# CS7351 传感系统原理与设计
# Principles and Design of Sensing Systems

## Sensors-Magnetometers & Robotic Perception
## (磁场传感器与机器人)

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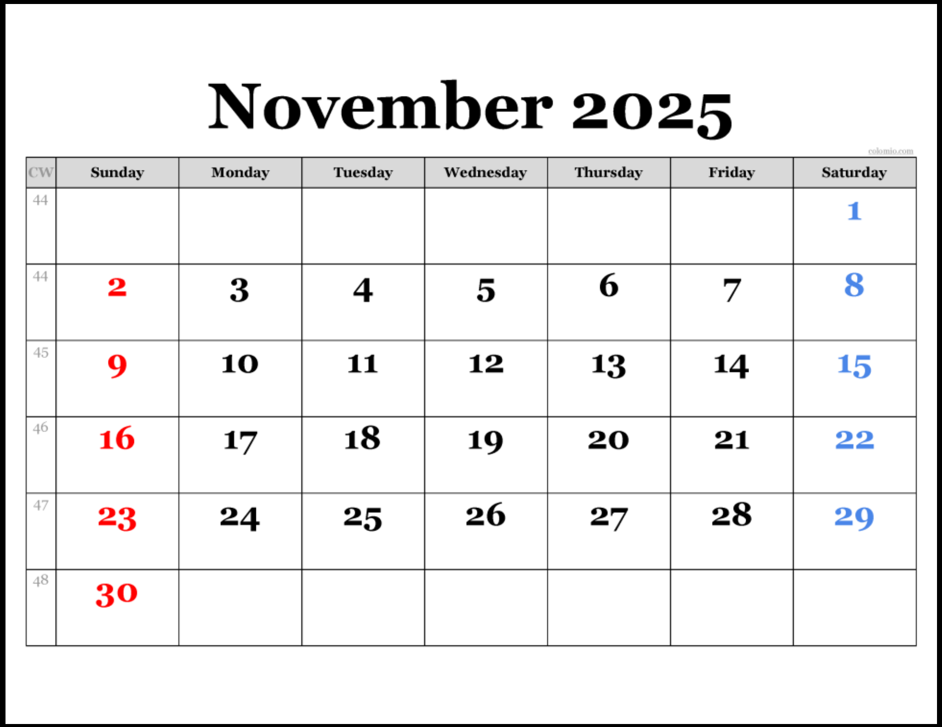
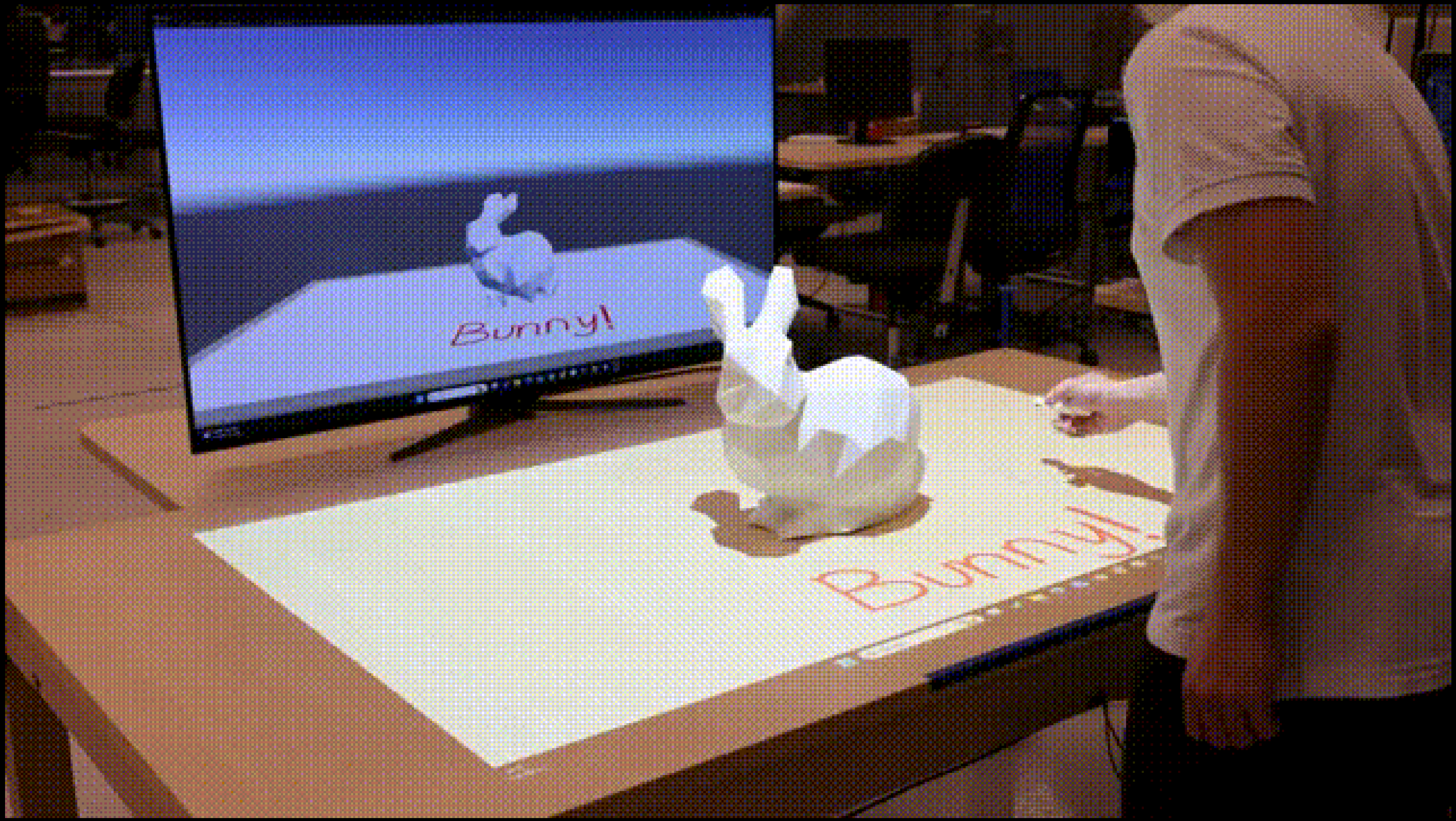
2025年秋季

# 课程调整

- 11月4-8日（教学周第8周）需要参加国际会议
- 调课方案：
  - ~~方案一：11月8日（周六）上午10点~~
  - **方案二：11月9日（周日）上午10点**



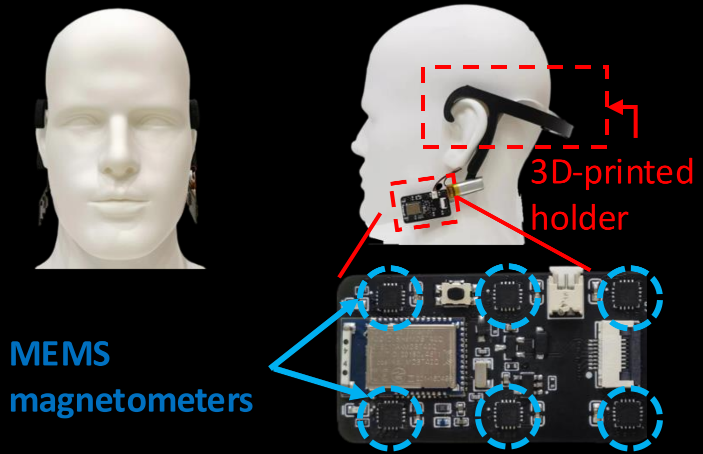
# Engaging Office Environment: 3D Desk Surface




**MagDesk: Interactive Tabletop Workspace Based on Passive Magnetic Tracking**
UbiComp 2024, Kunpeng Huang, Yasha Iravantchi, Dongyao Chen, and Alanson Sample

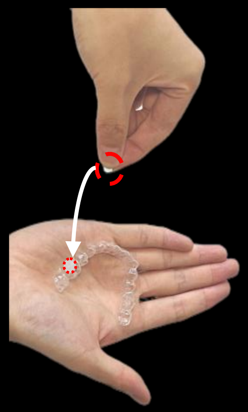
# Toothbrushing and Silent Communication

**MagX can be mounted as earables**




**Transform everyday objects with magnets**


Tooth brush


Tooth brace

**Interactive applications**


**Tooth brush monitoring**

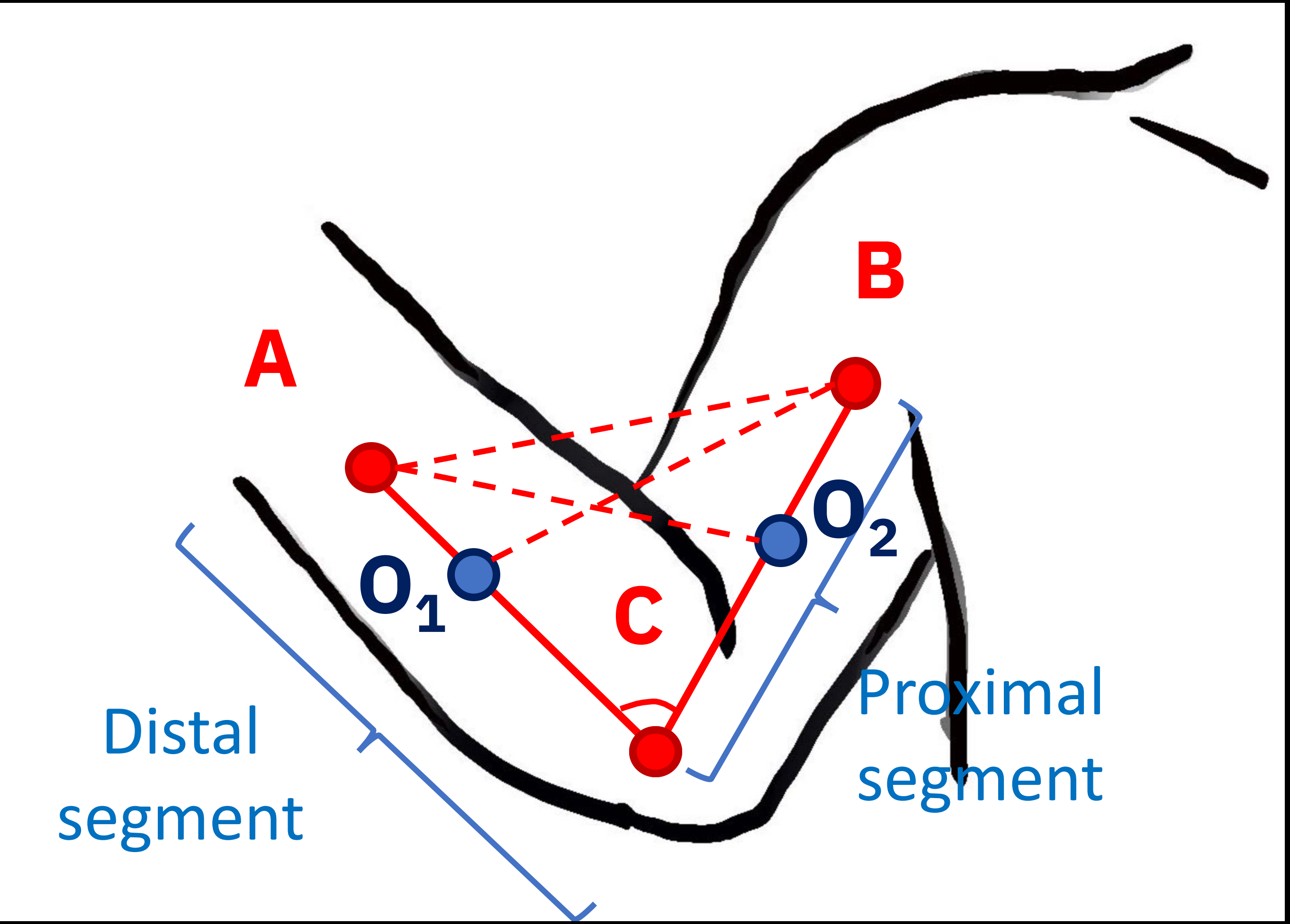

**Silent speech in crowd**

# Magnetic Tracking for Motion Capture

**<u>Motion capture</u> (mocap) systems**

- Crucial for applications such as sports analytics and healthcare
- Millimeter-level accuracy relies on million-dollar devices

# Key Challenges




To derive ∠C, with trigonometry, we can measure the lengths of edges AC, BC, and AB

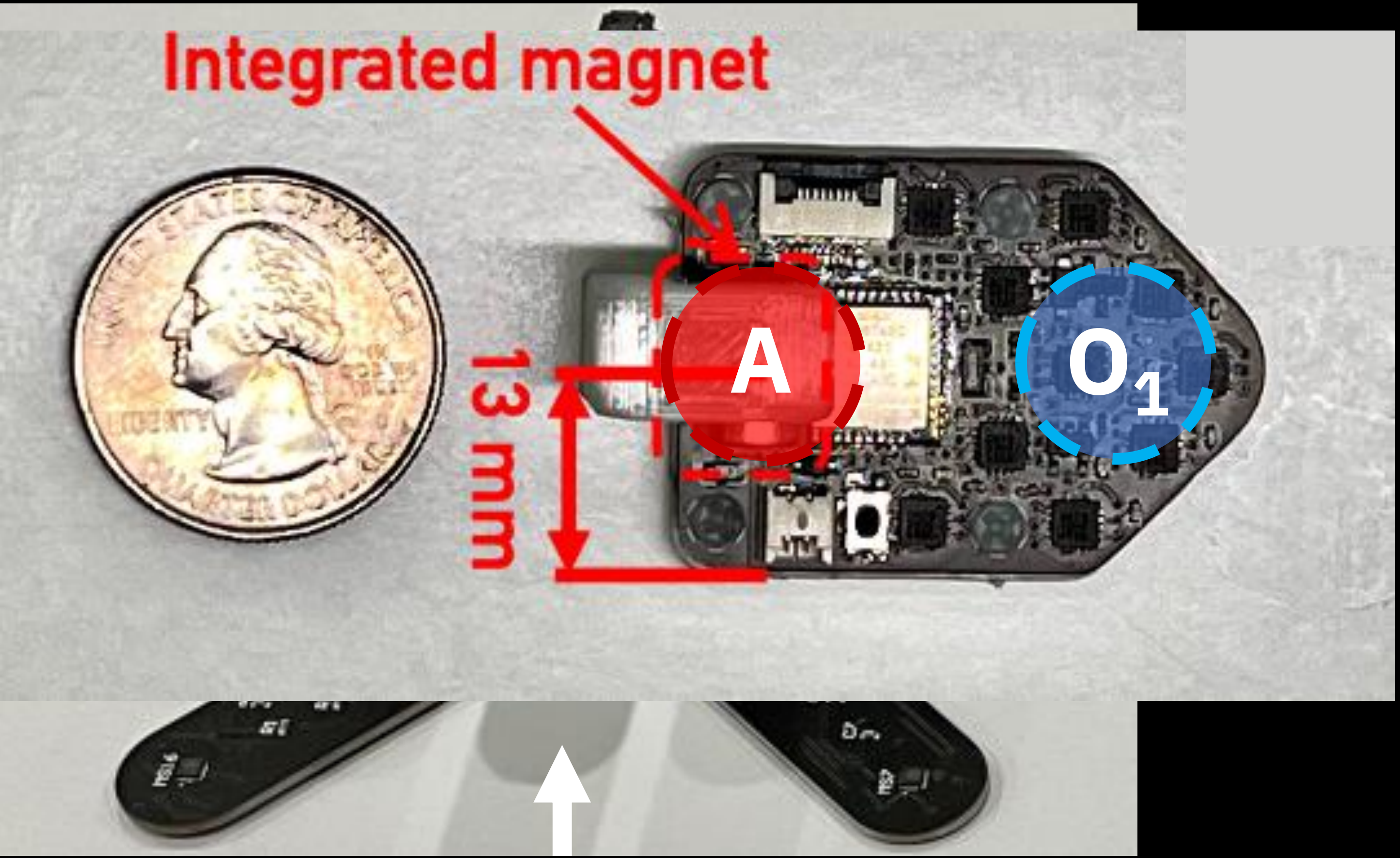
With magnetic tracking, we can measure the length of AB

<u>Challenges</u>:

- Locating the position of C
- Measuring AC and BC reliably

Can we measure the joint angle **without** locating the center?

# Reducing the Sensor Size



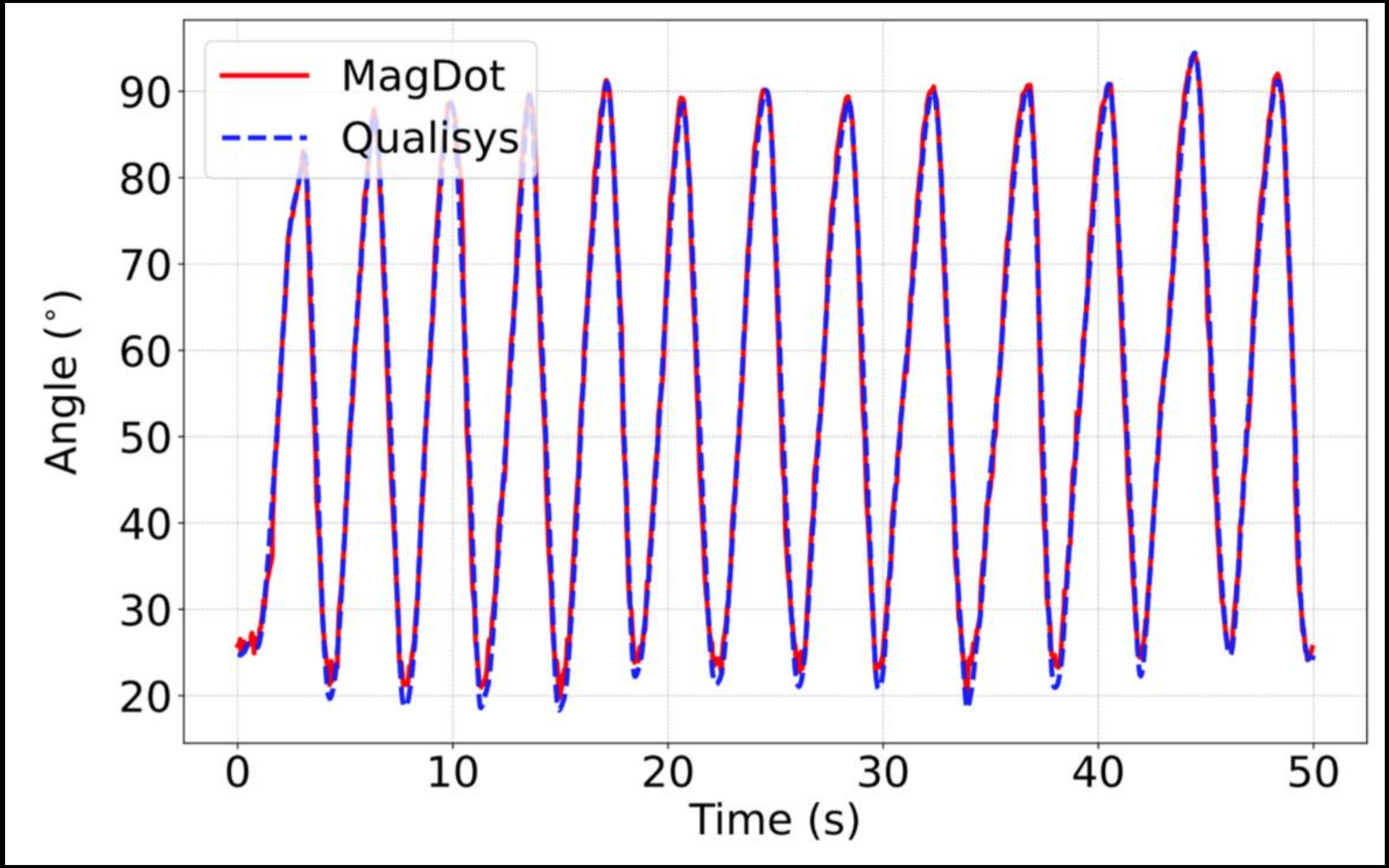

Knee

Shoulder

Chen D, Luo Q, Chen X, Wang X, Zhou C. MagDot: Drift-free, Wearable Joint Angle Tracking at Low Cost. UbiComp 2024

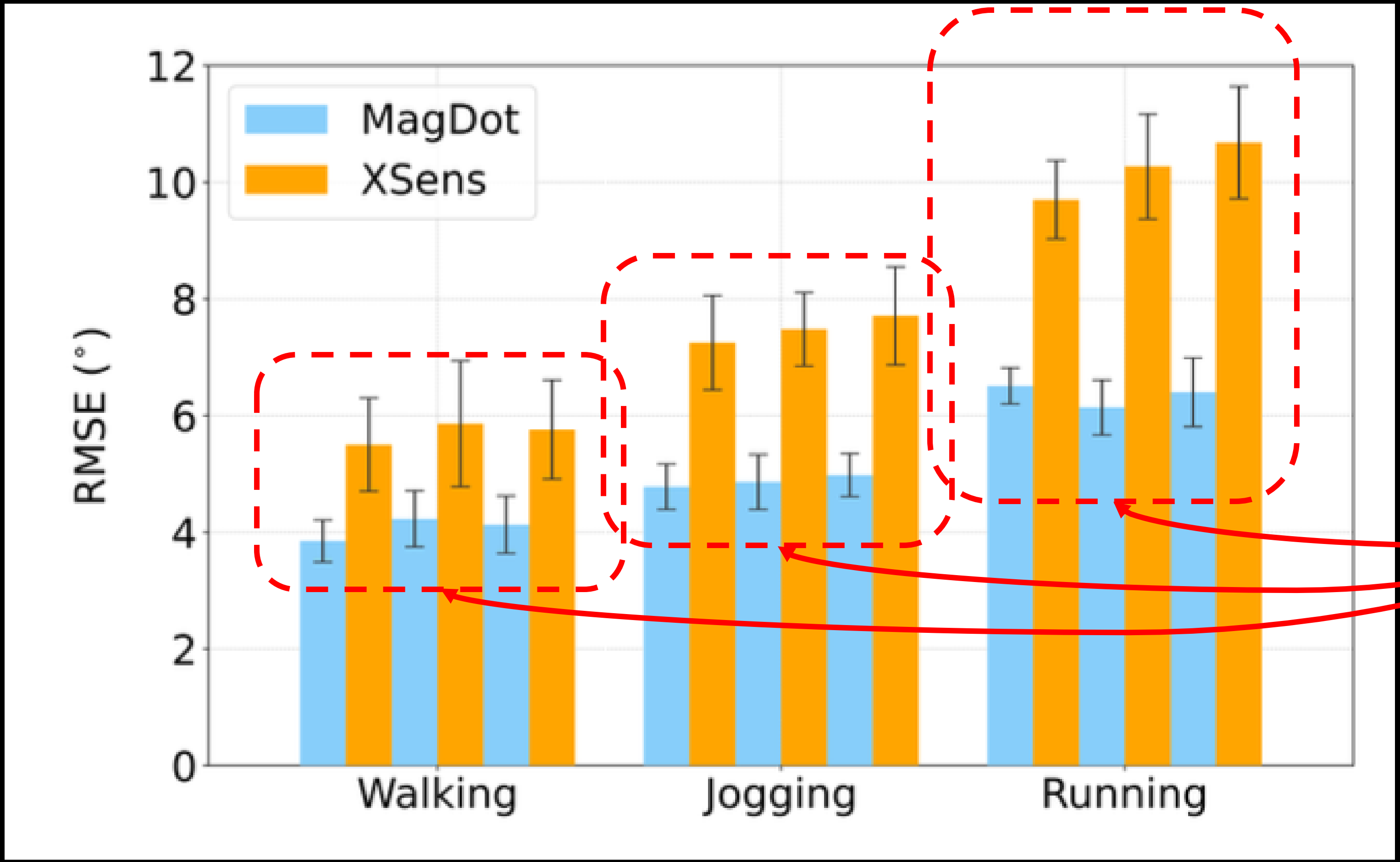
# Evaluation Settings

# Evaluation: 1D joint movement




MagDot can achieve tracking accuracy of **2.72**, **4.14**, and **4.61** degrees for elbow, knee, and shoulder, respectively.

