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

Sensors-Magnetometers (磁场传感器)

陈东尧
上海交通大学
chendy@sjtu.edu.cn
2025年秋季

司南

World first compass

~206 BC

Credit: https://www.pngwing.com/en/free-png-ysqvv

Innovations of Perception Devices

…

Thermometers reflects temperature

Cameras captures visible lights

Ultrasound leverages the acoustic echo

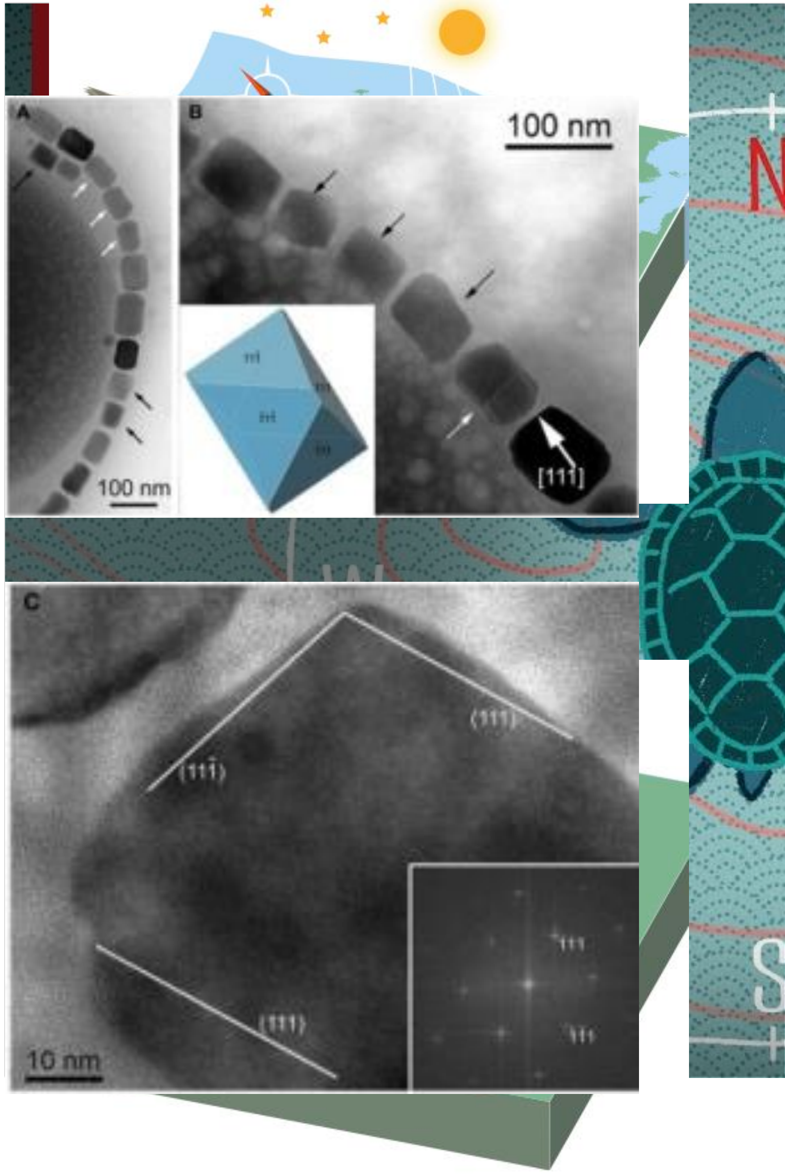
Perception is Essential for CPS Systems

- For example, smartphones, virtual reality devices, and self-driving cars supports several sensing modalities for unique tasks

Magnetoreception

- Some organism, e.g., migratory birds and fish, can sense the earth magnetic field
- It is beyond pointing south. For example, in the homing phase, animals tend to use magnetoreception for fine-grained guidance
- Multiple aligned nanometer-grade magnetosomes serve as small “compasses”

Long-distance phase

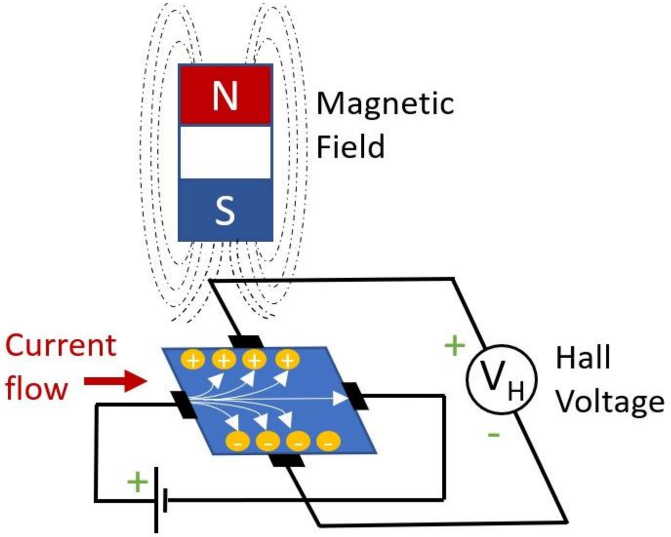


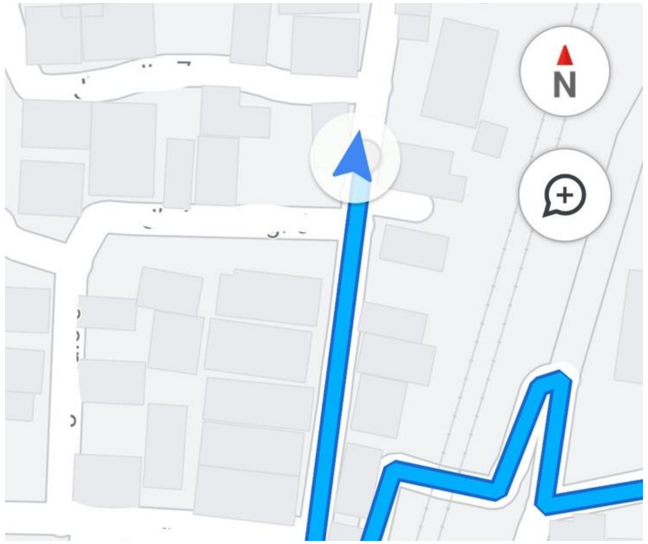
Pósfai, Mihály; Lefèvre, Christopher T.; Trubitsyn, Denis; Bazylinski, Dennis A.; Frankel, Richard B. (2013)
Mouritsen, H. Long-distance navigation and magnetoreception in migratory animals. Nature 558, 50-59 (2018).

