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FootStep-Tracker: An Anchor-Free Indoor Localization System via Sensing the Foot Steps

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Outline

1. Background
2. System Overview
3. Step Length Estimation
4. Moving Direction Estimation
5. Global Trace Estimation
6. Performance Evaluation
7. Conclusion

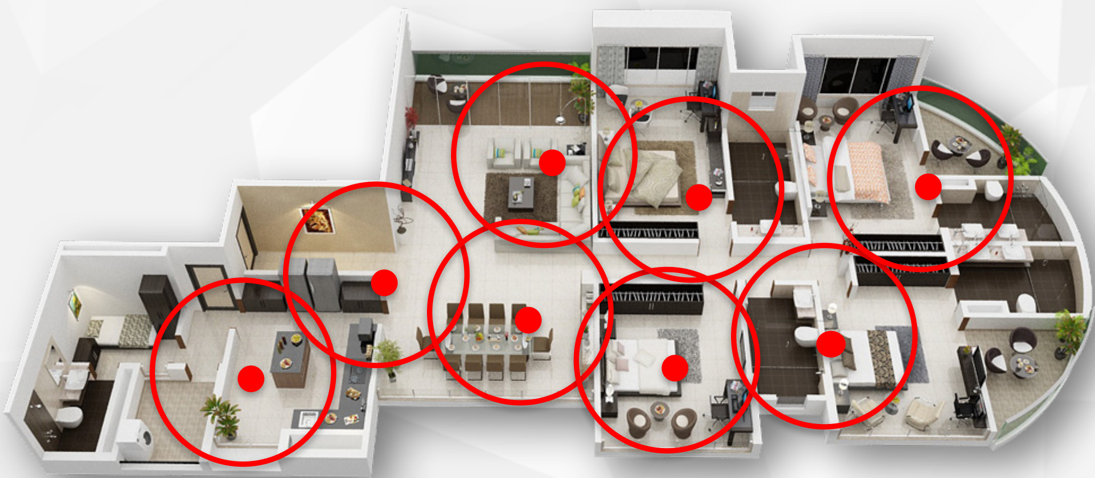
Background-Motivation

Indoor Localization

Context-Aware Services

Location-Based Services

Background-Motivation



Wi-Fi or Bluetooth-based schemes

- Impossible or expensive to deploy a large number of devices as the localization infrastructures
- Not scalable to any other situations without these infrastructures

Design an anchor-free approach for indoor localization without any requirement for the infrastructure.

Background-Limitation of Prior Art

Wearable-based Solutions

- Approach:
  - Leverage the devices with embedded inertial sensors, such as smart phones or wearable bracelets, to position and track the users.
- Limitations:
  - Putting a device in pant pockets or on a wrist cannot accurately capture a user’s movements, including moving directions and distances.
  - Estimating moving distance by counting foot steps is not adaptive to the variation of a user’s moving activities with varying step lengths.
  - Anchor nodes still need to be leveraged to help determine their exact positions in the map.

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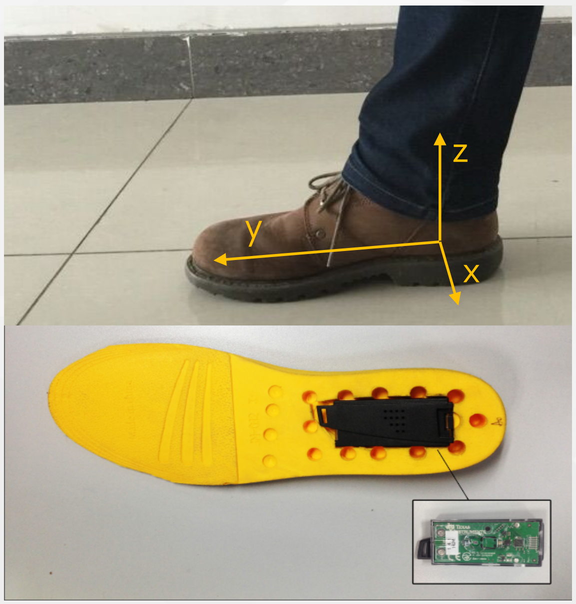
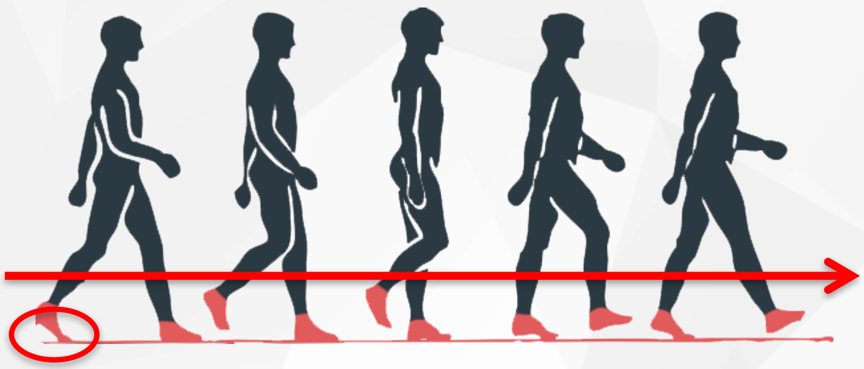
System Overview: FootStep-Tracker

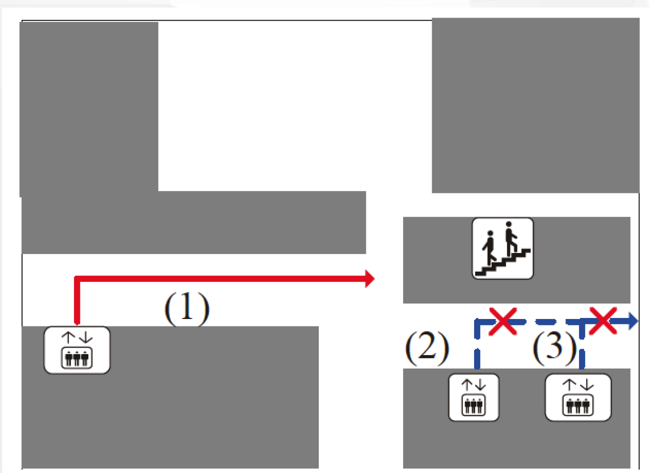


Our Solution: An anchor-free indoor localization scheme purely based on sensing the user's footsteps

Observation: The moving activities can be accurately inferred from the footsteps by leveraging the sensors embedded in shoes, such as accelerometers and gyroscopes

System Overview: FootStep-Tracker





FootStep-Tracker

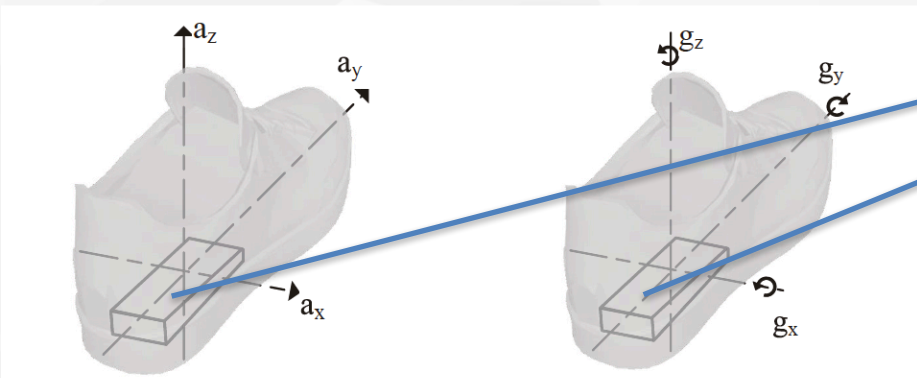
- Accurately perceive the user's moving traces, including moving direction and distance, by leveraging accelerometers and gyroscopes.