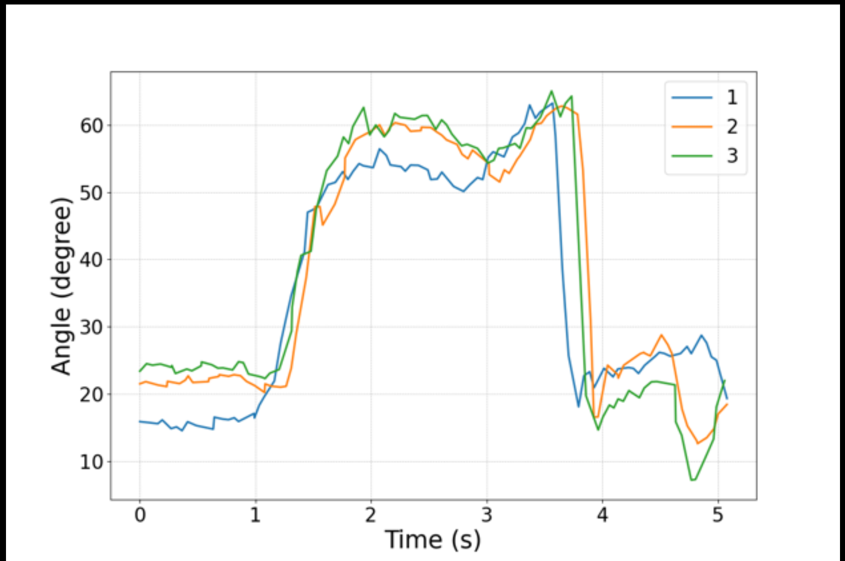
# Evaluation: MagDot is Drift-free Compared with IMU (i.e., gyroscope + accelerometer)

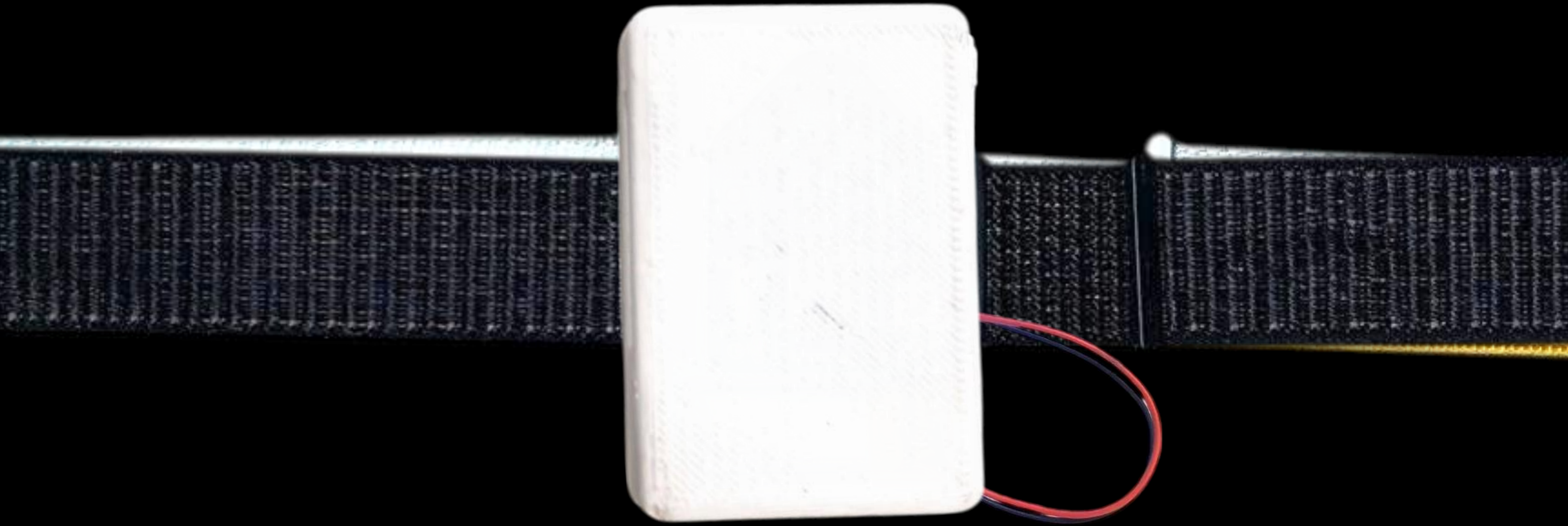


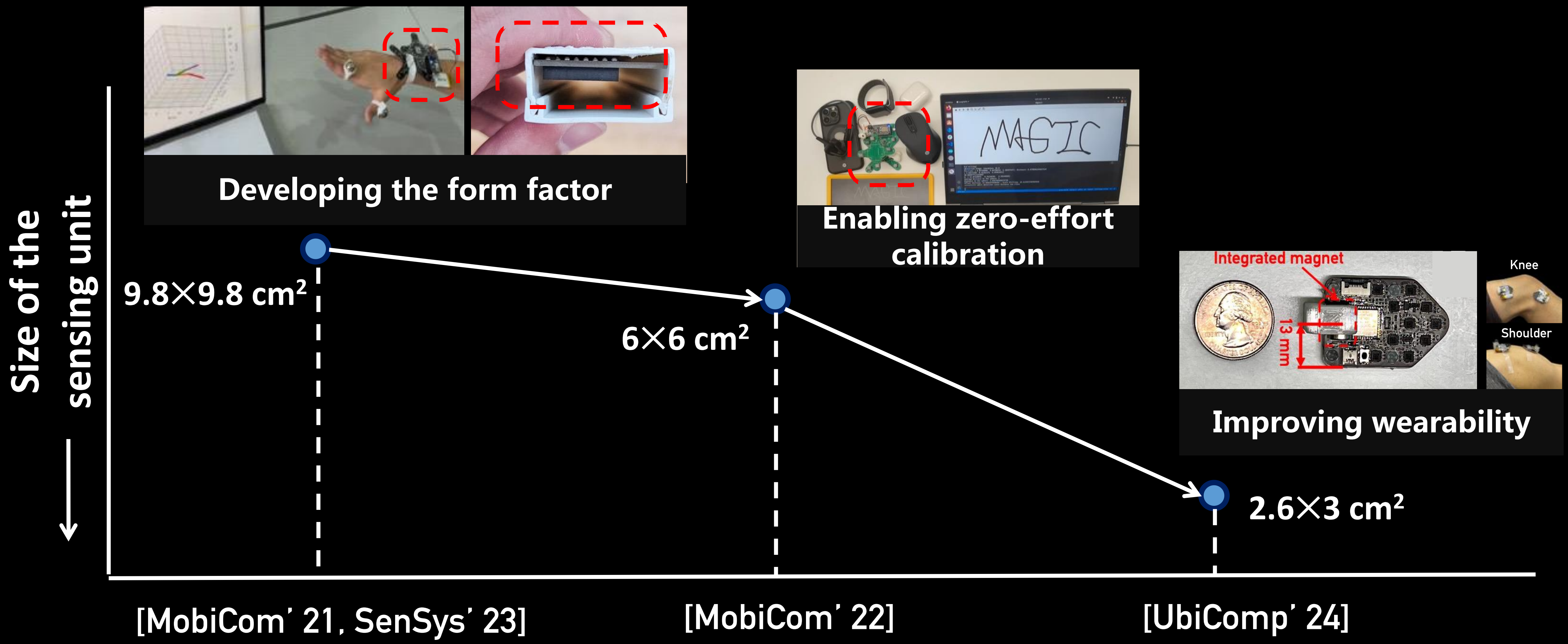

More intense activities **aggravate the drifting error** of IMU-based methods!


XSens IMU

# Testing Our System on Basketball Players







Developing the form factor
Enabling zero-effort calibration
Integrated magnet
13 mm
Knee
Shoulder
Improving wearability
Size of the sensing unit
9.8×9.8 cm²
6×6 cm²
2.6×3 cm²
[MobiCom' 21, SenSys' 23]
[MobiCom' 22]
[UbiComp' 24]

# Neodymium passive magnets

The magnetic field is constant, durable

It is passive

Low cost

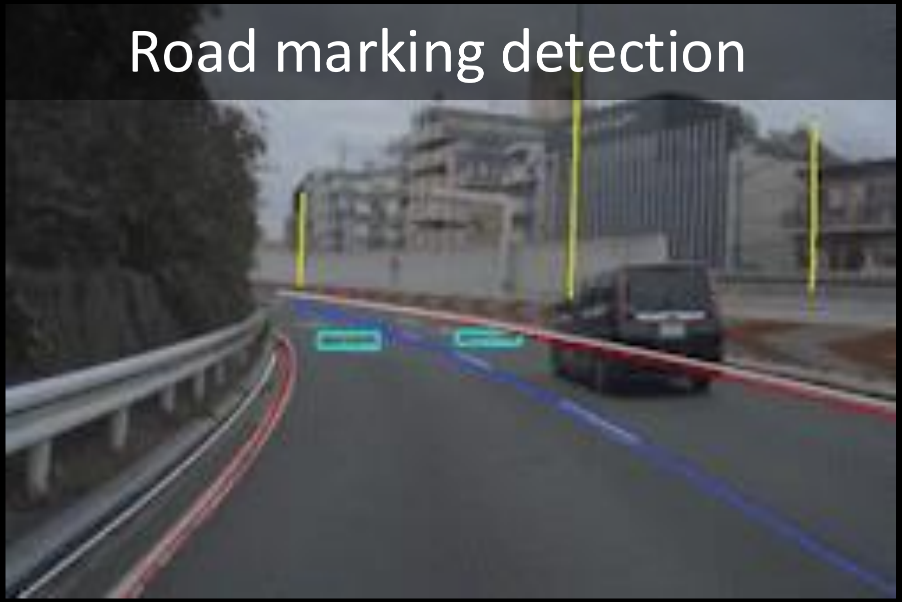
# METRO

## Magnetic Road Markings for All-weather, Smart Roads

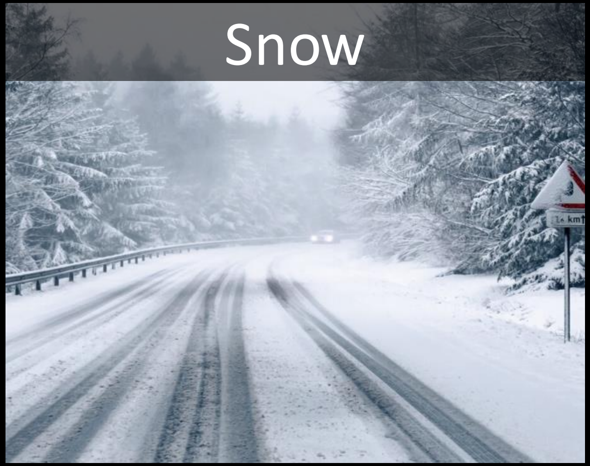
ACM SenSys 2023, Nov.14

**Jike Wang**, Shanmu Wang, Yasha Iravantchi, Mingke Wang, Alanson Sample, Kang G. Shin, Xinbing Wang, Chenghu Zhou, Dongyao Chen

# Background and Motivation


Road surface markings are **safety-critical** traffic infrastructure



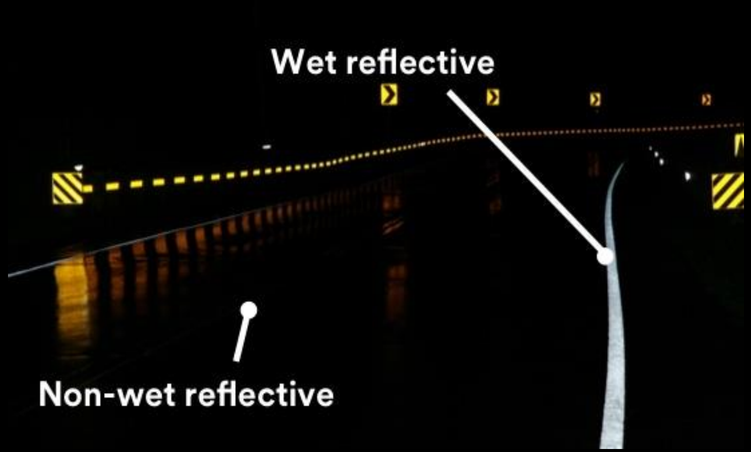



Adverse weather conditions

Wear and tear

The **poor visibility** of road markings is the major hurdle for driving safety and efficiency

# Current Paradigm is Limiting




Reflective road marking

Raised pavement marker

Down-pointing arrow

These markers only convey **limited information** and may still be **occluded** by adverse conditions

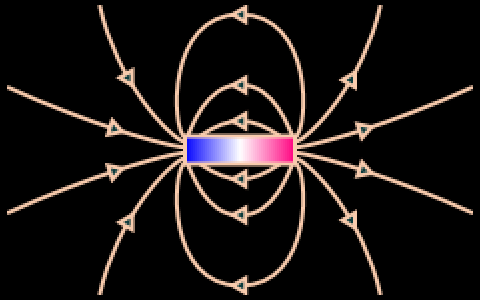
# Occlusion-free Solutions

- Radio frequency identification (RFID)
  - High cost (>$1,000)
  - Multi-path effect
- Millimeter wave
  - Obstacle occlusion
  - Multi-path effect
- Near-field communication (NFC)
  - Short range (<10 cm) and low speed (<1 m/s)
- Magnetic sensing
  - **Robust, cost-effective and highly accurate**

Impinj R420 RFID reader


Millimeter-wave radar

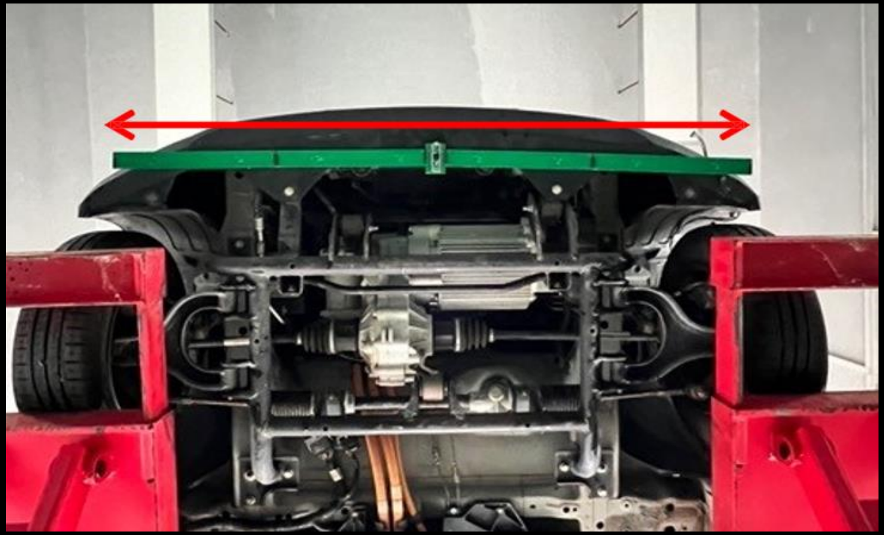

NFC-enabled payment


Magnetic field

# Our Solution: METRO

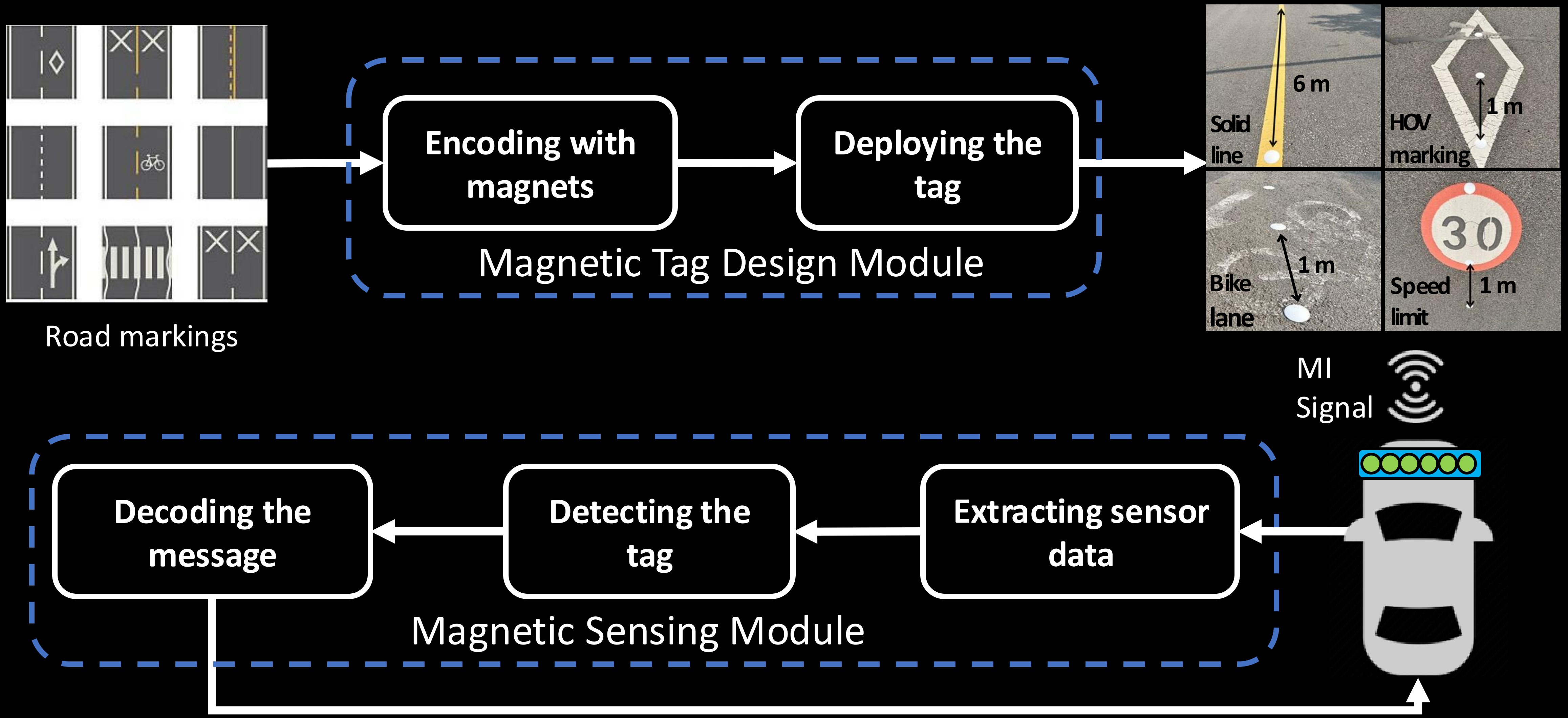
- A novel all-weather road marking infrastructure utilizing passive magnets and an automotive-grade magnetic sensing framework


On-road magnetic dots



Sensor array attached in car’s bumper

# The Overview



# Challenges for Designing METRO

## Three key challenges:

1. How to encode diverse road information with passive magnets?
    - High encoding capacity

2. How to achieve robust sensing in harsh on-road scenarios?
    - Varying speed/headings
    - Real-world disturbances

3. How to deploy METRO in real-word road environments?
    - High durability
    - Low cost

# Encoding Scheme of METRO

- Two types of road surface markings [1]

Longitudinal markings (e.g., lane lines)

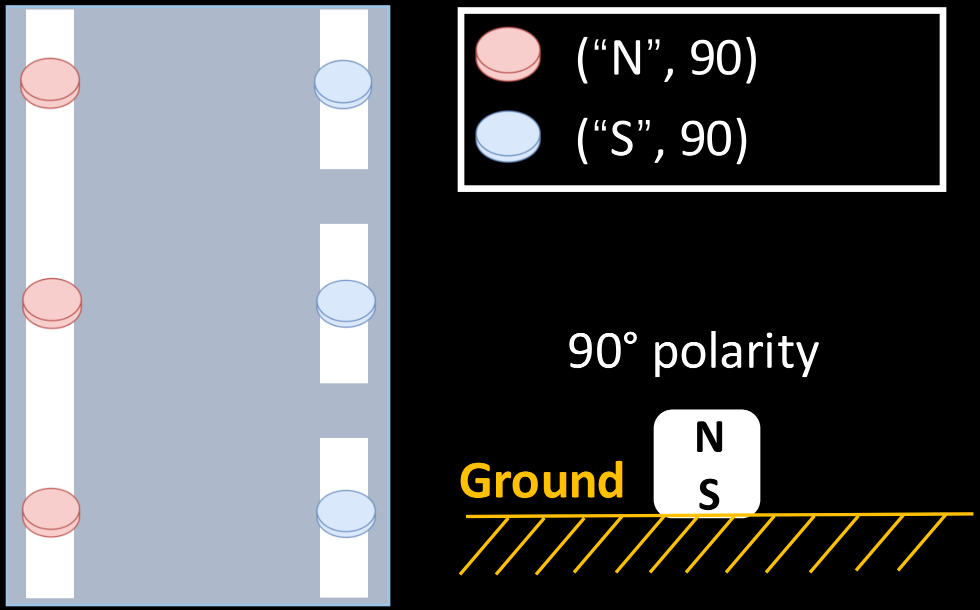
Transverse markings (e.g., arrow markings)

[1] Federal Highway Administration. 2022. Manual on uniform traffic control devices. https://mutcd.fhwa.dot.gov/. (2022).

