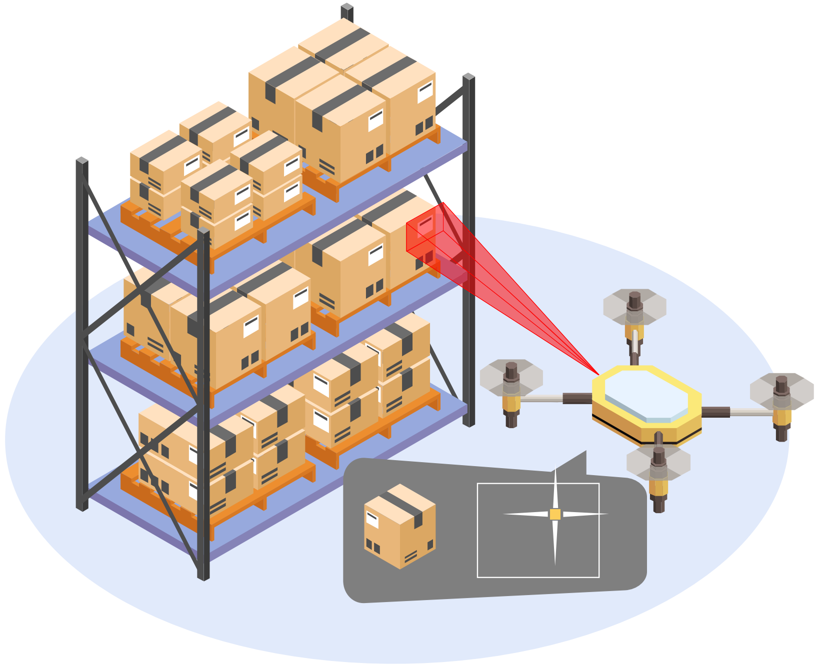
AIM: Acoustic Inertial Measurement For Indoor Drone Localization and Tracking

Yimiao Sun[1], Weiguo Wang[1], **Luca Mottola[2]**, Ruijin Wang[3], Yuan He[1]

[1] Tsinghua University
[2] Politecnico di Milano and RI.SE Sweden
[3] University of Electronic Science and Technology of China

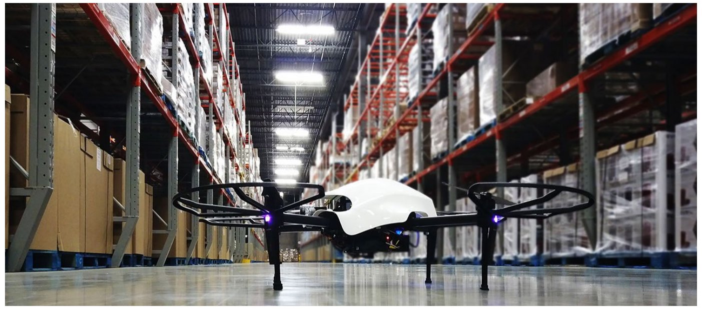
Emerging Indoor Drone Application



Indoor Warehouse

Inventory

Logistics



Surveillance

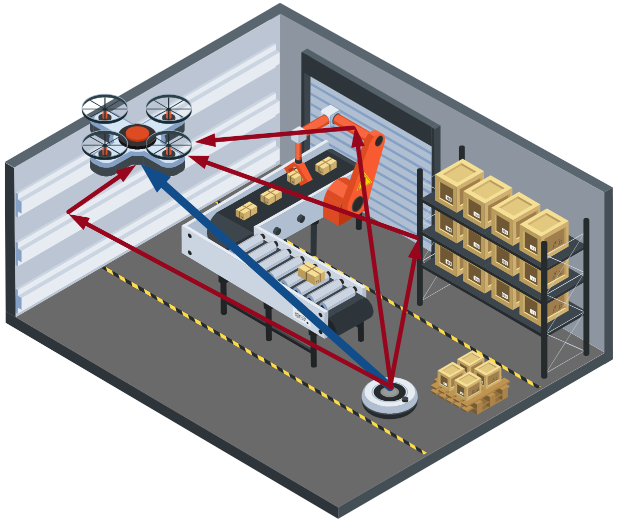
Dilemma of Indoor Drone Tracking

GPS-denied

IMU-based methods

suffer from error accumulation due to lack of absolute coordinate.

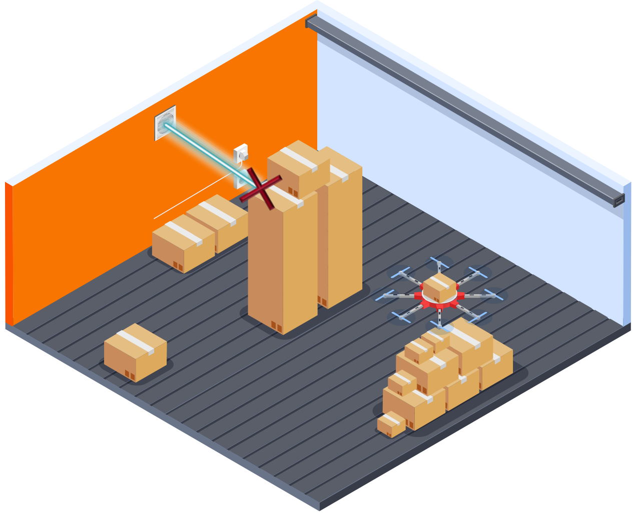
Rich mutipath



RF-based methods

suffer from signal distortion due to rich multipath on metal.

