although using the phase difference from the two positions with the small separation can get a unique angle, the noise like multi-path effect would influence the measured phases, there would exist large fluctuation in angles, so angle smoothing is required. Usually, the phases collected by the antenna is not uniform, so is the angle distribution, thus it is not suitable to use the common smooth algorithms, e.g., low-pass filter. Taking the noise \( \mu \) into consideration: \( \cos \alpha = \frac{\lambda}{d} \Delta \phi + \mu \frac{\lambda}{d} + \frac{n_4}{d} \), when \( d \) is very small, \( \mu \) has much influence on \( \cos \alpha \).

While when \( d \) increases, such distortion effect decreases, but there exist redundant angles in the results, only one of them is the true value. Hence, we can derive two sets of angles from two phase separations: a small one and a large one, then use the unique angles from the small separation to filter the several angle candidates from the large separation, thus, we get a relative accurate angle profile with less fluctuation [12]. Note that, too large separation will bring too much environmental change and break the restraint of the angle estimation method. Thus, we set the small separation around 5-8cm and the large separation within 15cm empirically when the antenna is in front of the packages about 1m.

C. Linear Fitting

With the smoothed angles at different positions from an angle profile for a certain tag, we can use the linear model as Eq. 4 to fit them, then derive the two important indicators (\( h \) and \( \ell_0 \)) of that tag for the later relative localization comparison.

VI. DETERMINE PACKAGE ORIENTATION FOR EACH SINGLE PACKAGE

To reconstruct a single package, it makes the same sense to determine the package orientation, so we just need to identify the bottom face of this package, and estimate the relative rotation angle of the vertical sides against the antenna plane in a specified coordinate system. The basic idea of our approach is that we attach a set of passive RFID tags on the package under special rules, then employ one antenna to do 1-dimensional mobile scanning to build the angle profiles for each tag. Next, we compare them to determine the relative positions of the tags, thus we can further realize the 3D reconstruction for a single package.

A. Deploy Reference Tags

In order to determine the package orientation only by 1-dimensional mobile scanning, we need to deploy the tags in an efficient way. The design principle of the tag deployment is to use as fewer as tags to depict the package uniquely, accurately and conveniently. So, we make two rules as follows:

Rule 1: The orientations of the tags should be along different orthogonal axes. As the package can be with any orientation in the 3D space, we should pay attention to ensuring there are always enough effective tags reflecting the signals to the antenna. As the 3D space can be defined with three orthogonal axes, we can just let the tags deployed along these axes alone, as shown in Fig. 8(a). With this rule, tags along one direction at most are in the blind direction, so other tags can get enough power to reflect their signals to the antenna effectively.

Rule 2: The tags should be deployed along different orthogonal axes. As for identifying the bottom face of the package, it is the same to find which tags are along the vertical axis and what order these tags are. So, there should be at least three tag pairs (four tags) along three orthogonal axes separately, as shown in Fig. 8(b). Under this rule, whatever the orientation of the package is, there is always one tag pair along the vertical axis, so we can transform the identification of the bottom face of the package into finding the vertical tag pair and determining their orders along the vertical axis.

Combining the above two rules, Fig. 8(c) illustrates a possible tag deployment satisfying these two rules. No matter what orientation the package is, there are four tags at least to avoid the signal blind direction. Also, there is always one tag pair along the Z axis. By determining the tags’ order of this tag pair, we can derive which side of the package is on the ground then.