# Encoding Longitudinal Markings

- N/S polarity for the upside
  - Solid line: {“N”, 90°}
  - Dashed line: {“S”, 90°}

Longitudinal markings (e.g., lane lines)

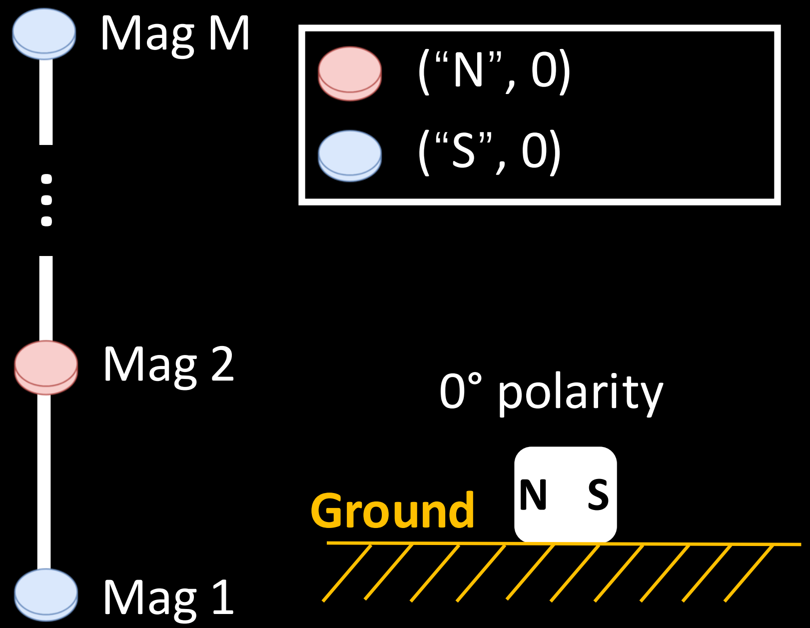



Longitudinal markings encode by METRO

# Encoding Transverse Markings

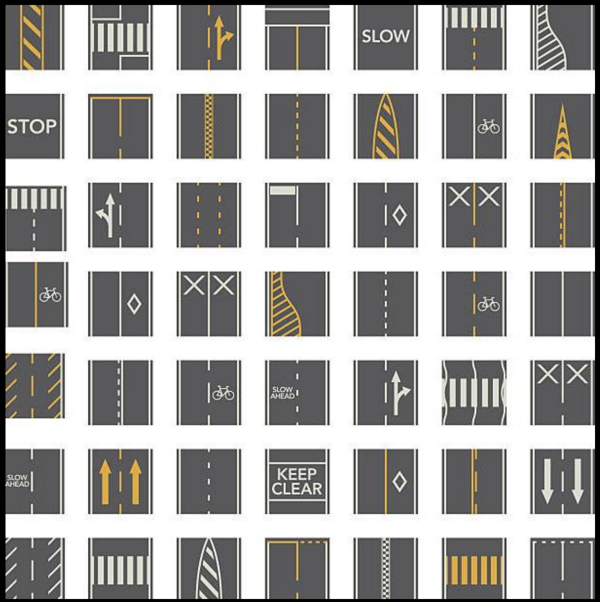
- N/S polarity for the forward

Transverse markings (e.g., arrow markings)

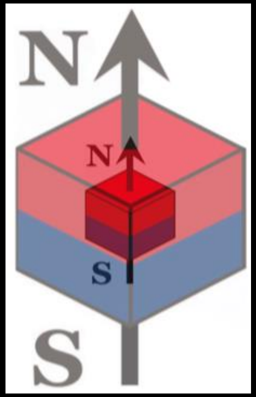



Transverse marking encoded with polarity

# How to Encode Diverse Transverse Markings?



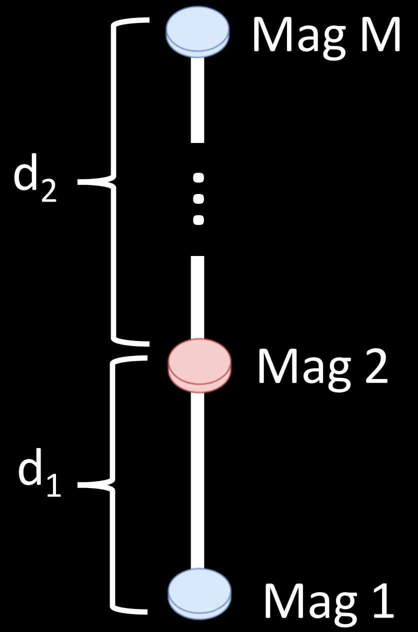

**200** types



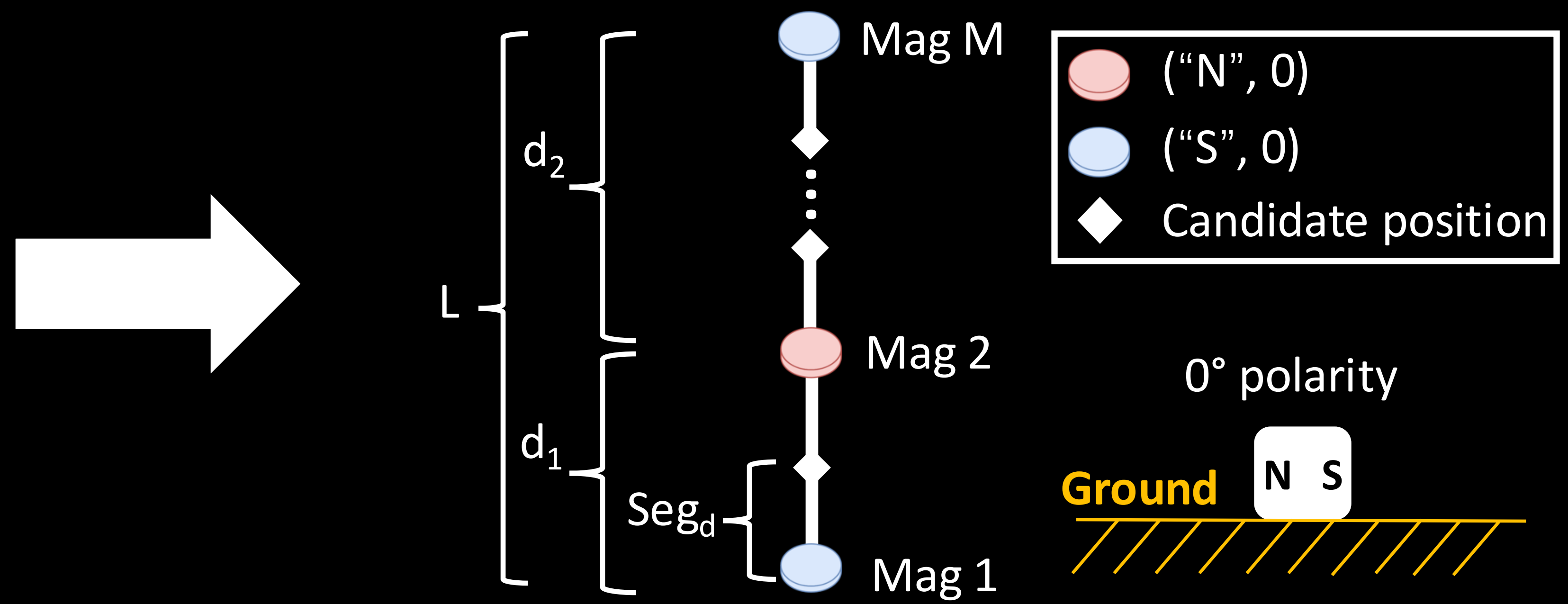

**2** types

# Introducing: Inter-magnet Distance

- METRO introduces **distance ratio** (i.e., ratio of inter-magnet distance)



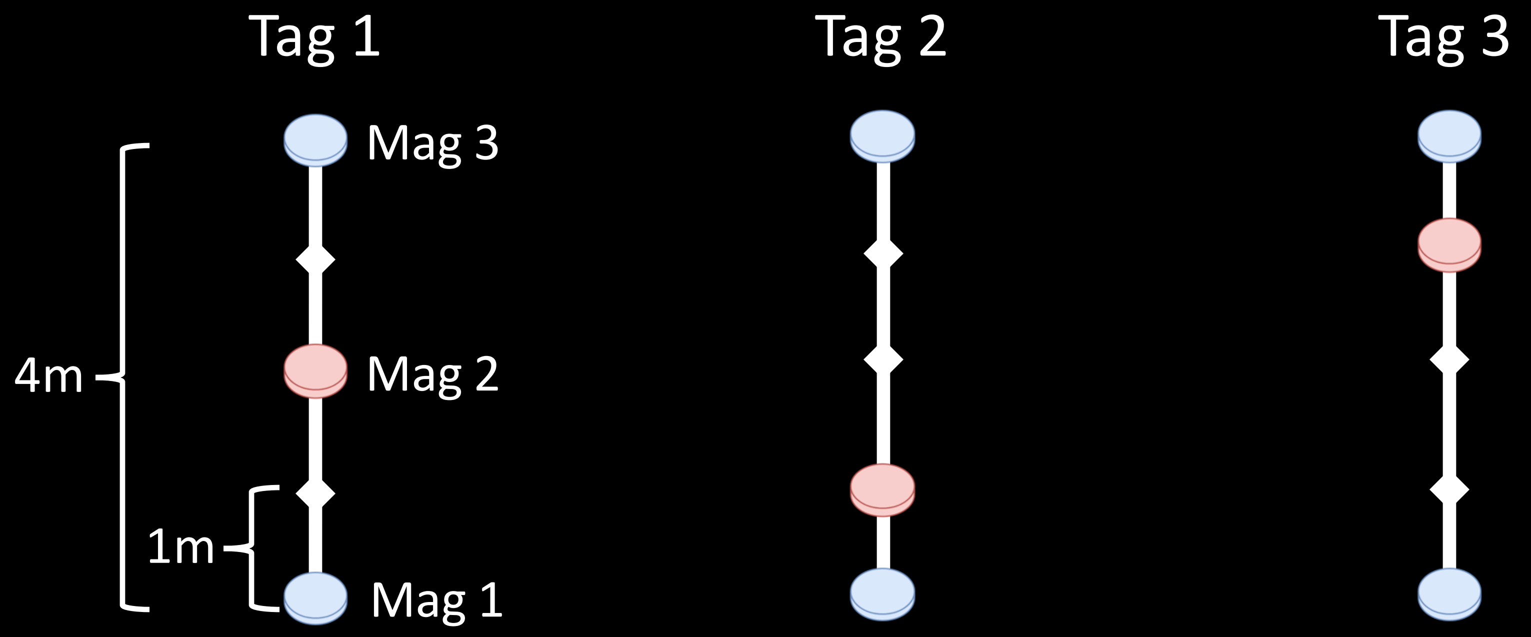

Only use the N/S polarity




Transverse marking denoted as {"SNS", 0°, M, L, $Seg_d$, $d_2/d_1$}

# Exemplary Transverse Markings

- Given M=3, L=4 m, $Seg_d$=1 m, METRO can encode **24** unique messages



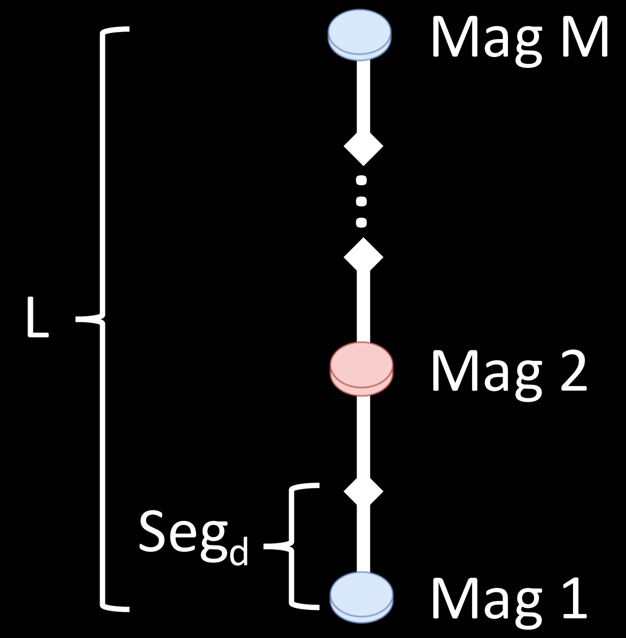

| | Tag 1 | Tag 2 | Tag 3 |
|---|---|---|---|
| Polarity: | “SNS” | “SNS” | “SNS” |
| Distance ratio: | 2m/2m=1 | 3m/1m=3 | 1m/3m=1/3 |

# Encoding Capacity Analysis

- Encoding capacity

$$C = 2^M \cdot \binom{L/Seg_d - 1}{M - 2}$$

- With M = 3, L = 4 m and $Seg_d$ = 0.1 m, METRO can reliably encode **248** unique messages



# How to Achieve Robust Magnetic Sensing?

- METRO needs to tackle unique challenges to facilitate the **harsh on-road scenarios**

High speed (e.g., >50 mph)

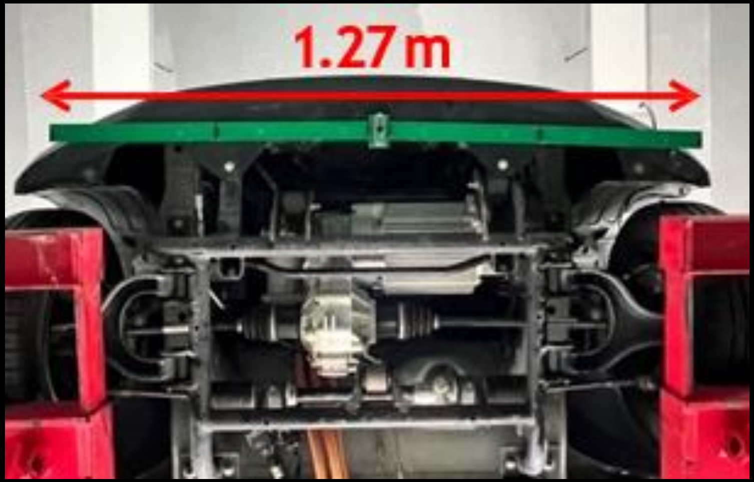
Adverse weather

Rough pavements

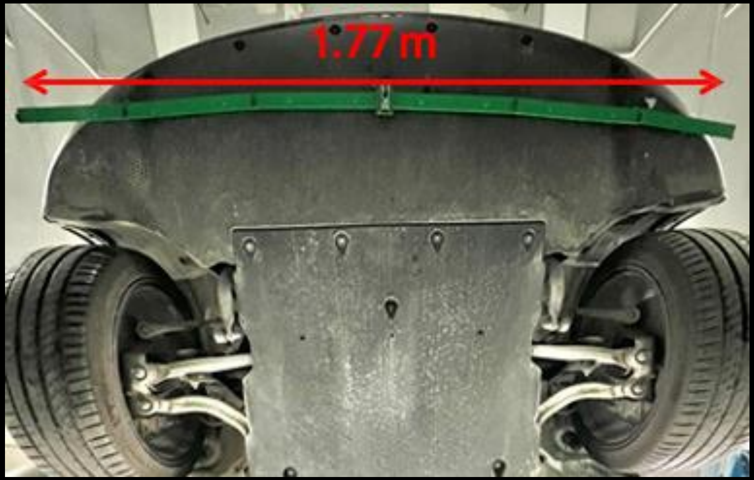
We propose an **automotive-grade magnetic sensing framework** that constitutes novel hardware and software designs

# Hardware Design

- Modular design for the magnetic sensor array
  - A Teensy 4.1 MCU
  - 12 MLX90393 magnetometers
- Hardware cost: < $85
- The sampling rate: >350 Hz



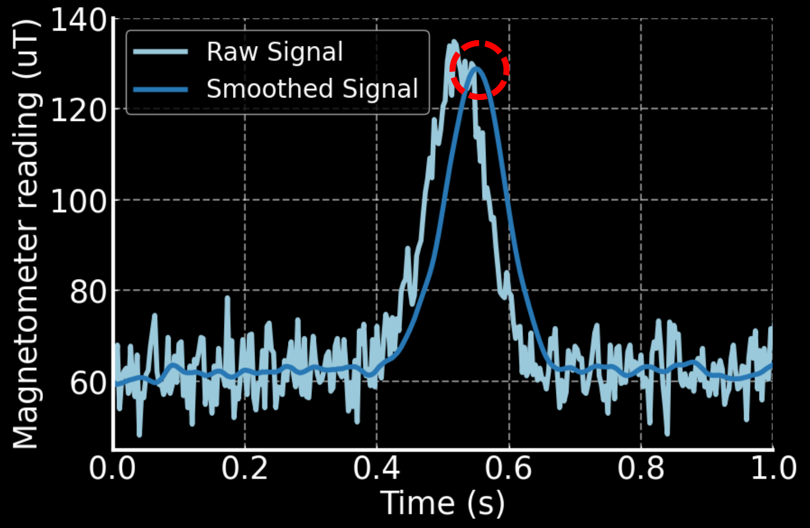

On a smart electric car



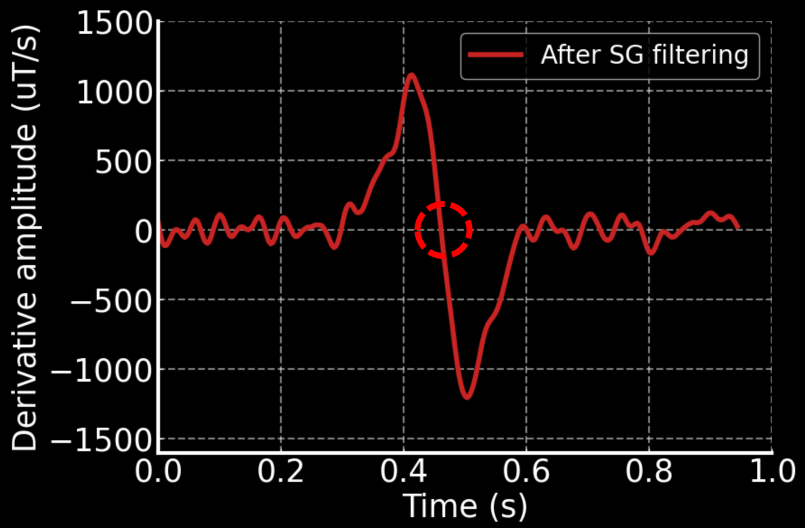

On a Tesla Model Y

# Sensing Algorithm

- **Derivative-based** peak detection algorithm
- Three key steps, total time delay <25 ms
  - Preprocessing, derivation, peak/valley detection




Raw peak signal with “N” polarity




First derivative signal

# Integrated Noise Cancellation

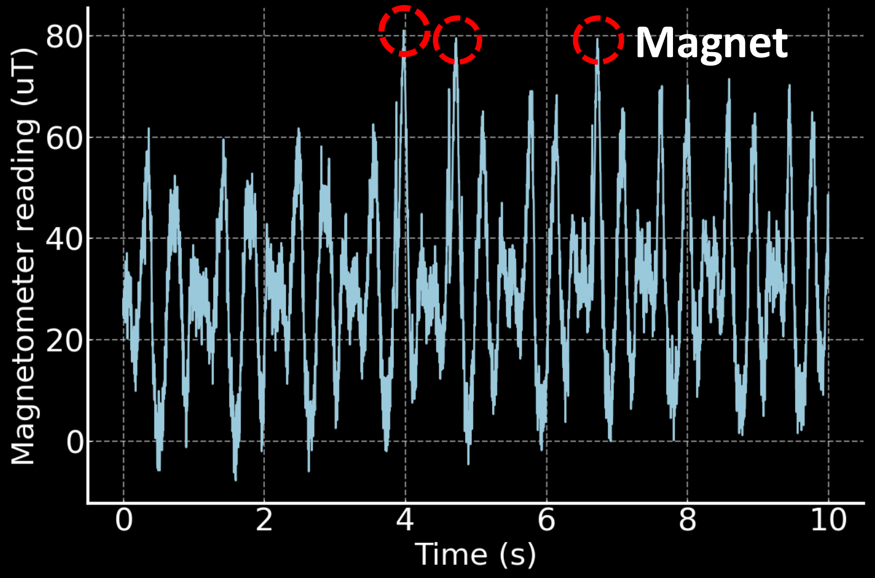
- Environmental disturbances can be eliminated by the derivative-based sensing algorithm
  - On-road infrastructures
  - Surrounding vehicles


On-road infrastructures

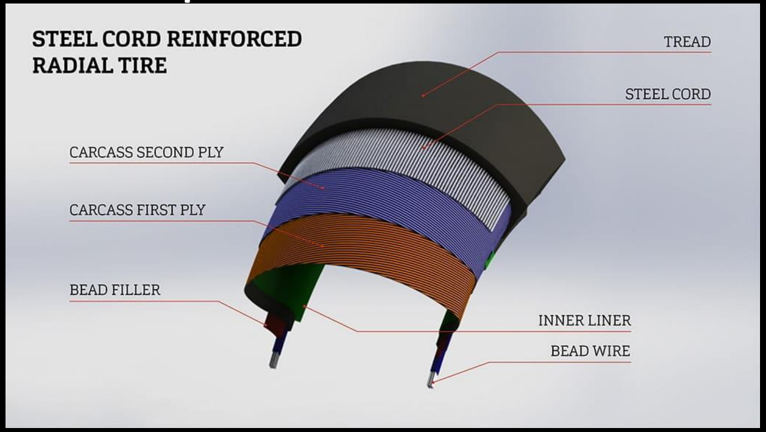

Surrounding vehicles

# Integrated Noise Cancellation (Cont.)

- Dynamic noises from the ego car
  - Observation: the wheel rotation incurs severe periodic magnetic noise
  - Issue 1: the magnetic field varies with different vehicles and road conditions
  - Issue 2: The frequency of the noise varies with the speed