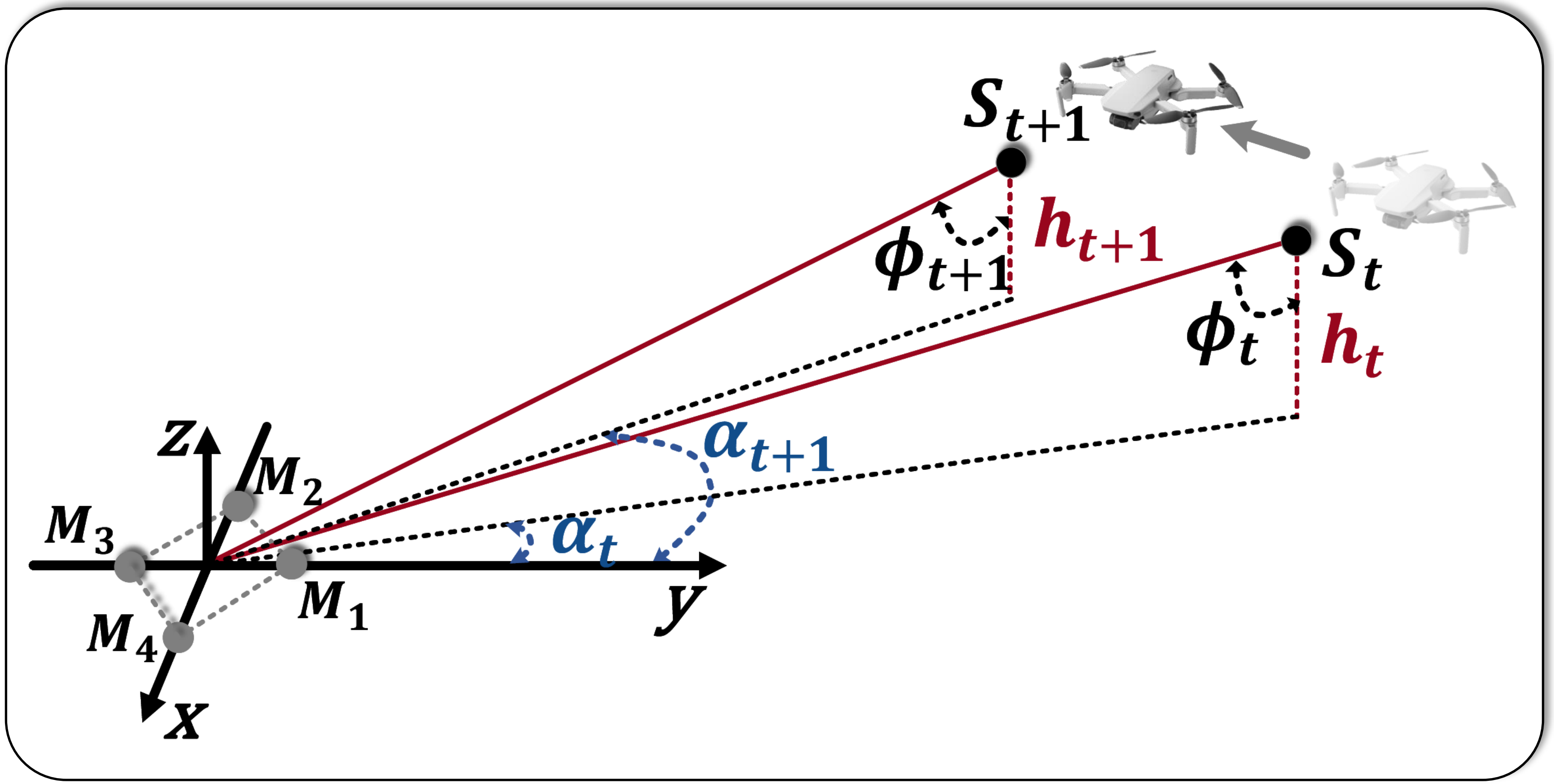
Frequent NLoS



Infrared-based methods

suffer from target loss due to frequent NLoS

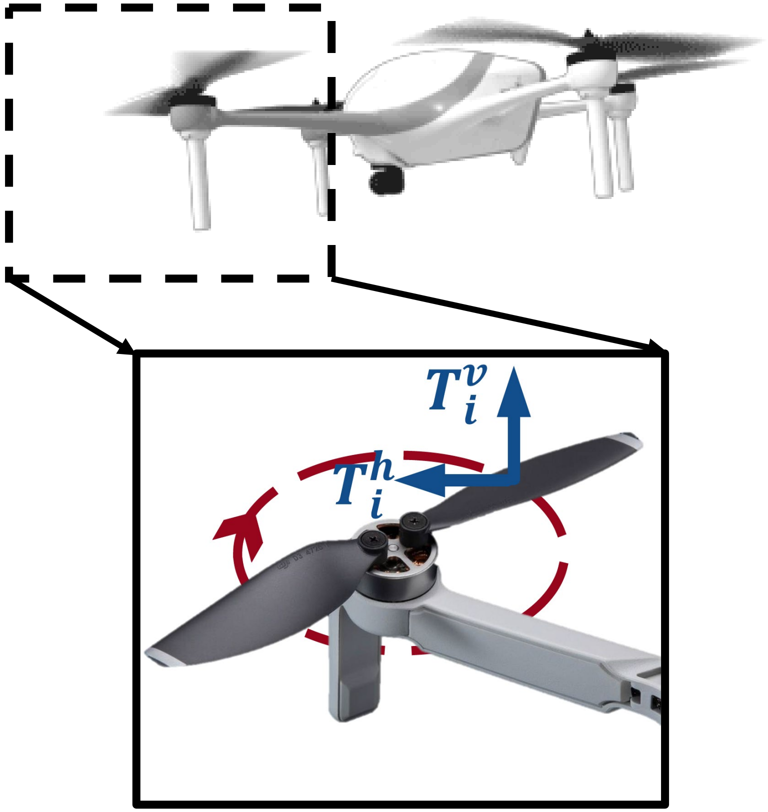
Our Method

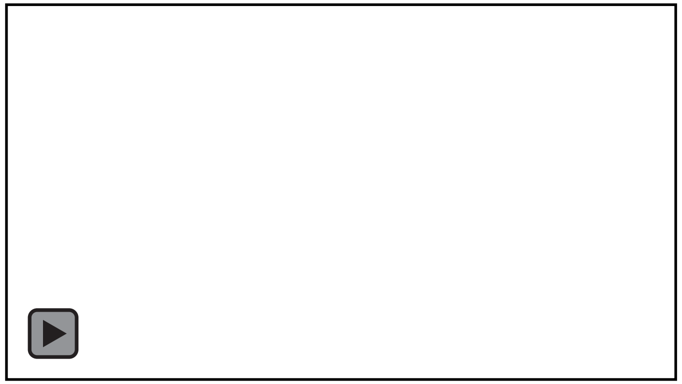


- **Mean Error**
  - 1.43m in LoS
  - 1.89m in NLoS
- **Error Comparison**
  - 46% less than UWB in NLoS
  - 57% less than GPS in outdoor

