Lane Keeping through RFID

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***Abstract*—In this paper we present a prototype method for guiding a user to a target by introducing RFID-lanes. The user is equipped with a portable RFID reader, which measures the phase of RFID tags arranged at known positions on the floor, forming lanes. By calculating the Rate Of Change (ROC) of the phase measurements of each tag along discrete time-steps, motion of the user can be accurately tracked, while proper direction-guidance is updated. The proposed method, calculates the user's direction of motion, by sorting the measured phase-ROCs from the nearby tags while keeping track of the user's position by feeding the phase-ROCs in a particle filter. Simulations and experimental results show precise localization and guidance while maintaining real-time computations.**

***Index Terms*—RFID, guidance, tracking, blind, RFID-lanes, particle filter, phase, portable reader**

I. Introduction

In this paper, we present a novel RFID-based system for both navigation and tracking in indoor and outdoor environments. As shown in Fig. 1 the user is equipped with a prototype portable reader, built using Commercial Off The Shelf (COTS) components, that can measure the phase from nearby UHF-RFID tags. The reader queries the RFID tags placed at lane patterns to obtain phase measurements.

Navigation within the lane is accomplished by estimating the user's direction of motion and giving corresponding auditory and visible cues (e.g., turn left/right, keep moving forward, etc.). As the user/reader moves, the rate of change (ROC) of phase measurements collected by each RFID tag, participating in the lane, changes. The tag with the highest rate of decrease denotes the "estimated" current direction of the user. In addition, the user's position is estimated, using particle filters, thus improving the accuracy of the direction estimation and notifying the user when the objective is attained. The filters are updated, based on phase-ROC measurements received from the tags, forming the RFID-lanes.

Prior art on target navigation and localization comprises techniques using different means and data. Some representative techniques are:

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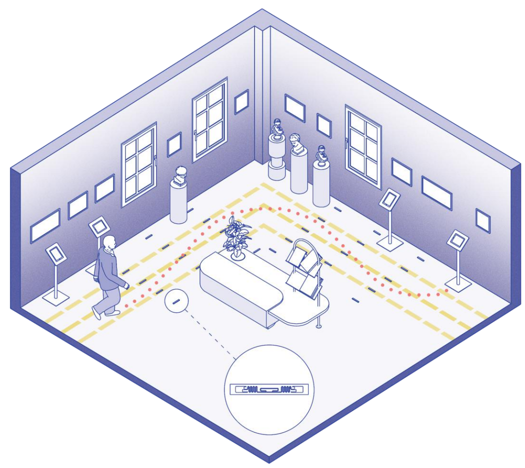


Fig. 1. Illustration of the navigation and tracking principles in an indoor environment (a museum). RFID tags are placed on the floor, forming lanes.

- RSSI : The power of the received signal from reference RFID tags is exploited in [1]. However, multipath and shadowing have a significant impact on RSSI, resulting in poor localization accuracy.
- Phase of Arrival (POA): POA has been used in many ways in literature achieving high localization accuracy. In [2], [3] phase measurements from multiple antennas mounted on a robot are used to locate tags exploiting Synthetic Aperture Radar (SAR) techniques. Authors in [4] present an orientation-aware phase model that estimates the 3D position and orientation of a tag starting from a known initial position of the tag.
- Multi-frequency: Authors in [5], [6] use a variety of frequency channels to pinpoint the target and address the issue of multipath. Nevertheless, these techniques were developed for US standards and could not be used in Europe due to the very narrow bandwidth (865-868MHz).
- Non-RFID methods: Vision [9] or sound [8] based systems, smartphone sensing and an Augmented Reality (AR) application [7] and other RF technologies like WiFi or Bluetooth [10] are only a handfull of the techniques discussed in bibliography.
- Fusion methods: The authors of [11], [12] integrate RFID readings with data from other sensors to predict a target's direction and position. [11] uses RFID phase data and an

inertial measurement unit (IMU) to estimate the distance and angle of a desired RFID tag, whereas [12] uses odometry data paired with POA to determine the pose of a robot in regard to a target tag.