W/ the wheel noise

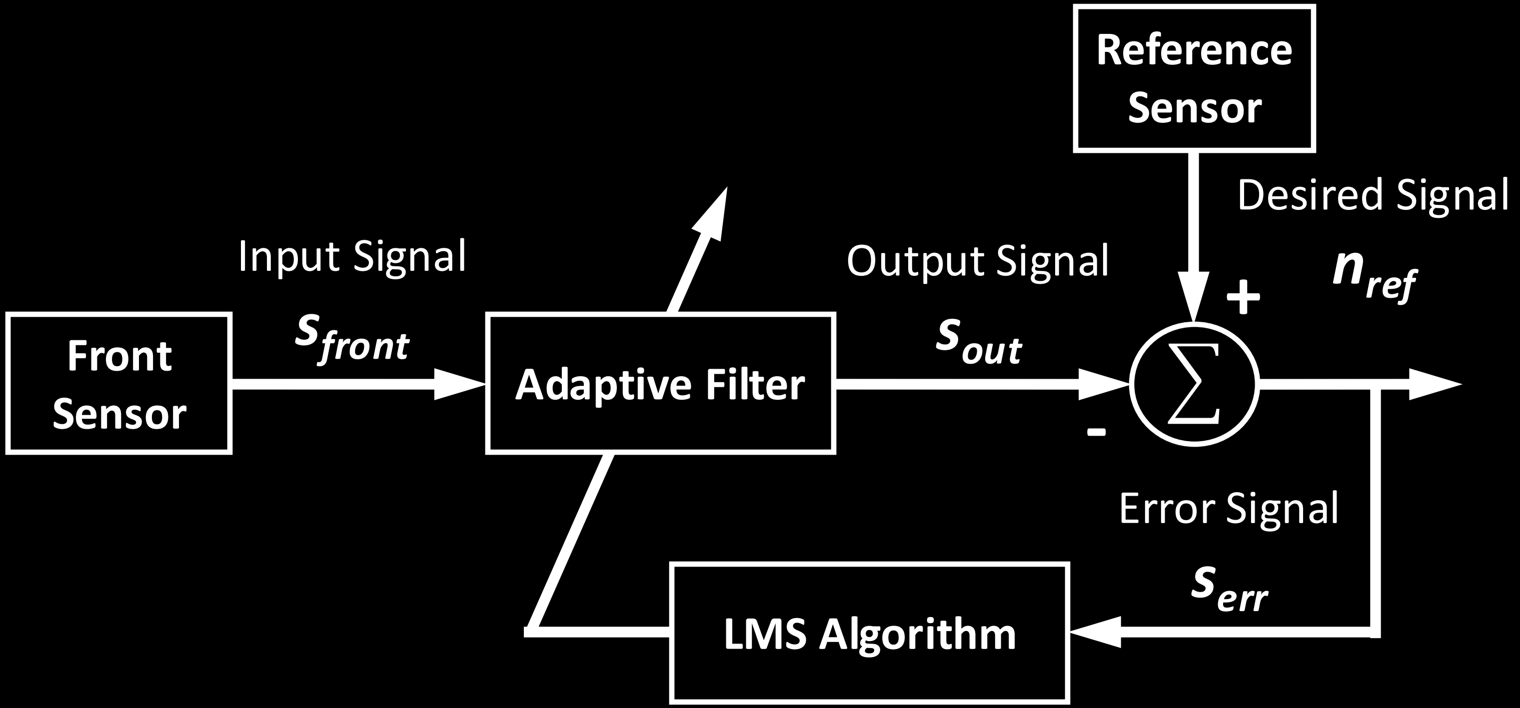



28.8%

Accuracy

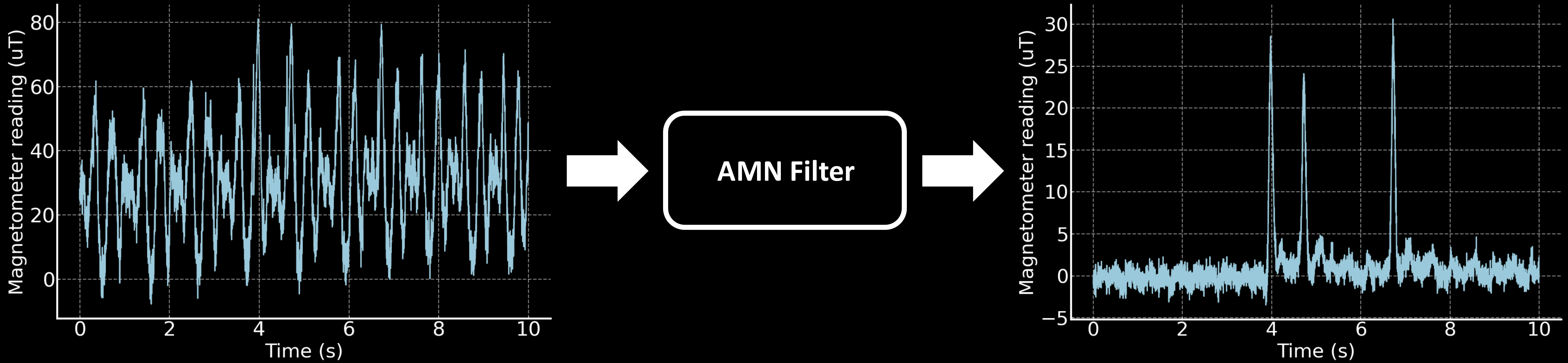
# Integrated Noise Cancellation (Cont.)

- Solution: LMS-based *adaptive magnetic field neutralization* (AMN)


Adaptive filter with Least Mean Square

# Integrated Noise Cancellation (Cont.)




W/ the wheel noise

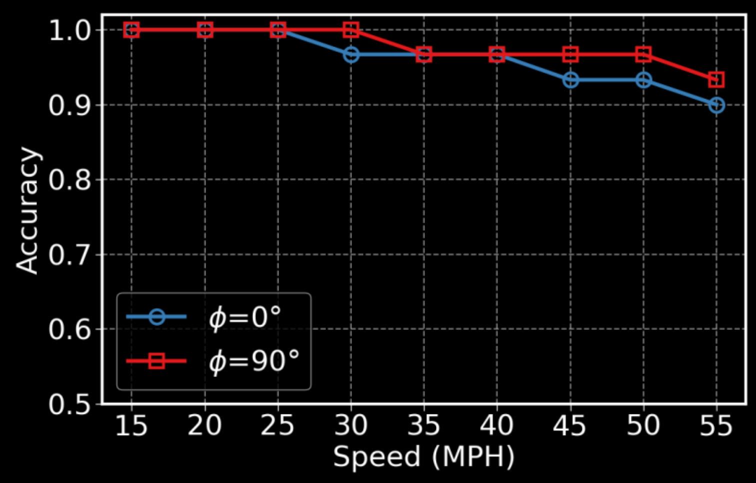
Filtered by AMN

**96.7%**

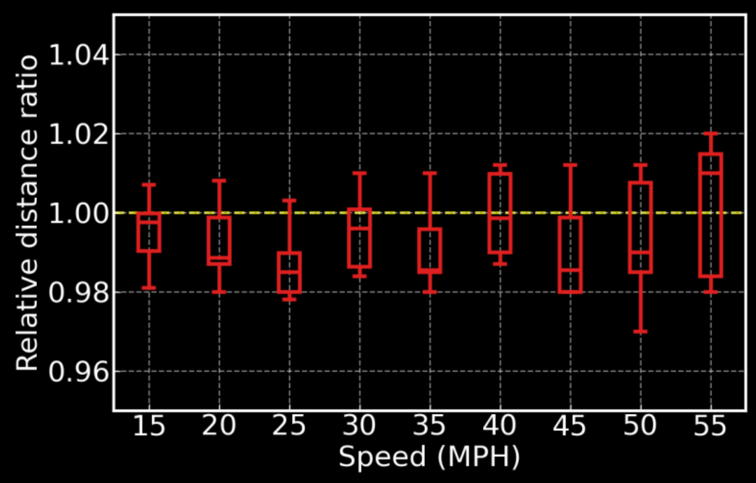
Accuracy with AMN

# Evaluation: Vehicle Speed

- Speed: 15-**55** mph (24-**88** km/h)
  - Test tags: tag {“N”, 90°} and tag {“NNN”, 0°, 3, 4m, 1m, 3/1}
- Results
  - The accuracy of detecting 90° and 0° magnets exceeded **93%** and **90%** at **> 50** mph
  - Overall detecting accuracy over **97%**



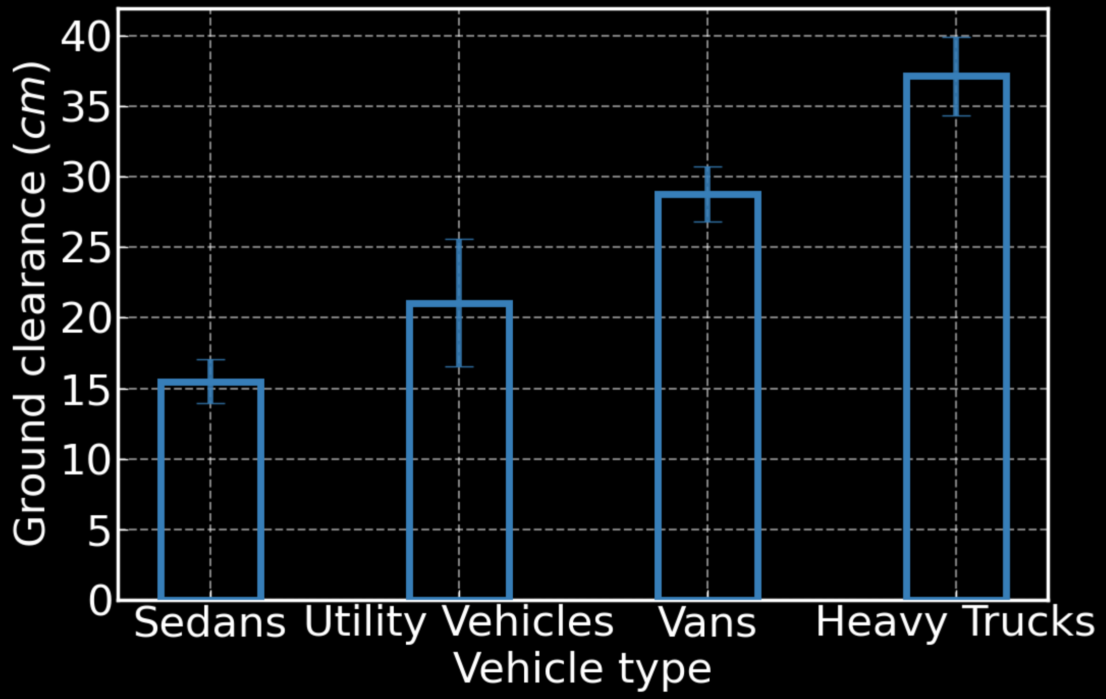

Accuracy w/ different polarities




Distance ratio result

# Evaluation: Ground Clearance

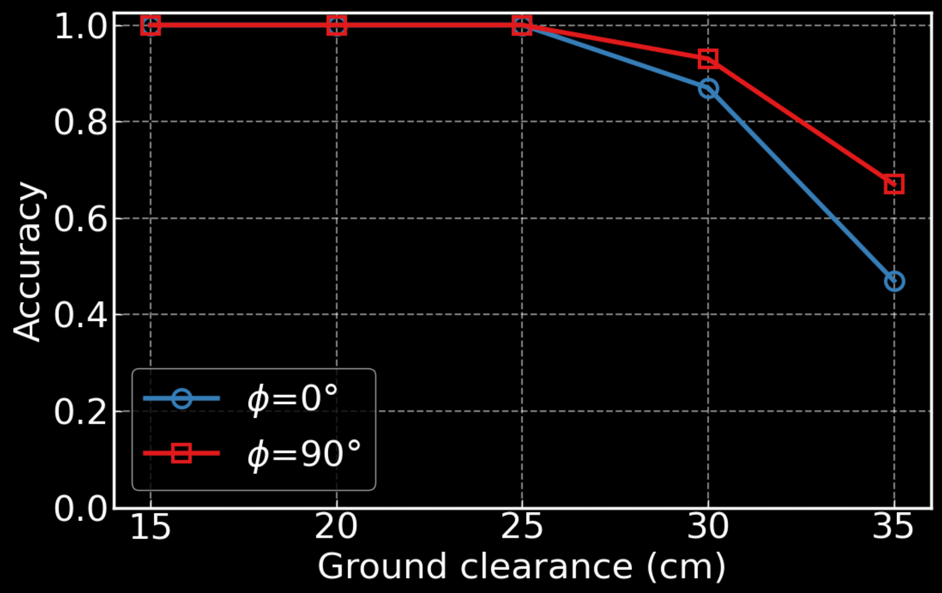
- Measure the ground clearance of four different vehicle types
- Ground clearance: 15-35 cm



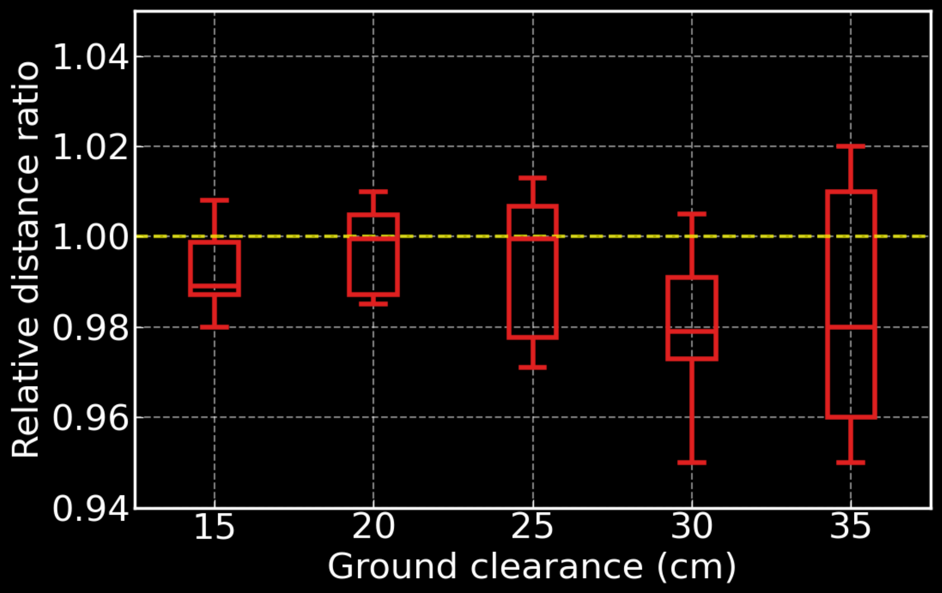

Ground clearances of different cars

# Evaluation: Ground Clearance (Cont.)

- Results
  - Even at 30 cm, the performance of 90° and 0° magnets are **93%** and **87%**
  - The overall accuracy exceeded **97%** within a ground clearance of **30** cm




Accuracy w/ different polarities




Distance ratio result

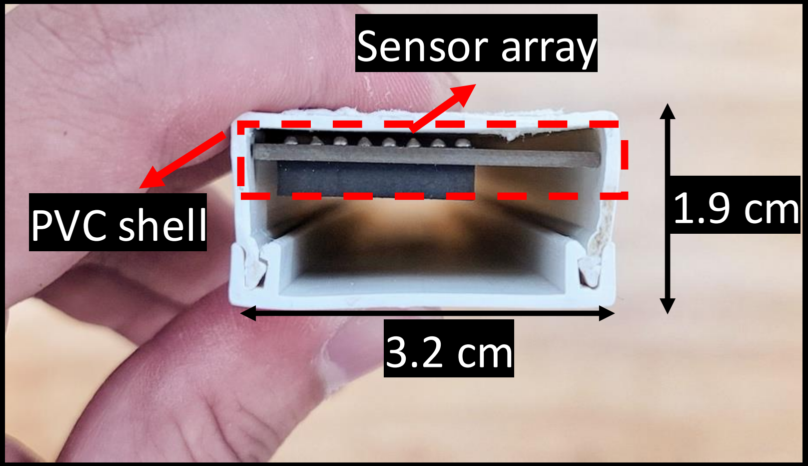
# How to Deploy METRO in Real-world Roads?

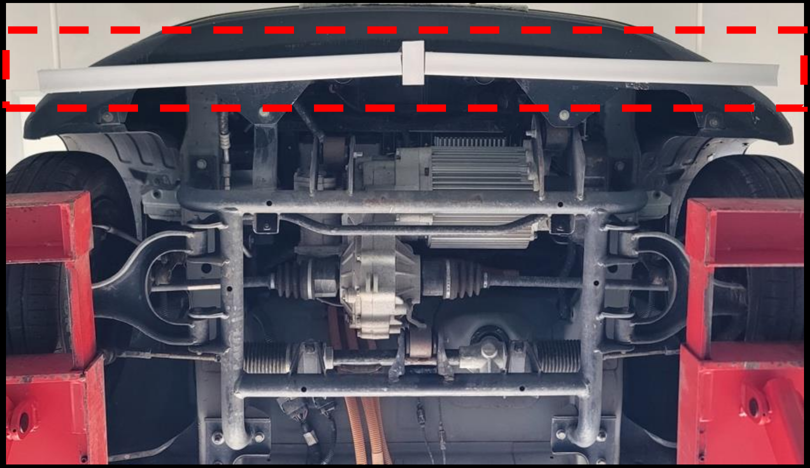
Achieve a **highly durable** and **cost-effective** deployment for

- METRO’s sensor array
- METRO’s magnetic tag

# Deployability of METRO's Sensor Array

- Protect the sensor array with a PVC shell
- Installed the sensor array under the front bumper of a compact EV for a month
  - A total travel distance of over **150** km

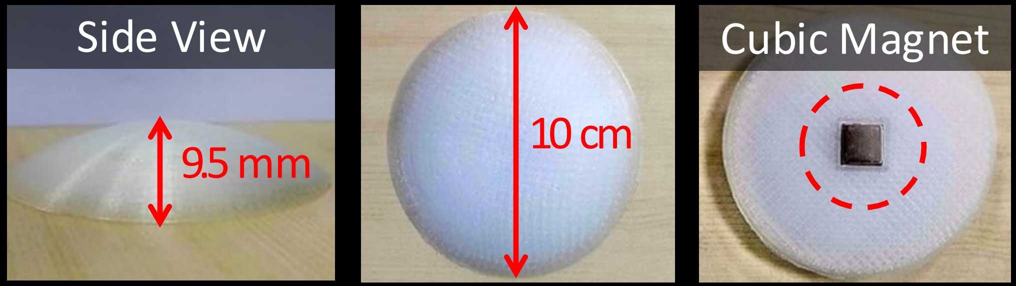


No sensor malfunctions/anomalies to METRO's sensor array

# Deployability of METRO's Tag

- High durability
  - Use cubic N52-grade passive magnets
  - With a 3D-printed protective shell
- Low cost
  - Each magnet: **$1**
  - Line marking: **$0.17** per meter
    - Traditional line marking: $0.21-7.70 per meter [2]
  - Transverse marking: **$3** per tag



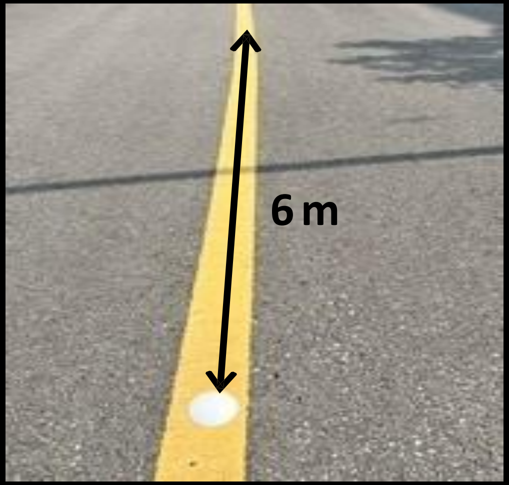


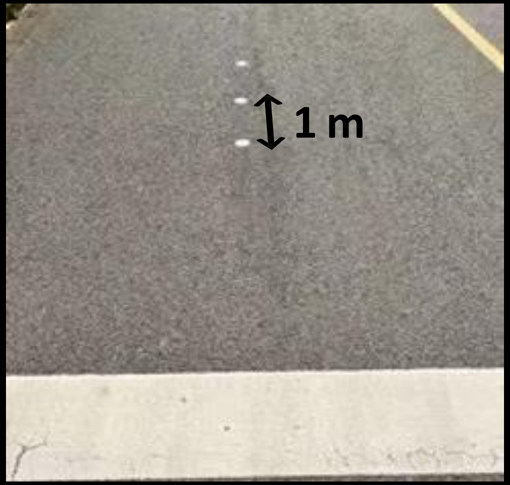
METRO tags in all-weather conditions

[2] 2005. Cost-Benefit Analysis. https://www.fhwa.dot.gov/publications/ research/safety/humanfac/04142/costest.cfm. (2005)

# Deployability of METRO’s Tag (Cont.)

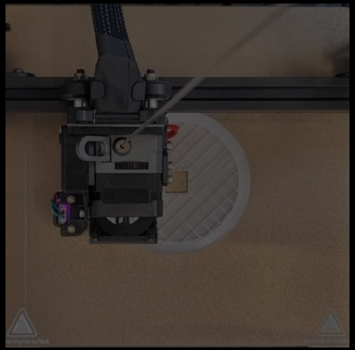
- Deployed the tags on a busy public road for one month
  - An average daily traffic volume exceeding **2,200** vehicles




No damage or demagnetization to METRO’s magnetic tags

# Manufacture and Deployment of METRO’s Tag



1. Print the protective

3. Add adhesive

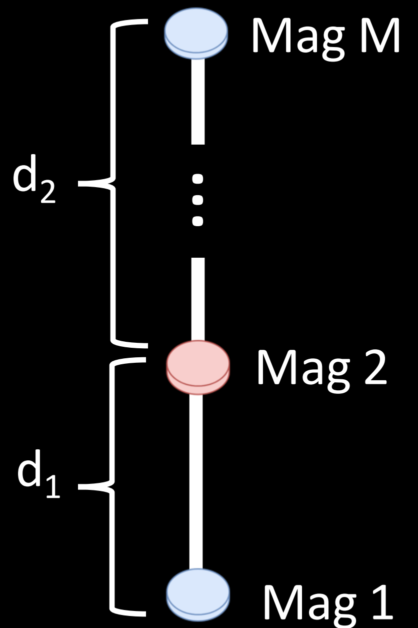
4. Deploy the tag

6. One-month deploym

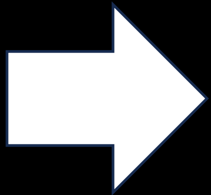
# To summarize

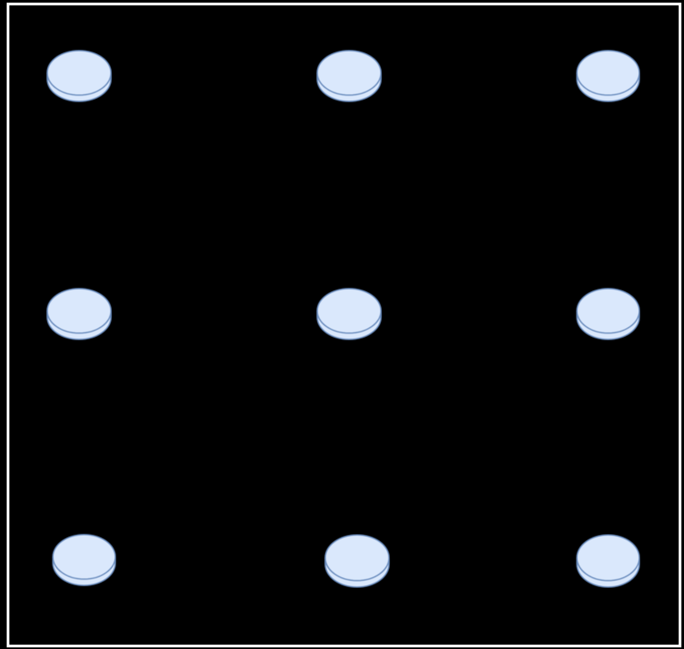
- METRO is a novel **all-weather** road marking infrastructure. It leverages magnetic sensing to achieve **accurate**, **robust**, and **cost-efficient** perception of road markings.
- METRO is tested and verified on REAL-WORLD ROADS!