- Detect the user's activities, such as ascending/descending the stairs or taking an elevator, correlate with the positions of the stairs and elevators, and determine the global moving traces by leveraging the space constraints in the map.

System Overview: System Deployment

CC2541
SensorTag

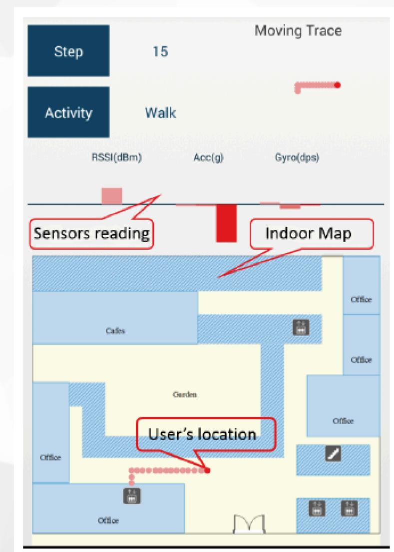
Sampling frequency: 20Hz for both accelerometer and gyroscope



(a) Axes of accelerometer. (b) Axes of gyroscope.

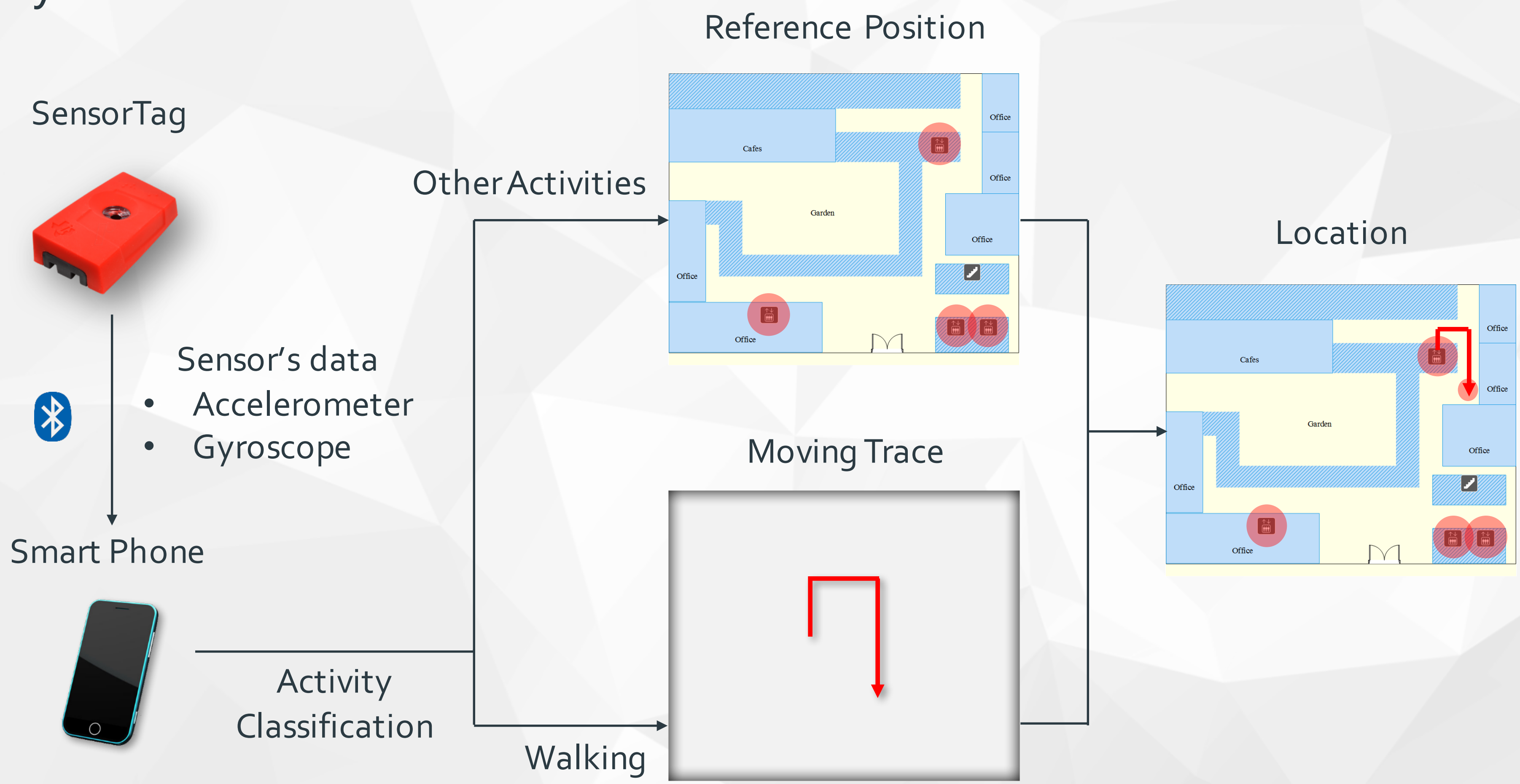
SensorTag coordinate system

Android Phone

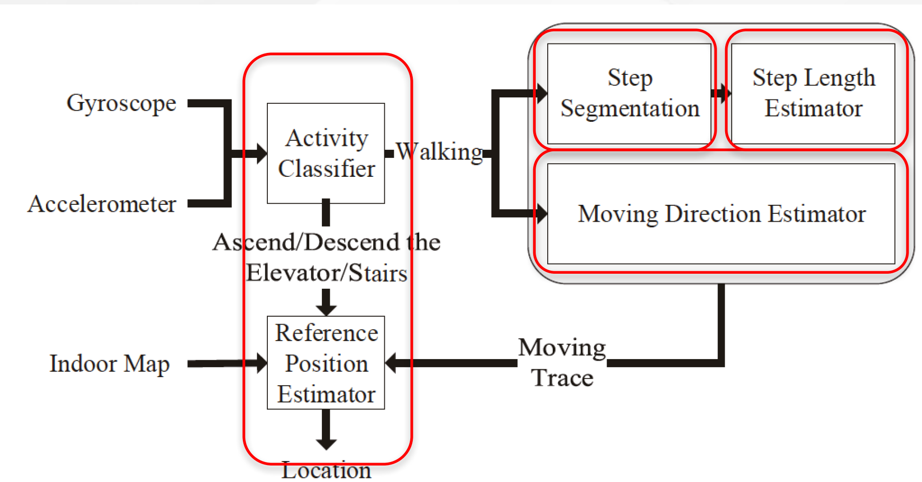


Application

System Overview: Work Flow



System Overview: Framework



Framework of FootStep-Tracker

The components of FootStep-Tracker:

