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Tracking of RFID Tags Moving on a Conveyor Belt Using Inverse SAR Approach

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***Abstract*—This paper proposes a novel method for tracking the moving items attached with ultrahigh frequency(UHF) radio frequency identification tags (RFID) on a conveyor belt. The localization method is based on phase measurements which is sampled from the radio signal backscattered from the tag antenna to reader antenna. The basic idea behind our method is that a virtual antenna array can be built by exploiting the priori knowledge that the speed and trajectory of the conveyor is known in advance. Thus an inverse synthetic aperture (SAR) can be formed. In order to alleviate the device heterogeneity, phase difference is leveraged to calculate the holographic image, which can be used to reconstruct the tag's absolute trajectory moving on a conveyor belt. Our approach is illustrated in numerical simulations. Finally the performance of our method is also investigated in a real conveyor belt scenario. The experimental results demonstrate that our design is robust to device heterogeneity and is able to achieve fine-grained localization.**

Keywords—RFID; synthetic aperture; tracking; phase measurement

I. INTRODUCTION

Wireless positioning technologies have gained increasing attention in the academic and industrial areas. Ultrasonic, infrared, geomagnetic and computer vision have all been utilized in location sensing[1]. Compared with other techniques, RFID is being rapidly deployed in indoor localization because of its low cost and high positioning accuracy. A butterfly tracking system is presented in[2]. The UHF RFID tag is attached to the butterfly to follow the activity and movements in an indoor room. Hainan Airline leverages RFID for baggage sortation. The accurate tracking enables the sorters quickly and correctly find out the target baggage[3]. Another application of RFID is robot navigation and object manipulation, which is presented in [4]. The RFID based system proposed in can locate object to a median of 1.28 cm and identify the orientation to a median of 3.3 degrees.

Early RFID localization work focused on received signal strength (RSSI). The classic RSSI based method is LANDMARC, which deploys reference tags at known positons and then estimate the target's position based on the k-nearest neighbor algorithm[5]. One assumption for this kind of methods is that the signal is propagating in a free space. However, RSSI is not a reliable indicator for position in a multipath environment especially when the tag is moving. Tag's orientation and antenna gain all will affect the RSSI measurements.

There is growing interest in using phase information for indoor localization. Phase based methods can be classified into two categories, i.e. angle of arrival (AOA) and synthetic aperture(SAR). AOA pinpoints RFID tags by leveraging the phase difference between the received signals at different antennas[6]. One major limitation for AOA is the restriction of antennas spacing which is less than half a wavelength. Different from AOA methods, SAR method propsed in[7] measure phase values by employing a moving antenna to emulate the antenna array. However, device heterogeneity is not considered in the paper.

Two main challenges facing accurate tracking of mobile RFID tags. First, the fast changing environment with multipath reflections of RF signals and varied tag's orientation[8], which make most localization methods fail to achieve high precision. Second, device heterogeneity will cause different measurements of both RSSI and Phase values at the same position[3]. Therefore, the fine-grained localization will not be achieved without considering these two challenges.

This paper proposes a novel location methods for tracking moving RFID tags on a conveyor belt. Phase measurement is exploited in our method because commercial off the shelf(COTS) RFID reader supports high resolution of phase report with accuracy about 0.0015 radians. The inverse synthetic aperture can be formed by utilizing the priori information of the conveyor. Device heterogeneity is alleviated by subtracting the phase measurements sampled from two successive virtual antenna elements.

The rest of the paper is organized as follows. The background of phase measurements is introduced in section II. We present the proposed approach in section III. Section IV gives the simulation results of our method. The performance of our method is tested in a real conveyor scenario in section V. Finally, section VI concludes our work.

II. BACKGROUND

Ultra-high frequency (UHF) RFID system communicates through backscatter radio link. Fig. 3 displays the backscatter communication between a reader and a tag. Passive RFID tag has no battery. Instead, they draw power from the reader, which transmits electromagnetic waves that induce a current in the tag's antenna. The RF signal transmitted by the reader is reflected off the tag, received back at the reader and processed to decode the data. The tag will reply the reader's query by changing the impedance on its antenna and modulates its data on the backscatter signals using ON_OFF keying.

