Tagoram: Real-Time Tracking of Mobile RFID Tags to High-Precision Accuracy Using COTS Devices

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Outline

01. Motivation
02. State-of-the-art
03. Overview
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05. Movement with unknown track
06. Implementation & Evaluation
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1 Motivation
Imagine you can localize RFIDs to within 0.1cm to 1 cm!
Imagine you can localize RFIDs to within 0.1cm to 1 cm!
Imagine you can localize RFIDs to within 0.1 cm to 1 cm!
Demonstration

http://young.tagsys.org/tracking/tagoram/youtube
High-Precision RFID Tracking Using COTS Devices

Drawing in the Air

30cm

40cm
TrackPoint Deployed at Airports

(a) Version 1.0

(b) Version 2.0

(c) Internal structure

(a) Two TrackPoints

(b) Version 2.0
2 State-of-the-art
RFID Tracking & Localization

State-of-the-art

LANDMARC
Lionel M. Ni

2004
RFID Tracking & Localization
State-of-the-art

- **LANDMARC**
  - Lionel M. Ni
  - 2004
  - 1120mm

- **Spatial based**
  - P. Nikitin
  - 2010
  - 680mm

- **Diff based**
  - C. H. Williams
  - 2010
  - 280mm

- Additional references:
  - [1] Lionel M. Ni, Yunhao Liu, et al. LANDMARC: Indoor Location Sensing Using Active RFID Wireless Networks.
RFID Tracking & Localization

State-of-the-art

Diff based
C. H. Williams

Spatial based
P. Nikitin

AOA based
S. Azzouzi

Holographic
R. Miesen

[1] Lionel M. Ni, Yunhao Liu, et al. LANDMARC: Indoor Location Sensing Using Active RFID Wireless Networks


RFID Tracking & Localization

State-of-the-art

- AOA based by S. Azzouzi
- Holographic by R. Miesen
- PinIt by Jue Wang
- RF-Compass by Jue Wang

[1] Lionel M. Ni, Yunhao Liu, et al. LANDMARC: Indoor Location Sensing Using Active RFID Wireless Networks


RFID Tracking & Localization
State-of-the-art

[1] Lionel M. Ni, Yunhao Liu, et al
LANDMARC: Indoor Location Sensing Using Active RFID Wireless Networks


New measurement results for the localization of UHF RFID transponders using an angle of arrival (AOA) approach. IEEE RFID 2011.


 PinLt
Jue Wang

RF-Compass
Jue Wang

BackPos
Tianci Liu

RF-IDRaw
Jue Wang

2004
2010
2011
2013
2014
RFID Tracking & Localization
State-of-the-art

[1] Lionel M. Ni, Yunhao Liu, et al. LANDMARC: Indoor Location Sensing Using Active RFID Wireless Networks


BackPos
Tianci Liu

RF-IDRaw
Jue Wang

WE ARE HERE
RSS based Methods

RSS is not a reliable location indicator especially for UHF tags
State-of-the-art Techniques

2 Phase based Methods

PinIt (SIGCOMM 2013)

RF-Compass (MobiCom 2013)

Needs to deploy dense reference tags
Summary of Challenges

- **Need mm-level localization accuracy achieved**
  - especially for mobile tags.

- **Small overhead, COTS devices**
  - infeasible for using many references for a tracking system spanning a long pipeline.

- **Fast-changing environment**
  - multipath reflection of RF signals
  - varied orientation of tags
  - Doppler effect
3 How Tagoram works?
Overview the basic idea
Backscatter Communication

1. **Battery free**
2. **Double distance**
3. **Continuous wave**
4. **Device diversity**

\[ \theta = \left( \frac{2\pi}{\lambda} \times 2d + \theta_T + \theta_R + \theta_{TAG} \right) \mod 2\pi \]
COTS RFID Reader

0.0015 radians (4096 bits) \approx 0.038mm accuracy

Impinj Reader
Problem definition

Utilizing antennas’ locations, sampled phase values and timestamps to find out the tag’s trajectory $f(t)$?

\[
\begin{align*}
&\{(\theta_{1,1}, t_{1,1}), (\theta_{1,2}, t_{1,2}) \ldots, (\theta_{1,N}, t_{1,N})\} \\
&\{(\theta_{2,1}, t_{2,1}), (\theta_{2,2}, t_{2,2}) \ldots, (\theta_{2,N}, t_{2,N})\} \\
&\vdots \\
&\{(\theta_{M,1}, t_{M,1}), (\theta_{M,2}, t_{M,2}) \ldots, (\theta_{M,N}, t_{M,N})\}
\end{align*}
\]

$M \times N$
Tagoram

Case 1. Controllable Case

Case 2. Uncontrollable Case
Movement with Known Track

Controllable case

Our goal is to find the tag’s trajectory with a known track.
Virtual Antenna Matrix

Inverse Synthetic Aperture Radar

\[ f(t_0) \]

Initial position

Conveyor

\[ V \]

\[ A_1 \]

\[ A_{1,1} \]

\[ A_{1,2} \]

\[ A_{1,3} \]

\[ A_{1,4} \]

\[ A_2 \]

\[ A_{2,1} \]

\[ A_{2,2} \]

\[ A_{2,3} \]

\[ A_{2,4} \]
RF Hologram

Surveillance region $W \times L$ grids

RF Hologram $W \times L$ pixels
The key is

How to define the likelihood?
RF Hologram

Naïve Hologram

Device diversity

Augmented Hologram

Thermal noise

Differential Augmented Hologram
Naïve Hologram

The real signal

The theoretical signal

A virtual interfered signal
Naïve Hologram

**Definition:** The naïve hologram is an image in which the pixel value $x_{w,l}$, indicating the likelihood that the corresponding grid $X_{w,i}$ is the initial position, is calculated by

$$x_{w,l} = \left| \sum_{m=1}^{M} \sum_{n=1}^{N} S(X_{w,l}, A_{m,n}, \theta_{m,n}) \right|$$

where $S(X, A, \theta) = e^{i(h(X,A)-\theta)}$. The term $i$ denotes the imaginary number and the term $e^{i\theta}$ represents a complex exponential.
If $X$ is the initial location, the waves add up constructively.
Naïve Hologram