- **Activity Classifier & Reference Position Estimator**. Estimate the user's activities and corresponding reference positions for a given indoor map.
- **Step Segmentation**. Split the sequential sensor data of walking into segments; each segment represents the complete process of a footstep during walking.
- **Step Length Estimator**. Estimate the distance of each foot step in the horizontal line during walking.
- **Moving Direction Estimator**. Estimate the turning angle of foot steps and thus the moving direction during walking.

System Overview: Challenges

Challenge 1

Difficult to accurately estimate the user's horizontal step movements, as the sensors in the shoes actually capture the foot's movements in the air

Challenge 2

Difficult to accurately estimate the user's moving direction during the movement

Challenge 3

Essential to determine the absolute moving traces instead of the relative moving traces in the indoor map

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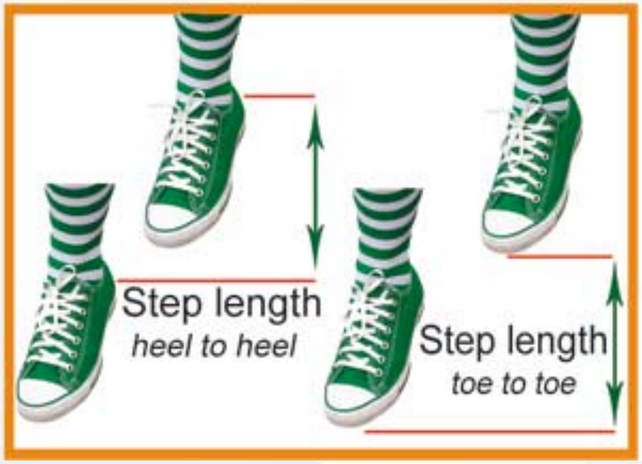
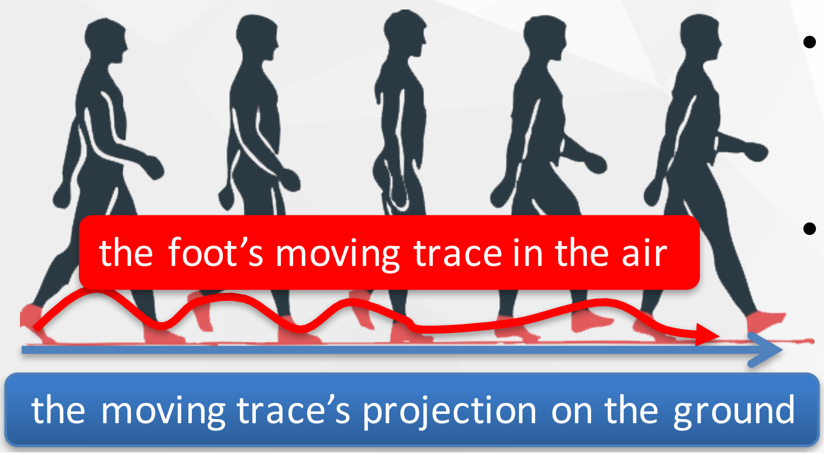
Step Length Estimation