Magnetic Sensing on CPS Systems

- MEMS magnetometers leverages Hall-effects to sense magnetic field

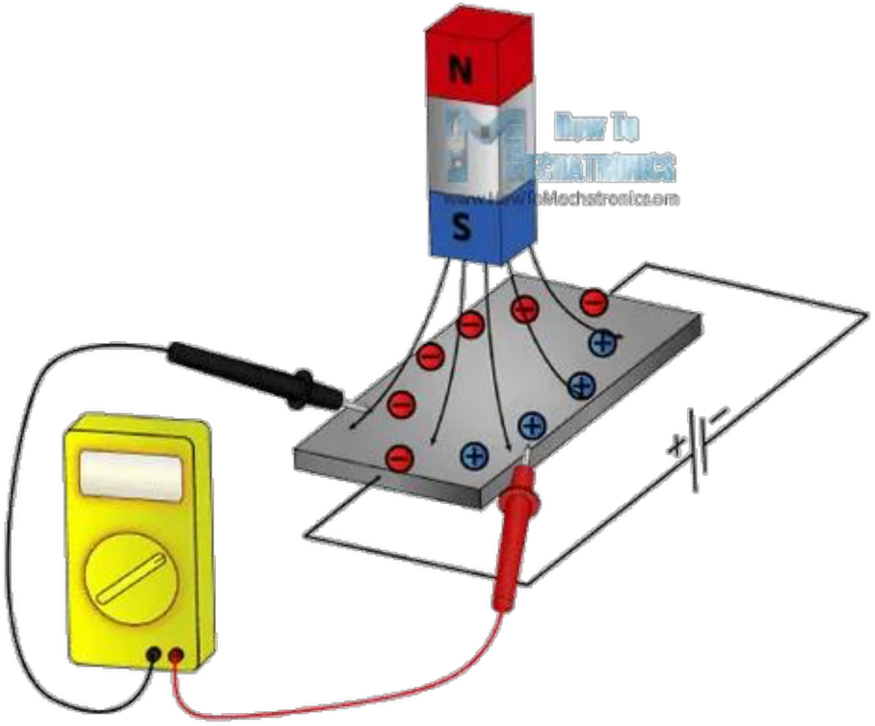
Current systems <u>underutilize</u> magnetic sensing ➔ **Can we do more?**





What are magnetometers

- Hall-effect magnetometers measures the magnetic field strength



Exemplary Applications

- Compass

Two Major Problems

- Are there any useful information can be used for addressing important problems?
  - What sensor should we use?
  - How can we process the information?
- What should we do to make our system **practical**?
  - How to achieve real-world problem?

Today’s Outline

- How to build a magnetic sensing platform
- How to address the calibration our platform in the real-time?

MagX

/ˈmæg ˈeks/

Untethered, Mobile Hand Tracking with Passive Magnets

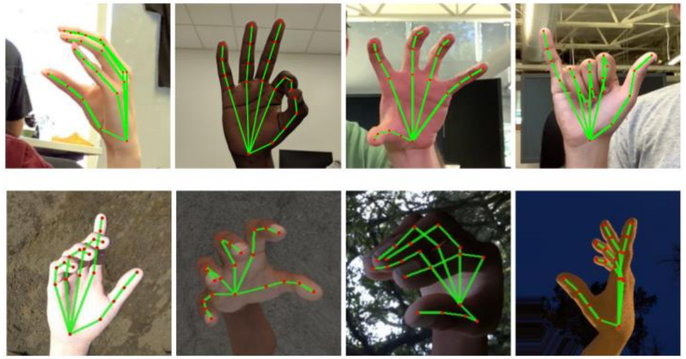
Dongyao Chen, Mingke Wang, Chenxi He, Qing Luo, Yasha Iravantchi, Alanson Sample, Kang G. Shin, Xinbing Wang, **MagX: Wearable, Untethered Hands Tracking with Passive Magnets**, *MobiCom 2021*