# A Step Forward




1D tag





2D magnetic tag


• • •

Enabling critical robotic scenarios

# Polaris

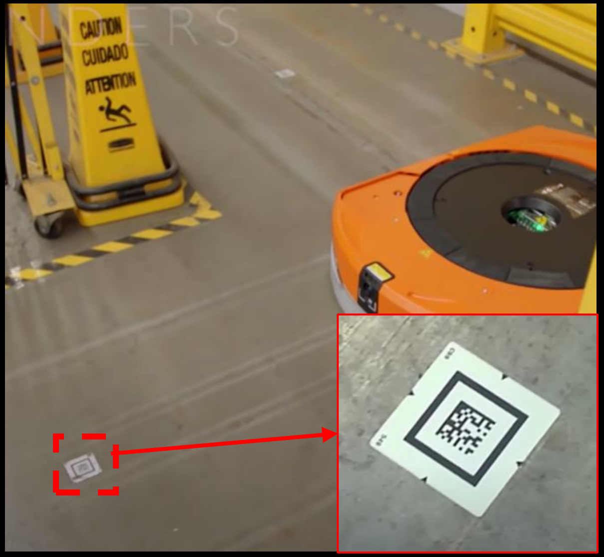
## Accurate, Vision-free Fiducials for Mobile Robots with Magnetic Constellation

ACM MobiCom 2024

**Jike Wang**, Yasha Iravantchi, Alanson Sample, Kang G. Shin, Xinbing Wang, Dongyao Chen

# Background and Motivation

- Fiducial marking is indispensable in mobile robots, including their pose calibration, contextual perception, and navigation




Ground-mounted 2D barcode for navigation

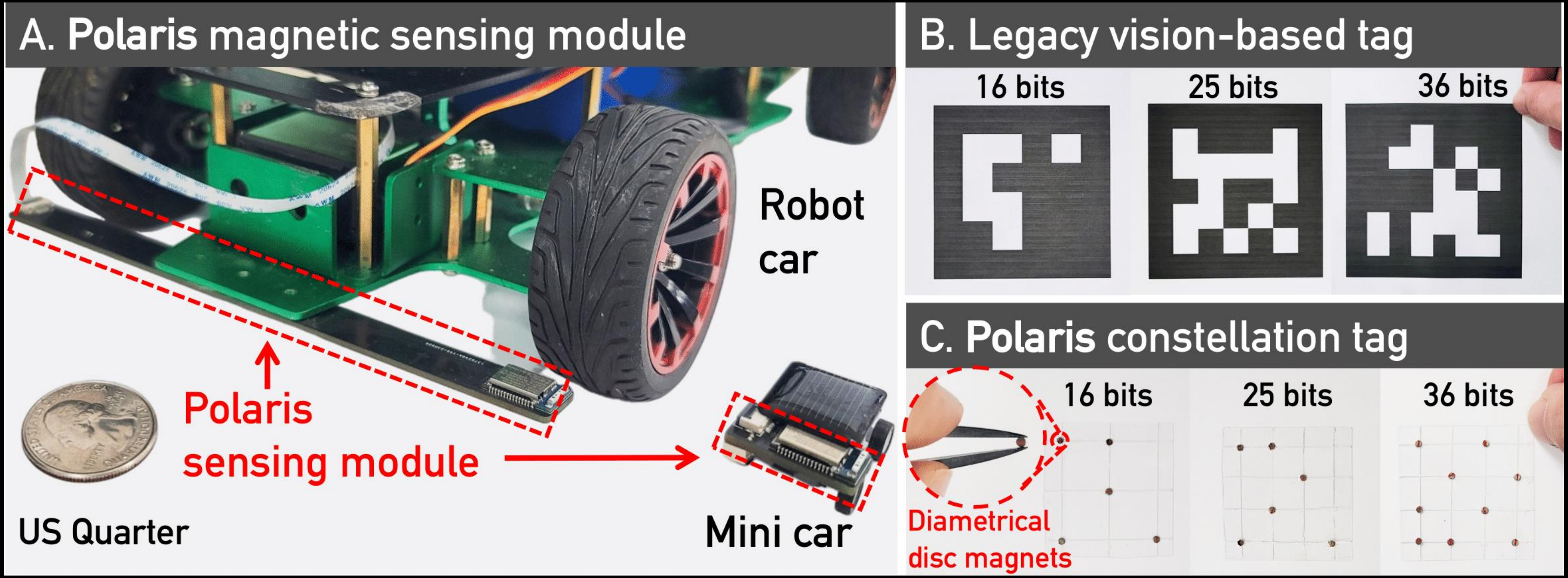


Visual fiducials for precise docking task

# Current Limitations

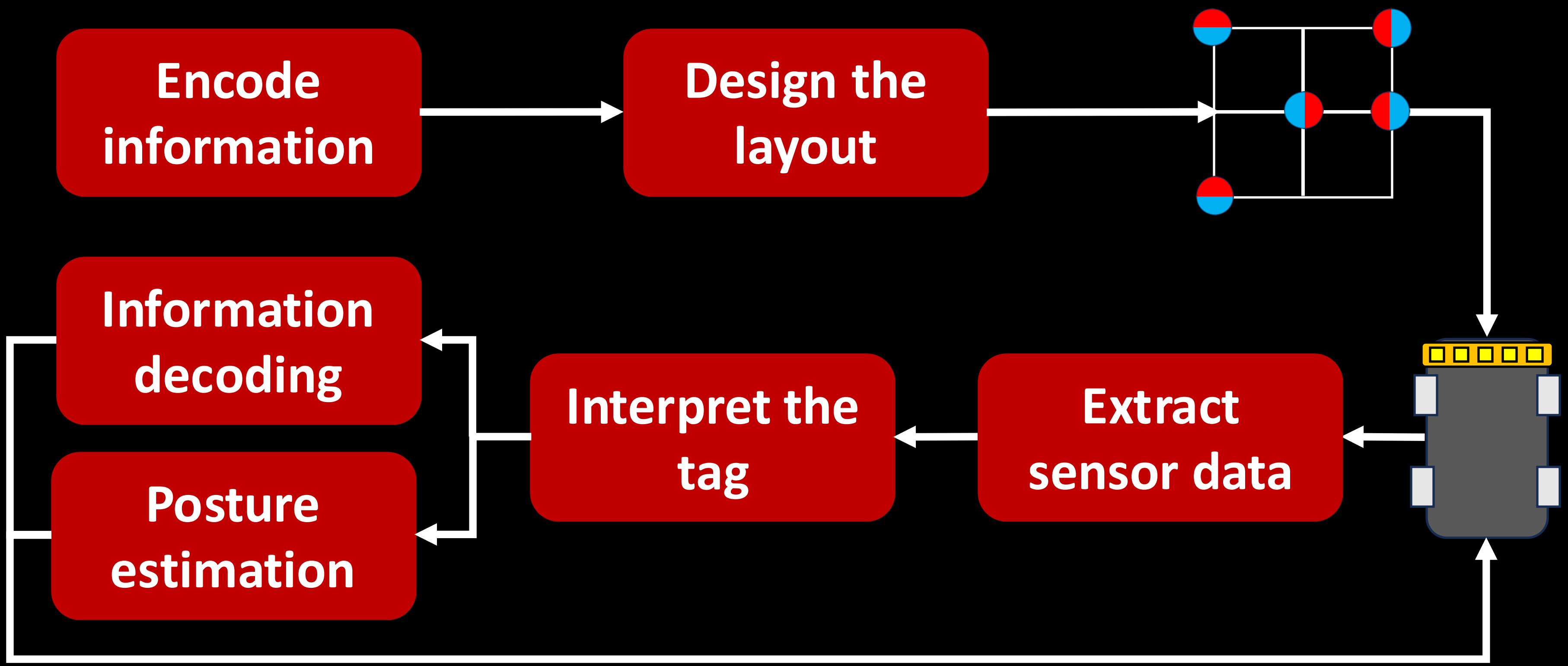
- Reliability
  - Susceptible to visual occlusions
- Energy overhead
  - Camera/LiDAR require substantial computation resources
- Privacy concerns
  - Active camera can cause severe privacy threats

# Our Solution: Polaris




Polaris system. (A) shows the magnetic sensing array of Polaris on different robotic systems; (B) and (C) compare the legacy ground-mounted vision-based tags with Polaris tags.

# System Overview



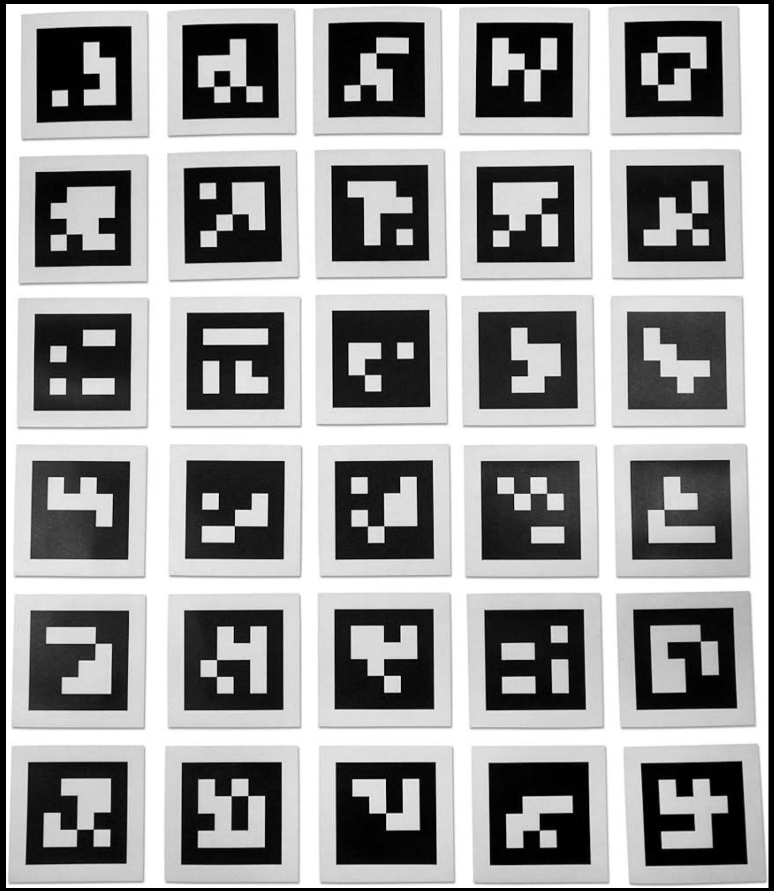
# Challenges for Designing Polaris

Two key challenges:

1. How to achieve compact and high-capacity tag design?
    - High encoding capacity, sufficient error correction

2. How to achieve robust and energy-efficient sensing framework?
    - Effectively detect and localize each magnet with millimeter-level accuracy

# How to achieve compact and high-capacity tag design?



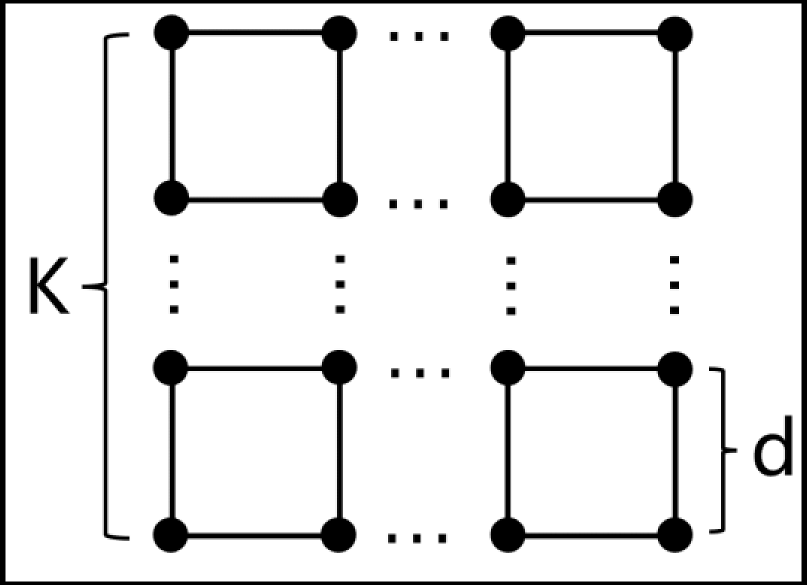
Existing visual fiducial tags

?

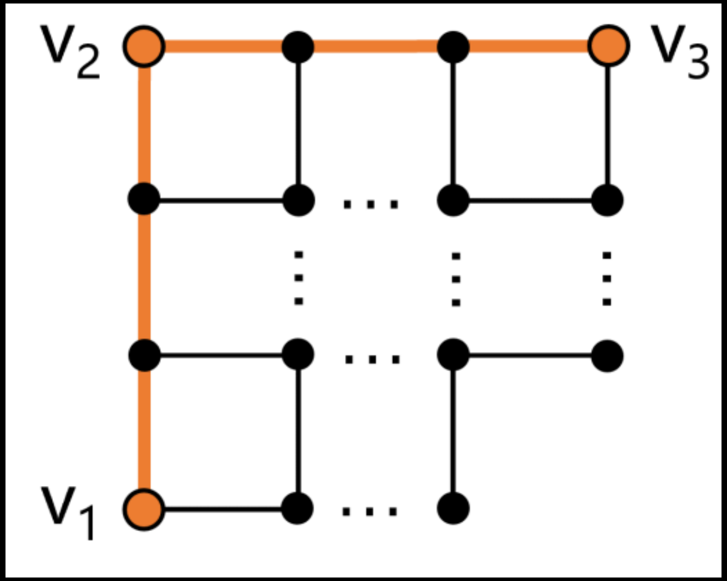
Passive magnet

# Tag Design: Magnetic Orientation-shift Keying

- To support the ground-mounted usability, i.e., reliable posture estimation and rich encoding capacity , we propose a 2D, chessboard tag layout



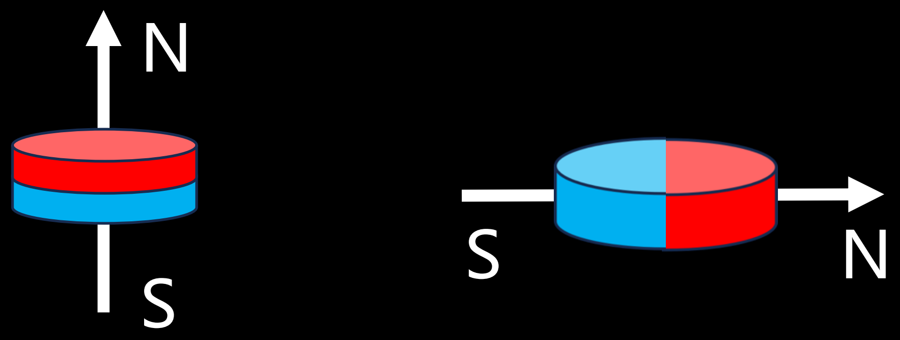

2D tag layout




Position-detection pattern

# Tag Design: Magnetic Orientation-shift Keying

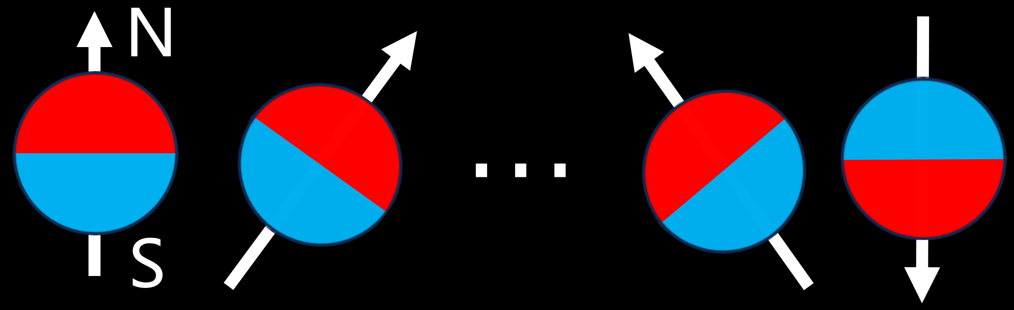
MOSK utilizes and augments the polarity configurations of a diametrically magnetized disc magnet to embed information.




Axially magnetized

Diametrically magnetized

Two magnetization directions

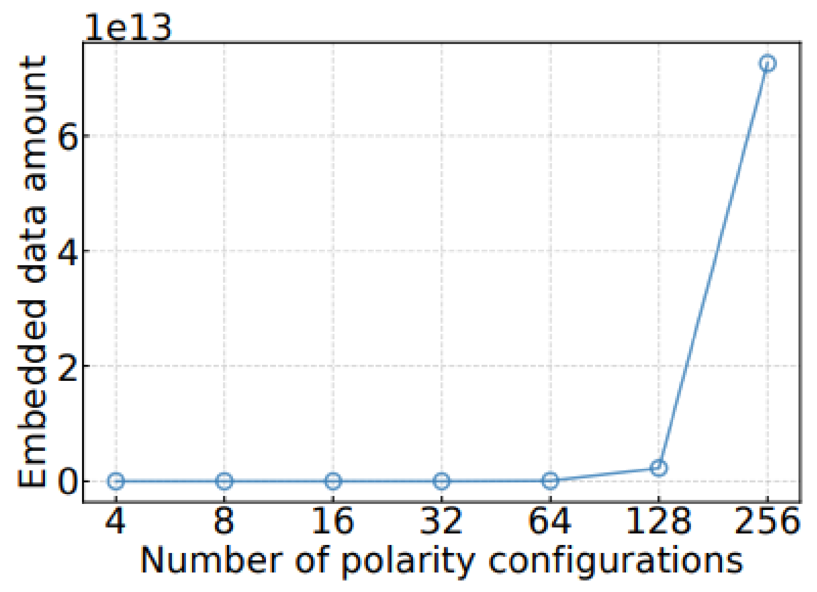



Polarity configuration of disc magnets

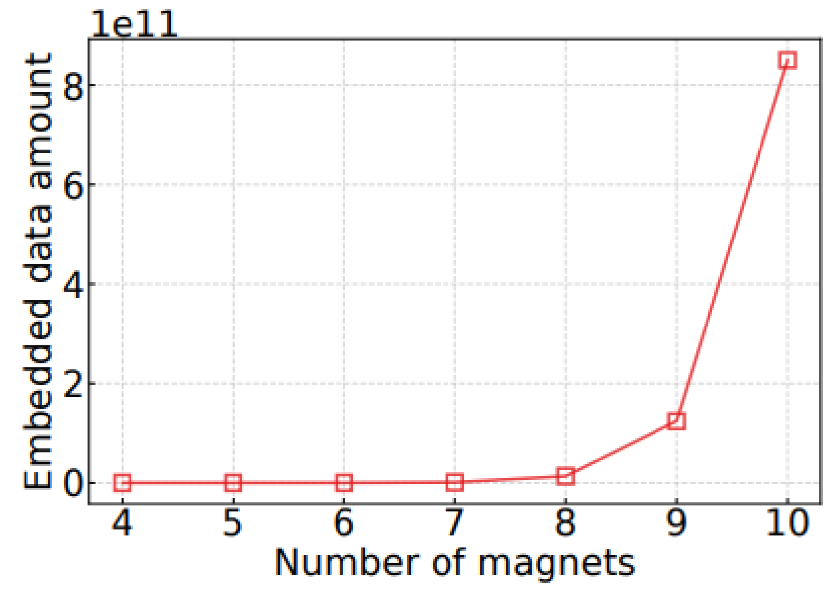
# Encoding Capacity

$$C = P^M \cdot \binom{K^2 - 1}{M - 3}$$

M: number of magnets
K: order of the grid
P: number of polarity configurations



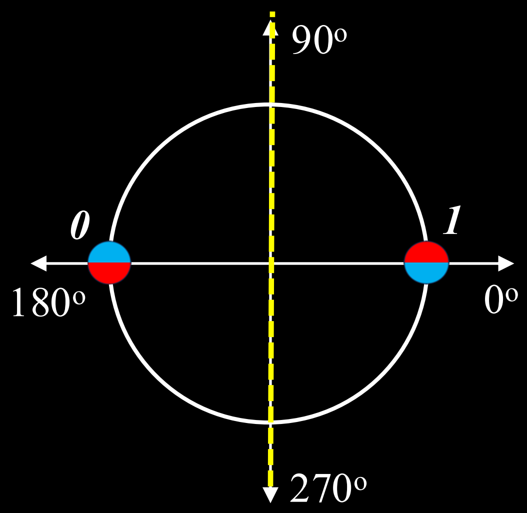

(a) Varying $P$, $K$=4, $M$=5



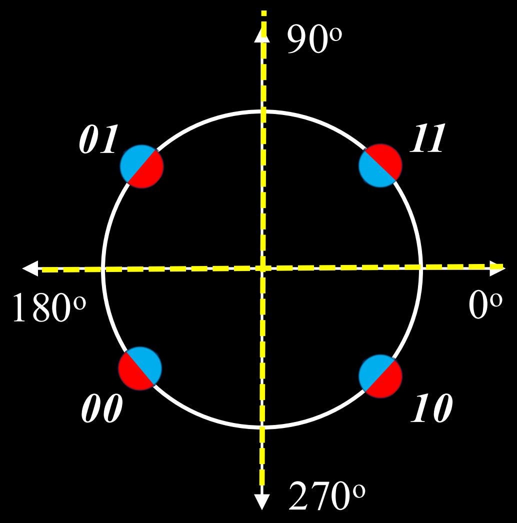

(b) Varying $M$, $K$=4, $P$=8

The extended number of orientations and magnets can **exponentially** enhance the encoding capability