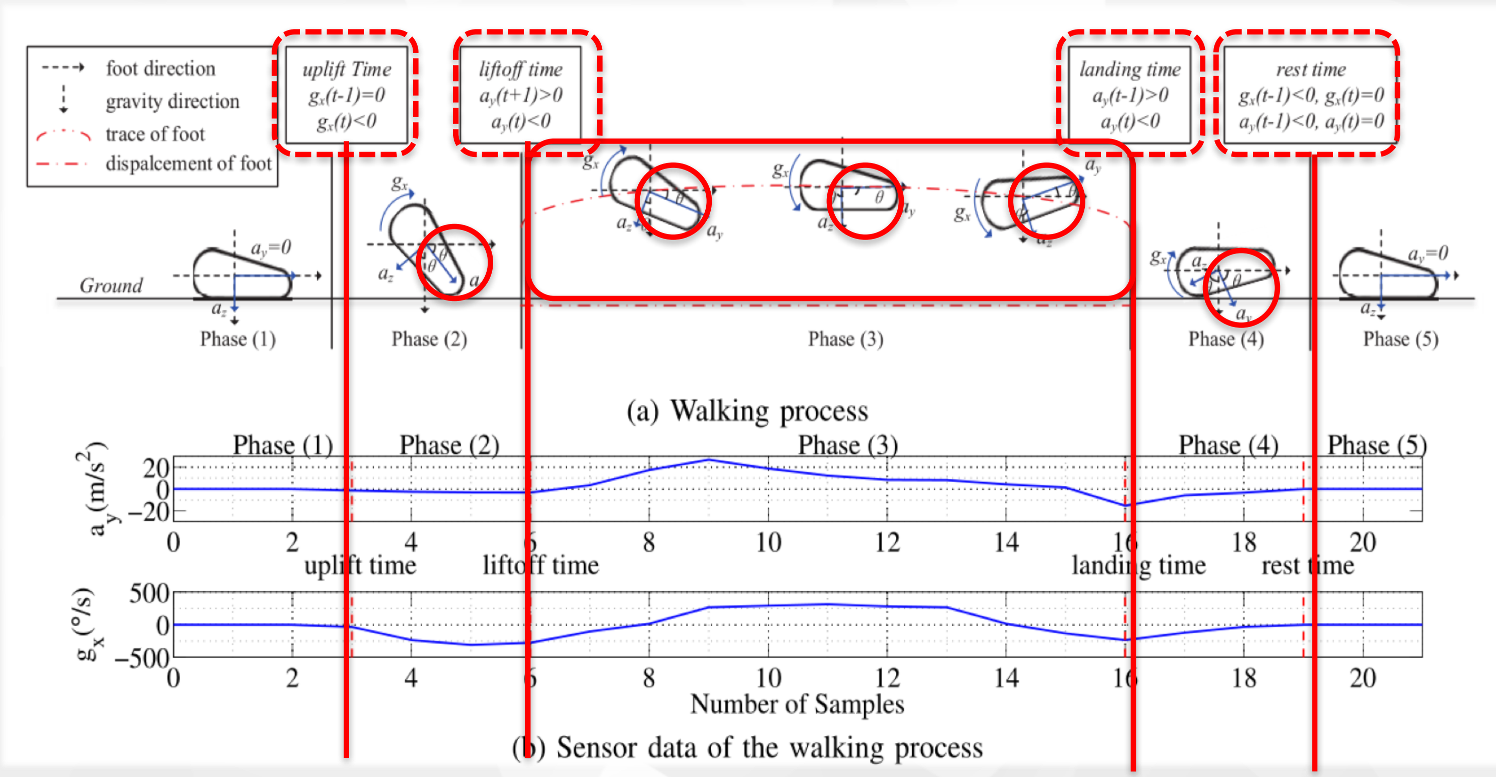




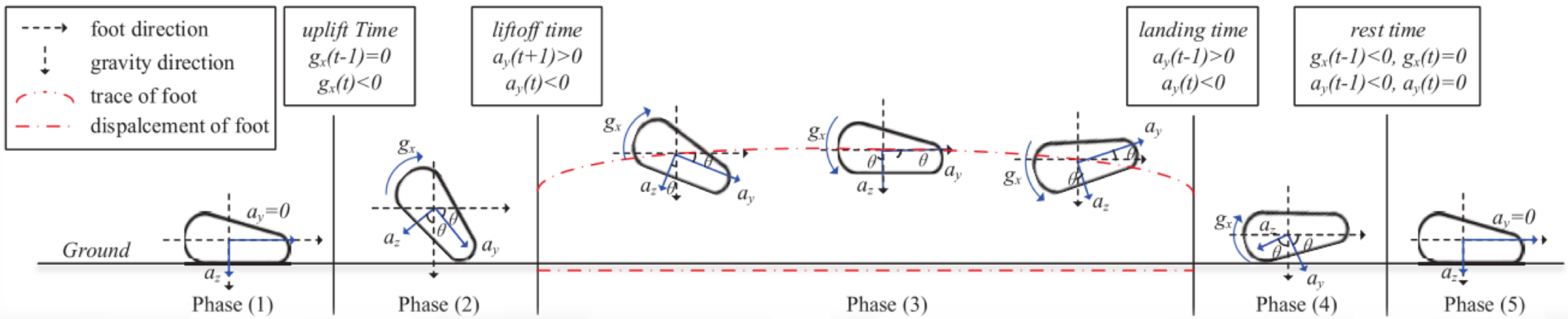
- **Motivation**
  - To estimate the moving trace, previous work assumes the step length for a specified user to be constant during a period of time.
  - The user may be walking with small steps or jogging with large steps. It is essential to estimate the length of steps in a real-time approach.
- **Challenge**
  - The step length is not exactly the length of the foot's moving trace in the air. Instead, it is the moving trace's projection on the ground.
  - Cannot directly derive the step length from the double integral on the acceleration measurement of the ay axis.

Step Length Estimation: Observation & Intuition

Critical Time Extraction.



Step Length Estimator



Track the angle rotation between ay and the horizontal direction.

$$\theta(t) = \int_{T_u}^{t} g_x(t)\ dt,\ \ t \in [T_u, T_r] \qquad (3)$$

Project the moving trace in the air to the trace on the horizontal ground.

$$a_f(t) \models a_y(t)cos(\theta(t)) + a_z(t)sin(\theta(t)),\ \ t \in [T_l, T_d] \qquad (2)$$

Step Length Estimation

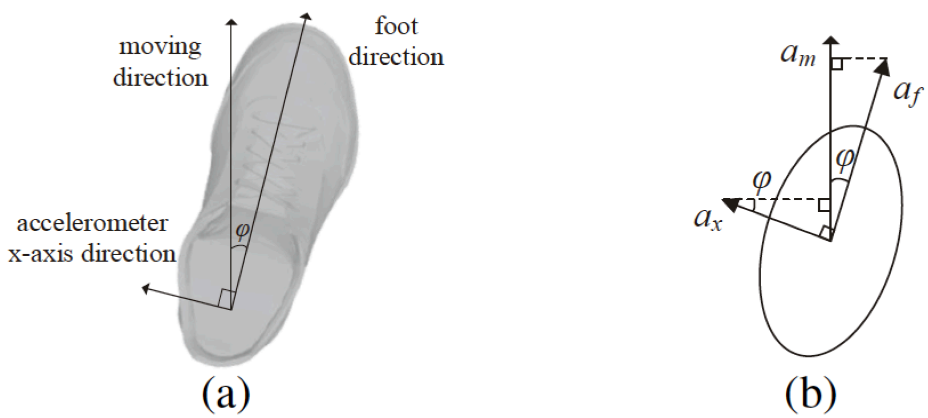


Fig. 9. The toe-in and toe-out situation.

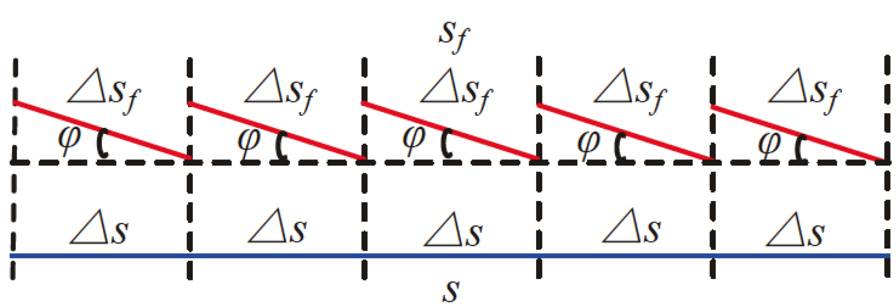


Fig. 10. Estimate the angle φ.

Tackle the toe in and toe out issue

Compute the forwarding acceleration in the horizontal moving direction.

$$a_m = a_f cos(\varphi) + a_x sin(\varphi)$$

Estimate the angle ψ.

$$\varphi = arccos(\frac{\Delta s}{\Delta s_f})$$

$$\varphi = arccos(\frac{s}{s_f})$$

Estimate the step length by computing the double integral formulation.