Nintendo Power Glove

Oculus

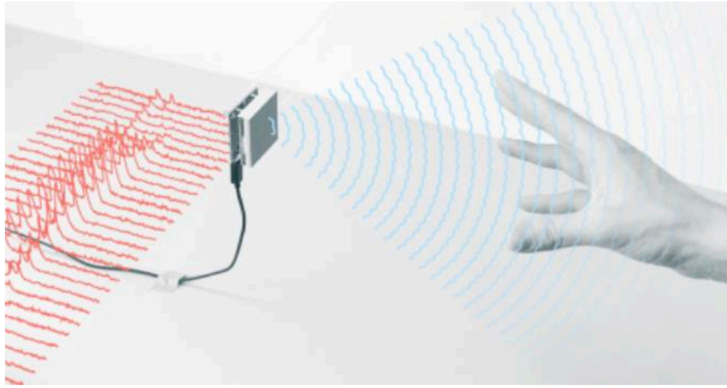
UltraLeap

Google's Hand-tracking Tool

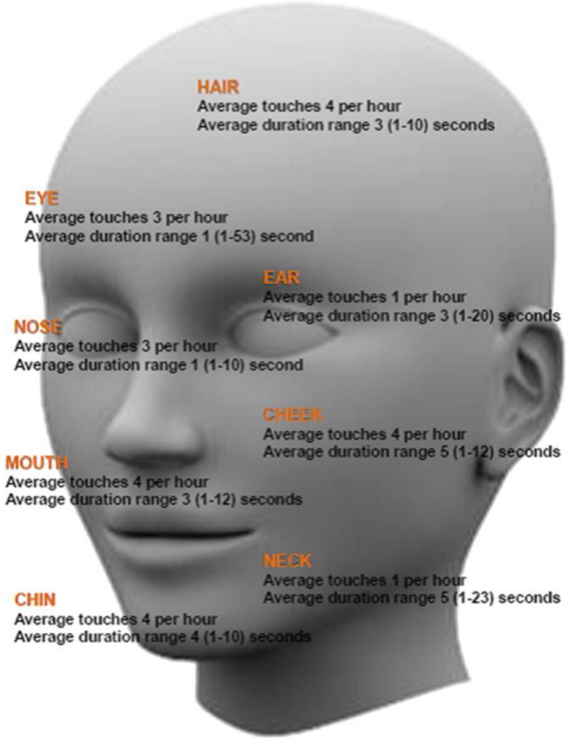


Microsoft's HandPose

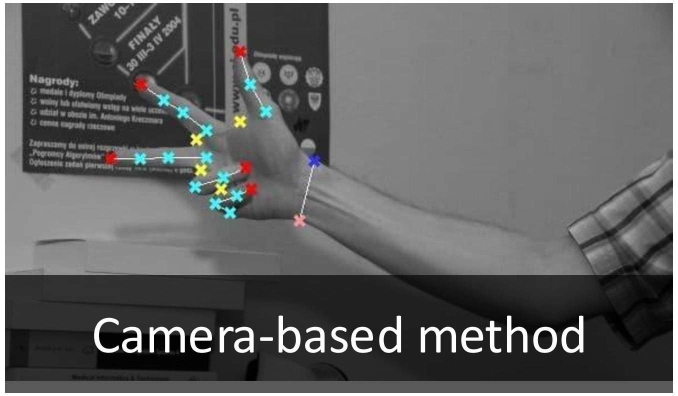
Google's Project Soli



Detecting the face touching behavior

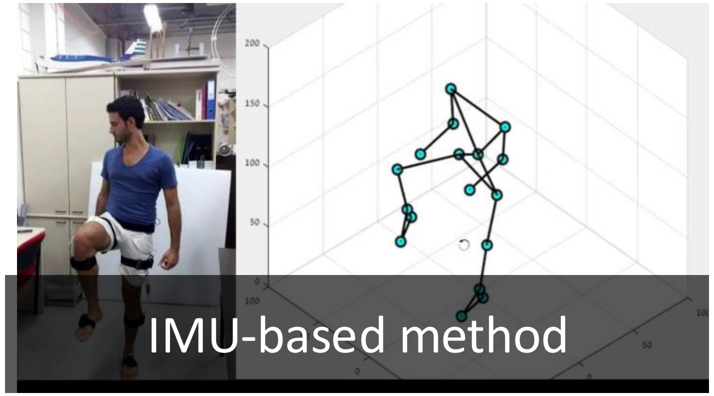


- Detecting unhealthy behavior, e.g., face touching, for personal hygiene



Camera-based method

RF-based method

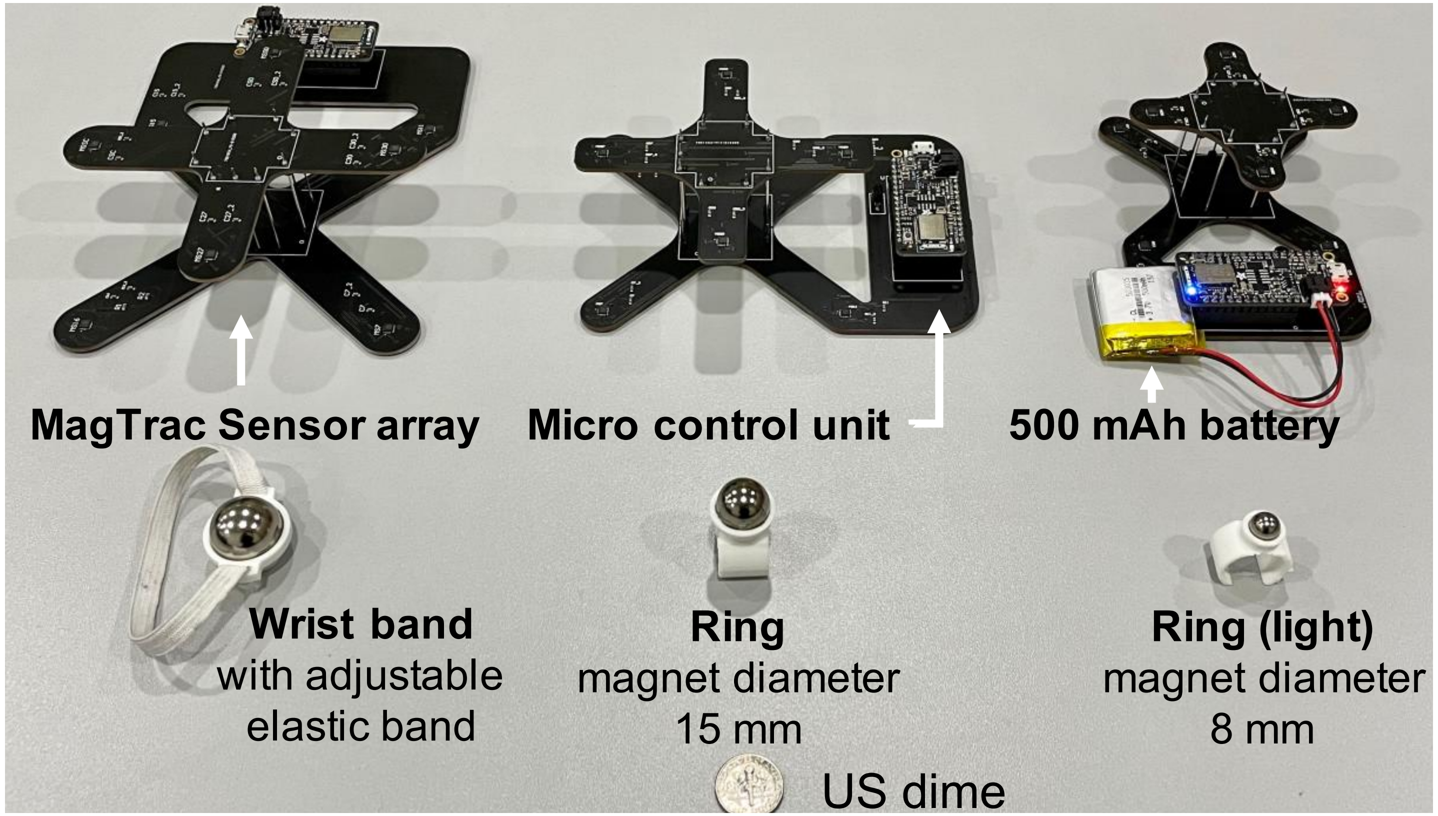


IMU-based method

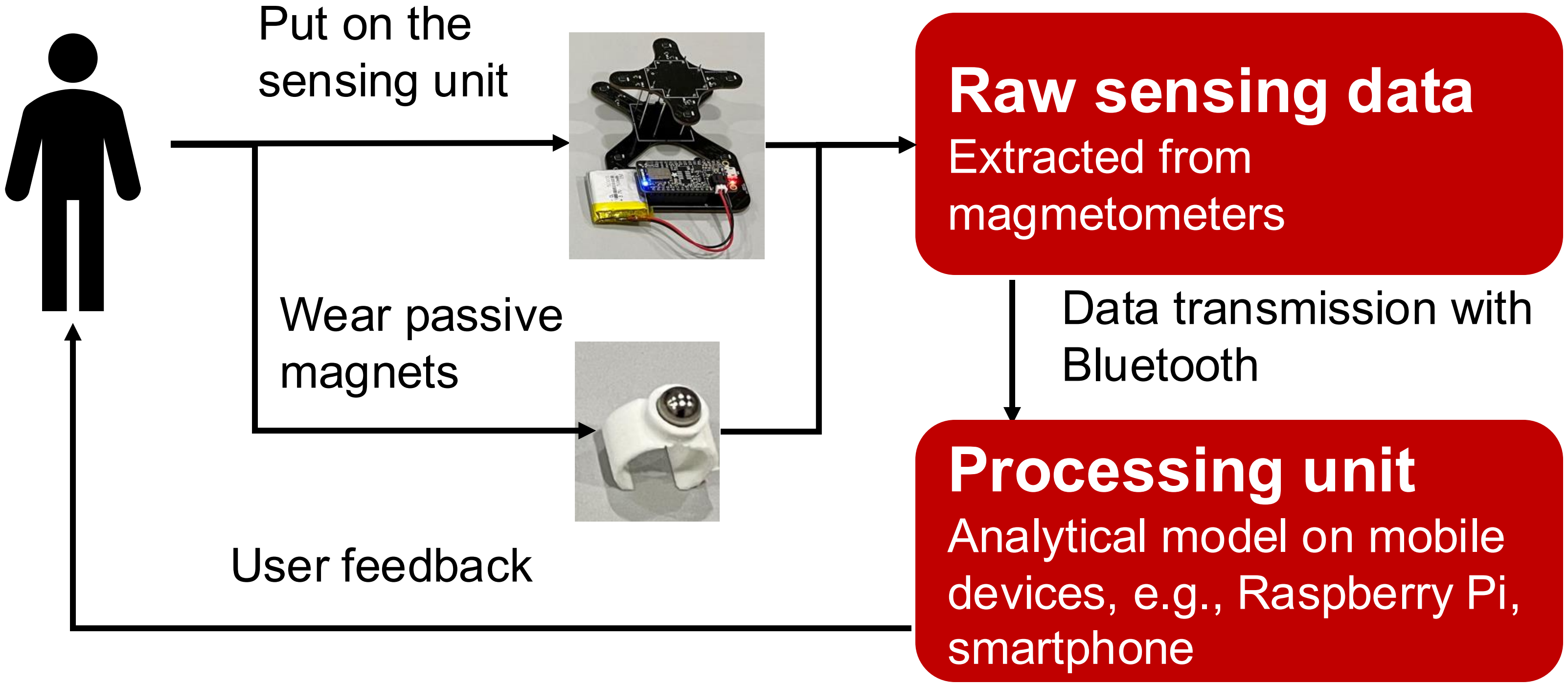
	Accuracy	Sensing range	Resilient to NLoS	Privacy preserving	Power Consumption
Vision-based	Low	Large	No	No	Intense
RF-based	High	Directional	No	No	Moderate
IMU-based	Drifting issue	N/A	Yes	Yes	Intense
Magnetic Tracking	Yes	30cm	Yes	Yes	Ultra Low

Introducing MagX