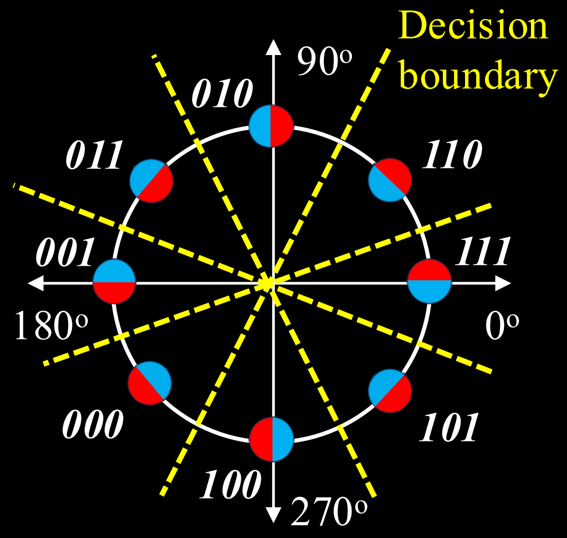
# Magnetic Orientation-shift Keying (MOSK)




(a) 2-MOSK




(b) 4-MOSK



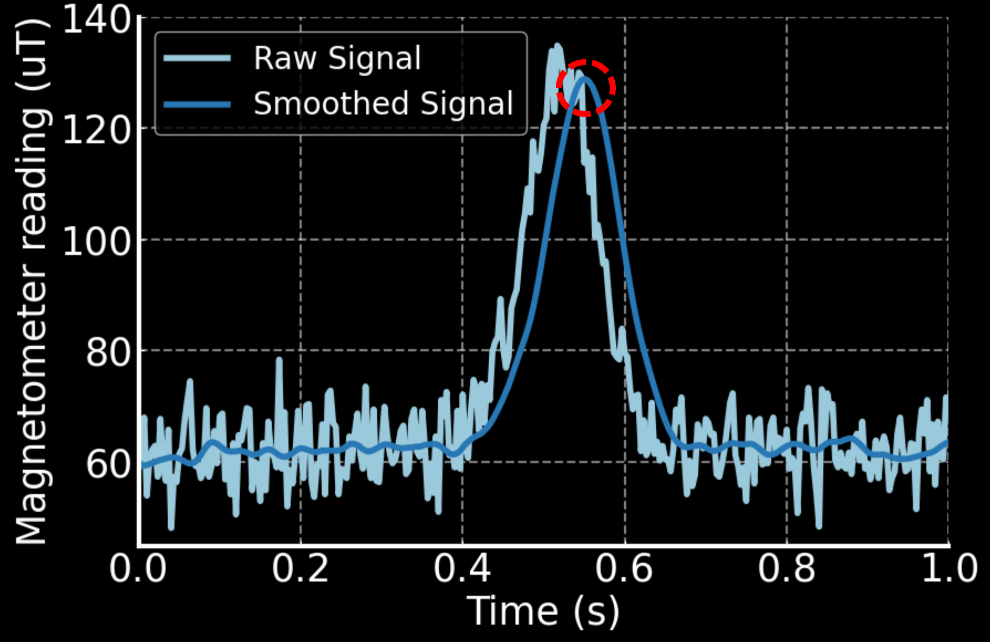

(c) 8-MOSK

# Robust and Energy-efficient Sensing Framework

- Polaris’ sensing module performs four tasks
  - Detect the magnet(s)
  - Recognize the polarity orientation
  - Localize the magnet(s)
  - Reconstruct the tag

# Detect the Magnet

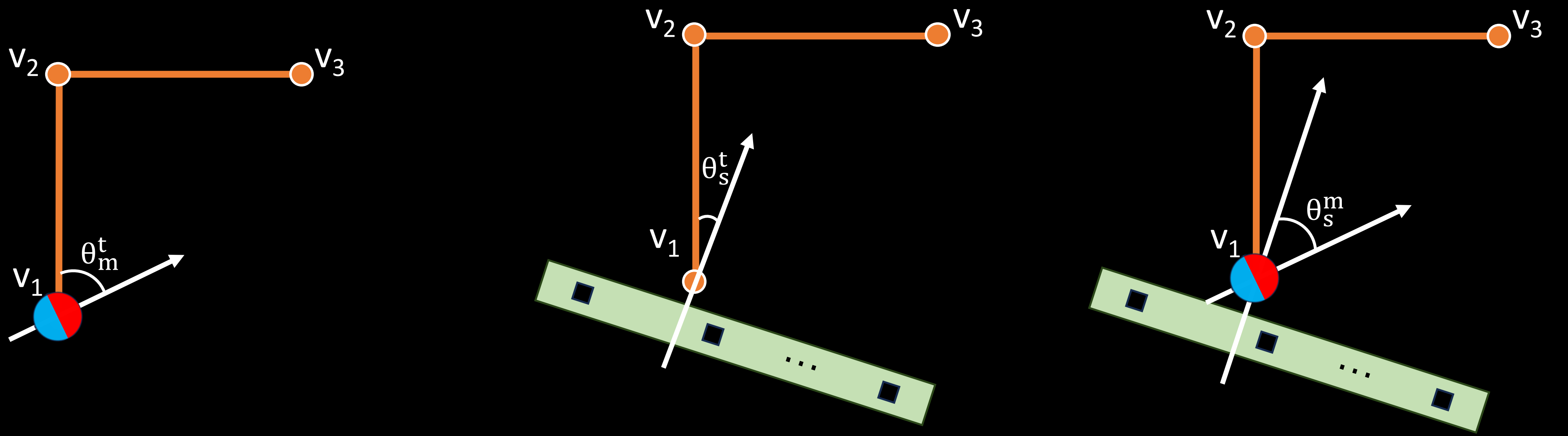
- We can detect the presence of a magnet using METRO's peak-detection algorithm




Raw peak signal with "N" polarity

# Recognize the Polarity Orientation

- Polaris needs to derive the polarity orientation of each magnet relative to the position-detection pattern of the 2D tag, i.e., the value of $\theta_m^t$




(a) the polarity orientation of each magnet

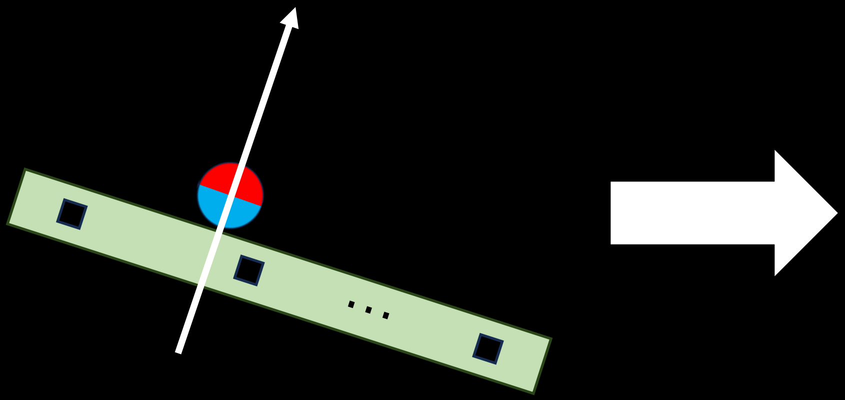
(b) the relative orientation of the sensor array to the tag

(c) the relative orientation of the sensor array to the magnet

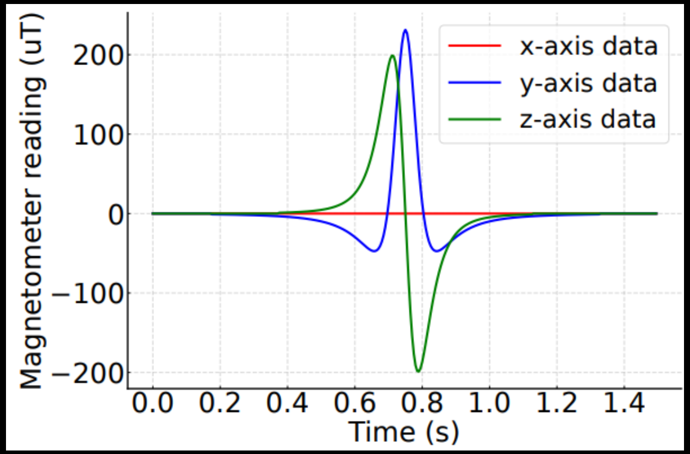
We have $\theta_m^t = \theta_s^t + \theta_s^m$

# Recognize the Polarity Orientation (Cont.)

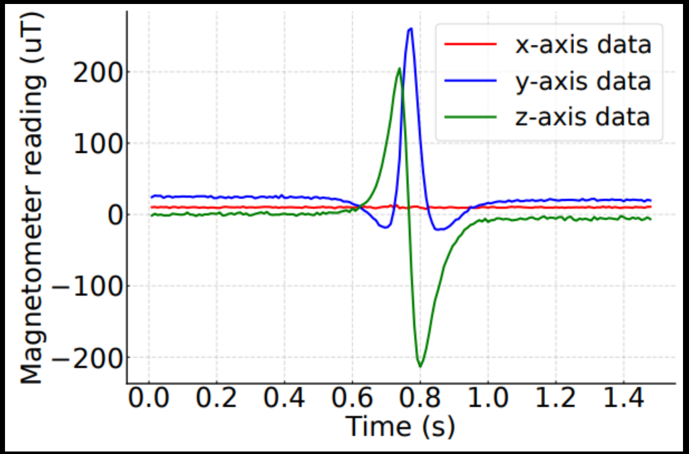
- $\theta_s^t$ is the relative heading angle of the tag to the sensor array, which can be determined by the posture estimation
- To obtain $\theta_s^m$ , we leverage the mathematical model of disc magnets and propose a unique analytical scheme




$\theta_s^m = 0°$




(a) Simulated (synthesized) data

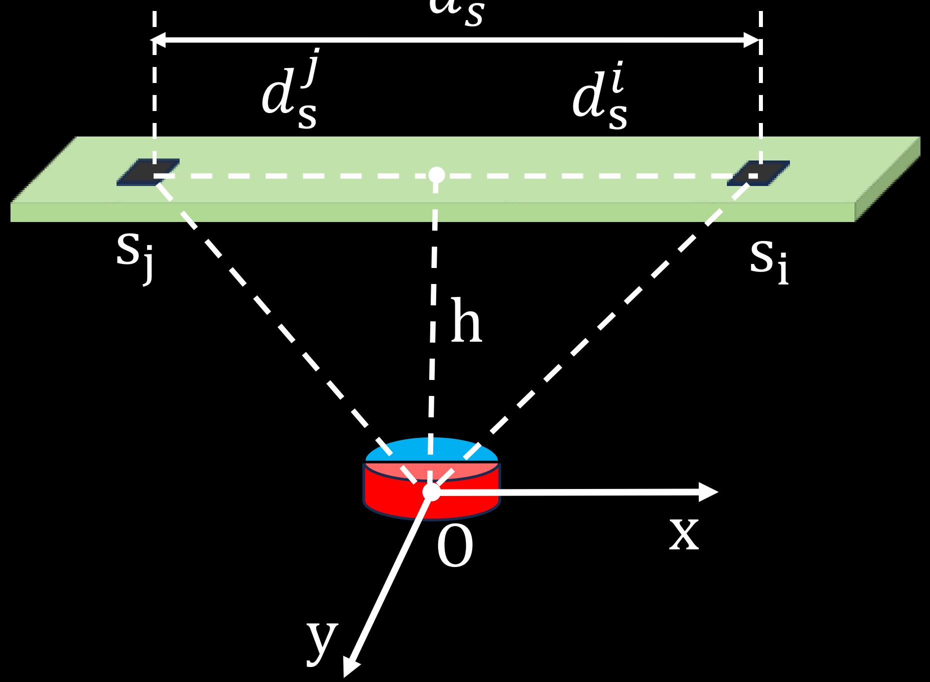



(b) Real-world measurement

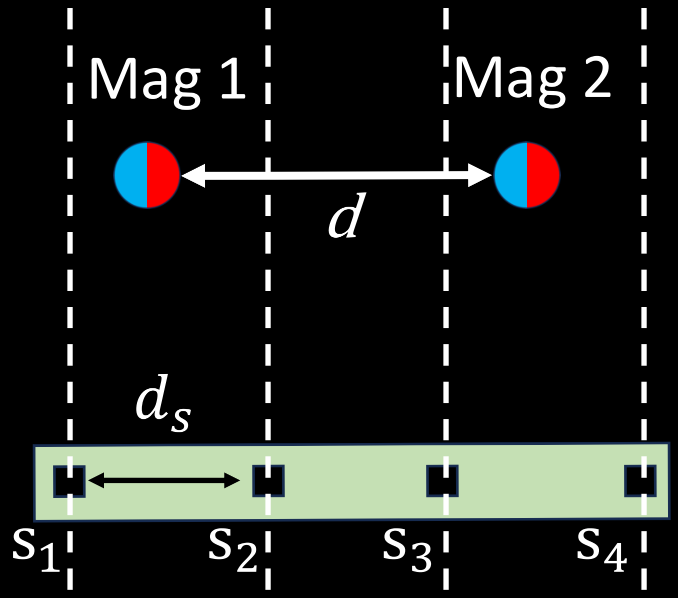
The simulated (synthesized) data indicates a close similarity with real-world measurement!

# Localize the Magnet

- We present an effective method for locating a magnet with two adjacent magnetometers, $s_i$ and $s_j$



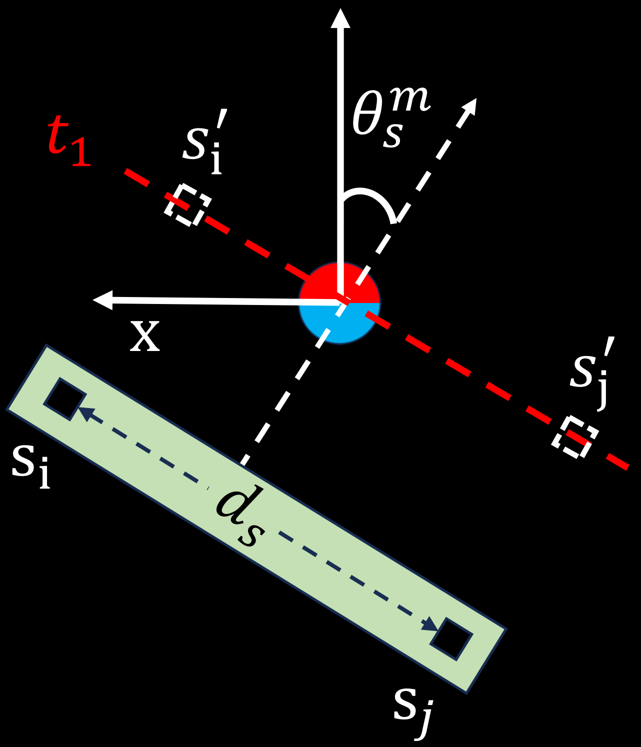

(a) Movement modeling




(b) Worst-case scenario

The maximal inter-sensor distance $d_s$ should be $d/2$

# Localize the Magnet (Cont.)




Arbitrary headings

We have

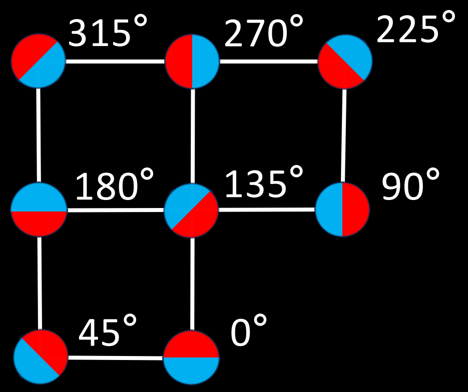
- $d_s^i + d_s^j = d_s$
- Position of $s_i'$: $(d_s^i \cos\theta, d_s^i \sin\theta, -h)$
- Position of $s_j'$: $(-d_s^j \cos\theta, -d_s^j \sin\theta, -h)$
- Measured magnetic fields: $B_m^i$, $B_m^j$
- Theoretical magnetic fields: $B_t^i$, $B_t^j$

$$\min_{d_s^i, d_s^j} \left(\frac{B_t^i}{B_t^j} - \frac{B_m^i}{B_m^j}\right)^2 + (d_s^i + d_s^j - d_s)^2$$

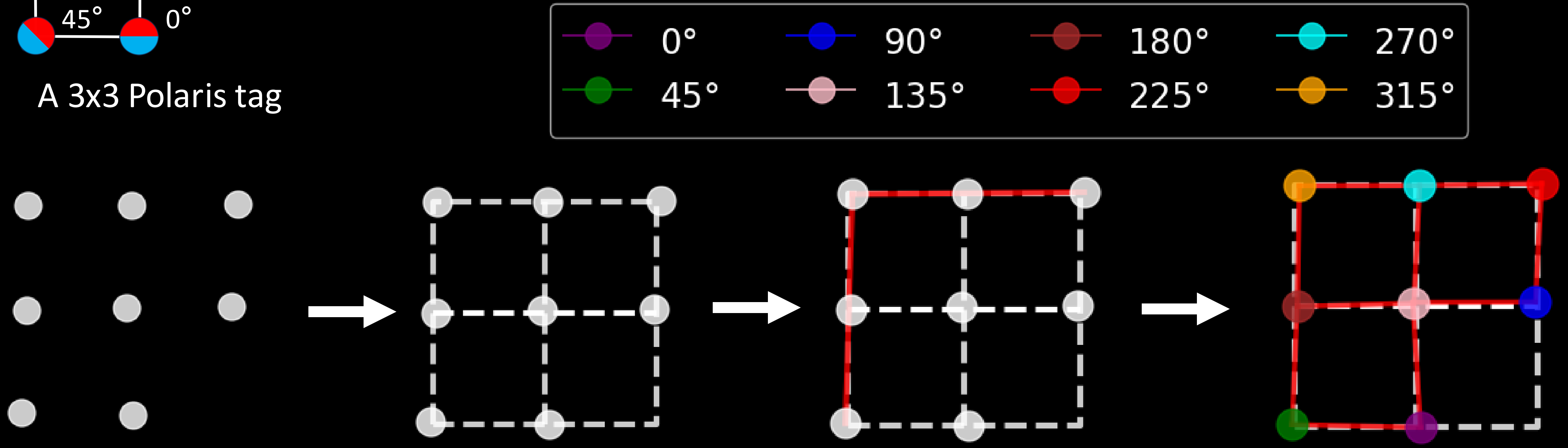
$$\text{s.t.} \quad 0 \leq d_s^i, d_s^j \leq d_s.$$