B. Determine Package Orientation

To determine the package orientation, it demands to identify the bottom face of the package and the relative angle of the vertical sides in a specified coordinate system. Considering our assumption that one side of the cube package must be parallel to the ground, when we deploy the tags of a package like the solution described in Fig. 8(c), we can identify which tag pair is along the Z axis and what order the tag pair is instead. In this case, let the antenna do mobile scanning along the X or Y axis only once, we can determine the orientation
where \( \phi \) represents the spacing at relative angle \( \phi \). Hence, if the spacing of the perpendicular points for a tag pair along a certain axis is 0, it is probable that the tag pair is along the \( Z \) axis, except for some special cases where there is a tag pair along the \( X \) axis, then there are two tag pairs that their perpendicular points spacings are equal to 0, we will discuss it later. After identifying which tag pair is along the \( Z \) axis, we can determine the tags’ order by comparing their perpendicular distances extracted from their angle profiles. As the antenna is above all the tags, the tag with the smaller perpendicular distance of the vertical tag pair should be above the other along the \( Z \) axis. However, such comparison ignores the relationships of the perpendicular distances for other tags, it is easy to make a wrong decision with only one comparison results. Note that, the spacings of the perpendicular points of the tags should stay the same when the package is upside down, as the package rotates around the \( Y \) axis by 180°. So we can estimate the relative angle of the package first, then use the relationships of the perpendicular distances among different tag pairs to vote for the tags’ order of the vertical tag pair, then determine the bottom face of the package. When selecting the tag pairs among all the tags on the package, it is significant to avoid the tags in the blind direction by filtering the tags with relative weak RSS compared with other tags on the package. The angle estimation is based on the spacings of the perpendicular points for different tag pairs, as:

\[
\arg\min_{\phi} \sum_{i=1}^{N} ||\delta_i' - \delta_i(\phi)||
\]

where \( N \) is the number of tag pairs, \( \delta_i' \) is the spacing between the perpendicular points of a tag pair by measurement, \( \delta_i(\phi) \) represents the spacing at relative angle \( \phi \) theoretically.

Now, considering the case shown in Fig. 8(c) for example, we illustrate how to deal with the special cases where there are two tag pairs whose perpendicular point spacings are both equal to 0. As the antenna moves along the \( Y \) axis, the perpendicular points of the tag pair on the same surface \( \{T_3, T_1\} \) or \( \{T_5, T_h\} \) are at the same point. With the relative order of the tag pair \( \{T_1, T_2\} \), as the tag \( T_1 \) is on the left of \( T_2 \) along the antenna moving direction, there are four possible cases of the package orientation, as shown in Fig. 8(c) and Fig. 9. Any of these possible cases can transform into another case by rotating along the \( Y \) axis, but the relationships of their perpendicular distances differ, so we can use these relationships to vote for which case is the most possible case. As we assume that the antenna is above all the tags and ahead of all the tags along the \( X \) axis positive direction, let the perpendicular distances for \( T_1, T_3, T_5 \) be \( h_1, h_3, h_5 \), then for the case as Fig. 8(c): \( h_1 < h_3, h_3 < h_5 \), for the possible case1 (Fig. 9(a)): \( h_1 < h_3, h_3 < h_5 \), for the possible case2 (Fig. 9(b)): \( h_1 > h_3, h_3 < h_5 \) and for the possible case3 (Fig. 9(c)): \( h_1 > h_3, h_3 > h_5 \). There are multiple tag pairs for the comparison, here we list part of them for explanation. Then, by comparing the relationships of different tag pairs, we vote for the possible cases, and select the case with the highest score as our estimation result.

C. Discussion

There must be a side of the package parallel to the ground: As we assume that there must be a side of the packages parallel to the ground (which means the package is on the ground or on other packages, not leans), thus the state of the package is limited, the angle estimation is restricted to along the \( Z \) axis. If not, the searching space of finding the optimal angle expands, the simple solution is to add one more mobile scanning along the direction different from the previous one, the 3D reconstruction can be realized as well.

There may exist serious tag missing when many packages are stacked closely: As packages are stacked in storage, the large amounts of tags and small separations between the tags from different packages may cause the coupling effect or the interrogation failure [16–20]. But it exceeds the research fields of this paper, so we ignore it now.

The difference of the perpendicular distances for the tag pair parallel to the antenna plane may be much smaller than that for the tag pair perpendicular to the antenna plane with the same tag spacing: As shown in Fig. 10, the tag pair \( \{T_1, T_2\} \) is perpendicular to the antenna plane, while the tag pair \( \{T_2, T_3\} \) is parallel to the antenna plane. Their tag spacings are the same, as \( \Delta d_h = \Delta d_v \), but their perpendicular distance differences are not similar. Suppose the distance from \( T_1 \) to the antenna is 1m, the tag spacing is 0.2m, so the perpendicular distance difference between \( T_2 \) and \( T_3 \) is only 1.65cm, which is much smaller than that between \( T_1 \) and \( T_2 \) (20cm). Since the distance difference is so small, the relationship of such tag pair is probably to be wrong. So, it is better to set weights for the tag pairs based on their perpendicular distance differences when voting for multiple possible package orientations.
VI. DETERMINE PACKAGE STACKING FOR MULTIPLE PACKAGES