- A fully untethered on-body tracking system utilizing passive magnets and a novel magnetic sensing platform



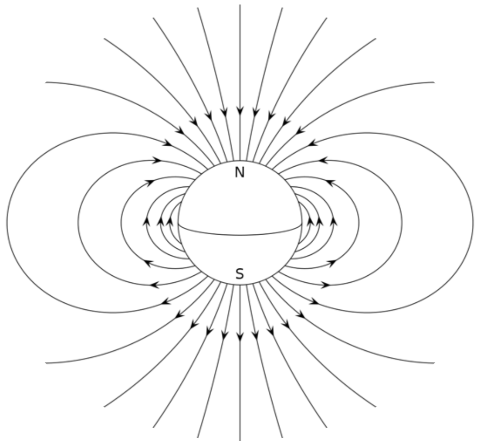
The Overview



Tracking Passive Magnet on Mobile Platform

- The **dipole** magnetic field model

$$\vec{B} = \frac{\mu_0}{4\pi}\left(\frac{3(\vec{m}\cdot\vec{r})\vec{r}}{|\vec{r}|^5} - \frac{\vec{m}}{|\vec{r}|^3}\right)$$

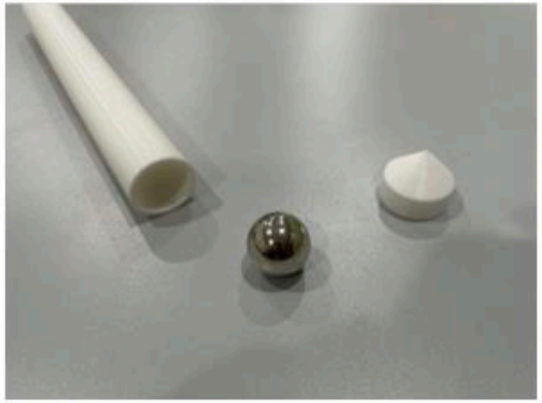


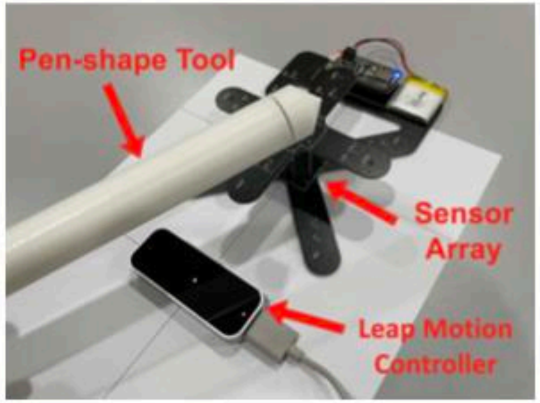
- The sensor reading can be denoted as the **linear combination** of each **magnet's field** and the **background magnetic field**:

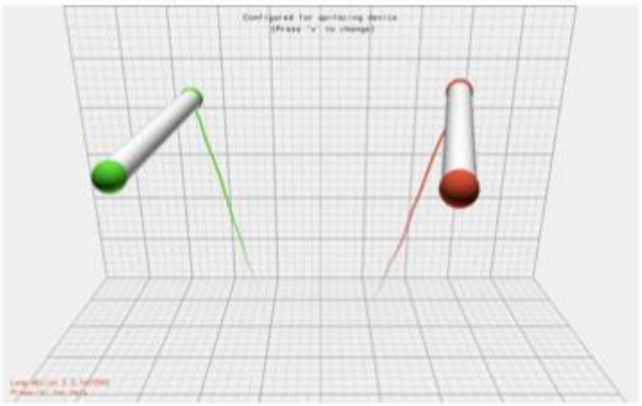
$$\overrightarrow{B_i} = \vec{G} + \sum_{j=1}^{j=M} \frac{\mu_0}{4\pi}\left(\frac{3(\overrightarrow{m_j}\cdot\overrightarrow{r_{ij}})\overrightarrow{r_{ij}}}{\left|\overrightarrow{r_{ij}}\right|^5} - \frac{\overrightarrow{m_j}}{\left|\overrightarrow{r_{ij}}\right|^3}\right)$$