Nonlinear-constrained optimization problem

# Real-world Tests of Tag Reconstruction Steps

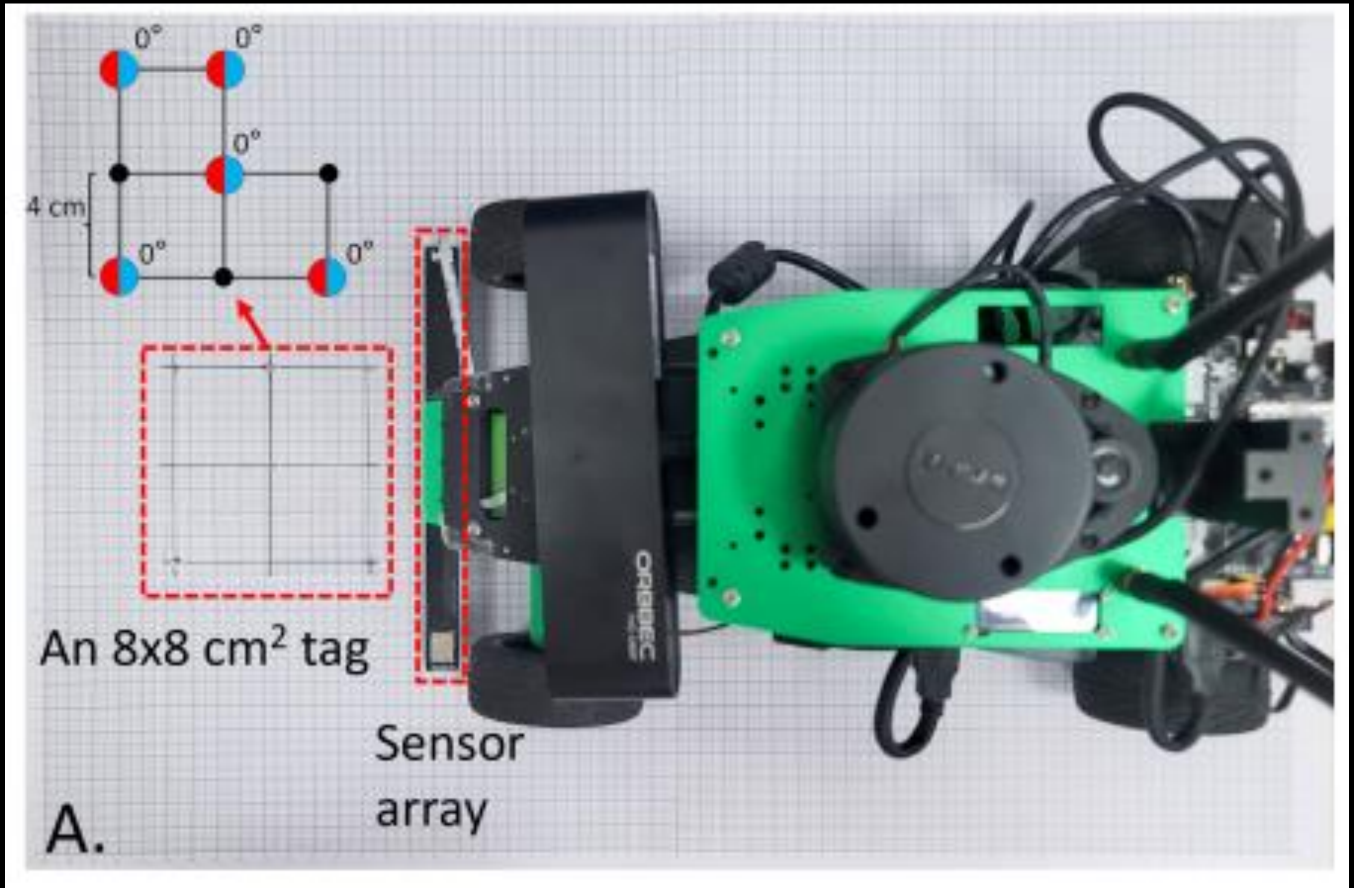



A 3x3 Polaris tag



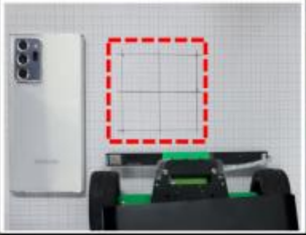
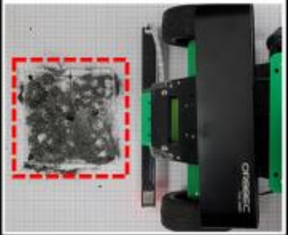
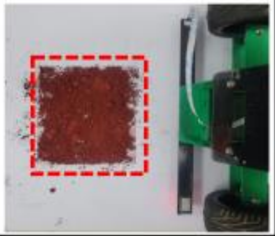
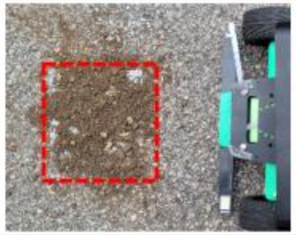

(a) Detect each magnet (b) Localize each magnet (c) Reconstruct tag layout (d) Determines the polarity

# Evaluation on Robot Car



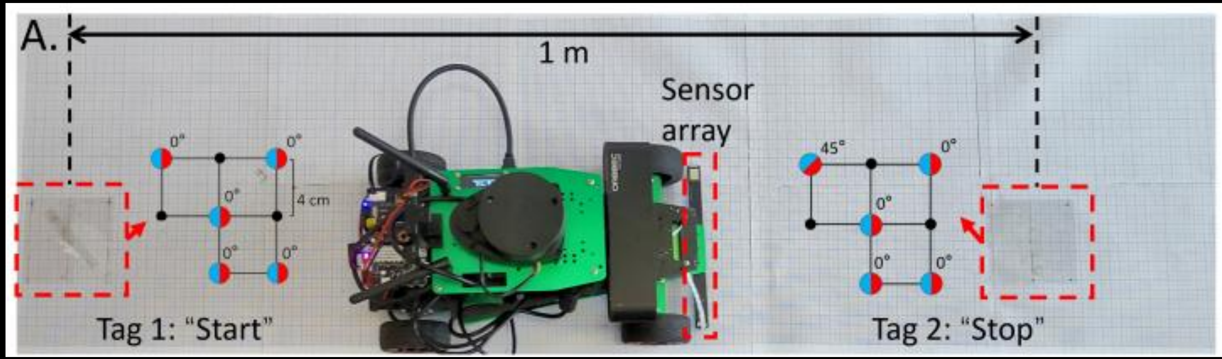
# Real-world Interference

- Analyze the resilience of Polaris against various real-world noises, including magnetic, non-magnetic, and ferromagnetic objects

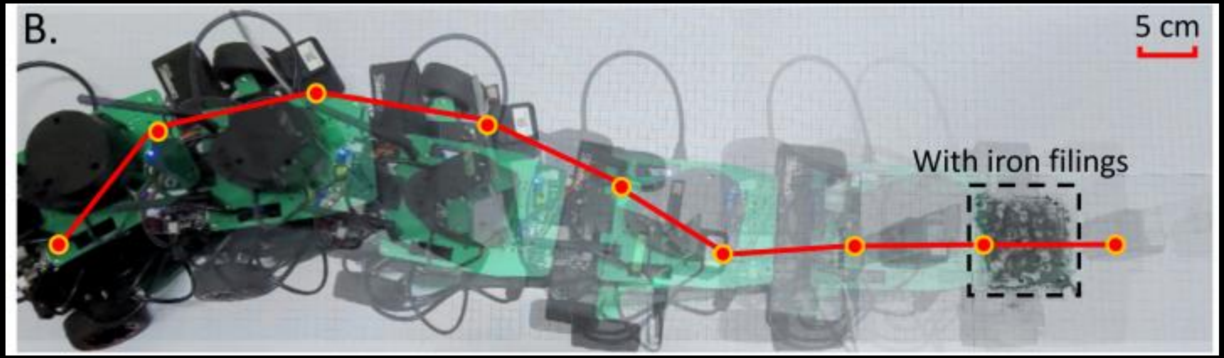
| Real-world interference | Smartphone | Metal chair | Metal umbrella stand | Iron filings | Iron oxide ($Fe_2O_3$) | Dirt | Muddy water |
|---|---|---|---|---|---|---|---|
| Experimental settings |  |  |  |  |  |  |  |
| Angular Err. (Mean, STD) | (1.10, 0.28) | (1.29, 0.40) | (1.65, 0.47) | (1.33, 0.57) | (1.93, 0.30) | (1.12, 0.23) | (1.24, 0.66) |
| Localization Err. (Mean, STD) | (1.91, 0.32) | (2.15, 0.65) | (2.21, 0.51) | (2.63, 0.47) | (2.89, 0.64) | (1.98, 0.34) | (2.10, 0.46) |

The performance of Polaris under real-world interference. Units of angular and localization errors are ∘ and $mm$, respectively

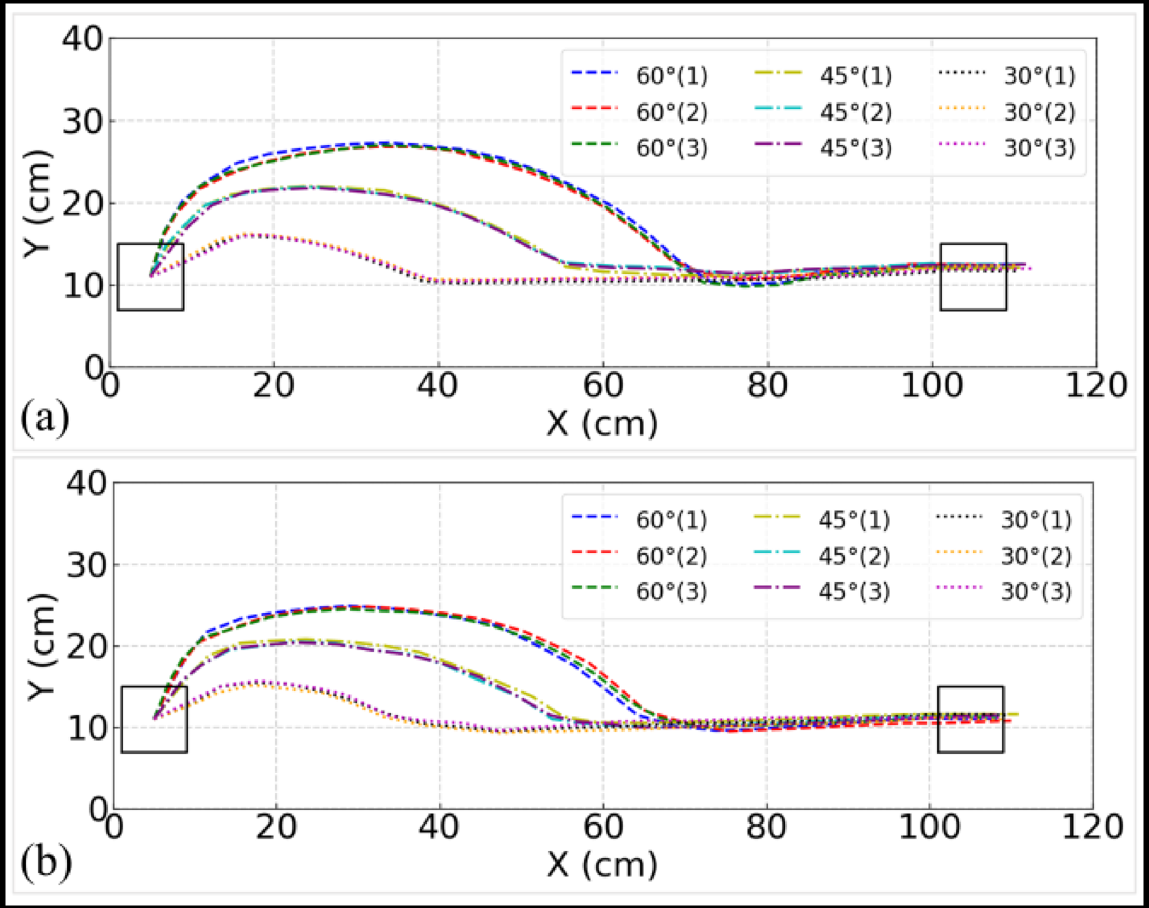
# End-to-End System: Trajectory Calibration




The experimental setup



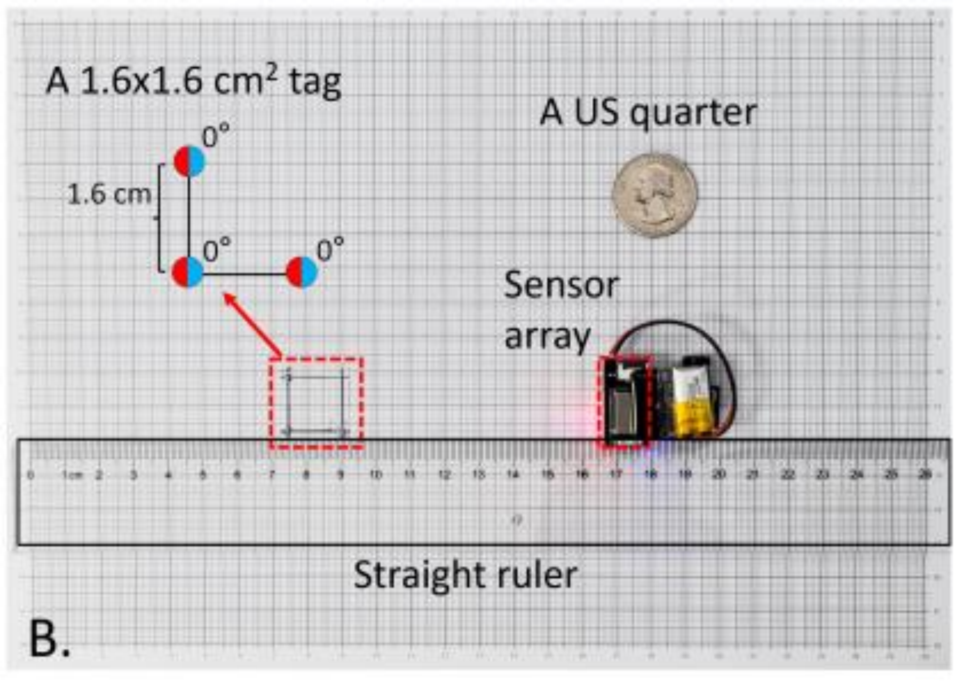

A trajectory calibrated by Polaris with iron filings




Results of trajectory calibration. (a) w/o interference (iron filings); (b) w/ interference.

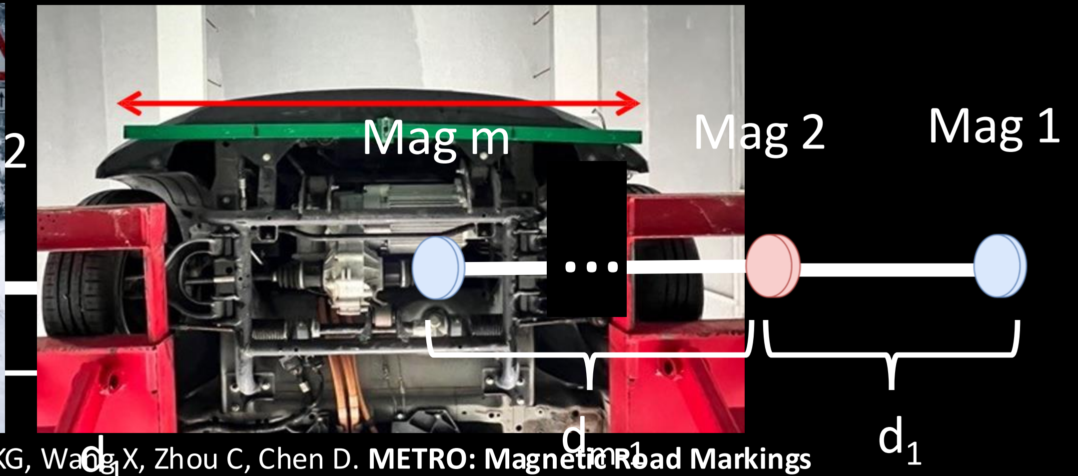
# Evaluation on Mini Car

- We integrate the sensing pipeline into a ESP32 S3 chip, the time of detect each magnet only takes 0.75 s
- The BER result is 0.033
- The localization accuracy is 0.58 mm
- The posture estimation accuracy is 0.997°



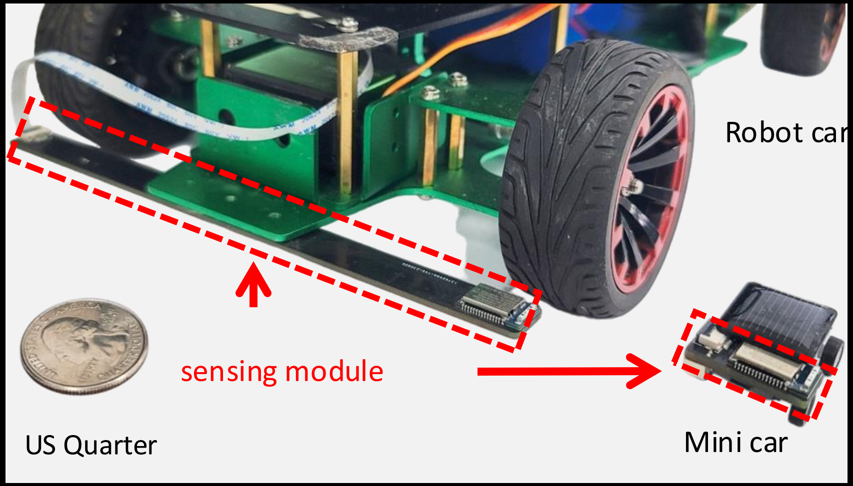
# 挖掘空间和极性的多样性

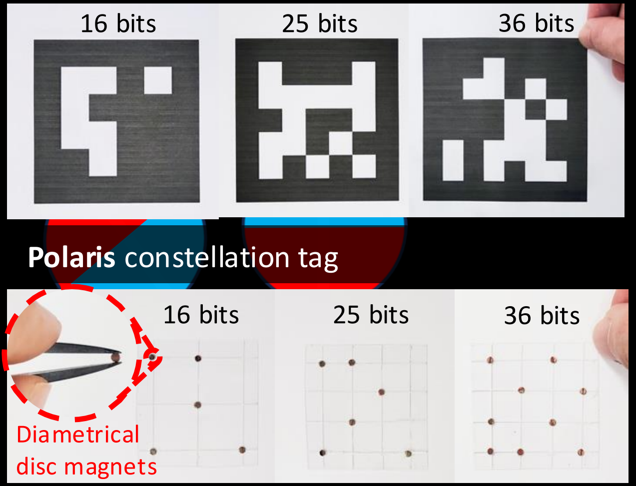
- 空间多样性


Wang J, Wang S, Iravantchi Y, Wang M, Sample A, Shin KG, Wang X, Zhou C, Chen D. **METRO: Magnetic Road Markings for All-weather, Smart Roads.** SenSys 2023

- 极性多样性




磁场校准码达到和传统二维码同等的编码效率

Wang J, Iravantchi Y, Sample A, Shin KG, Wang X, Chen D. Polaris: Accurate, Vision-free Fiducials for Mobile Robots with Magnetic Constellation MobiCom 2024

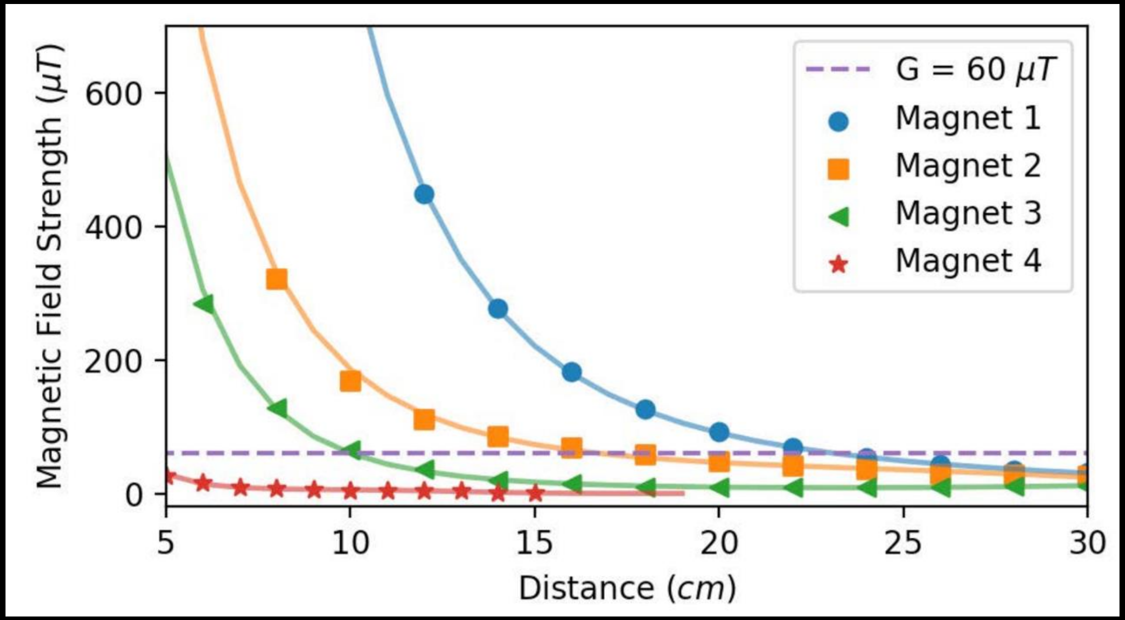
# Summary

Magnetic sensing is an unique sensing modality for CPS systems, with key advantages:

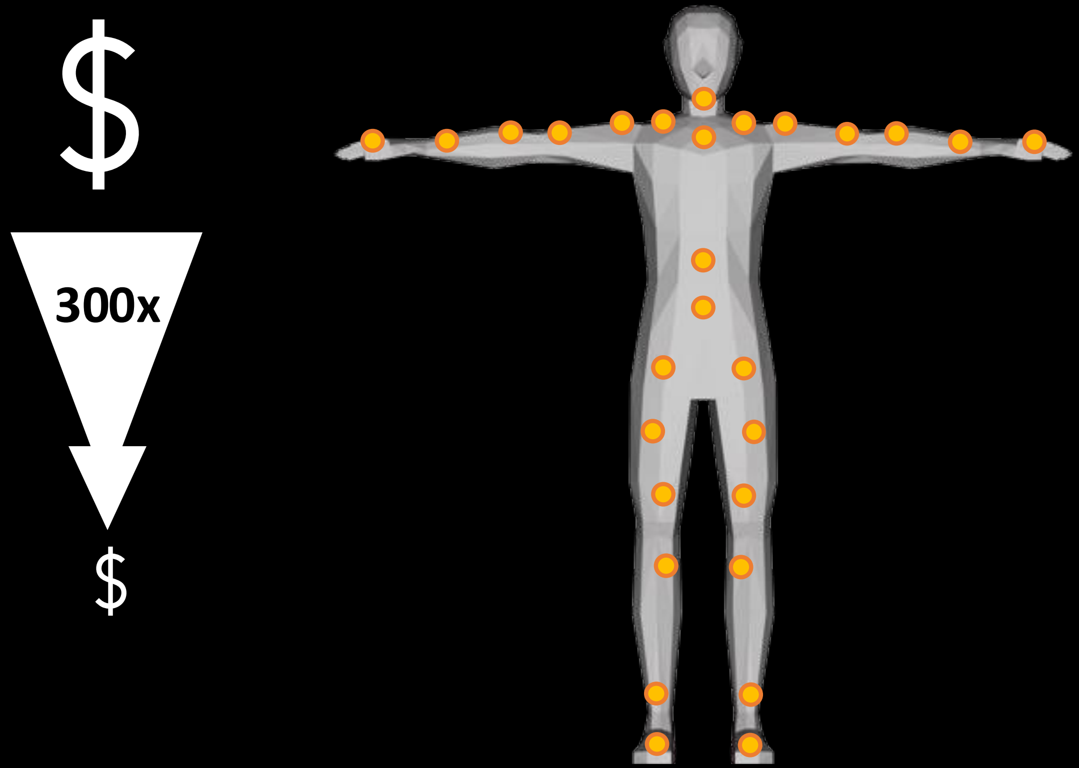
- Fine-grained sensing
- Resilience (e.g., nLoS and multipath)
- Energy efficiency
- Low cost