In this work, we estimate only the phase-ROC, in order to guide a moving person to a preset target while his location is monitored in real-time by phase readings obtained from stationary RFID tags placed at lane formations. The algorithm retains high localization accuracy for all trials, including multipath rich environments by utilizing particle filters and estimating the location of the moving human in subsequent time instants. A handheld reader locates itself in the monitored area and provides auditory and visible directions to lead the user to the preset target.

The aim of this work is to examine its possible use in guiding blinds along "RFID-lanes". However, the method could also be applied for vehicle/robot-guidance. The fundamental concept is that the method would keep the RFID-reader inside the lane.

The contribution of the proposed method can be summarized as follows:

- The estimated phase-ROC measurements from RFID tags positioned in lane-formation are used as spatial indicators.
- Phase measurements are unwrapped in separate time windows and the phase-ROC can be calculated even with partial phase sequences.
- The proposed handheld reader carried by the user makes use of COTS hardware components.
- All information gathered from the interrogated tags is processed locally to produce **real-time** localization and guidance.
- The concept of RFID lanes is introduced enabling the application of the method in both indoor and outdoor environments.
- The proposed approach might be used in a number of settings, but is envisioned as a supporting system for blind.

II. Proposed method

Consider a human or machine carrying an RFID-reader, that should be guided to a certain target. RFID tags are laid out in lanes on the floor throughout the area of interest; the reader should be kept in the center of such lanes. The reader collects phase and RSSI data, associated with each RFID tag and outputs audio and visual feedback (or controls the motor) to guide one to the destination.

A. Measured Data

All RFID tags are fixed at known locations as shown in Fig. 2. The antenna's position at time-step j is given by $\mathbf{A}_{ant,j} = [x_{ant,j}, y_{ant,j}, z_{ant,j}]$ and the fixed position of the i_{th} tag is $\mathbf{A}^i_{tag} = [x^i_{tag}, y^i_{tag}, z^i_{tag}]$. The corresponding distance between the antenna and the i_{th} tag at time j is:

$$||\mathbf{A}_{ant,j} - \mathbf{A}^i_{tag}||_2 = \sqrt{(x_{ant,j} - x^i_{tag})^2 + (y_{ant,j} - y^i_{tag})^2 + (z_{ant,j} - z^i_{tag})^2}.$$

The measured phase is denoted as:

$$\phi^i_j = (\phi^i_{prop,j} + \phi^i_o + \phi^i_{noise,j} + \phi^i_{mult,j}) mod(2\pi), \quad (1)$$

where $\phi^i_{prop,j} = \frac{2\pi}{\lambda} 2d^i_j$, corresponds to the phase due to the round trip distance $2d^i_j$ between the i_{th} tag and the reader at time j, ϕ^i_o is the phase offset of the i_{th} tag, $\phi^i_{noise,j}$ is the measurement noise and can be simulated by $\mathcal{N}(0, \sigma^2_{phase})$ $\phi^i_{mult,j} = \tan^{-1}(\frac{A sin\theta}{1+A cos\theta})$ is introduced to account for multipath. $A = \frac{A_{NLoS}}{A_{LoS}}$ with A_{LoS} being the direct Line-Of-Sight (LOS) vector of magnitude and A_{NLoS} the as Non-Line-Of-Sight (NLOS).

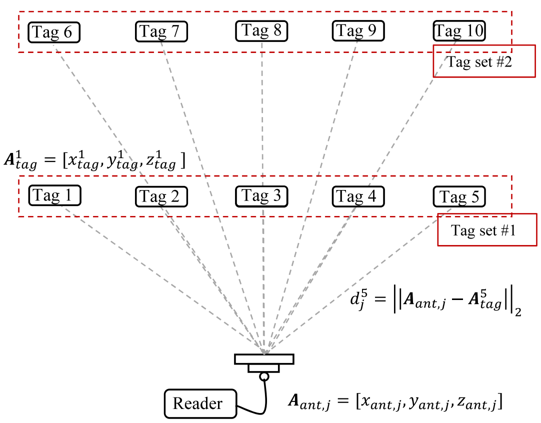


Fig. 2. A portable reader interrogates RFID tags at time instant t_j.