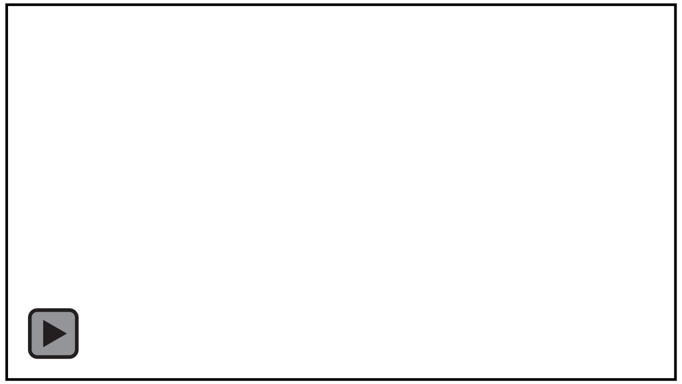
An acoustics based inertial measurement working in both LoS and NLoS.

Insight

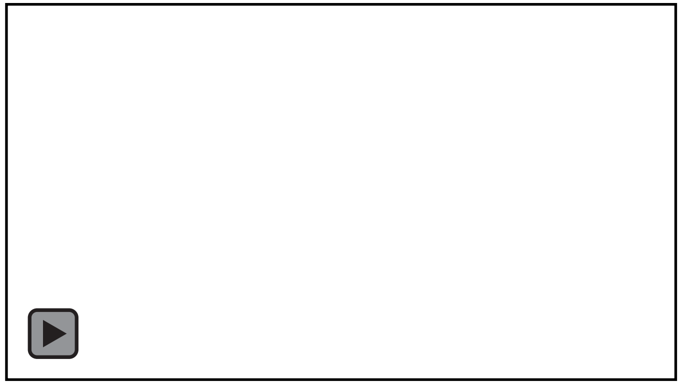




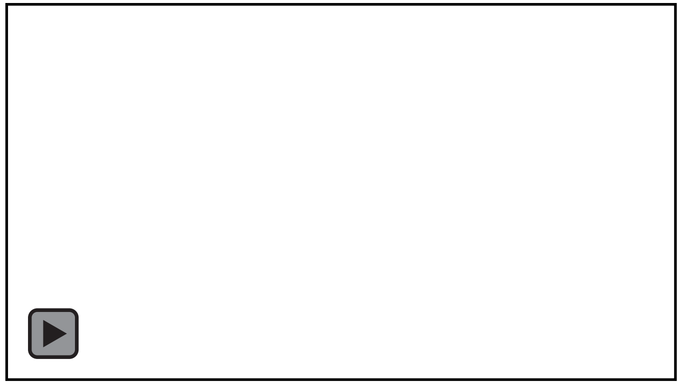
Hovering Motion



Yaw Motion



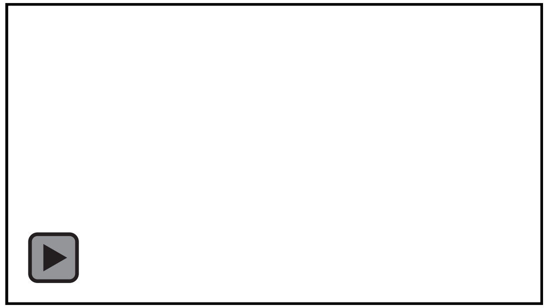
Vertical Motion



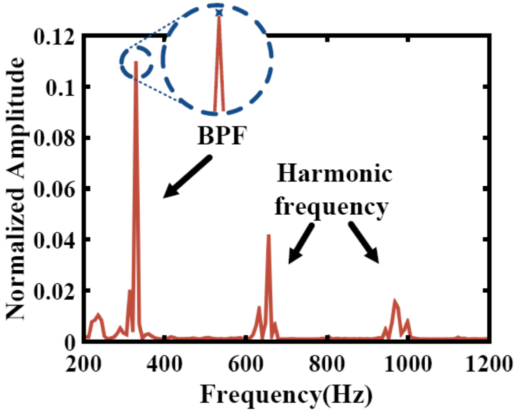
Horizontal Motion

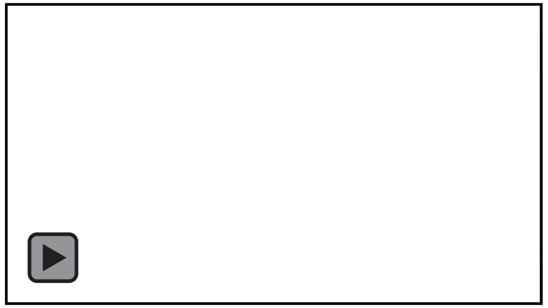
Different motions lead to <u>unique dynamics of propellers</u> and fuselage.

