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Multi-tag RFID System Enables Localization and Tracking

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Abstract. In many applications, we have to locate and track the object. RFID technology has been widely adopted in logistics, one of whose most promising applications is to play an important role in high tracking accurately. In this paper, a new localization and tracking scheme by an antenna arranged in advance and multiple tags attached to the object has been proposed, a fine-grained backscatter positioning technique detects phase which is used to reflect positional relationship between the tag and the antenna, but challenged by its periodicity and tag’s diversity. Some phase changes of multiple tags construct a series of velocity chains, and the relationship between velocity projections solve the velocity of the object. Our system exhibits several benefits: 1) Only arrange one antenna. 2) Battery-free RFID avoids increasing the burden of power and load on the mobile platform. Many experiments have been conducted on linear motion and nonlinear motion. Compared with the other two schemes, our scheme has obvious advantages in accuracy and efficiency.

1. Introduction

Typically, a RFID system includes one reader, many tags and some antennas, and passive RFID system communicates using a backscatter radio link, the antenna of the tag, no battery equipped, induces a voltage from the reader’s antenna, and therefore produces a signal that can be detected [1].

As one of the most promising applications, the RFID positioning has been received a lot of attentions [1-7]. These work can be classified into three groups. (1) Received Signal Strength (RSS) based methods [2][3]. As a way to indicate the measurement distance, RSS is widely used in various wireless signal positioning. However, its obvious drawback is the accuracy of positioning which is not easy to improve, and it is highly susceptible to interference from the external environment, so it is not a reliable indicator. (2) AOA based methods [4][5]. Multiple antennas receive the signals and estimate their angles through the phase differences, but the distance between the antennas needs to be less than half wavelength, and T. Liu, et al. [6] introduce the concept of the virtual antennas to limit the positioning area and avoid the limitation of the distance between the actual antennas. (3) Phase based methods [1][7][8]. Reader supports fine-grained resolution in detecting the phase of received RF signals, with accuracy which is about 0.0015 radians, that is, millimetre-level displacement can be detected. But the phase used to locate the object is challenged by two factors: (a) Different tags have different unknown initial phase rotation, and the different readers and antenna also have different influence on the phase. (b) The phase is periodic such that the linear relation with distance behaves effective within half a wavelength only, increasing the position ambiguity.

In this paper, the phase is used to get the high resolution after overcoming these two challenges. Our system achieves good tracking performance with extremely low layout cost without compromising accuracy.
2. Multi-tag RFID system

This section briefly introduces the application principle of RFID and explores the way that phase is used to reflect distance, and then establish a mathematical model of multi-label system.

2.1 RFID system

2.1.1 Backscatter Radio Link

Figure 1 provides a conceptual diagram of the radio wave propagation between an RFID reader and a passive RFID tag. $R$ is the distance between reader and tag, $\lambda$ is the carrier wavelength, in this paper, for an RF carrier wave at frequency $f = 920.625$ MHz, the relation between frequency and wavelength is given by $\lambda = \frac{c}{f} = 32.57 cm$, where $c$ is the speed of EM wave in communication medium ($3 \times 10^8$ m/s), [8] in addition to the RF phase rotation over distance, the reader’s transmit circuits, the tag’s reflection characteristic, and the reader’s receiver circuits all introduce some additional phase rotation $\theta_T, \theta_{TAG}$, and $\theta_R$ respectively.

![Figure 1. Conceptual diagram of radio wave propagation between RFID reader and tag.](image)

2.1.2 RF phase

As shown in Figure 1 the total distance traversed by the signal is $2R$. The total phase rotation can be expressed as

$$\theta = 2\pi \times \frac{2R}{\lambda} + \theta_T + \theta_R + \theta_{TAG} \quad (1)$$

Equation (1) can be easily found that the phase is a periodic function with period $2\pi$ radians, after collecting the phase information, how many cycles the wireless signal has traversed in this distance cannot be known, which is called phase ambiguity.[11]

Thermal noise and other noise sources, such as external interference, can also affect the reported RF phase, some empirical studies are conducted over 30 tags with various frequencies and distances. One set of results measured at a distance of 5 meters and the 924.375 MHz is depicted in Figure 2. Phase measurement results follow a typical Gaussian distribution with a standard deviation of 0.059 radians.