Initially, let's assume a multipath-free environment. For a selected period of time dt sequential phase measurements are collected from all tags. To calculate the phase-ROC for each tag the phase measurements have to be unwrapped and filtered. After unwrapping and filtering (using a second degree Savitzky–Golay filter), $\phi^i_j = \phi^i_{prop,j} + \phi^i_o$. Let $d\phi^i_j = \phi^i_j - \phi^i_{j-1}$ denote the difference of phases measured from the same tag i at time instances t_{j-1}, t_j. Subtracting ϕ^i_j from ϕ^i_{j-1} removes the ϕ^i_o term and dividing by $dt_j = t_j - t_{j-1}$ results in the phase-ROC of tag i in time window $[t_{j-1}, t_j]$ which is expressed as:

$$\dot{\phi}^i_j = \frac{d\phi^i_j}{dt_j} = \frac{\phi^i_j - \phi^i_{j-1}}{dt_j} = \frac{4\pi(d^i_j - d^i_{j-1})/\lambda}{dt_j} \quad (2)$$

All rates are kept in a vector, where each column represents one of the surrounding tags and each row represents a time frame. The phase-ROC matrix $\mathbf{D}$ is denoted as follows:

$$\mathbf{D} = \begin{bmatrix} \dot{\phi}^1_1 & \dot{\phi}^2_1 & ... & \dot{\phi}^N_1 \\ \dot{\phi}^1_2 & ... & ... & ... \\ ... & ... & ... & ... \\ \dot{\phi}^1_M & ... & ... & \dot{\phi}^N_M \end{bmatrix}, \quad (3)$$

where N is the number of tags and M is the number of time-steps $t_1, t_2, ..., t_M$ which form the time set at which the estimations will take place.

B. Direction Estimation

To estimate the direction of the reader each time, the minimum of the ROCs of all tags is calculated:

$$\min \mathbf{D}[j,:] = \min([\dot{\phi}_j^1, ..., ..., \dot{\phi}_j^N]), \tag{4}$$

Theoretically, the tag with the lowest rate of change is the one that the user is moving toward. In practice, more processing is necessary to update the direction-guidance (audio and visual feedback, e.g. turn left/right, continue straight, etc.) of the user.

C. Location Estimation

In the remaining document, we consider the reader, being held at a constant known height $z_{ant,j} = z_{ant}$. The phase-ROC of tag i in a time frame is proportional to the rate of change of the reader's location, as shown in (2). We seek the solution along the $x - y$ plane. This rate of change corresponds to the reader's radial velocity as measured from each tag. Fig. 3 depicts a reader's path from time instance t_{j-1} to time instance t_j. The reader is interrogating adjacent tags in order to calculate phase-ROCs. This rate of change represents the reader's radial velocity as measured from tag i. Fig. 4 displays the traveled path of the reader from time instance t_{j-1} to t_j. Using (2) the radial speed vectors' magnitude $\|\vec{V_t^i}\|$ and angle $\angle\vec{V_t^i}$ are given by:

$$\|\vec{V_j^i}\| = \frac{(d_j^i - d_{j-1}^i)}{dt_j} = \frac{\lambda}{4\pi}\frac{d\phi_j^i}{dt_j}, \tag{5}$$

$$\angle\vec{V_j^i} = \angle(\mathbf{A}_{ant,j-1} - \mathbf{A}_{tag}^i), \tag{6}$$

where $\mathbf{A}_{ant,j-1}$ and $\mathbf{A}_{tag}^i$ are the positions of the antenna and tag i at time instant t_{j-1} correspondingly. The radial velocity vector $\overline{\mathbf{V}}_j$ represent an estimation of the reader's velocity for the specific time window. To calculate the speed vector an optimization problem needs to be solved, formalised as [13]:

$$min\{(|V_j^i - \vec{V_j^i}|) \mid (\vec{V_j^1}, \angle\vec{V_j^1}), ..., (\vec{V_j^N}, \angle\vec{V_j^N})\}, \tag{7}$$

where $\vec{V_j^i}$ is the projection of speed vector $\overline{\mathbf{V}}_j$ at the radial direction of $\mathbf{A}_{ant,j-1}$ towards tag i.