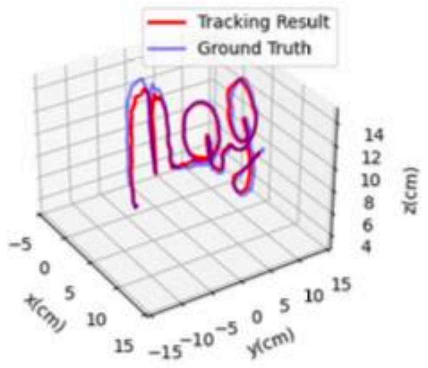
Ground Truth Collection

- Collecting the ground truth is **essential** for evaluating our performance
- Our proposed a LeapMotion-based platform for data collection
  - Can track at an accuracy of within 2.5 *mm*

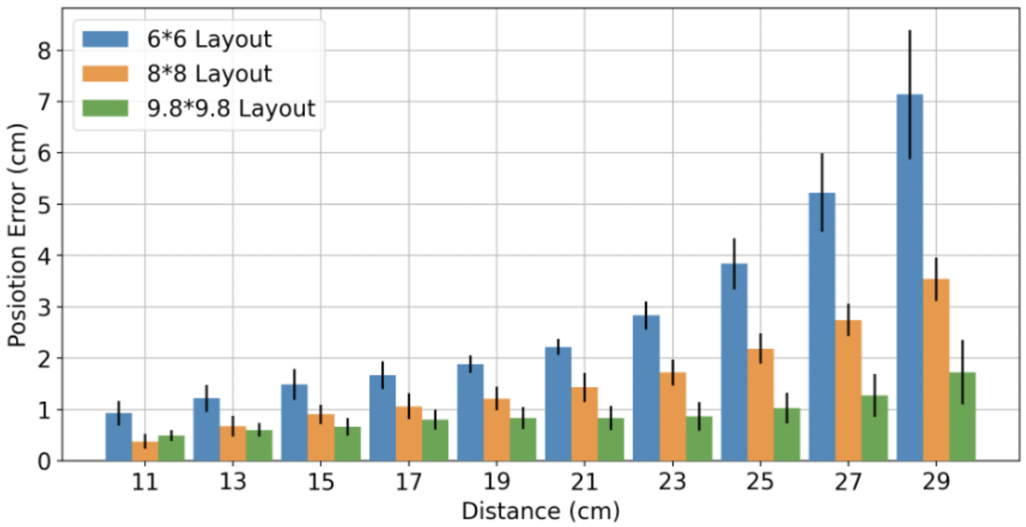




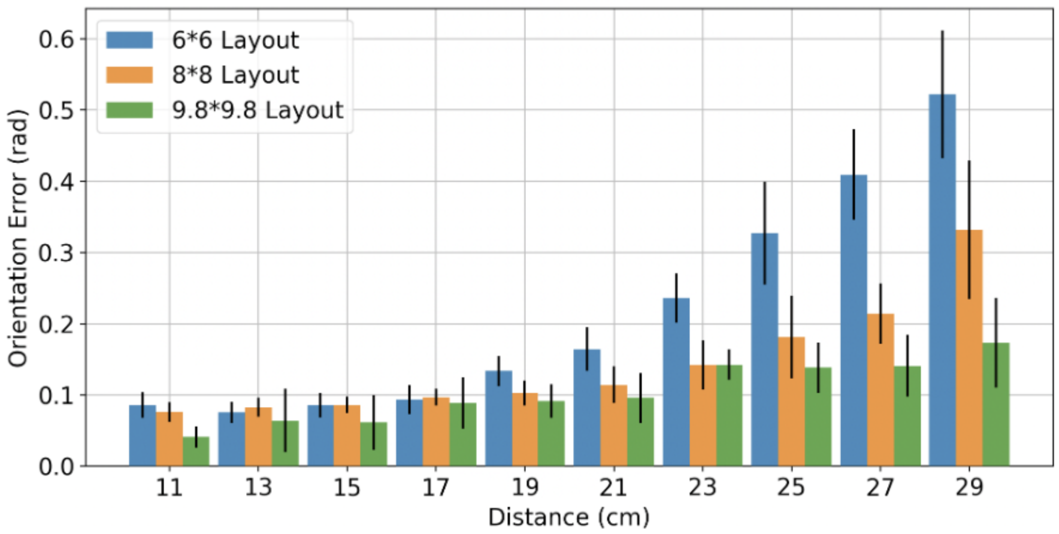




Performance Evaluation



(a) Position error of tracking **one** magnet



(b) Orientation error of tracking **one** magnet

- MagX can achieve **millimeter** accuracy within **~25 cm** distance (9.8*9.8cm^2 layout)

System Overhead

For the sensor array

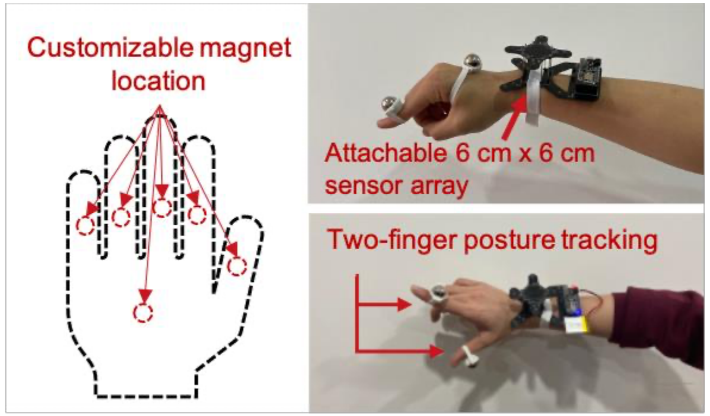
MagX incurs **0.22 W** power drain , **8-hour** usage on small battery pack (**500 mAh**)

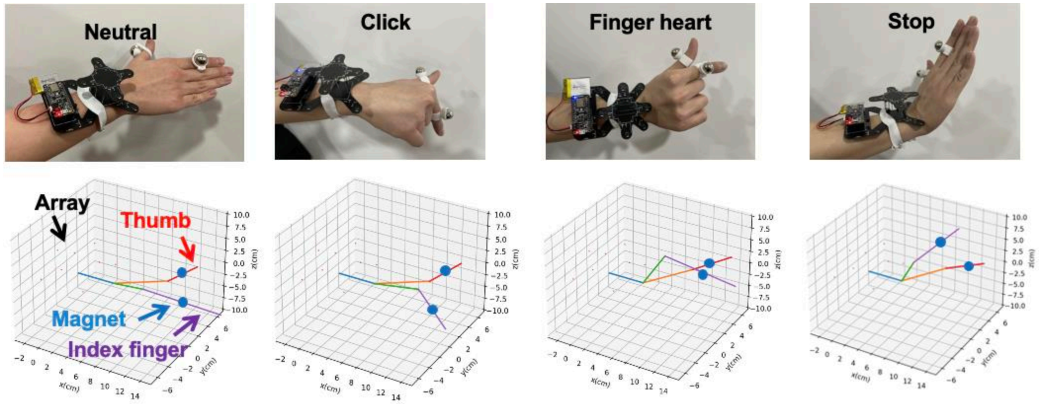
For the mobile device

Computing Modality	CPU Usage	Average FPS	Power Drain (W)
Raspberry Pi	181.21%	1213.89	0.64
Raspberry Pi Zero (emulated)	23.79%	514.23	0.16