# Future Directions

Pushing the limitation of magnetic sensing **range**

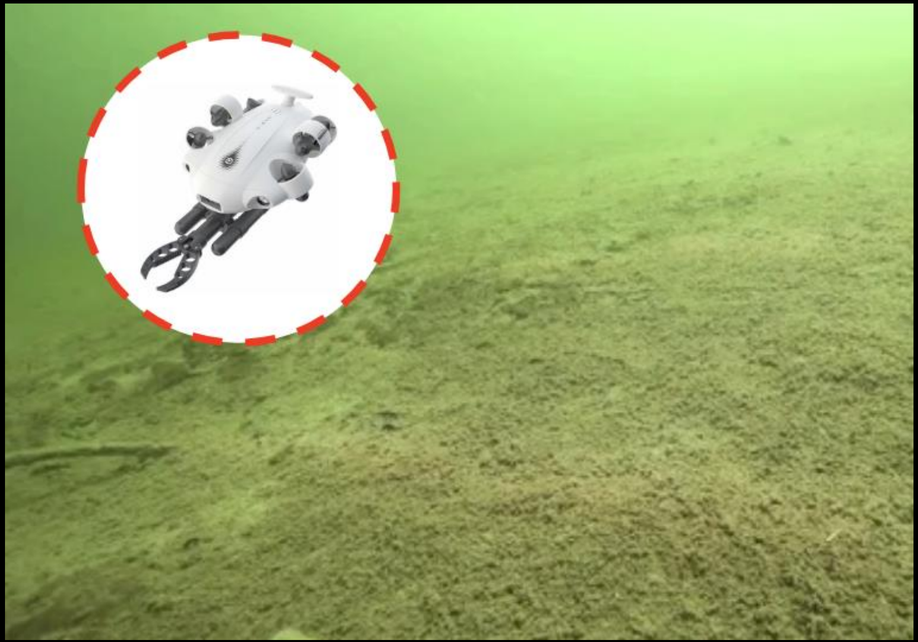



Bringing motion capture sensing to millions

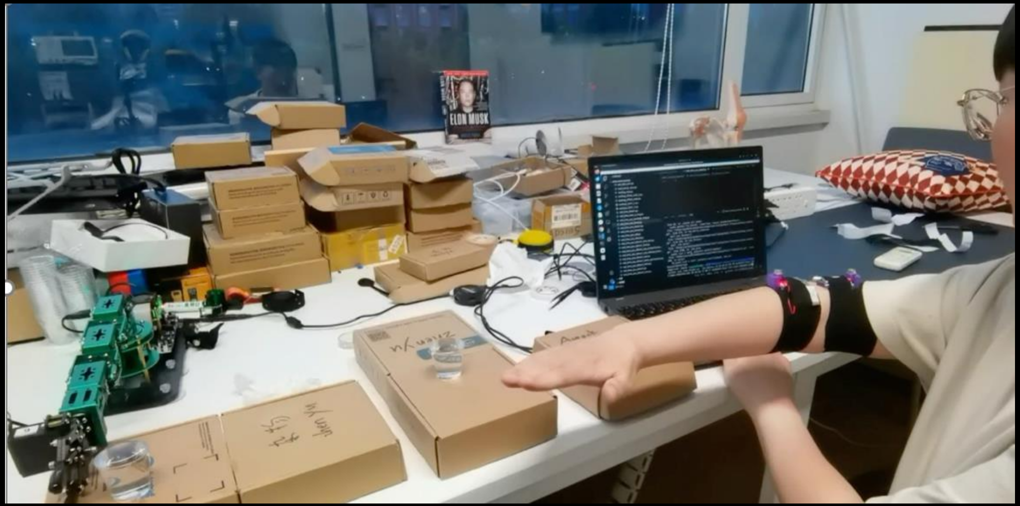


# Future Directions

Sensing in extreme conditions



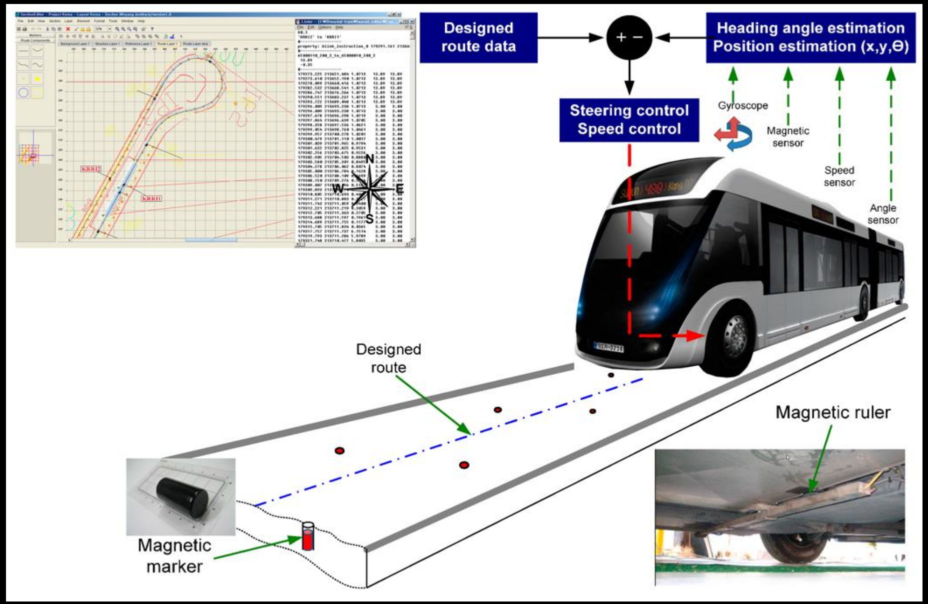
Enhanced robot-human interaction, e.g., motion teleportation



# Backup Slides

# Existing Magnetic Road Marker Systems

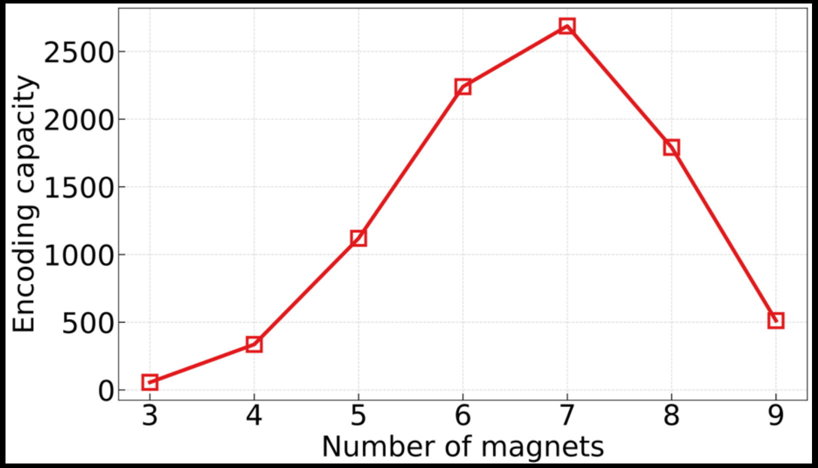
- Passive magnetic pavements have been deployed on the road to facilitate vehicle posture estimation and achieve road tracking

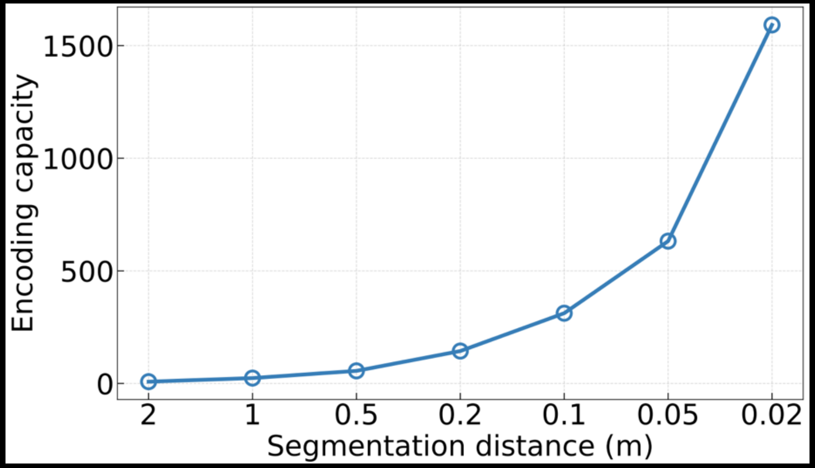

Such systems require vehicles to follow the magnetic path strictly and can not encode rich road information

# Encoding Capacity Analysis

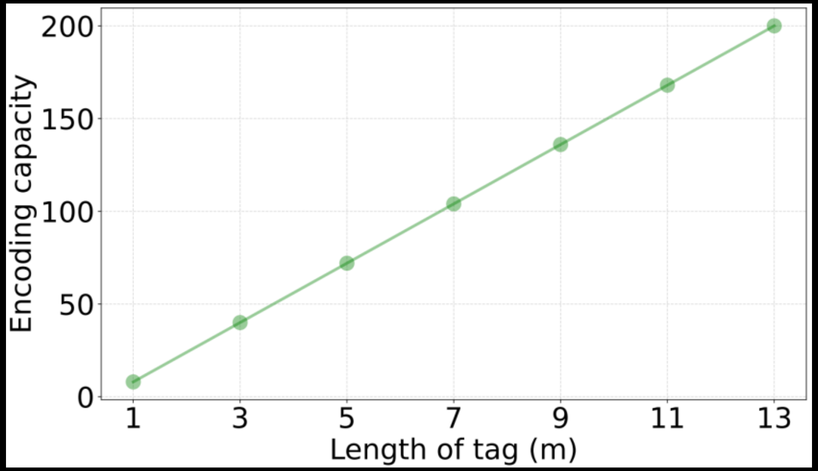
$$C = 2^M \cdot \binom{L/Seg_d - 1}{M - 2}$$




Varying M, L = 4 m, $Seg_d$ = 0.5 m




Varying $Seg_d$, M = 3, L = 4 m




Varying L , M = 3, $Seg_d$ = 0.5 m

# Vehicle Motion Analysis

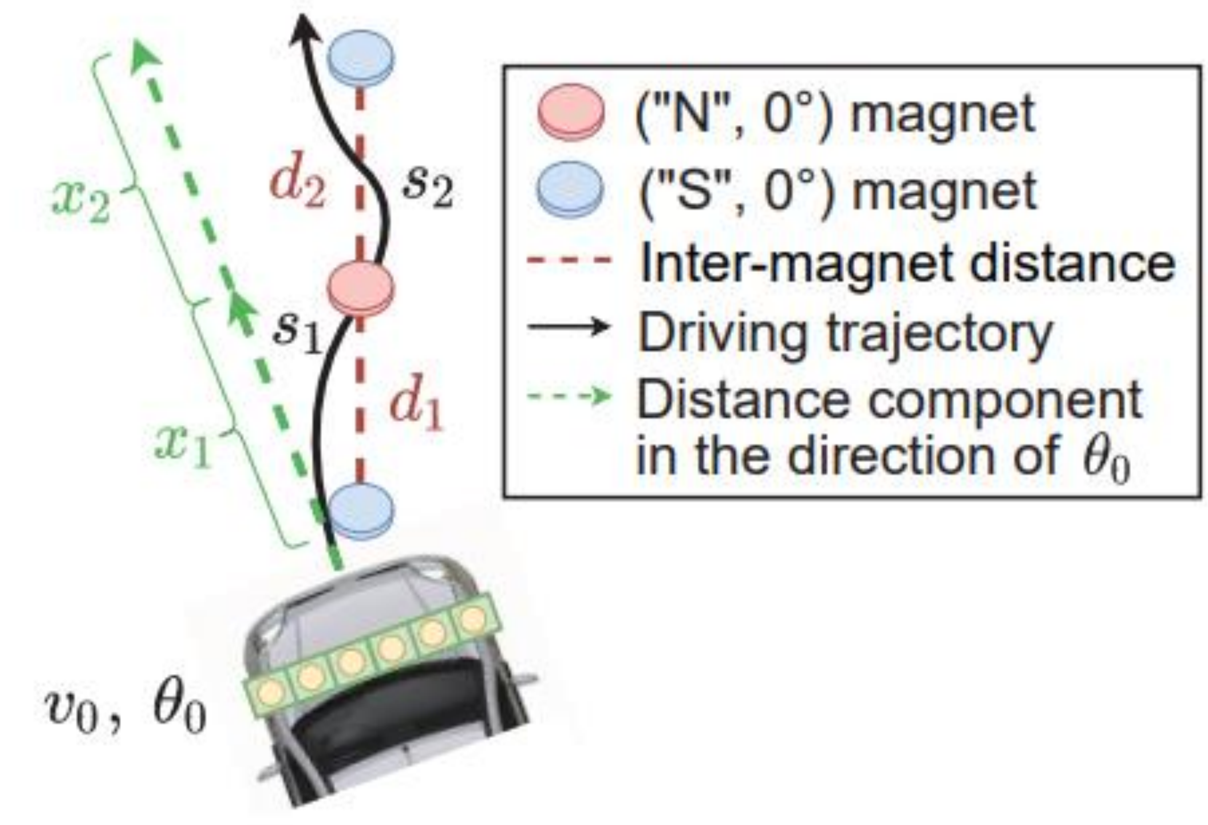
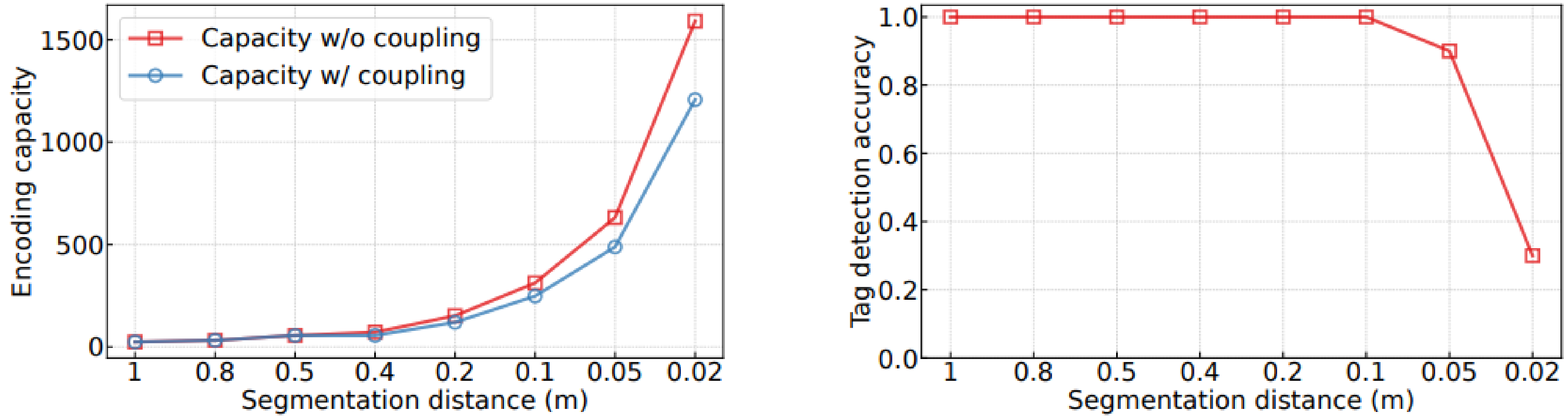



**Figure 4: The vehicle motion when detecting a tag.**

# Encoding Capacity Analysis

$$C = 2^M \cdot \binom{L/Seg_d - 1}{M - 2}$$




(a) Encoding capacity under different segmentation distances

(b) Detection accuracy with different distances

**Figure 17: The impact of segmentation distances.**

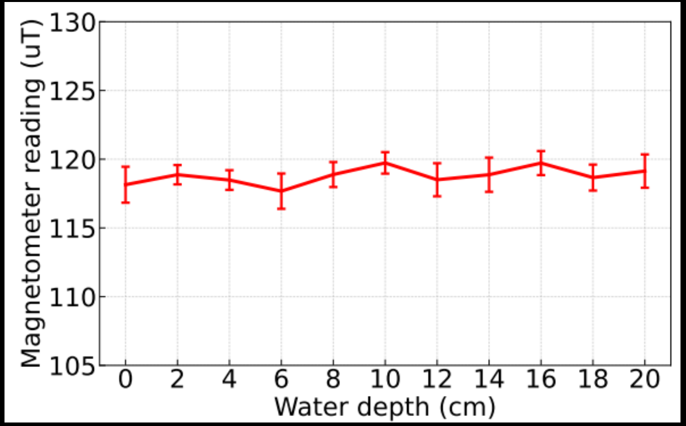
# Evaluation: Watery Disturbance

| | Cost | Chip | Size (mm) | Range (m) |
|---|---|---|---|---|
| Type 1 [24] | $8.4 | Alien Higgs 3 | 31.7 × 12.8 × 4.8 | 6 |
| Type 2 [23] | $14.4 | NXP UCODE 8 | 51 × 36.3 × 7.5 | 10 |
| Type 3 [22] | $12.8 | Monza R6-P | 138.8 × 42 × 12 | 20 |

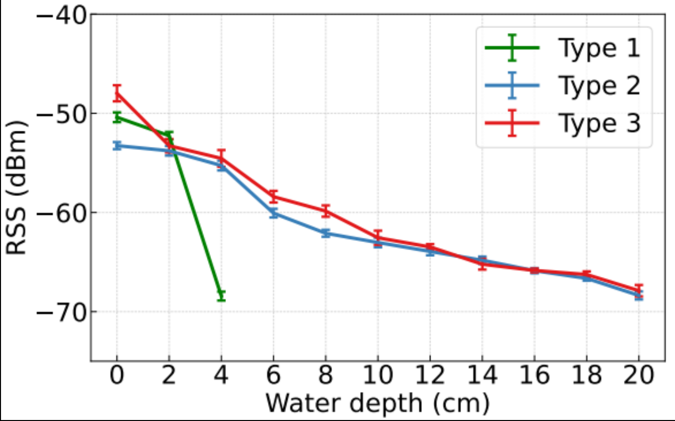
The three types of rugged RFID tag

Testing scenario

Three rugged RFID tags

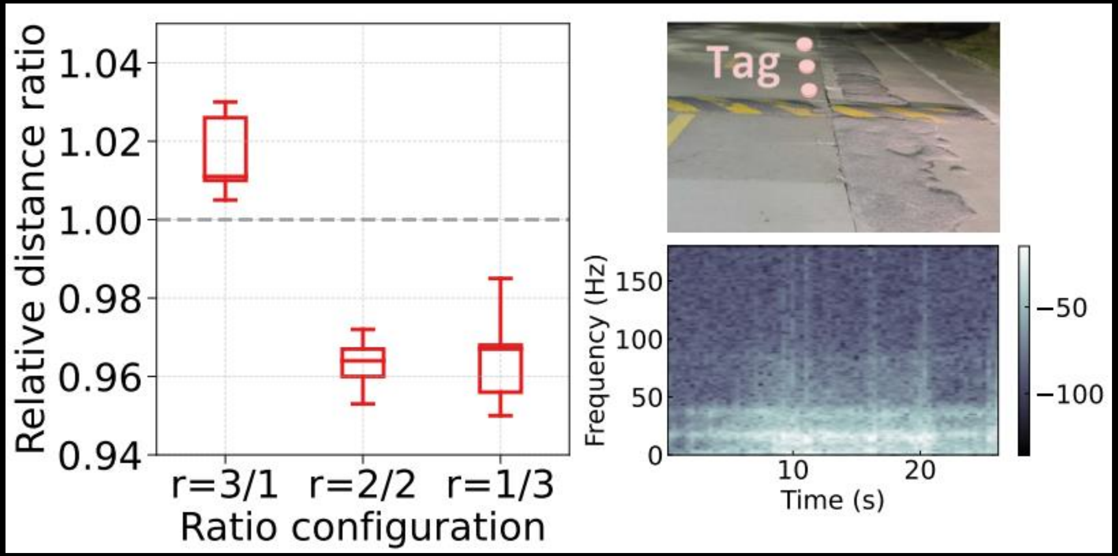


Impact on magnetic field

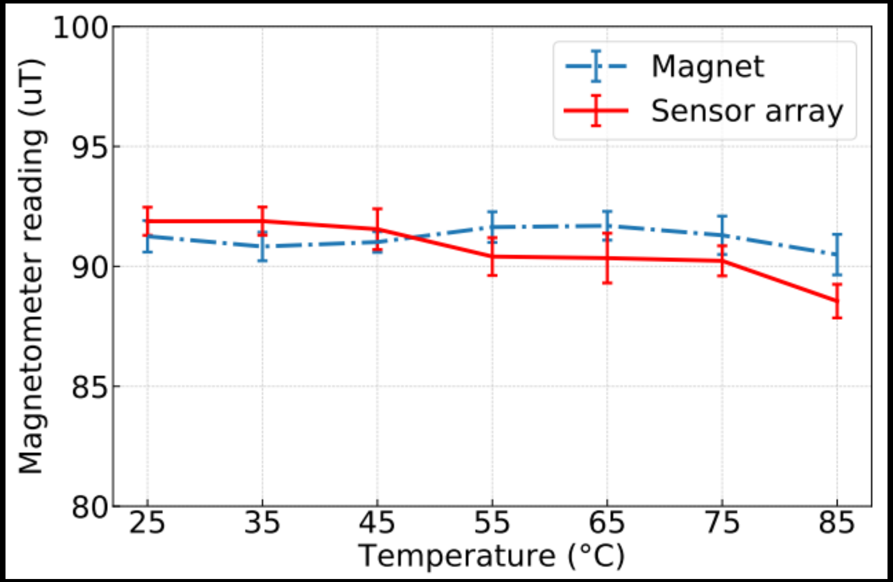


Impact on RSS

# Evaluation: Road Roughness and Temperature




Distance ratio on rough roads




Impact of temperature

# Usability of METRO

- Assess the usability when road markings are occluded


A, D, and G show the no-coverage scenario. B, E, and H represent the light snow condition. C, F, and I emulate the heavy snow setting

| | | Straight Arrow | | | Left Arrow | | | Straight-Right Arrow | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | No Snow | Light Snow | Heavy Snow | No Snow | Light Snow | Heavy Snow | No Snow | Light Snow | Heavy Snow |
| METRO | Accuracy | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| | Distance Ratio | 0.99 | 0.99 | 1.01 | 1.00 | 0.99 | 1.01 | 0.99 | 0.98 | 0.98 |
| YOLOv7 | Accuracy | 100% | 80% | 0 | 100% | 80% | 0 | 100% | 70% | 0 |
| | Confidence | 0.97 | 0.85 | 0 | 0.95 | 0.81 | 0 | 0.91 | 0.78 | 0 |

Comparison of METRO and vision-based method