$$S = \int_{T_l}^{T_d} \int_{T_l}^{t'} a_m(t)\ dtdt'$$

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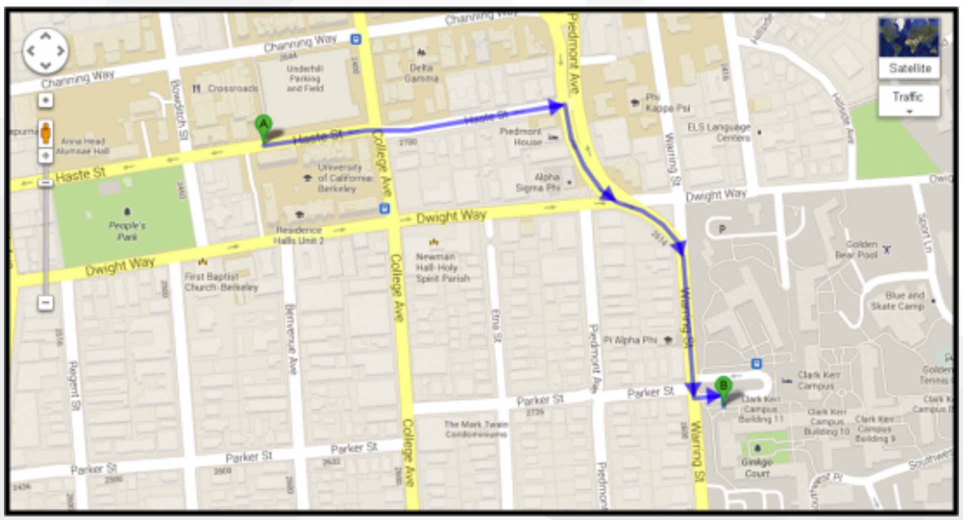
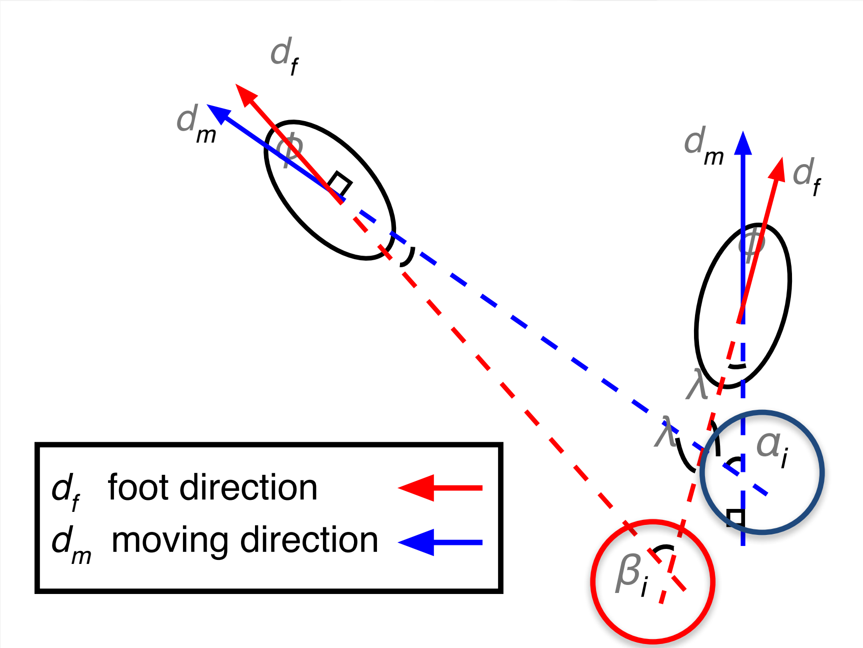
Moving Direction Estimation

- **Motivation**
  - To depict the user’s moving trace, we also need to figure out the user’s moving direction.
  - It is essential to estimate the moving direction according to the angle rotation of the foot direction.



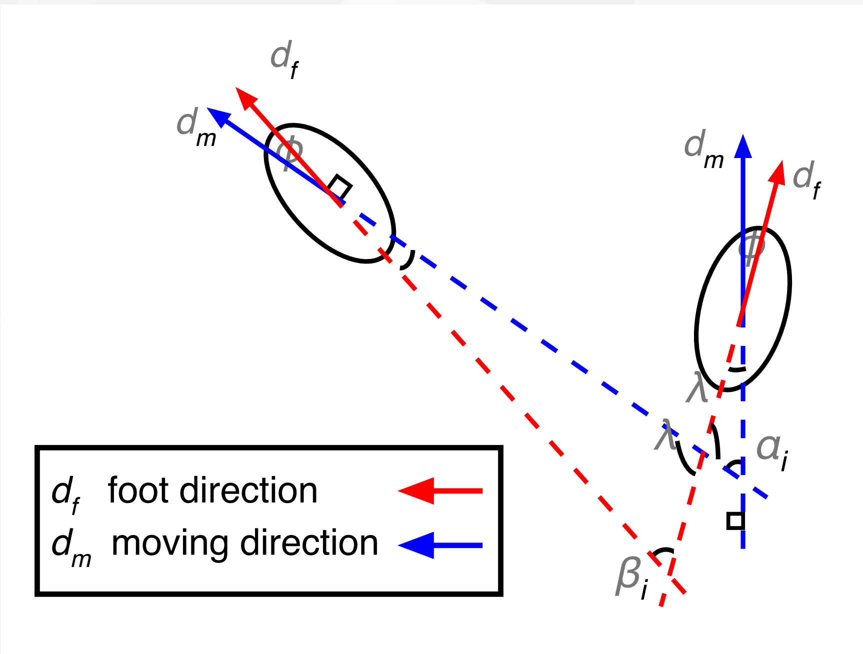
Moving Direction Estimation



- **Observation**
  - The degree of toe-in and toe-out is almost constant in a fairly long time interval.
  - As the user is walking, the angle variation of the foot's forwarding direction is very close to the angle variation of the moving direction.

Theorem 1. *Assume the angle φ between the foot direction, i.e., d_f, and moving direction, i.e., d_m, is invariable. Then the degree of the turning, i.e., α_i, is equal to the relatively variety angle of moving direction, i.e., β_i.*

Moving Direction Estimation



- **Solution**
  - Continuously track the angle rotation rates in the axis gz with the gyroscope.
  - For each step, compute the integral of the rotation rates from the liftoff time to the landing time.

$$\alpha_i = \beta_i = \int_{T_l}^{T_d} g_z(t)\ dt$$

  - Compute the sum of the angle change after n steps.