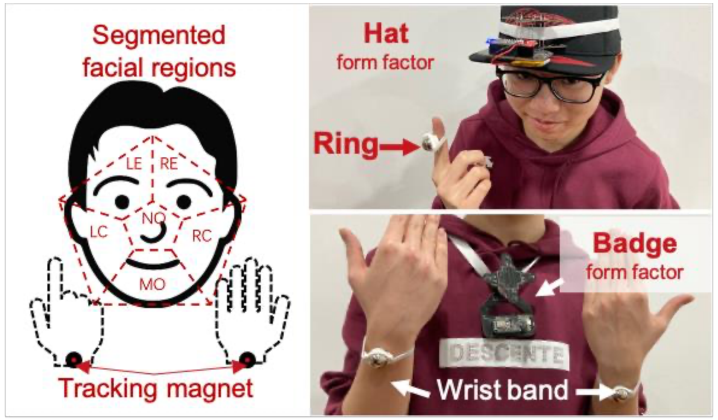
Exemplary Use Cases

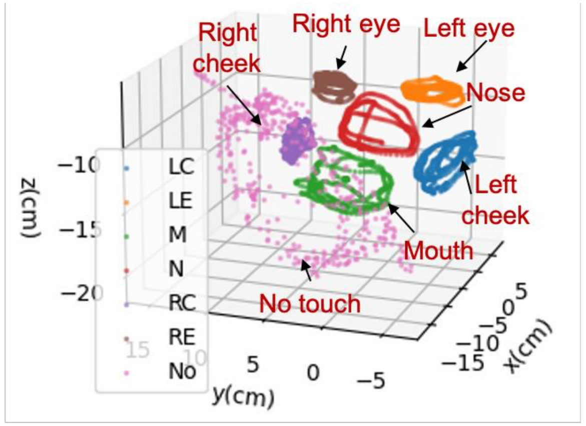
AR interaction

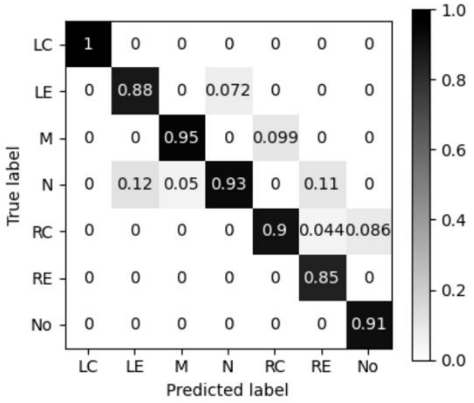




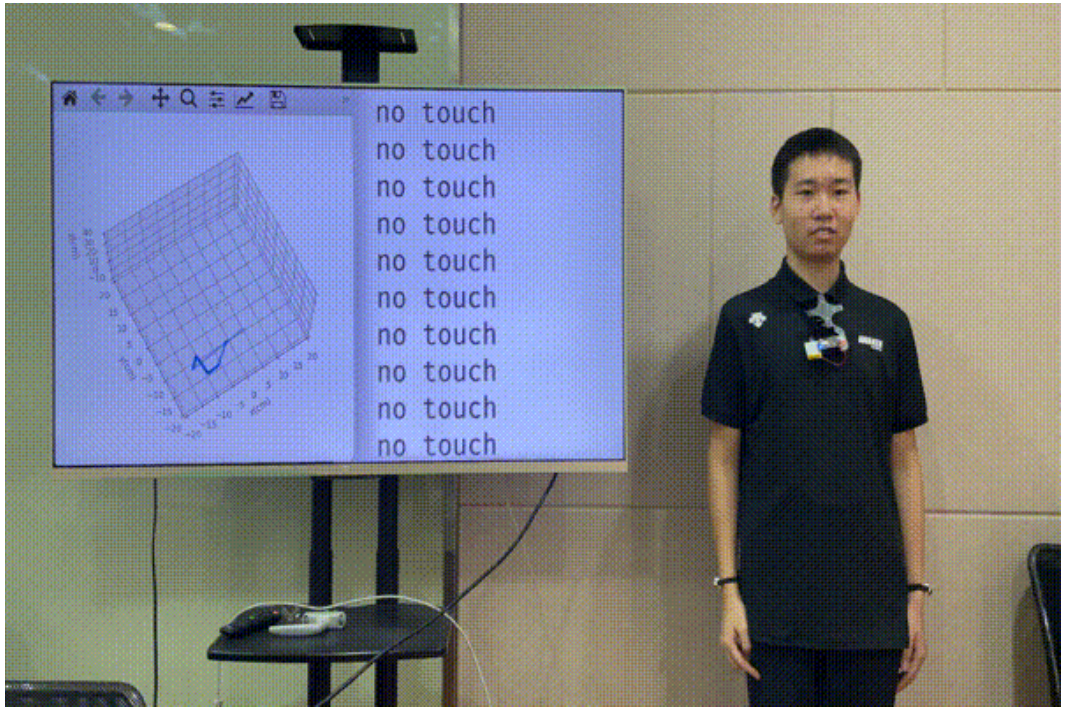
