RIM: RF-based Inertial Measurement

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Motion Estimation

Robot Navigation
VR Gaming
Sports Analytics

Mobiles & Wearables
Robots
Drones
Inertial Measurement Unit

**Motion Parameters**
- Moving Distance
- Heading Direction
- Rotating Angle

**IMU**
- **Accelerometer**: Measuring the linear acceleration
- **Gyroscope**: Calculating the angular velocity
- **Magnetometer**: Reporting the absolute orientation

$21.74$ billion IMU market by 2022!

**Significant limitations in precise and robust motion estimation:**
- **Accelerometer**: Noisy readings, step counting for distance
- **Gyroscope**: Accumulative errors due to integration
- **Magnetometer**: Environment interference, cannot infer heading direction
Existing Wireless Localization & Tracking

Mainly use geometric channel parameters like AoA, ToF

- Require phased arrays
- Multiple APs with precise location and/or orientation info
- Degenerate or fail in complex multipath scenarios
- Address only locations, but not motion parameters

Multipaths is still enemy!
RIM: RF-based Inertial Measurement

• Turns COTS WiFi radio into precise IMU that measures multiple motion parameters at centimeter accuracy:
  • Moving distance, Heading direction, Rotating angle

One single arbitrarily placed AP
COTS WiFi receiver

• One single arbitrarily placed AP, without knowing its location/orientation
• No additional infrastructure
• Not require large bandwidth or many phased antennas
• No need of a priori calibration
• Works anywhere the AP signal reaches, be there LOS or through multiple walls

How to achieve all these features in one system?
Spatial-Temporal Virtual Antenna Retracing (STAR)

Multipath Profiles as Virtual Antennas!

1 antenna

1D STAR

Aligned virtual antennas

\[ \hat{\nu} = \frac{\Delta d}{\Delta t} \]

\[ d = \int_{t_0}^{t_k} \hat{\nu} dt \]

Moving distance
STAR in 2D space

- Line: 2 directions
- Triangle: 6 directions
- Quadrangle: 12 (6) directions

Identifying the aligned antenna pair will give the moving direction

- \( m \) antennas → \( m(m-1)/2 \) lines → \( m(m-1) \) directions → \( 2\pi/(m \times (m - 1)) \) orientation resolution

Heading direction
STAR in 2D space

6-element hexagonal array:
• 12 different directions in total and thus an orientation resolution of 30°
• Build from two COTS WiFi radios without phase synchronization

Translational motion:
• At most three aligned pairs

Rotational motion:
• All adjacent pairs will be aligned
Super-Resolution Virtual Antenna Alignment

How to accurately pinpoint the space-time point that two virtual antennas are aligned with each other, at sub-centimeter resolution?

\[ \Delta d = \frac{\lambda}{2} \]

\[ \text{e.g., } 1\text{cm error} = \sim 50\% \text{ error in speed} \]

\[ = 30^\circ \text{ heading error} = 22^\circ \text{ rotation error} \]

Time Reversal Resonating Strength

Virtual Massive Antennas
Time Reversal Resonating Strength (TRRS)

- **Time-Reversal Focusing Effect**: The received CSI, when combined with its time-reversed and conjugated counterpart, will add coherently at the intended location but incoherently at any unintended location, creating a spatial focusing effect.

\[
\kappa(h_1, h_2) = \frac{\left(\max_i |(h_1 \ast g_2)[i]|\right)^2}{|\langle h_1, h_1 \rangle \langle g_2, g_2 \rangle|}
\]

- **STAR Resolution**
  - The peak value as high as possible
  - The peak width as narrow as possible
  - The above two properties as robust as possible

\[
\kappa(H_1, H_2) = \frac{|H_1^H H_2|^2}{\langle H_1, H_1 \rangle \langle H_2, H_2 \rangle}
\]
Virtual Massive Antennas

• Overcome distortions in TRRS: Leveraging consecutive multipath profiles as massive virtual antennas

\[ \kappa(P_i(t_i), P_j(t_j)) = \frac{1}{V} \sum_{k=-V/2}^{V/2} \tilde{\kappa}(H_i(t_i + k), H_j(t_j + k)) \]
**TRRS Matrix**

Normal retracing

Deviated retracing

Noticeable TRRS peaks still exist, albeit weaker:

- Focus on relative TRRS peaks within a window instead of the absolute values

Which antenna pair(s) is aligned and what is the alignment delay?
Tracking Alignment Delay

- Continuously track alignment delay via Dynamic Programming

\[
S(q_i \sim q_{jn}) = \max_{l \in [-W, W]} \left\{ S(q_i \sim q_{kl}) + S(q_{kl} \sim q_{jn}) \right\}
\]

\[
S(q_{kl} \sim q_{jn}) = e_{kl} + e_{jn} + \omega C(q_{kl}, q_{jn})
\]

\[
n^* = \arg \max_{n \in [-W, W]} \left\{ S(q_i \sim q_{jn}) \right\}
\]
Detecting Aligned Pairs