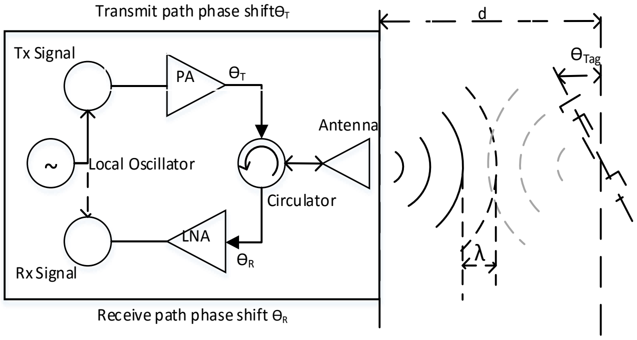

Fig. 1. Radio wave propagation between reader and tag

A. RF phase

Most COTS RFID reader can report phase value θ, which is the phase shift between the transmitted and received signal. Whenever a tag is interrogated by a reader, phase report is generated. As illustrated in Fig. 3, d is the distance from tag to reader. The total propagation distance of RF signal from the reader to the tag and back again is 2d. However, reader's transmitter, receiver circuits, and tag's antenna will all contribute extra phase rotations, which make the measured phase not purely related with distance between reader and tag. The measured phase is a function of the wavelength λ and total propagation distance 2d[9]. The formula can be express as:

$$\theta = (\frac{2\pi}{\lambda}\times 2d + \theta_T + \theta_R + \theta_{Tag}) \bmod 2\pi \qquad (1)$$

Where θ_T , θ_R and θ_{Tag} are the additional phase rotations introduced by reader transmitter, receiver and tag respectively. They are what we call device diversity.

B. Phase resolution

Most commercial off the shelf (COTS) RFID devices support fine-grained resolution in detecting the phase of received RF signals. They are able to report the phase values as a phase difference between the transmitted and received signal. The reader employed in our design is sirit Infinity 610. The phase estimate is reported as a hexadecimal number scaled from 0 to 2π and the resolution is about 0.005 degree, as shown in Fig. 2. In theory, the positioning resolution based on the measured phase values can achieve the accuracy of 320*0.005/360=0.004mm, which makes the phase measurements has the potential to locate the mobile tag along the conveyor with the accuracy of mm level.

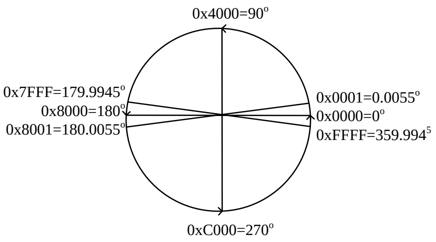

Fig. 2. Mapping of phase to the 16-bit reported value

III. INVERSE SAR LOCALIZATION TECHNIQUE

Assume an UHF RFID tag is moving on a conveyor belt within a surveillance region interrogated by m stationary antennas denoted as $\vec{A} = \{\vec{A}_1, \vec{A}_2 ... \vec{A}_m\}$.

The hypothetical position of the moving tag can be expressed as:

$$\vec{r}(t) = \vec{r}(t_0) + \int \vec{v}(t)dt \qquad (2)$$

Where $\vec{r}(t)$ is the tag's position at time t . $\vec{r}(t_0)$ is the initial position. As long as the initial position can be estimated correctly, the tag's position at random time can be inferred through (1).

If we ignore the device heterogeneity, the hypothetical phase value $\phi_h(t)$ measured by antenna $\vec{A}_i$ can be calculated by:

$$\phi_i(t) = \frac{4\pi}{\lambda} | \vec{r}(t) - \vec{A}_i | \bmod 2\pi \qquad (3)$$

The moving tag passes the antenna $\vec{A}_i$ and n phase measurements are generated, which can be denoted as:

$$\theta_i(t) = \{\theta_1(t_0), \theta_i(t_1) ... \theta_n(t_n)\} \quad (4)$$

Given the hypothetical phase measurements and the actual phase measurements, the maximum value of the following probability equation will be obtained if the tag starts with the correct initial positon:

$$P\left(\vec{r}(t_0)\right) = \left| \sum_{i=1}^{m} \sum_{j=1}^{n} e^{j\left(\phi_i(t_j) - \theta_i(t_j)\right)} \right| \qquad (5)$$

The rationale behind the function above is that the summation of these phase measurement difference between the hypothetical and the actual represents the likelihood of the tag being at the correct initial position. If the point is far away from the actual initial position, the signals superimpose at random phase angles and the summation is relatively lower than the points near the correct position.

However, as we mentioned before, device heterogeneity is a challenging factor that should not be neglected. In order to mitigate the effect of device heterogeneity, we adopt the method of phase difference.

Note that $\theta_i(t) = \frac{4\pi}{\lambda}\left(|\vec{r}(t_0) + \int \vec{v}(t)dt - \vec{A}_i| + \mathrm{c}\right) \bmod 2\pi$ where $c = \theta_T + \theta_R + \theta_{Tag}$. The heterogeneity can be weakened significantly by subtracting $\theta_{differ} = \phi_i(t_1) - \theta_i(t_1)$.