Insight

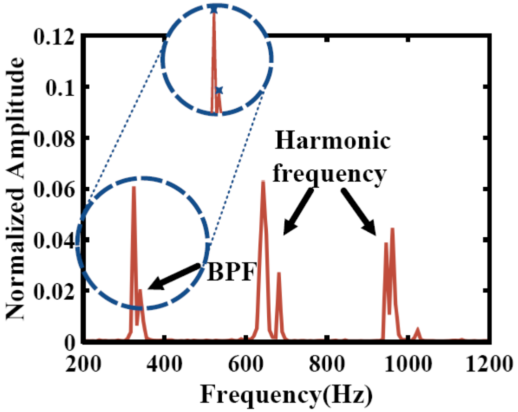


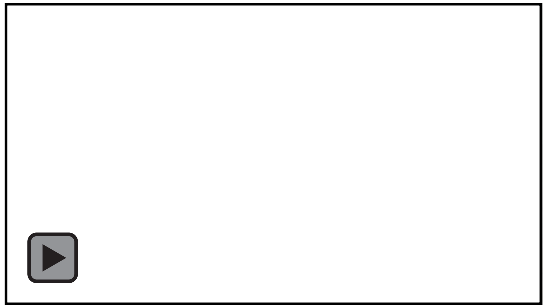
Hovering Motion



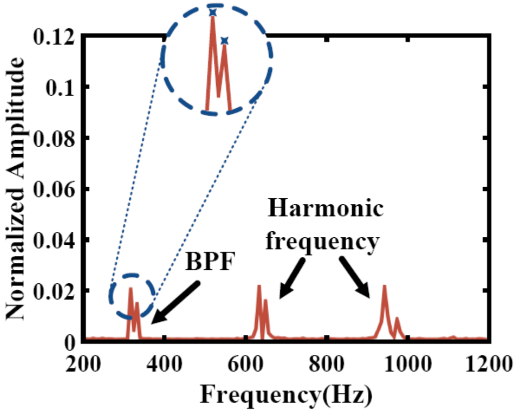


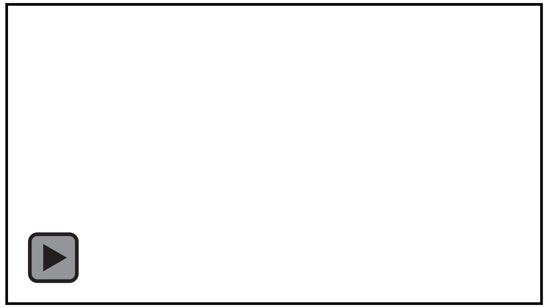
Yaw Motion



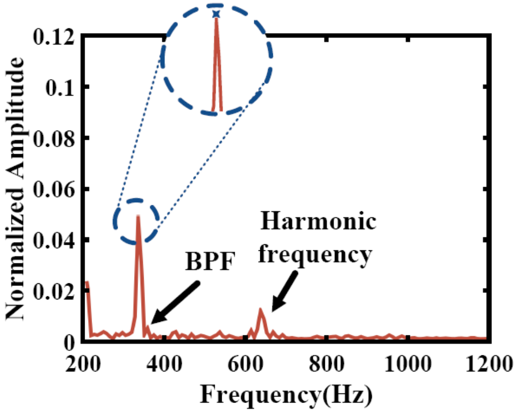


Vertical Motion





Horizontal Motion



Unique dynamics of propellers lead to <u>distinct acoustic features</u>

AIM Overview

Acoustic Inertial Measurement

with both frequency and spatial domain

Frequency domain / Spatial domain	**Single** Peak	**Multiple** Peak
Unstable DoA	Vertical linear motion	Horizontal linear motion
Stable DoA	Hovering motion	Yaw motion

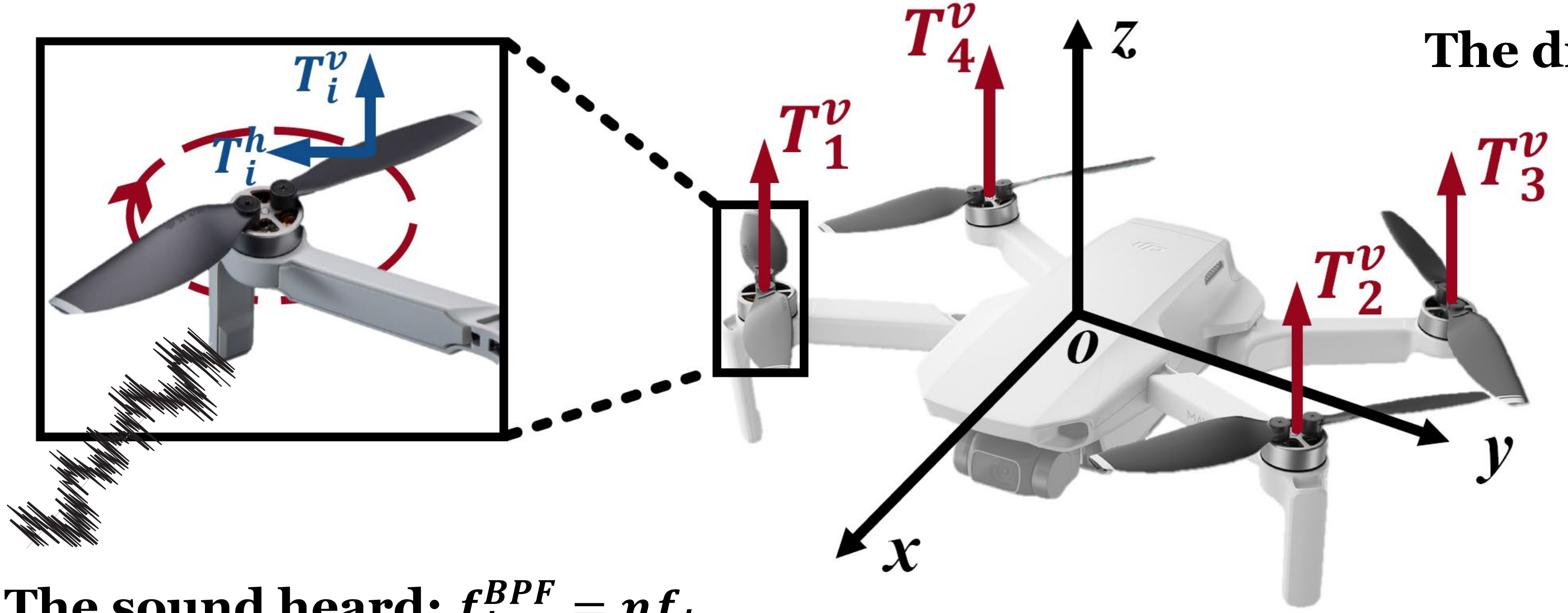
Entirely passive scheme

Work across LoS & NLoS

Scalable to arbitrary range

No hardware modification

Preliminary



The drag force: $T_i^v = k^v f_i^2$

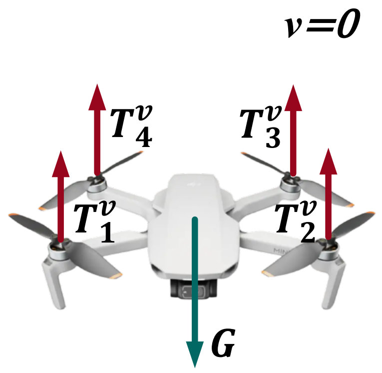
The sound heard: $f_i^{BPF} = nf_i$

The sound can be quantified based on drone's structure.