Estimating a target's dynamic state may be divided into two steps: i) prediction and ii) update. The prediction stage addresses the temporal evolution of the target state based on past states, whereas the update stage addresses the modification of the predicted state based on newly obtained measurements. With this structure in consideration, particle filters are used to solve the tracking problem. Particle filters can address the location estimation problem by utilizing a set of weighted particles, each of which represents a probable state with a certain probability. The set of particles is given by:

$$\{\mathbf{X}_j^n, w_j^n\}, n \in [1, N_p], \tag{8}$$

where $\mathbf{X}_j^n = \{x_j, y_j\}$ is the state vector and w_j^n is the significance weight of n-th particle at time instant t_j. The corresponding algorithm can be decomposed in the following 5 steps:

1) Initialization: A swarm of N_p particles, indicating potential user's positions, is produced uniformly throughout the area of concern. Each particle is assigned a weight of $1/N_p$. To reduce the amount of particles required while maintaining an equal particle density, knowledge of the obstacles in the search area or the characteristics of the antenna could be investigated.

2) Prediction: At the prediction step the states of all particles are altered. The state of each particle changes based on the velocity-vector of each particle given by (7). The velocity-vector is calculated using only the three tags with the minimum rate of change and the new state is revised by:

$$\mathbf{X}_j^n = \mathbf{X}_{j-1}^n + \overline{\mathbf{V}}_j^n dt_j \tag{9}$$

3) Update Step: To update the weights the theoretical/expected phase-ROCs $\dot{\phi}_{j,expected}^i$ are calculated presuming a transition from position $\mathbf{X}_{j-1}^n$ to position $\mathbf{X}_j^n$. The calculated weights for each tag are summed up and the weight of each particle is updated by:

$$w_j^n = \left[\sum_{i=1}^{N} |\dot{\phi}_{j,expected}^i - \dot{\phi}_j^i|\right]^{-1}, \tag{10}$$

The weight of the particle is maximized at the location that is nearest to the reader's real position. A probability distribution is created by normalizing the weights:

$$w_j^n = \frac{w_j^n}{\sum_{n=1}^{N_p}} \tag{11}$$

4) State Estimation: After updating the weights of all particles, the state estimate is calculated as the weighted sum of all particles' states:

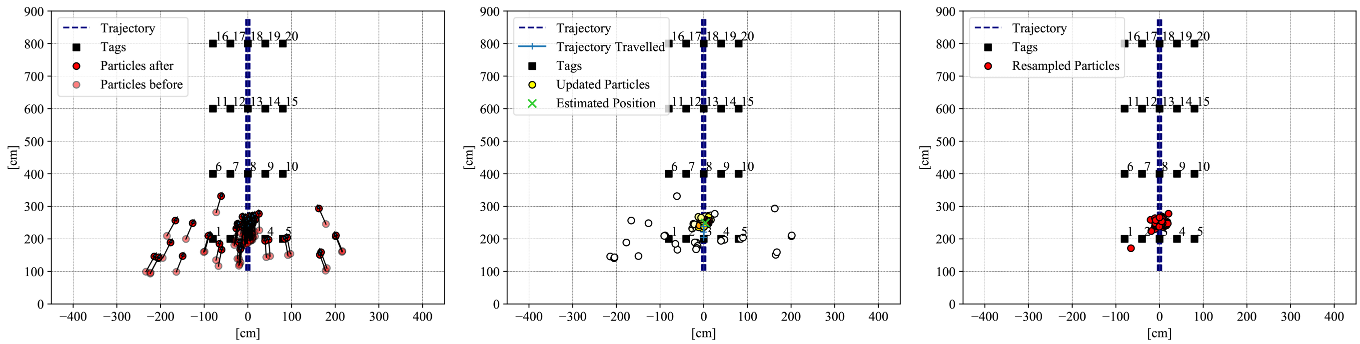
$$\overline{\mathbf{X}}_j = \sum_{n=1}^{N_p} \vec{X}_j^n w_j^n \tag{12}$$

5) Particle Resampling: Particle degeneracy in standard particle filters significantly reduces filter precision. The term "particle degeneracy" refers to the fact that after a few rounds, almost all of the particles have been given a weight close to zero. Stratified resampling is used to prevent the issue of degeneracy by discarding particles that have a very low weight and substitutes them with new particles that have a higher probability. Noise is added to spread duplicates of "important" particles, resulting in a collection of locations in which the probability distribution is represented by the majority of the particles.