Then our new probability equation is calculated by:

$$P\left(\vec{r}(t_0)\right) = \left|\sum_{i=1}^{m}\sum_{j=1}^{n} e^{j\left(\phi_i(t_j) - \theta_i(t_j) - \theta_{differ}\right)}\right| \qquad (6)$$

IV. SIMULATION

We simulate a mobile RFID tag moving along a circular track at a constant speed of 0.3m/s, as shown in figure 3. The radius of the track is 1 m and the track's center is at x=1.5m and y=1.5 m. Four antennas are located at the four corners of a square with 3m length. The actual starting point of the tag is at (0.5 1.5). In each trial, the phase measurements are simulated with random error. Throughout our simulation, the inverse aperture length is 1.5m.

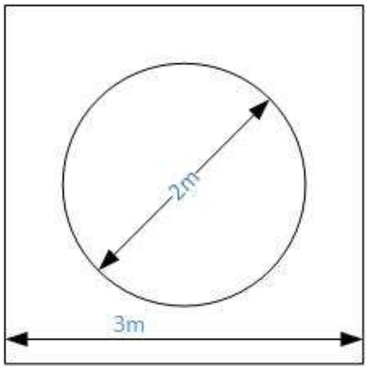

Figure 3. Simulation layout

A. *Illustration of inverse synthetic aperture*

In the first simulation, we illustrate inverse SAR through holographic image. The tag is interrogated 32 times by each antenna. A holographic image is calculated by utilizing (5) with each pixel expressed as:

$$P(x,y) = \frac{\left|\sum_{i=1}^{m}\sum_{j=1}^{n} e^{j\left(\phi_i(t_j) - \theta_i(t_j) - \theta_{differ}\right)}\right|}{\max\left(P(x,y)\right)} \qquad (7)$$

The holographic image is an image displaying the likelihood of each pixel to be the initial position. At the image pixels distant from the starting point, the signals will cancel each other and result in low level of probability. On the contrary, if the image pixel is the initial point, the hypothetical phase values will be equal to the measured ones, the maximum probability will be achieved according to 6. In this trial, the pixel (0.51, 1.5) has the maximus pixel value and is assumed to be the initial point. The deviation from the actual initial point is 0.01m. The performance of our method is better than most other existing localization methods.

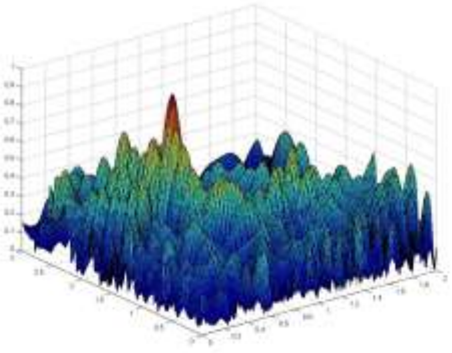

Fig.4 The holographic image with resolution $2m \times 3m$. The pixel with highest probability is (0.51,1.5).

B. *Impact of the number of phase measurements*

In the second simulation run, we will investigate the impact of the number of phase measurements on the performance of our method.

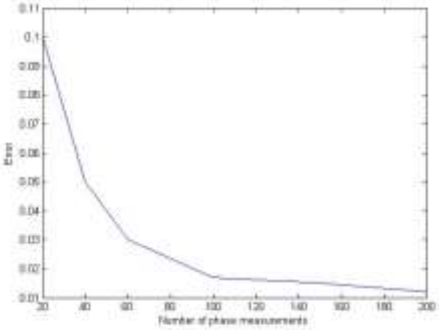

Figure .5 Impact of number of phase measurements

We have test the performance of our inverse SAR method on different phase measurements. Apparently, the performance is better with the number of phase measurements increasing as show in figure 4. As long as the phase measurement exceeds 40, the accuracy of our method improves significantly. When the phase measurements is greater than 100, the error decreases slightly. Actually, the computation burden will increase drastically with the growing number of phase measurements. Therefore, in order to achieve the real time tracking and keep the accuracy, the proper number of phase measurements should be in the range of [40 100].

C. *Robustness to device heterogeneity*

In the third simulation, we investigate the robustness of our method to device heterogeneity. As indicated in (1), different tags and different reader antennas all will introduce additional phase rotations, which will cause positioning error. We propose using phase difference to reduce the effect of device heterogeneity as much as possible.