Observation

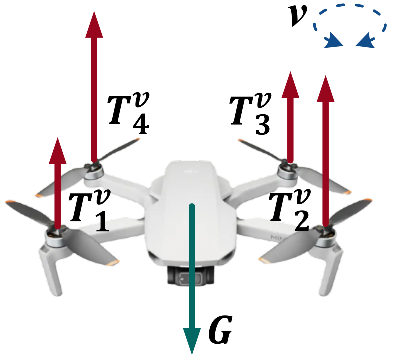
Hovering Motion

$$f_1 = f_2 = f_3 = f_4$$



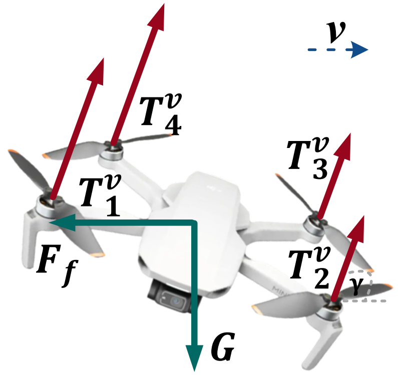
Yaw Motion

$$f_1 = f_3, f_2 = f_4$$



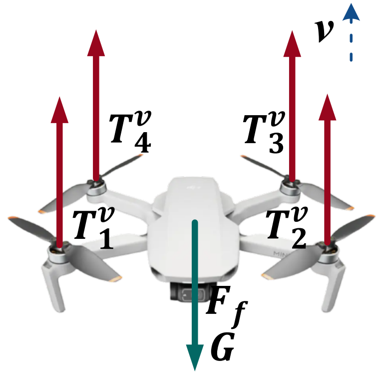
Vertical Motion

$$f_1 = f_2 = f_3 = f_4$$



Horizontal Motion

$$f_1 = f_4, f_2 = f_3$$



How to disambiguate motions with the same number of frequency band?