$$\alpha = \sum_{i=1}^{n} \alpha_i$$

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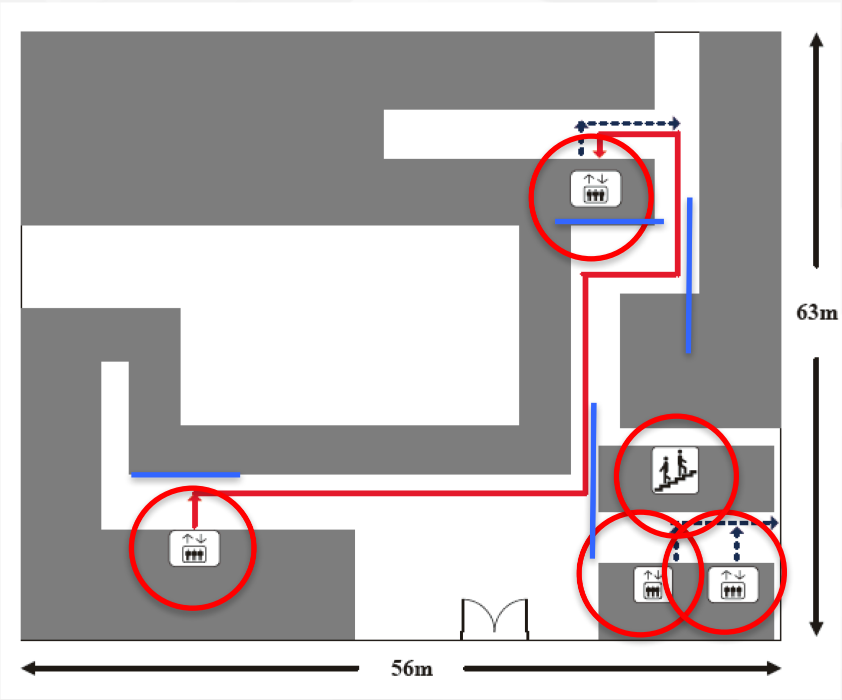
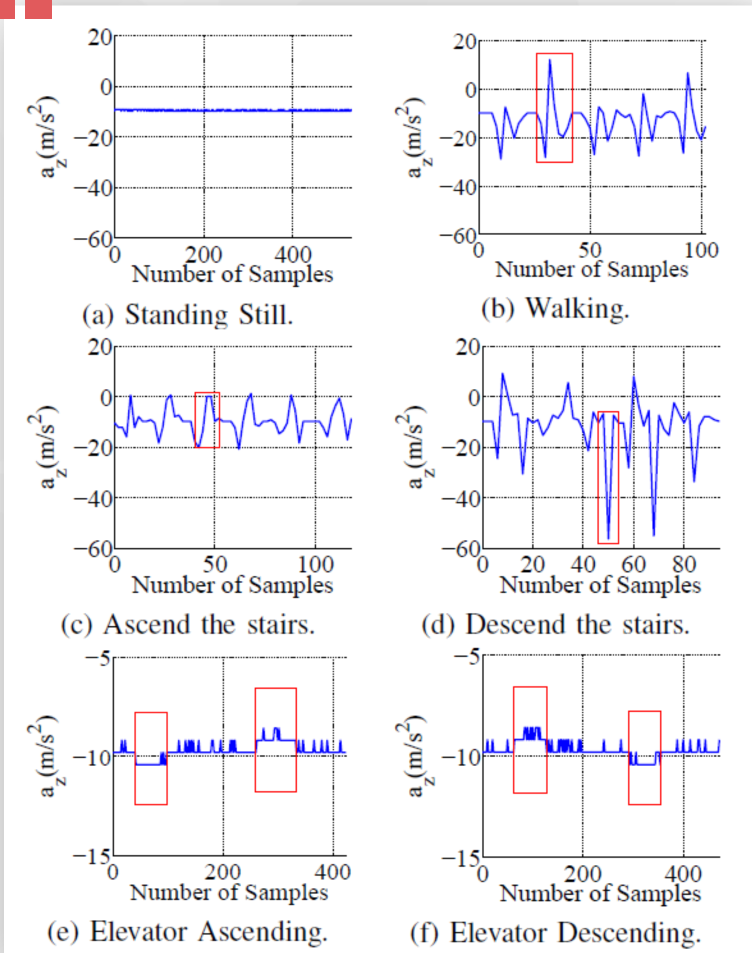
Global Trace Estimation

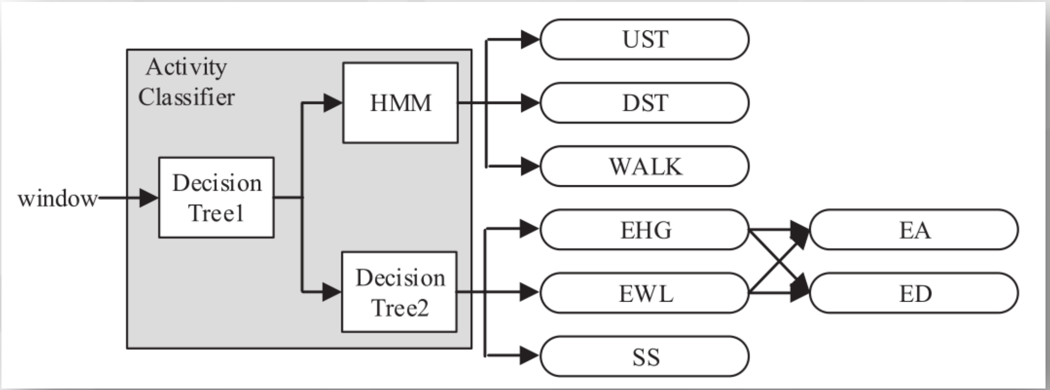


- **Motivation**
  - The ability to continuously track the user and estimate the relative moving trace of the user
  - The relative moving trace still needs to be fixed into the global indoor map.
  - Two clues are leveraged to derive the global moving trace:
    - The moving trace is constrained by the topological structure of the indoor environment.
    - Reference positions are derived according to the reference activities.

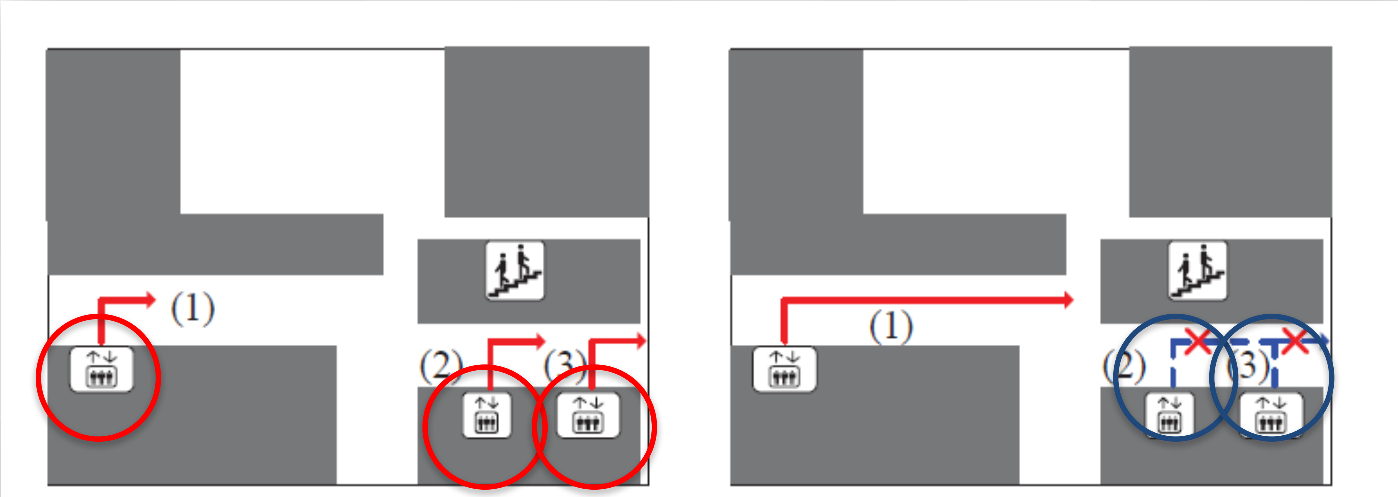
Global Trace Estimation



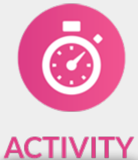
- **Activity Classifier**
  - **Extract different patterns and thresholds** for different activities including standing still, walking, ascending or descending stairs, and taking an elevator.
  - Propose an activity classifier based on the **Decision Tree** and **Hidden Markov Model** to classify these activities.