![Figure 2. Phase distribution.](image)
2.2 Processing Phase
A tag can be interrogated for about 300 times after the reader is set in a suitable mode. If the displacement of the same tag between two adjacent samples is less than half a wavelength, then the respective unknown periods of the two samples are equal or a difference in one period. The number of tags attached to the objects is \( m \), if \( m = 10 \) is supposed, the sampling time interval of the same tag is about \( 1/30 \)s, half a wavelength is about 16cm, So the maximum moving speed of the object is about 480 cm/s, which has met the movement requirements of most indoor robot movements. At the same time, reducing the number of tags can also increase the speed limit. According to the premise of this setting, the relationship between the phase based on the adjacent position and the moving distance can be derived.

\[
\Delta \theta_{i,n}^0 = \theta_{i,n+1}^0 - \theta_{i,n}^0 \quad (2)
\]

\[
\Delta \theta_{i,n} = \begin{cases} 
\Delta \theta_{i,n}^0 & |\Delta \theta_{i,n}^0| < \pi \\
\Delta \theta_{i,n}^0 + 2\pi & \Delta \theta_{i,n}^0 \leq -\pi \\
\Delta \theta_{i,n}^0 - 2\pi & \Delta \theta_{i,n}^0 \geq \pi 
\end{cases} \quad (3)
\]

\[
\Delta d_{i,n} = \frac{\Delta \theta_{i,n}^0}{\pi} \quad (4)
\]

Where the phase \( i(i = 1, \ldots, m) \)-th tag at \( n \)-th sampling obtained is expressed as \( \theta_{i,n} \), \( \Delta \theta_{i,n} \) is the phase difference, \( \Delta d_{i,n} \) is the displacement of the tag during the sampling interval. Since above equation has taken a phase difference the antenna and tag diversity has been eliminated.

2.3 Speed Chain
The tags shown in Figure 3 is placed on the object in a known arrangement, and the displacement of the tag is much smaller than the distance between the antenna and the tag, so the displacement can be considered to be generated in the direction \( A \rightarrow f_{i,n}^e \). The superscript \( e \) refers to the coordinate system established in the application scenario, called \( e \)-frame, \( f_{i,n}^e \) indicates the position of the \( i \)-th tag at the \( n \)-th sample in \( e \)-frame, \( A \) is the position of the antenna in \( e \)-frame, \( v_{i,n}^e \) is the instantaneous velocity of the tag solved by the phase difference. \( \overrightarrow{V}^e \) is velocity of the mobile object.

![Figure 3. Multi-tag RFID system model](image)

After deciphering the instantaneous displacement of each tag, the instantaneous rate and velocity’s direction of each tag can be generated based on the timestamps recorded by the measuring device.

According to the distribution of the known \( m \) tags in the body coordinate system, called \( b \)-frame, the origin of \( b \)-frame is a point on the moving object, \( m \) virtual antennas are introduced to solve the problem of speed projection. As shown in Figure 4, \( VA_0 \) is located at the position of the original antenna \( A \). When the object moves, based on the displacement \( \Delta d_{1,n} \) of \( T_1 \) (refer to the first tag) in the direction of \( A \rightarrow T_1 \), the virtual antenna \( VA_1 \) is constructed such that \( T_0 \) simultaneously generates the displacement \( \Delta d_{1,n} \) in the direction of \( VA_1 \rightarrow T_0 \), and the other virtual antennas are constructed in such a way. And the result is that all instantaneous velocities are transferred, these velocities can be seen as being measured by some virtual antennas to the same tag.
The instantaneous velocities with the known rates and direction formed by the set of virtual antennas are the projections of the object's moving velocity in the corresponding directions, namely:

$$\vec{v}_n^e = \vec{v}_n^e \cos(\Delta \Theta_{i,n})$$  \hspace{1cm} (5)

$$\Delta \Theta_{i,n} = \Theta_i - \Theta_{i,n}^0$$  \hspace{1cm} (6)

Where $\Theta_i$ refers to the angle between the velocity of the object and the coordinate axis $X_e$, and $\Theta_{i,n}^0$ refers to the angle between the instantaneous velocity of the $i$-th label and the coordinate axis.

From equations (5) and (6), there are two unknown parameters, $\vec{v}_n^e$ and $\Theta_i$. The system of two tags can perform the calculation of the velocity chain and the tracking, but when the positions of the two tags and the antenna are located on the same line, the instantaneous velocity generated cannot be solved. To avoid this, at least 3 tags are selected, and the positions where the tags are placed cannot be collinear, and then the fitting calculation is performed.