The algorithm then repeats the process, going back to step #2 recursively until the reader's distance from the target is less than a predefined length.

III. SIMULATIONS

In this section the method is evaluated in simulated environments. Fig. 5 depicts a top view of the simulations' set-up. 20 tags were placed at known locations at a distance of 40 cm on the x-axis and 2 meters on the y-axis and 3 trajectories were assessed. To more closely approximate a real-world situation, phase noise and multipath were introduced to the



(a) Prediction (b) Update and state Estimation (c) Resampling

Fig. 3. Representation of the localization part of the algorithm in a simulated environment.

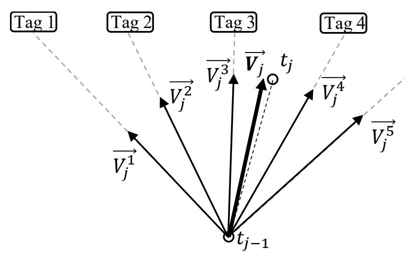


Fig. 4. Reader's speed approximation. The dotted line between time instance t_{j-1} and t_j denotes the trajectory followed by the reader.

phase measurements, and the radiation pattern of a standard UHF-RFID panel antenna was included. The multipath-model is presented in [15].

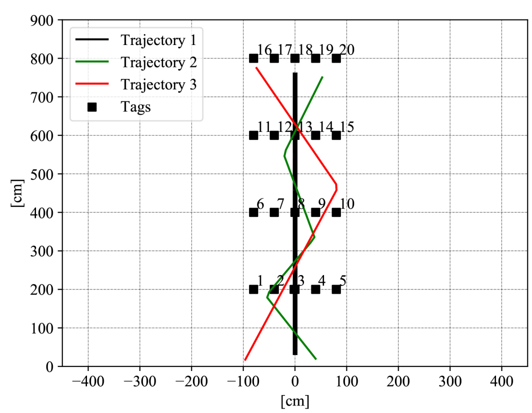


Fig. 5. Top view of the simulation setup and the simulated trajectories.

The localization part of the algorithm must be repeated numerous times, because both the initialization and resampling steps involve random processes. For each route, the algorithm was repeated 100 times, and the error was computed for each iteration as follows:

$$Error = \frac{\sum_{j=1}^{M} ||\overline{\mathbf{X}}_{j\_est} - \overline{\mathbf{X}}_{j\_real}||_2}{M} \tag{13}$$

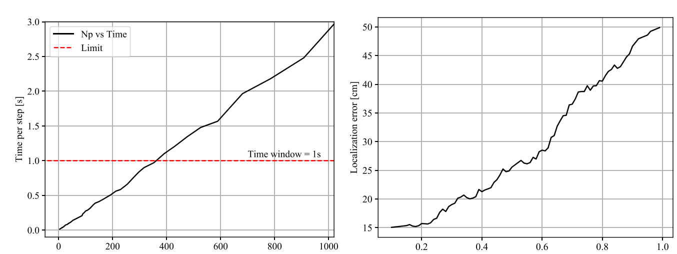
TABLE I
SIMULATION LOCALIZATION ERROR

Paths	Mean Error(cm)	Std (cm)
Trajectory 1	5.31	3.95
Trajectory 2	8.21	6.12
Trajectory 3	12.72	11.31

The mean absolute value of all errors and standard deviations for all runs along with the distance travelled per trajectory are presented in Table I.

A. Number of Particles

The quantity of particles affects how quickly and accurately the algorithm performs. A research on the impact of total number of particles for trajectory #1 was carried out, to determine the best N_p for the filter. The results are shown in Fig. 6a. The mean estimation error was kept low (less than 15cm) for the different values of N_p so the number of particles is selected taking into consideration only the time per iteration. Assuming maximum estimation time in the order of 250 ms Np should be set to 100. Fig. 6b presents the performance of the method with respect to increased multipath effects. The algorithm was still able to maintain a mean error less than 50 centimeters even for the worst case; i.e. $A = 1$.