A. Limitations of the 1-dimensional Mobile Scanning for Determining Package Stacking

When we determine the package orientation, we derive the indicators for the relative positions among the tags on a single package. As the geometry relationships of these tags are known, we can combine these indicators (perpendicular distance and perpendicular point) from different tags to estimate the indicators of the package’s center point. Then, similarly, we compare the indicators of the center points of different packages to determine their stacking situation. Note that, when we determine the package orientation, we only need to perform 1-dimensional scanning, but it may not support the package stacking determination due to the 3-DoF in the 3D space. As shown in Fig. 11, suppose the antenna is above all the packages and is in front of the packages along the X axis, it moves along the Y axis. It is easy to determine the packages’ orders along the Y axis by referring to their perpendicular points, but it may be a problem to determine their orders in the XZ plane. If the packages line up, that is, the packages are along the X axis or along the Z axis, as the left two cases shown in Fig. 11, we can determine their orders along their lining up direction by comparing their perpendicular distances of their centers. For instance, the perpendicular distance of package A should be smaller than others, so package A is ahead of other packages along the X/Z axis. If not, however, as the 2 × 2 package stacking in Fig. 11, we cannot identify the orders of the packages exactly along the X and Z axes at the same time only through the 1-dimensional mobile scanning. To solve this problem, our solution is to perform one more mobile scanning along the orthogonal direction of the previous scanning direction, so as to limit the number of the free dimensions in the 3D space. Note that, the more times of the mobile scanning is, the much more the cost will be, thus we adopt the mobile scanning twice as the least needed times.

B. Determine Package Stacking with a 2-dimensional Mobile Scanning

Through once mobile scanning, after determining the package orientation for each single package, we derive the indicators of the packages’ centers for the relative positions along the scanning direction, so we know their relative orders along that direction. Similarly, by performing the other scanning along the orthogonal direction of the previous one, we can get the packages’ relative positions along the new direction. Combining their relative positions along the two directions, the 3D space is divided into many pieces. For each piece, two dimensions are fixed, the packages in it are lining up, so we can use the perpendicular distances of the packages’ centers to determine their orders in the piece. Thus, all the packages’ relative positions in the 3D space are determined.

Taking the scene in Fig. 12 for example, there are eight packages in total (we use the packages’ centers to represent the corresponding packages). The dash lines are parallel to the different axes respectively. The antenna is above all tags. It performs a 2-dimensional mobile scanning along the X and Y axes. All of the tags are always at the same side against the antenna plane. For the scanning along the X axis, based on the perpendicular points of the packages’ centers, the packages can be split into two sets: \{P_2, P_3, P_6, P_7\} and \{P_1, P_4, P_5, P_8\}. In each set, the X coordinates of the packages are the same, as they share the same perpendicular points projected to the X axis. Similarly, based on the mobile scanning along the Y axis, the packages can also be split into two sets: \{P_3, P_6, P_7, P_8\} and \{P_1, P_2, P_3, P_4\}. Combining these two split results, we have four sets then: \{P_1, P_4\}, \{P_2, P_3\}, \{P_5, P_8\} and \{P_6, P_7\} (in Fig. 13). In each set, the packages share the same coordinates along the X and Y axes. Then, we just need to determine the packages’ orders along the Z axis. By referring to the perpendicular distances of the packages’ centers, we can identify the packages’ orders in each piece. As we determine the relative positions of each piece, and the packages’ relative positions in each piece, the stacking situation of these packages are determined, the 3D reconstruction for multiple packages is done.
A. Experiment Settings

We build a prototype of RF-3DScan, as shown in Fig.14. Hardware: Our system consists of one ImpinJ Speedway R420 reader, one Laird S9028 RFID antenna and multiple ImpinJ E41-B tags. The antenna is fixed on a moving car. Software: We adopt LLRP protocol to communicate with the reader, and use a special module to control the moving of the car. Our algorithms are implemented in MATLAB and the language Java. Deployment: We let the antenna be above the boxes and move at a constant speed of 0.12m/s. For diversity, we use three different sizes of boxes. For each box, there are six tags on it as shown in Fig. 8(c), the tag spacing of the two tags on the same surface is the same. The tag spacings of box1, box2 and box3 are 23cm, 17cm and 20cm.