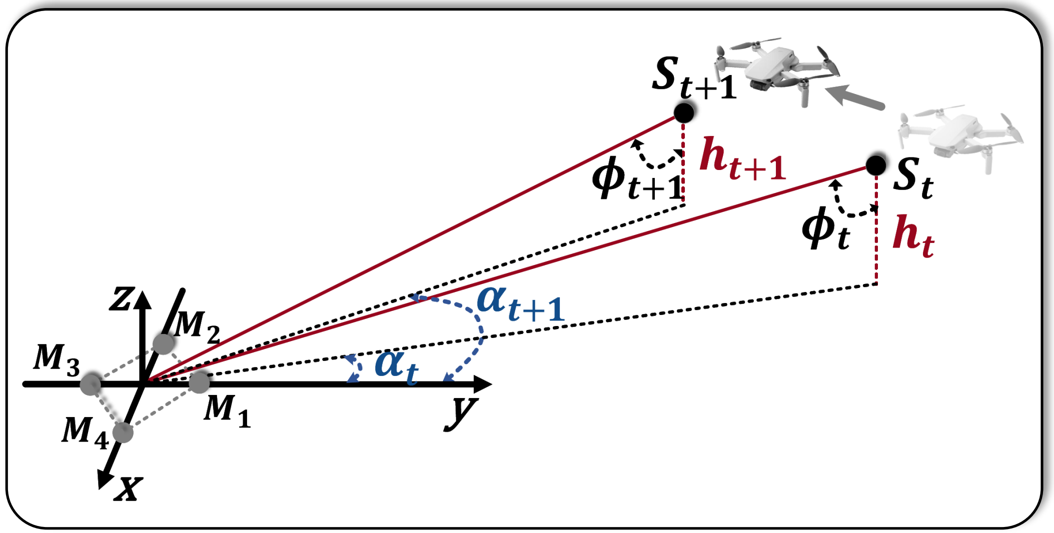
Motion Identification Scheme

Disambiguate motions with information in spatial domain

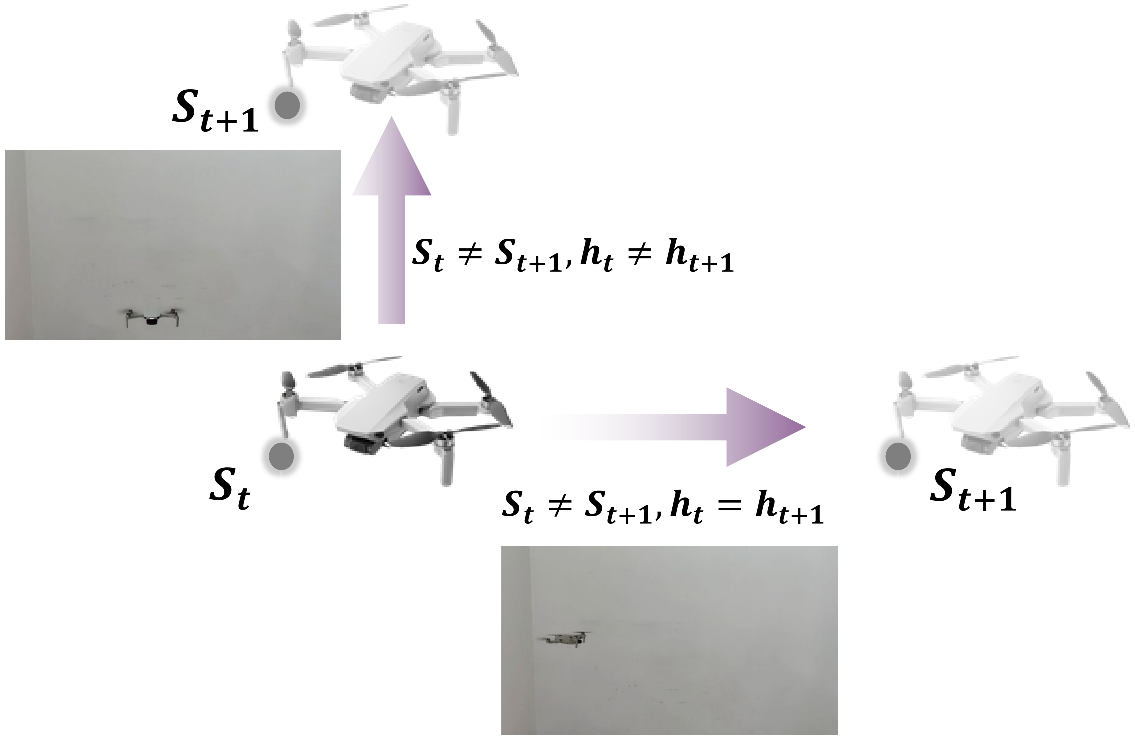
Frequency domain / Spatial domain	**Single** Peak	**Multiple** Peak
Unstable DoA	Vertical linear motion	Horizontal linear motion
Stable DoA	Hovering motion	Yaw motion

How to find the exact coordinates ?

Tracking Model



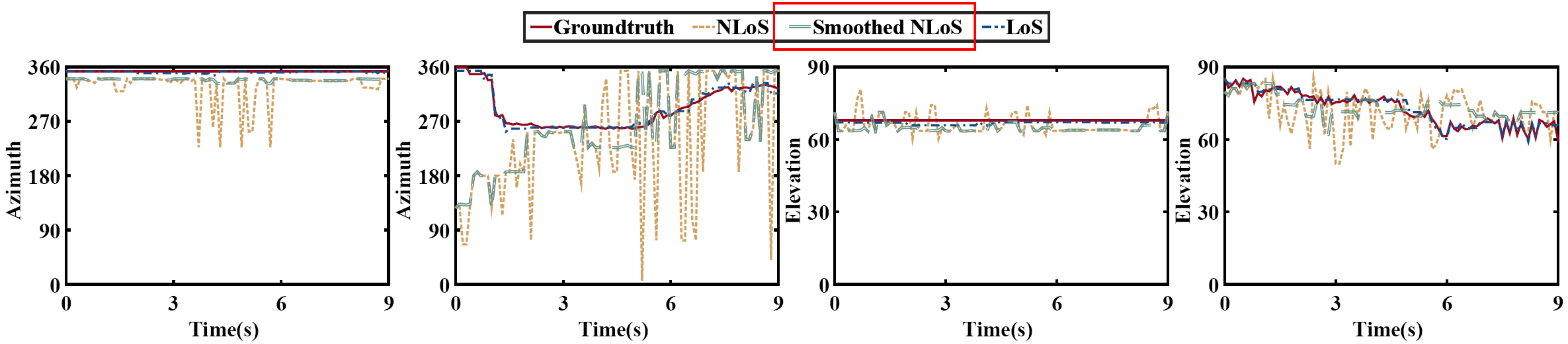
$S_t\ (h_t \tan\phi_t \cos\alpha_t\,,\, h_t \tan\phi_t \sin\alpha_t\,,\, h_t)$



In both dynamic equations, the only unknown quantity is the height h_{t+1}

For more detail, please refer to our paper.

Tracking in NLoS

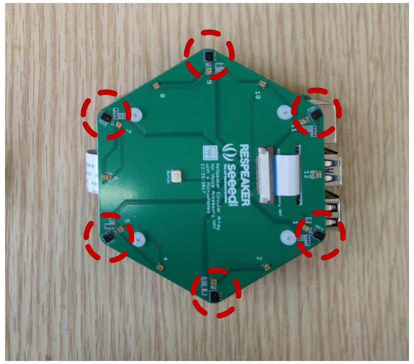


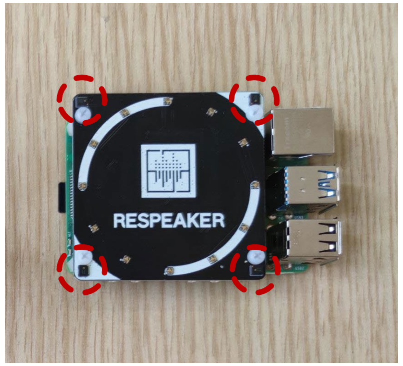
Stable azimuth **Unstable azimuth** **Stable elevation** **Unstable elevation**

Smoothed NLoS azimuth always indicates whether NLoS appears.

Evaluation

Microphone Array





6-Mic Array 4-Mic Array

(Sampling rate: 48kHz)

Baseline

UWB Node Infrared Camera

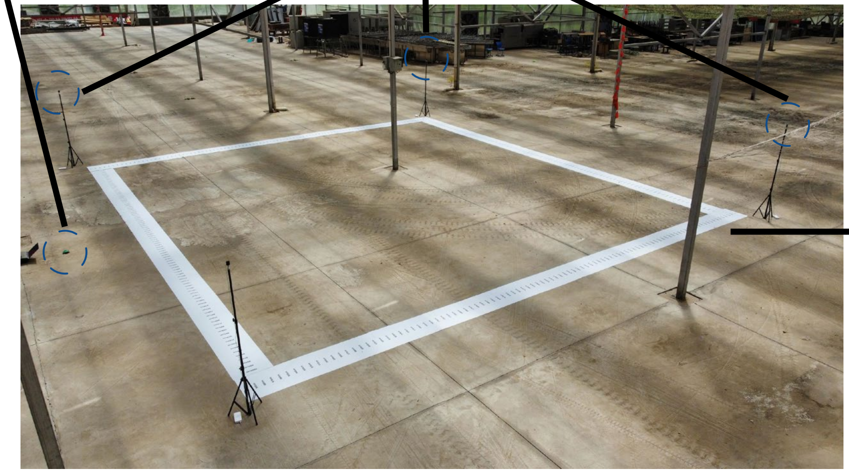
(Fixed on the tripods)