(a) N_P versus time per iteration (step). (b) Mean error vs Multipath

Fig. 6. Multipath and number of particles analysis.

B. Number of tags per RFID tag-set

The algorithm was applied in two distinct situations for each of the three routes in order to determine the number of tags per RFID tag-set. One with 5 tags, and one with 3 tags per group. For 100 trials per route, the mean error and standard deviation are computed. Due to the proximity of the tags and the impact of noise and multipath, a greater mean error was observed for the case of three tags per group.

IV. Experiments

The experiments were carried out in a corridor. Four checkpoints, with 5 RFID tags each, form an RFID lane for the experiments. The 20 tags (Alien ALN-9740 ”Squiggle” RFID tags with ”Higgs–4” IC at -19 dBm sensitivity) are placed on the floor, as shown in Fig. 7. Along each checkpoint, the 5 tags are spaced at 40 cm. The distance between successive checkpoints is 2 meters.

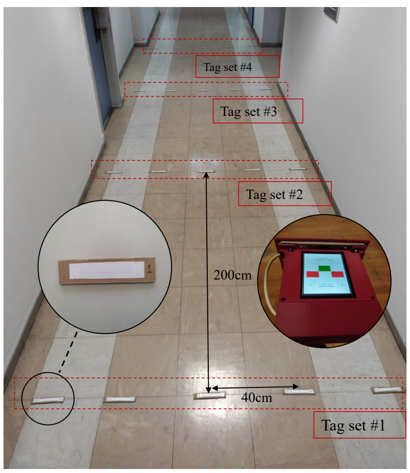


Fig. 7. The setup of the experiments.

The reader consists of a ThingMagic Sargas 2-Port UHF-RFID reader, a Laird Technologies PER86506 Antenna (Gain 6 dBic), a Raspberry pi 4 with a touch screen.

A. Guidance

As the user moves, three arrows are shown on the screen, accompanied by a sound of different frequency, instructing the user to move straight, left or right. The user interface is shown in Fig. 7. Guidance, i.e. continue straight, left or right, is given according to the measured ROC. Theoretically, the minimum ROC should be measured for the tag along the direction of the movement. However, as the tags forming a checkpoint are closely spaced and the distance of the reader from the tags could be large, the expected differences of the ROCs between adjacent tags are small; thus vulnerable to multipath and noise.

This is verified by the experiments, conducted along the corridor with only three tags, shown in Figs. 9 and 10. During the 1^{st} experiment, the user moved directly towards the central tag. During the 2^{nd} experiment, the user moved directly towards the left tag. Every 0.5s, the ROC was calculated for all three tags. Under ideal multipath-free, noiseless conditions, the blue ROC segment should be minimum throughout experiment 1 and the red ROC segment should be minimum throughout experiment 2. However, during experiment 1, all three colors take turns in the minimum position, while during experiment 2, the correct red color dominates with some interruptions by the blue ROC, which corresponds to the adjacent central tag.

If the user was forced to take instructions according to the minimum recorded ROC, he would be instructed to change directions almost during each iteration when moving towards the central tag, weaving in an annoying ”zigzag” fashion. By changing the rule to: ”Change direction only if there are three consecutive minimum ROC measurements of the outer-most RFID tags along each checkpoint”, a smooth guidance was accomplished. Under this condition, the user would properly never change his straight movement during experiment 1 and would correctly be instructed to turn right a total of four times during experiment 2, as shown with arrows in Fig. 10 - of course, after turning right during the first instruction the measurements would have changed. This rule guaranteed proper guidance in all experiments.