Global Trace Estimation: Solution



(a) Feasible traces. (b) Filter out infeasible traces.



Use **Activity Sensing** to figure out reference positions in the traces.

Use **Snake Game Strategy** to remove infeasible candidate traces.

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Performance Evaluation

Evaluate the Activity Classifier

	SS	EHG	EWL	UST	DST	WALK
SS	0.95	0.00	0.05	0.00	0.00	0.00
EHG	0.00	1.00	0.00	0.00	0.00	0.00
EWL	0.00	0.00	1.00	0.00	0.00	0.00
UST	0.00	0.00	0.00	0.99	0.00	0.01
DST	0.00	0.00	0.00	0.00	0.94	0.01
WALK	0.00	0.00	0.00	0.00	0.11	0.89

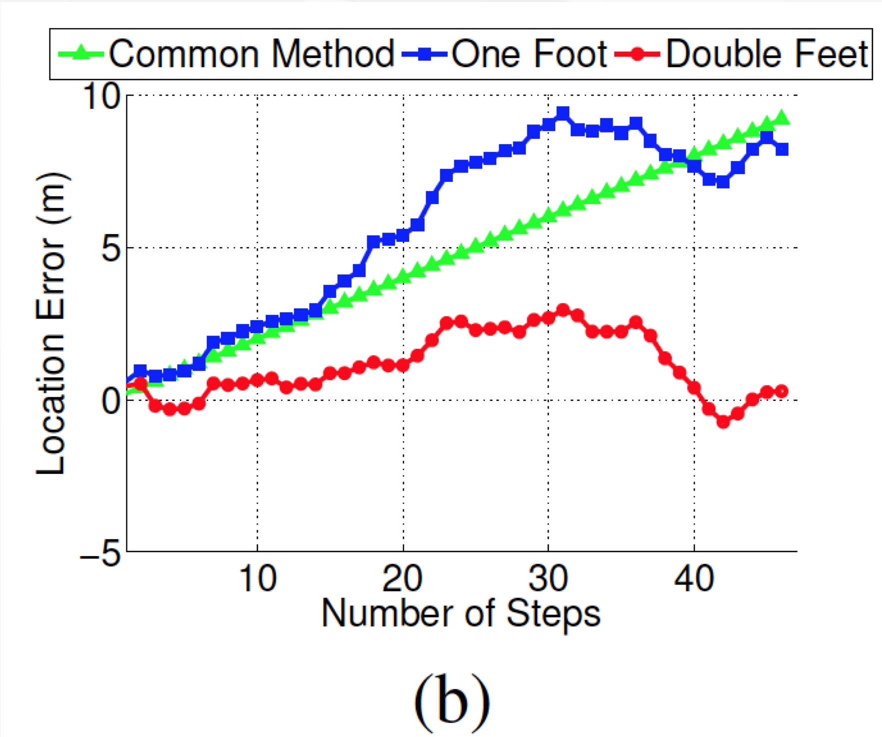
(a)

Activity Classifier Performance

Activity Classifier can accurately classify the corresponding six activities with an average accuracy of 96.2%.