Face touching detection

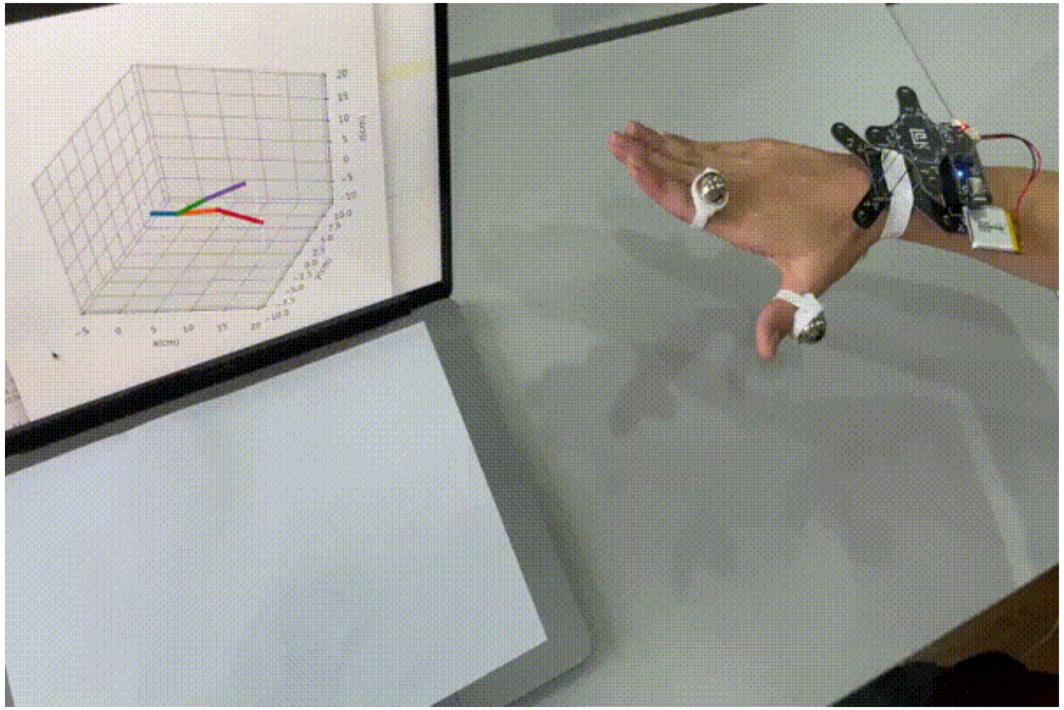






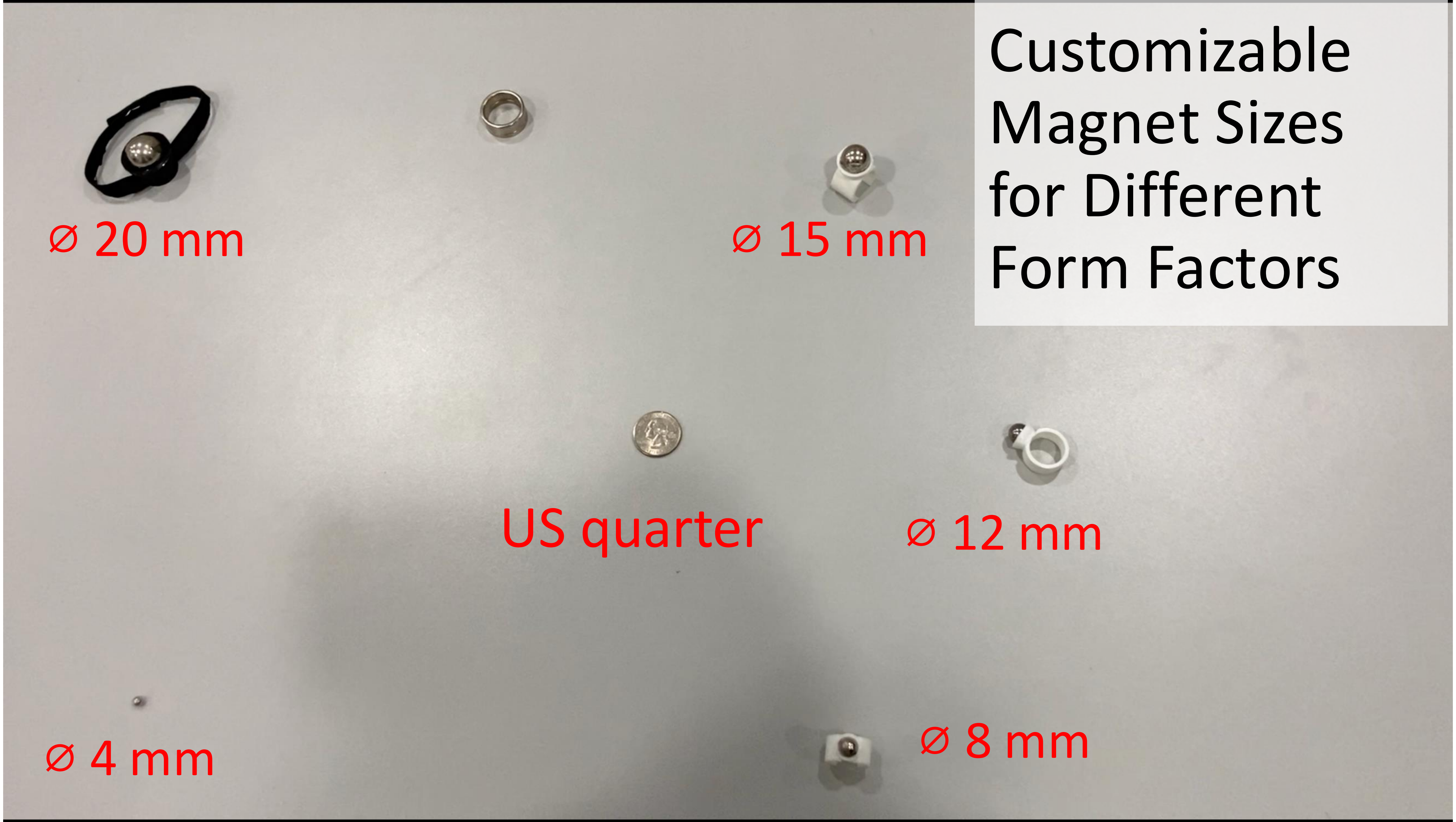
MagX in Action





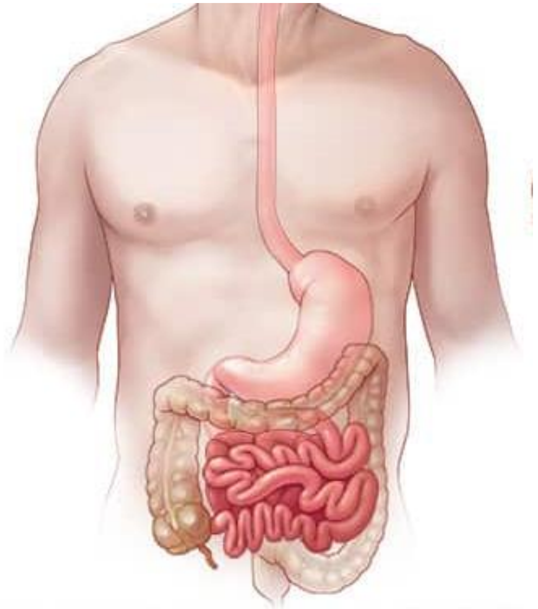
- Face touching detection
- AR interaction