The trajectory be segmented into a serials of uniform linear movement, and the following recursive equation is derived:

$$f_{i,n+1}^e = f_{i,n}^e + \vec{v}_n^e \Delta t_n$$  \hspace{1cm} (7)

Where $\Delta t_n$ is sampling interval, in linear motion, as long as we know the initial position, the trajectory can be tracked very quickly on the mobile terminal through the multi-tag system. In the scenarios of two-dimensional nonlinear motion, when the system generate a new set of virtual antennas, the relative deflection angles of $b$-frame and $e$-frame need to be known in advance. For most indoor mobile robots, the gyroscope used to obtain the attitudes must also be equipped.

3. Implementation and Evaluation

In this section, the positioning and tracking performance of linear motion and nonlinear motion scenarios separately are evaluated, and this multi-tag system is compared with two other systems that use RFID phase information to locate.

3.1 Equipment and platform

The operating frequency of Impinj R420 RFID reader is configured as 920.625Mhz. The reader mode is configured as MaxThroughput with the highest data rate. And the search mode is DualTarget to read continuously regardless of tag stated. Other configurations are not described. One 9dBc circular polarization antenna is connected. Most single-port tags are very sensitive to the orientation associated with the reader antenna, in order to avoid the direction of the tag during motion, the omni-directional tag Impinj H47 is chosen.[10]

In the linear motion scenarios, used a linear guide apparatus with adjustable speed is used. In the nonlinear scenarios, a smart car with a strapdown inertial navigation system experiments along a circular orbit with a radius of 1 meter.
3.2 Linear motion
In [6], the author proposes to use a plurality of antennas for arrangement, and to construct a hyperbolic curve by using virtual antennas with a distance less than half a wavelength. In [7], an arrangement in which one more tag and a plurality of antennas are added is employed, in the case where the distance between the tags is made smaller than a half wavelength, they achieve acquisition of the position and orientation of the object. Both of these solutions use RFID phase information for positioning. The data in the same environment is collected and compared with our proposed solution after processing.

In the experiment, the linear orbit is arranged between the position (-45, 55) and the position (125, 55). It is obvious from Figure 6 that the proposed multi-tag system can have good positioning and tracking performance. In the y-axis direction, the deviation between the position tracking mean and the actual track is 3.934cm, the standard deviation is 3.2281cm, and the deviation of the scheme 1 is 5.934cm, and the standard deviation is 6.6402cm, but the deviation and standard deviation of the scheme 2 are large. This is because it is not reasonable to eliminate the diversity of the system in the process of implementing its solution. It is unreasonable to rely solely on the calibration of the equipment. [12]

3.3 Nonlinear motion
In this part, for the tracking of nonlinear motion, our proposed solution needs to be matched with, for example, the strapdown inertial navigation system to obtain more accurate positioning.
In Fig. 7, the legend is the same as Fig. 6. The antenna to the ceiling in order is hoisted to prevent the influence of the tag’s orientation on the measurement result. The radius of the circular orbit is 0.8 meters, and the smart car and the circular track are combined. Measurements of nonlinear motion trajectories can be more easily compared to real trajectories. The centre of the circular orbit is (20, 20) on a 2-dimensional plane. In nonlinear motion positioning, multi-tag systems are still able to maintain good tracking performance. Compared with the other two methods, the multi-label system obtains a more accurate motion trajectory, but with the accumulation of measurement noise, the positioning performance of the multi-tag system will decrease. At the same time, in nonlinear systems, the positioning performance is also affected by the attitude of the auxiliary information.

4. Conclusion
This paper proposes a system based on RFID with multiple tags and single antennas, which can effectively reduce the requirements of environmental configuration and save costs under the premise of ensuring accuracy.

Secondly, the concept of virtual antenna is introduced and put the scattered projection relationship on the same tag to solve the motion velocity of the object. For linear systems, multi-tag can obtain excellent positioning and tracking ability. In nonlinear systems, the rotation information of the body coordinate system (b-frame) relative to the indoor coordinate system (e-frame) is needed, and then the tracking requirements in the nonlinear scene can be completed.

There are still many areas to be studied, such as the limited number of tags, the relationship between speed and the number of tags, the arrangement of tags to maximize tracking performance. For long-term trajectory tracking services, multiple sensor information can be used for fusion.

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