Performance Evaluation

Evaluate the Step Length Estimator

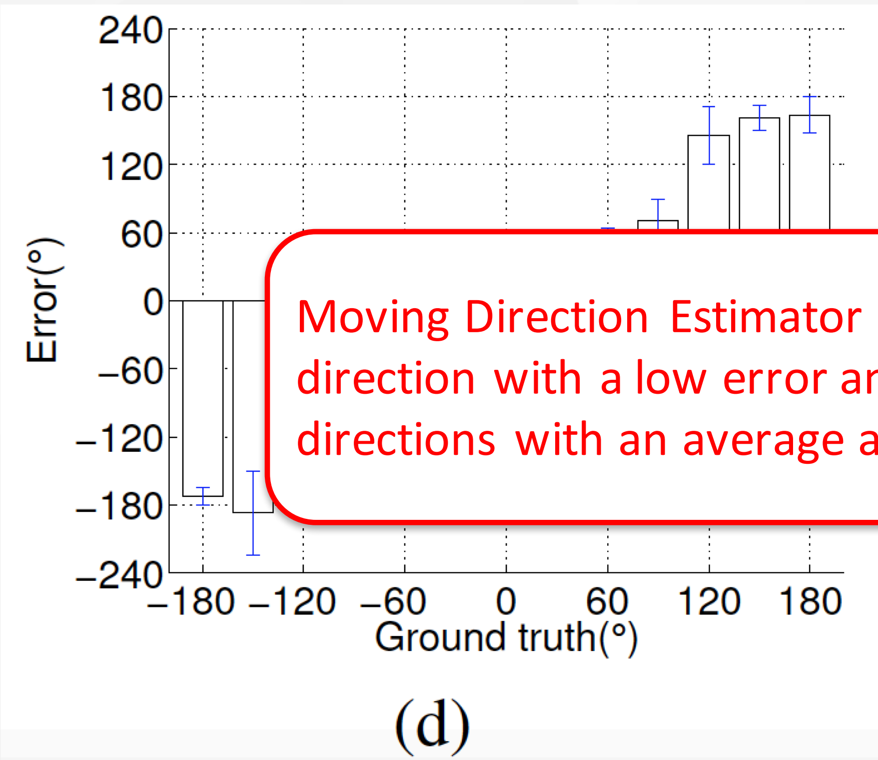


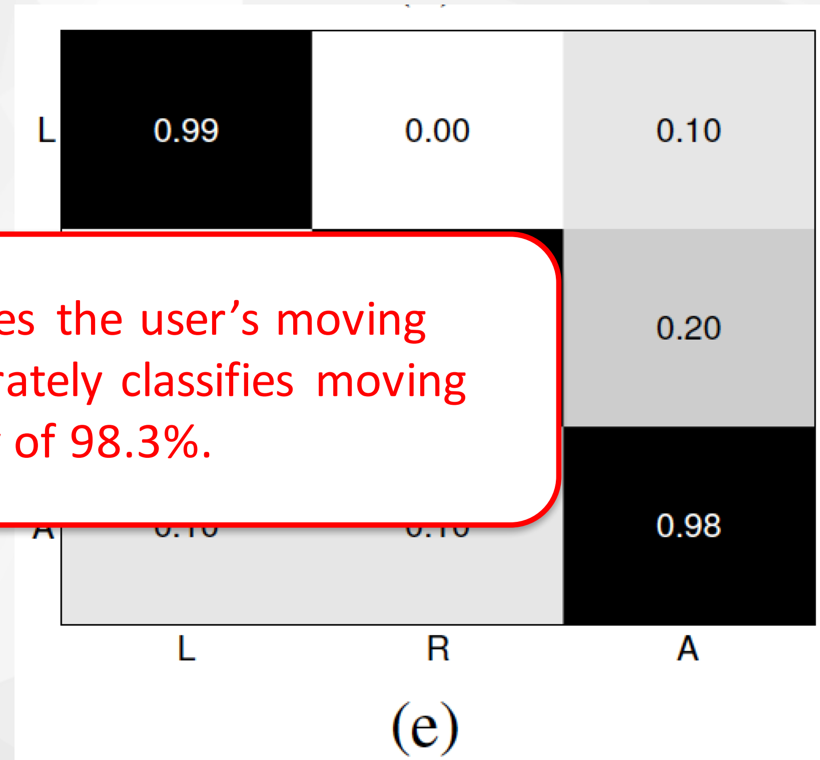
Location Error

Step Length Estimator accurately estimates the user's moving distance by effectively reducing the accumulated error to 0.2m after walking 63m.

Performance Evaluation

Evaluate the Moving Direction Estimator





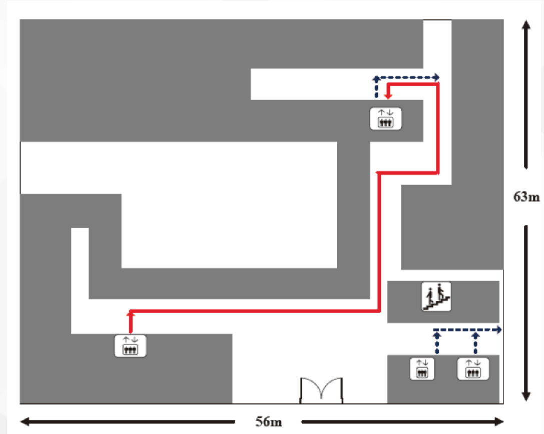
Moving Direction Estimator estimates the user's moving direction with a low error and accurately classifies moving directions with an average accuracy of 98.3%.

Moving Direction Estimator Performance.

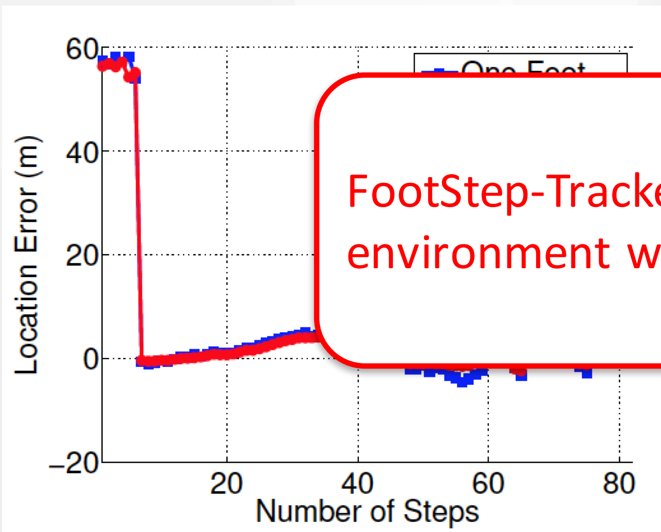
Classified Moving Direction Estimator Performance

Performance Evaluation

Case Study in a Real World Environment

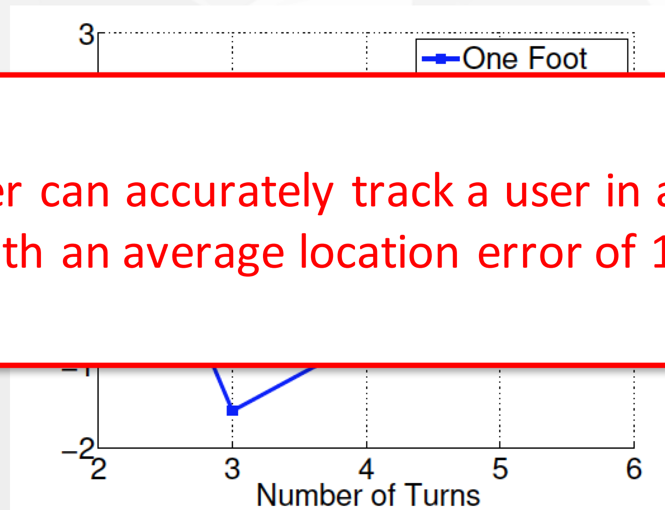


Walking paths in case study



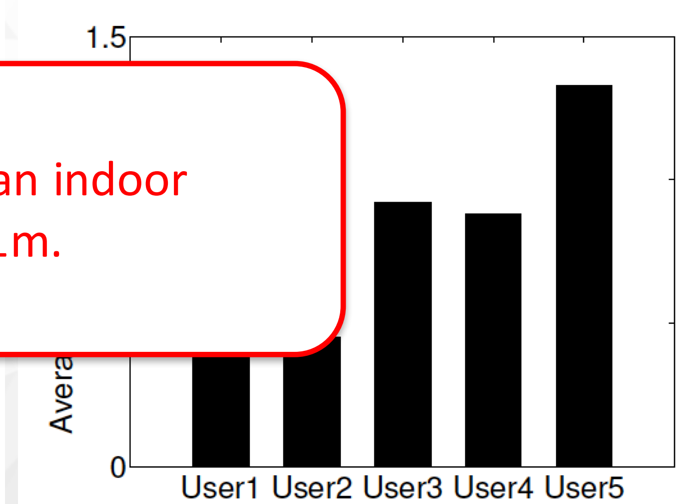
(f)

Location error with number of steps.



(g)

Location error with number of turns.



(h)

Location error for each user.

FootStep-Tracker can accurately track a user in an indoor environment with an average location error of 1m.

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Conclusion

We advance the state of the art from three perspectives:

- We propose an anchor-free indoor localization purely based on sensing the user's footsteps, without the support of any infrastructure.
- We propose efficient solutions to accurately estimate the moving direction and distance by only leveraging low-cost inertial sensors like the accelerometer and gyroscope.
- We leverage activity sensing to figure out reference positions during the process of tracking the user, so as to determine the exact moving traces in the indoor map.

Q&A

THANK YOU