DJI mini 2 Quadcopter

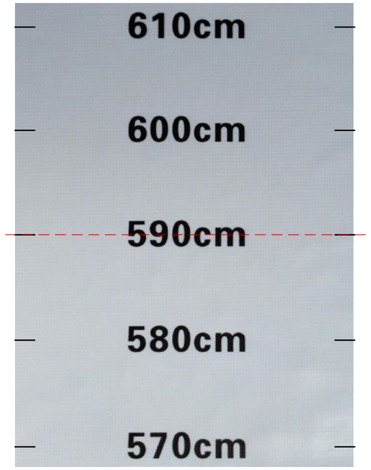
(Weight: 249g BPF: 328Hz)

Horizontal motions:
- Fly along the distance maker.
- Keep vertical coordinates unchanged.

Vertical motions:
- Climb or descent to a certain height.
- Keeping horizontal coordinates unchanged.



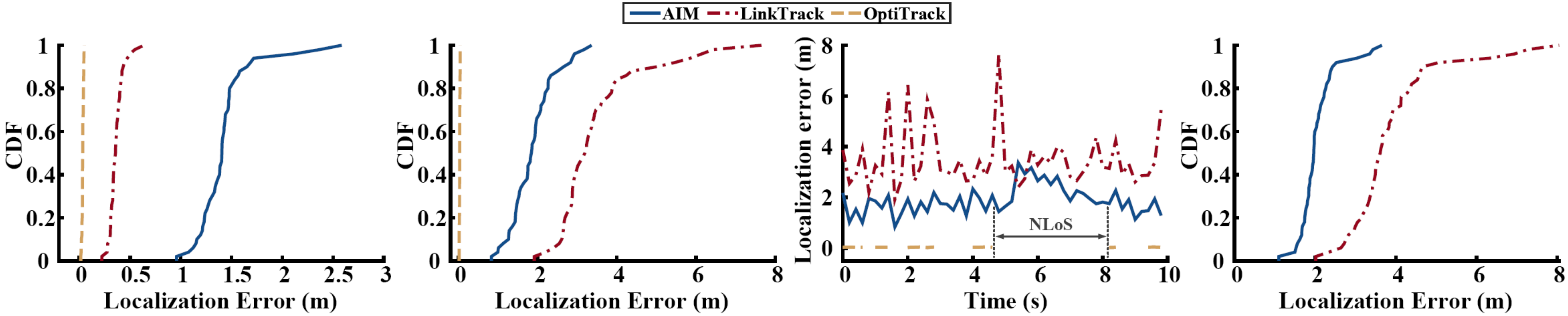
Experiment area



Distance Marker

(Imaged by the drone's camera)

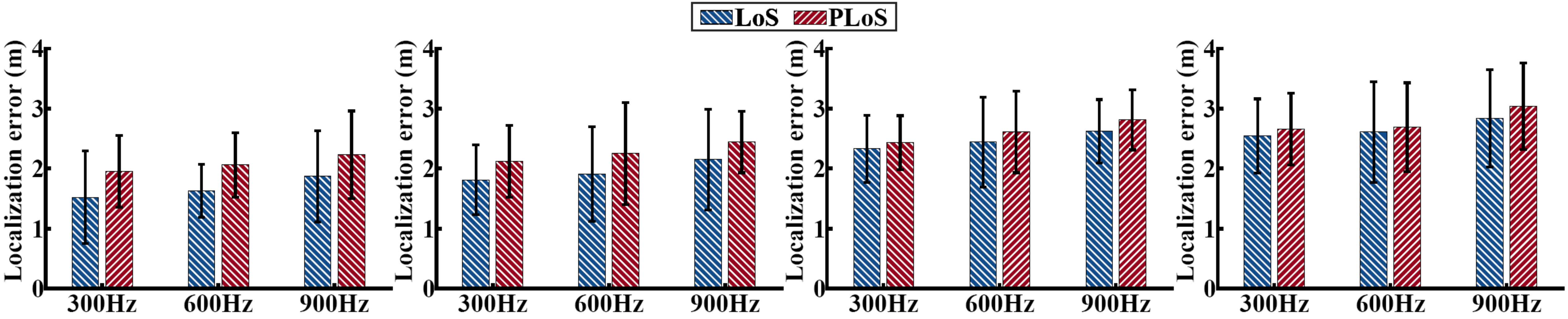
Overall Performance



LoS Scenarios **PLoS Scenarios** **Variation of errors** **NLoS Scenarios**

AIM outperforms LinkTrack <u>46% </u>in NLoS with a mean error of 1.89 m
AIM can constantly provide location updates when OptiTrack is down.