- Detect the top two aligned pairs by TRRS peaks, continuity and smoothness of the peak trace, and the orientations they indicate.
Putting It All Together

• Suppose the \( i \)th and \( j \)th antennas are detected to be aligned at time \( t \), with a separation distance of \( \Delta d_{ij} \) and an alignment delay of \( \Delta l_{ij}(t) \):
  
  • Moving distance: 
    \[
    d(t) = \int_0^t v(\tau) d\tau = \int_0^t \frac{\Delta d_{ij}}{\Delta l_{ij}(\tau)} d\tau
    \]

  • Heading direction: 
    \[
    \theta = \begin{cases} 
      \text{antenna } i \rightarrow \text{antenna } j, & \text{if } \Delta l_{ij}(t) \geq 0 \\
      \text{antenna } j \rightarrow \text{antenna } i, & \text{otherwise}
    \end{cases}
    \]

  • Rotating angle: 
    \[
    \Delta \theta = \begin{cases} 
      \frac{R}{r}, & \text{if rotation detected} \\
      0, & \text{otherwise}
    \end{cases}
    \]
Implementation

- Qualcomm Atheros 9k series chipset
- Running on Intel Galileo Gen2 board (built with an IMU)
- Antennas are spaced at a half wavelength distance (2.58 cm)
- Packet level synchronization (no phase sync required)
Evaluation

• A single AP, 7 different locations
• Both LOS and NLOS (40m away through multiple walls)
• 200Hz sampling rate on a 40MHz channel in the 5GHz band
Performance - Moving Distance

• On desktop: we move the array on a desk surface for traces around 1 m;
• On cart: we put the array on a cart and push it straight forward by more than 10 meters in different areas.
Performance - Heading Direction

• Traverse a 90° range with an increased step of 10°, together with each of their opposite directions

• >90% of heading errors are within 10°, with an overall average accuracy of 6.1°
Performance - Rotating Angle

• Median error of $30.1^\circ$, corresponding to an error of merely 1.3 cm in arc lengths (i.e., moving distances)
• Not as good as gyroscope (in short period)
Impacts of Different Factors

- **Total distance**
  - Box plots showing distance error against movement distance.

- **Sampling rate**
  - CDF graphs showing distance error against distance error.
  - Different colors represent different sampling rates (200Hz, 100Hz, 60Hz, 40Hz, 20Hz).

- **AP locations**
  - CDF graphs showing distance error against distance error.
  - Different colors represent different AP locations (AP loc. #1 to AP loc. #6).

- **Virtual antennas**
  - CDF graphs showing distance error against distance error.
  - Different colors represent different virtual antennas (V = 100, V = 50, V = 60, V = 50, V = 10, V = 5, V = 1).
Potential Applications - Handwriting

• Move the array by freely writing some letters on a desk surface

Mean error: 2.4 cm

By RIM

By Camera

20cm
Potential Applications – Gesture Control

• Integrating RIM into a pointer-like unit
• One WiFi NIC with three small chip antennas arranged in an “L” shape.

96.25% detection rate
Potential Applications – Indoor Tracking

Tracking by RIM only

2D hexagonal array, resolving sideway movement for AGVs

Tracking by RIM integrated with sensors

1D linear array (3 antennas), obtaining direction by IMU, augmented with a particle filter (PF)
Demo: A WiFi Ruler with RIM

True Distance = 10.27 m

Measure the perimeter of a big round table

Estimated Distance = 10.22 m

More interesting videos in our Demo session on Wednesday, August 21!
Discussions and Future Work

• **Angle resolution**: Current RIM only exploits discrete directions defined by the antenna array. On-going work has improved continuous directions with <10° error.

• **Limitation of rotating angle**: It remains open to estimate angular motion more accurately.

• **3D motion**: Current RIM only addresses 2D motion. A 3D array or enhanced solutions is needed for 3D motion.

• **Fusing inertial sensors**: Leverage the complementary advantages of both systems, as demonstrated by our application case of indoor tracking.
Conclusion

• We present RIM, the first RF-based inertial measurement system that estimates centimeter-level moving distance, heading direction, and rotating angle using commercial WiFi radios.

• RIM leverages rich multipaths as virtual antennas and contributes a novel super-resolution virtual antenna alignment algorithm.

• RIM works in large area with or without LOS using a single AP that is arbitrarily placed, opening up new directions and new applications of WiFi-based motion sensing.
Thanks!

Q&A

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“We can only see a short distance ahead, but we can see plenty there that needs to be done.” — Alan M. Turing