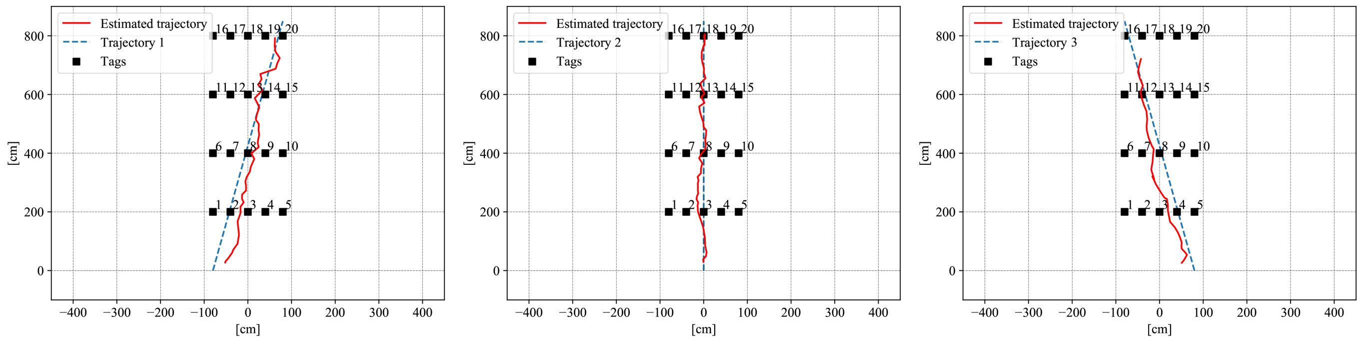
B. RFID Reader Tracking

In order to test the tracking-accuracy, we have conducted several experiments, moving along straight segments, three of which are shown in Fig. 8 with blue dotted lines. In all cases, accurate tracking was accomplished; yet modification to the theoretical particle filter algorithm, presented in Section II-C was necessary. During iterations, where phase-ROC data were unavailable to update the velocity vectors of the particles, the velocities from the previous iteration are used. This allows the particles to ”move” with the latest known velocity even when data are unavailable.

V. Discussion

This work presents an early-stage prototype RFID system for guiding a user along a lane, constructed by passive RFID tags at known positions. The method considers the rate of change of phase measurements and outputs the proper direction to keep one in the lane, while estimating one’s pose in real-time. Given the small tag-population and the high reader’s read-rate, sufficient phase-measurements for the estimation of the phase-ROC are expected for any typical human movement; e.g. consider 300 reads/s divided by 6 tags, results in 50reads/tag/s. Assuming a human moving at 50cm/s, this would result in 1 read per cm of displacement or 8 measurements per phase-cycle. The method is immune to the orientation of the reader-to-tag system, given that it accounts for the translational movement of the user and estimates the rate of change over several phase-cycles via phase-unwrapping. Experimental data validate the performance regardless of the user’s pace or distance traversed.

Further experimentation and scaling for larger indoor and outdoor areas is to be considered next, including waterproofing tags in plastic enclosures and and embedding in rigid mate-



(a) Trajectory 1 (b) Trajectory 2 (c) Trajectory 3

Fig. 8. Estimated trajectories vs travelled traces for all experiments.

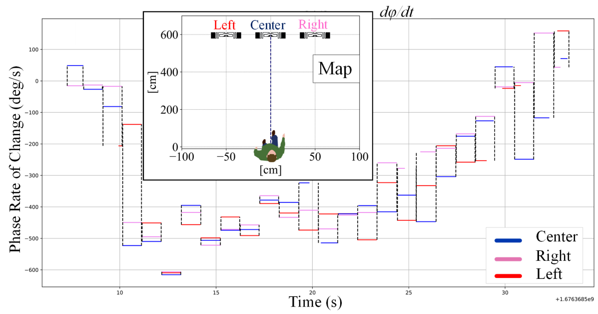


Fig. 9. Measured rate of change for three tags (path 1).

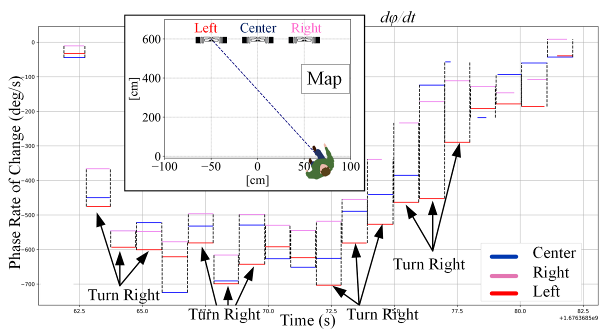


Fig. 10. Measured rate of change for three tags (path 2).

rials, in order to apply the method for our vision of Lane-keeping for the blind.

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