If $X$ is not the initial location, the waves canceled out.
Naïve Hologram

High PSNR
Influence from Thermal Noise

100 tags

$0^\circ \sim 40^\circ$

$920 \sim 926 \text{MHz}$

$-70 \sim -30 \text{dbm}$

Experiment

Modeling

Observations

CDF

$\theta \sim \mathcal{N}(\mu, \sigma)$

varying with $d$

$\sigma = 0.1$

$F(\theta; \mu, \sigma)$

$\theta \sim \mathcal{N}(\mu, \sigma)$
How to deal with thermal noise?

Augmented Hologram
Augmented Hologram

**Definition 2 (AH).** The augmented hologram is an image in which the pixel value $x_{w,l}$ is given by:

$$x_{w,l} = \sum_{m=1}^{M} \sum_{n=1}^{N} |S(X_{w,l}, A_{m,n}, \theta_{m,n})|$$

where

$$\|S(X, A, \theta)\| = 2 \times F(|h(X, A) - \theta|; 0, 0.1)$$

and $F(x; \mu, \sigma)$ is the cumulative probability function of Gaussian distribution $\mathcal{N}(\mu, \sigma)$. 

$$(h(X, A) - \theta) \sim \mathcal{N}(0, 0.1)$$

**Probability of $T \rightarrow A$**
Augmented Hologram

Shift

Ground truth

Result

scattered
Influence from Tag Diversity

Experiment

70 tags
100 times
At same position

Modeling

\[ \theta = \left( \frac{2\pi}{\lambda} \times 2d + c \right) \mod 2\pi \]

\[ c = \theta_T + \theta_R + \theta_{\text{TAG}} \]

Observations

Pass KS-test to be verified over a uniform distribution with 0.5 significant level.

Random test

Pass KS-test to be verified over a uniform distribution with 0.5 significant level.
How to eliminate tag diversity?

Differential Augmented Hologram
Definition 3 (DAH). The differential augmented hologram is an image in which the pixel value is calculated by

\[ x_{w,l} = \left| \sum_{m=1}^{M} \sum_{n=1}^{N} \|S(X_{w,l}, A_{m,n}, \theta_{m,n})\| S(X_{w,l}, A_{m,n}, \theta_{m,n}) \right| \]

where

\[
\begin{align*}
S(X_{w,l}, A_{m,n}, \theta_{m,n}) &= e^{j\theta_{dif}} \\
\|S(X_{w,l}, A_{m,n}, \theta_{m,n})\| &= 2 \times F(|\theta_{dif}|; 0, 0.1 \times \sqrt{2}) \\
\theta_{dif} &= (h(X_{w,l}, A_{m,n}) - \theta_{m,n}) - (h(X_{w,l}, A_{m,1}) - \theta_{m,1})
\end{align*}
\]

Using the difference of phase values
Differential Augmented Hologram

Ground truth

Result
Movement with Unknown Track
Uncontrollable case
Overview

1. Estimating Speeds, Fitting tag’s trajectory
2. Selecting the optimal trajectory
6 Implementation & Evaluation
Purely based on COTS devices
**Hardware & Software Introduction**

**Reader**
- ImpinJ R420 reader.
- 4 directional antennas

**Tag**
- Alien 2 × 2 Inlay
- Alien Squiggle Inlay

**Software**
- EPCglobal LLRP
- Java
A mobile object is emulated via a toy train on which a tag is attached.

A camera is installed above the track to capture the ground truth.

The system triggers the camera to take a snapshot on the train when firstly read.
Improve the accuracy by $48 \times, 30 \times, 28 \times$ and $8.5 \times$ in comparison to RSS, OTrack, PinIt and BackPos.
Controllable Case with Nonlinear Track

• The track’s internal diameter is 540mm
• The distance varies from 1m to 15m
Nonlinear track

- X-Axis: mean=4.14, std=2.95
- Y-Axis: mean=4.98, std=3.00
- Combined: 7.29

Accuracy (mm)
Under Uncontrollable Case

Achieve a median of 12.3cm accuracy with a standard deviation of 5cm.
Pilot Study
In two airports
Current workflow – Manual sortation

It is error-prone step to find the baggage from the carousel in manual sortation.
Our system: TrackPoint
Tracking Visualization

(a) TrackPoint & Visualization  (b) Display screen

(c) Screenshot  (d) TrackPoint & Visualization
Pilot site

Beijing Capital International Airport

Sanya Phoenix International Airport
Setup

• Each airport contains 5 TrackPoints, 4 visualization screens, and 22 RFID Printers.

• The two-year pilot study totally spent more than $600,000
Setup

- Consumed **110,000** RFID tags.

- Involved **53 destination airports**, **93 airlines**, and **1,094 flights**.
Tagoram achieves a median accuracy of 6.35cm in practice.
Conclusion

• Provides real-time tracking of mobile tags with accuracy to mm-level.

• Limits almost all negative impacts.
  • Multipath effect
  • Doppler effect
  • Thermal noise
  • Device diversity \[ \text{Not well-studied before} \]

• Implemented purely based on COTS RFID products.

• Systematically evaluated under indoor environment and at two airports.
Questions?

Thank you