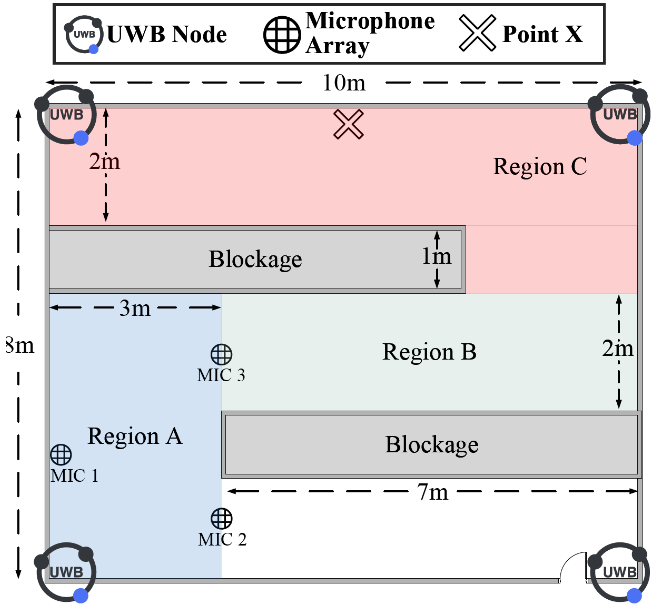
Impact of Environment Noise



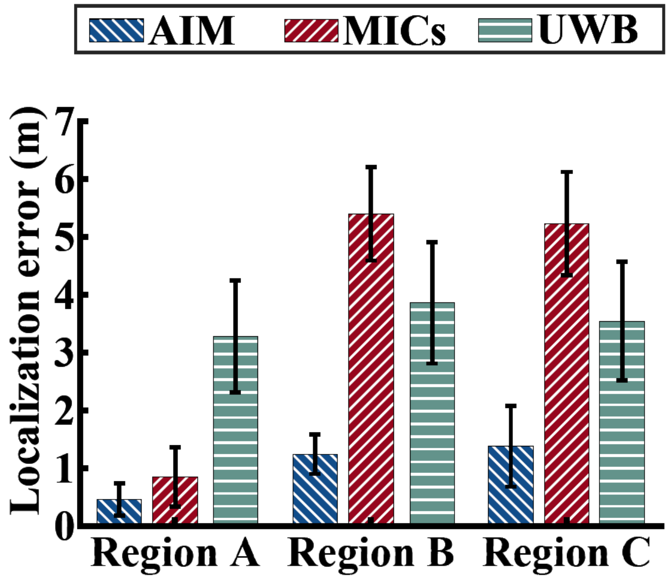
50dB 55dB 60dB 65dB

AIM is robust to moderate noise sources in the environment

Deployment in Real Warehouse



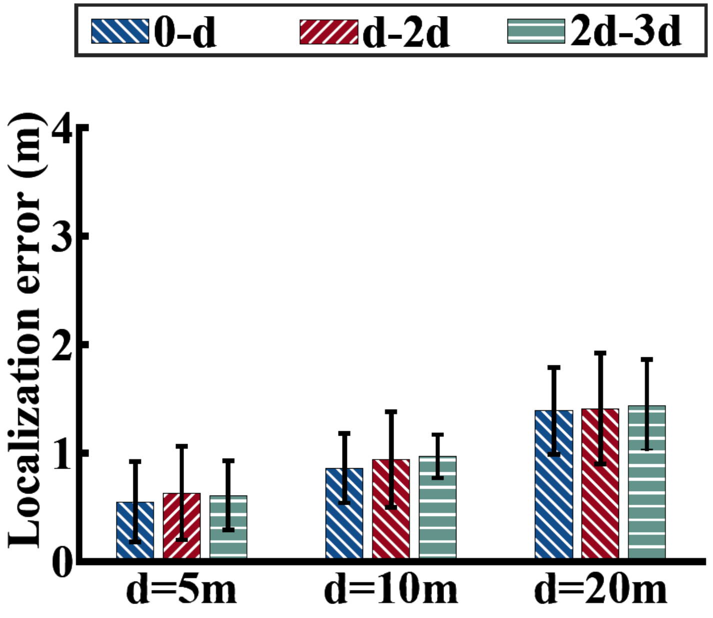
Layout of the warehouse



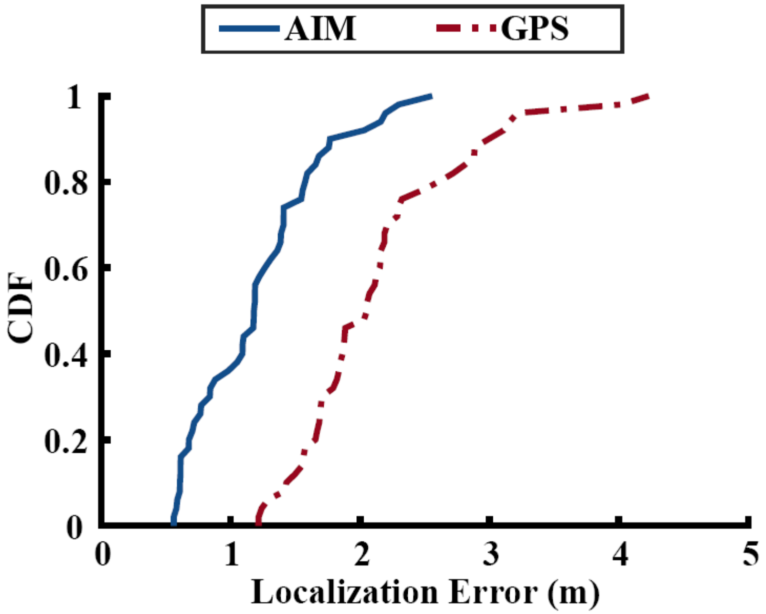
Accuracy in different regions

AIM outperforms UWB in the real warehouse environment

Scalability in Range and Outdoors



Accuracy at different distances



Comparison with GPS outdoors

AIM can extend to <u>any range</u> yet accuracy never degrades drastically.
AIM can function outdoors and outperform GPS <u>57 %</u> in 2D tracking .

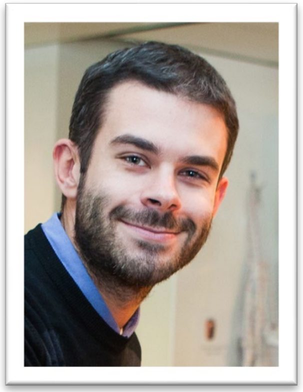
Summary

- **AIM** is the first-of-its-kind passive indoor drone tracking technique that works with a single 2D microphone array.
- The core innovation is that we explore **acoustics-based dynamics**, which bridges the drone's dynamics equations and acoustic features.
- AIM is able to localize a drone in any range and layout, with the mean errors **46%** less than UWB indoors and **57%** less than GPS outdoors.

Thank You!

Yimiao Sun

Weiguo Wang



Luca Mottola

Ruijin Wang

Yuan He

清華大學 Tsinghua University

POLITECNICO MILANO 1863

RI. SE Research Institutes of Sweden

电子科技大学 University of Electronic Science and Technology of China