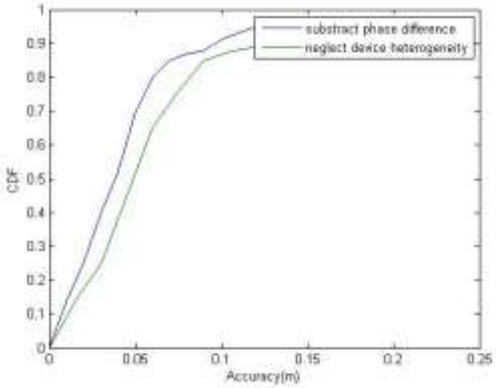

Figure 6. Cumulative error distribution

As show in figure 5, the median error is 0.06m and its 90th percentile is 0.112m if we subtract the phase difference. On the contrary, if the device heterogeneity is not considered, it will definitely affect the accuracy of the positioning and reduce the median error to 0.075m and 90th percentile to 0.141m. Simulation results verify that our method can effectively suppress the device heterogeneity.

V. MEASUREMENTS

Measurements were carried in the knowledge discovery laboratory of NTNU. We adopted a sirit Infinity 610 reader without any modification of the firmware. The reader is a multi-protocol radio frequency identification system that operates in the 860 – 960 MHz UHF band. The tag is actually located at $x_t = 1.2m$, $y_t = 0.3m$. The conveyor moves at a constant speed of 0.25 m/s .

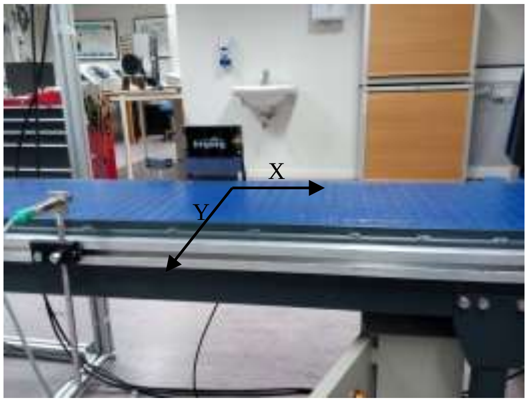

Figure. 7 Measurement setup in KDL lab

The tag is interrogated 31 times by the reader antenna. The inverse synthetic aperture length is 1.5 m and the holographic image calculated from the measured phase values is shown in figure 7. The maximum pixel value is at (1.18 0.39), which is 0.092m away from the real location. The x-axis and y-axis error distance are 2cm and 9 cm respectively. The positioning error mainly comes from multipath.

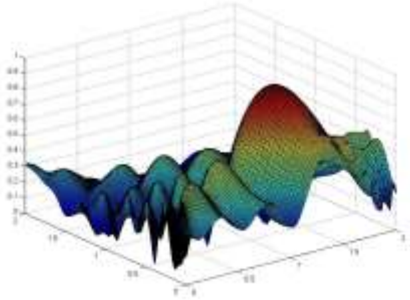

Figure 8. Holographic image of test data

We repeat the measurement many times in order to estimate the median error of x-axis and y-axis. The result is shown in figure 8. The x-axis, y-axis and combined dimension error are 1.2cm, 6.3cm, 6.41cm respectively. The accuracy of our method is satisfactory because compared to the x-axis position, the tag's y-axis positon is of less importance in the scenario of conveyor.

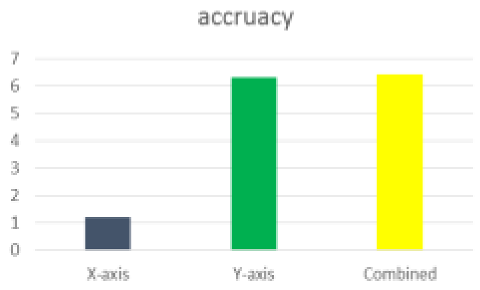

Figure 9. accuracy along x-axis, y-axis and combined dimension

VI. CONCLUSION

In this paper, we present a fine-grained tracking of mobile UHF RFID tag along a conveyor belt. Because the velocity and trajectory of the mobile tag is known in advance, an inverse synthetic aperture can be built based on the measured phase . As long as the initial point can be calculated, the tag's precise location at any time can be inferred. Holographic image calculated according to the inverse synthetic aperture can be utilized to estimate the starting point. In order to weaken the effect of device heterogeneity, we introduce phase difference into the calculation of holographic image. Simulations and experimental results in our lab demonstrate that our method is robust to device heterogeneity and achieve the accuracy of a few cm. Compared to the accuracy along the y-axis, the accuracy of x-axis is higher which is of more importance to us.

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