B. Micro-Benchmarks

Metrics: To evaluate the package orientation accuracy, we have two main metrics: bottom face accuracy, and angle error. The bottom face accuracy is defined as the number of the packages whose bottom faces are identified correctly out of the total package number. The angle error is the error between the estimated angle of the vertical faces against the antenna plane and the actual angle. For the package stacking, we use the metric ordering accuracy. The box is ordered correctly only when its detected order is the same with the actual order.

Orientation accuracy comparison with different scanning ranges: The most advantage of our approach compared to STPP is that we do not require large range scanning, we adjust the scanning ranges from 0.3m to 0.9m on a single side or both sides. Taking the scanning range of 0.3m for example, in terms of a single side, it means the antenna starts scanning from the box and moves 0.3m. While for both sides, the scanning range is 0.6m, centered on the box. The results are shown in Fig.15-16. From the results, we find RF-3DScan performs well as it achieves the average bottom face accuracies about 95% for both sides scanning, and about 70% for one side scanning range of 0.7m. While the accuracy of the one side scanning is not that good, STPP cannot deal with such limited scanning ranges.

Orientation accuracy comparison with different boxes: We put the box in front of the antenna plane about 1m, let the antenna perform both sides scanning of 0.5m 40 times for each box. As shown in Fig.17-18, the bottom face accuracy is above 87%, and the average angle error is below 4.4°. Compared with box1 and box3, box2 has less accuracy due to its smallest tag spacing.

C. Marco-Benchmarks

As STPP cannot handle the cases of limited scanning range, we compare RF-3DScan with STPP in the orientation accuracies of different boxes and different box-antenna distances.

Different boxes: We randomly choose box1, box2 or box3, and let the antenna be in front of the box about 1m, perform both sides scanning of 0.5m 120 times. As shown in Fig.22, the bottom face accuracy of STPP is about 81.7%, and RF-3DScan achieves the accuracy about 92.5%, slightly outperforming STPP by ×1.13. According to the CDF of the angle error as shown in Fig. 23, RF-3DScan performs better than STPP, as the median angle error of RF-3DScan is about 3.58° and that of RF-3DScan is 2.52°.

Different distances: We choose box1 and let the antenna perform both sides scanning of 0.5m 120 times. The distances are selected within [0.8m, 1.2m] randomly. As shown in Fig. 22, the bottom face accuracy of STPP is about 82.5%, while RF-3DScan achieves the accuracy about 93.3%, outperforming STPP by ×1.13. Fig. 24 shows the CDF of the angle error, from the figure, RF-3DScan still performs better than STPP, as its median error is about 2.13° and STPP’s is 3.62°.

Overall, our experimental results show that RF-3DScan scales better than STPP for different boxes and box-antenna distances, as the average bottom face accuracies of RF-3DScan and STPP are about 92.5% and 82.5%, while the average angle errors of them are about 4.08° and 5.05° separately.
IX. CONCLUSION

In this paper, we present RF-3DScan, an RFID-based system to perform 3D reconstruction on tagged packages. RF-3DScan can determine the package orientation for a single package with the 1-dimensional mobile scanning, and determine the package stacking for multiple packages with the 2-dimensional mobile scanning. The key innovation of this work is that we propose an angle-profile-based measurement for the relative localization, and we show the solution to use the relative positions of the tags on the packages to reconstruct the packages in the 3D space. In the future, we will further improve our approach, and we wish our work can benefit the logistic-related applications.

ACKNOWLEDGMENT

This work is supported in part by National Natural Science Foundation of China under Grant Nos. 61472185, 61373129, 61321491, 61502224; JiangSu Natural Science Foundation under Grant No. BK20151390. This work is partially supported by Collaborative Innovation Center of Novel Software Technology and Industrialization. Lei Xie is the corresponding author.

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