Customizable Magnet Sizes for Different Form Factors

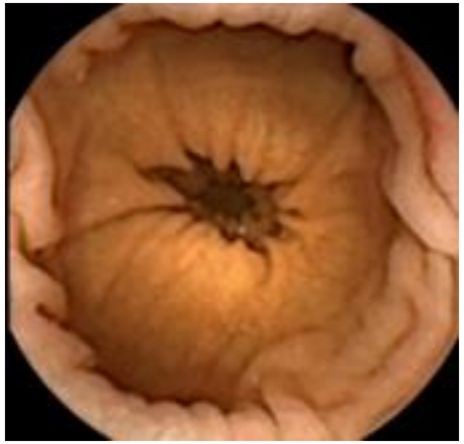


Procedure of Capsule Endoscopy

Endoscopy capsule

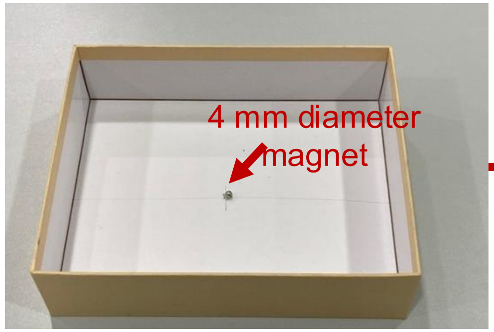


Gastrointestinal tract



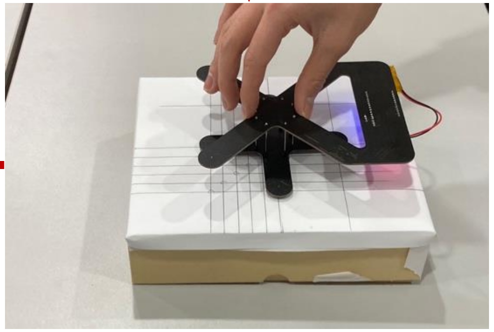
Internal imagery

Capsule Endoscopy demo

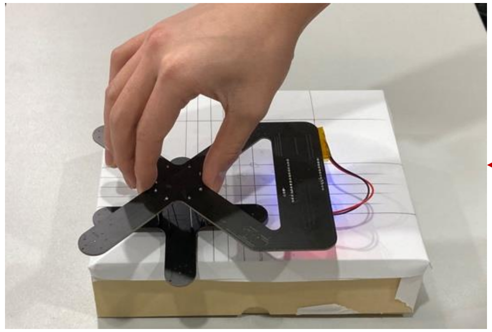


Magnet deployment

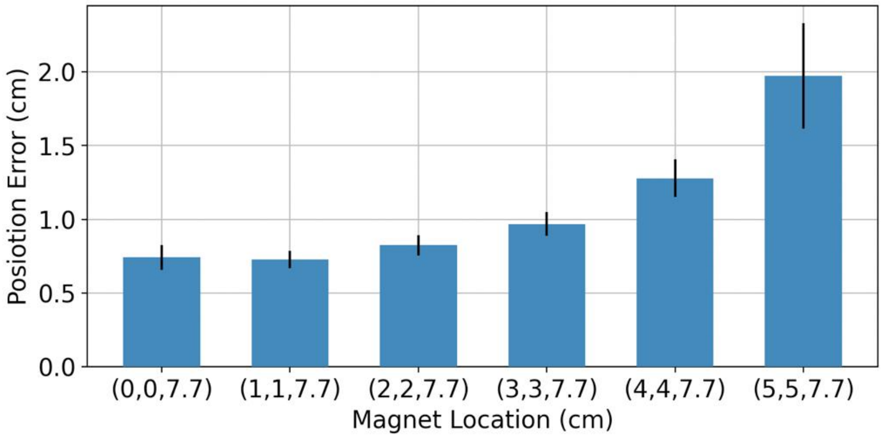
6.3 cm pork belly overlay



Tracker measurement



Adjust the placement



YES, MagX is open-source

open source hardware

https://github.com/dychen24/magx

Conclusion

- MagX is an untethered and fully mobile hand tracking system. It uses a novel magnetic sensing scheme to achieve high tracking performance.
- Future directions includes:
  - Addressing hard and soft iron disturbances
  - Redesigning the form factor

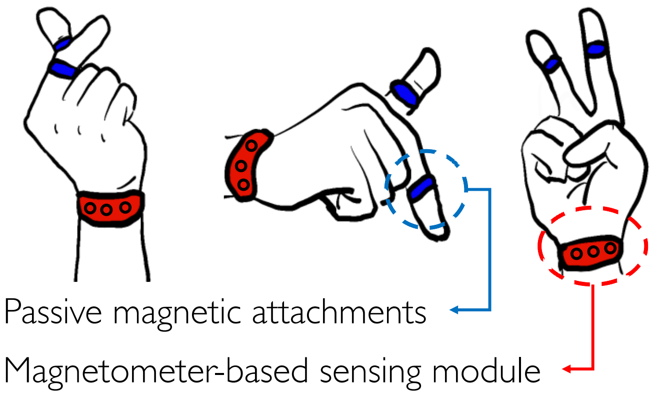
MAGIC

Automatic Calibration of Magnetic Tracking

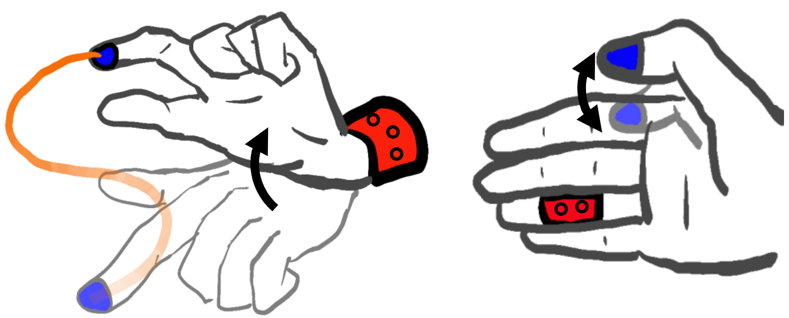
Mingke Wang, Qing Luo, Yasha Iravantchi, Xiaomeng Chen, Alanson Sample, Kang G. Shin, Xiaohua Tian, Xinbing Wang, Dongyao Chen, **Automatic Calibration of Magnetic Tracking**, *MobiCom 2022*

Recent Progresses in Magnetic Tracking

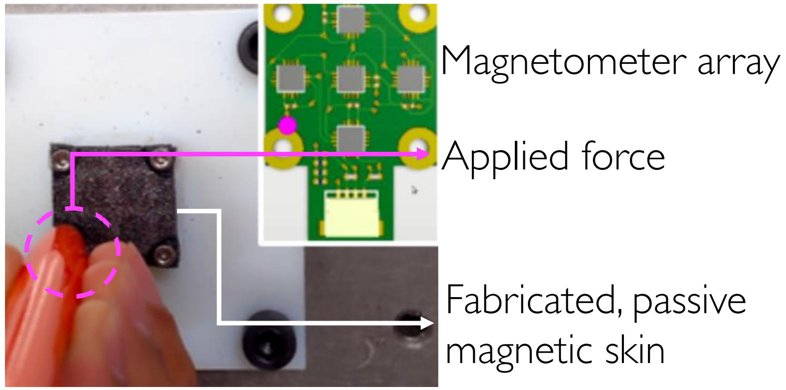
Fine-grained pose detection



Free-form, 3D input



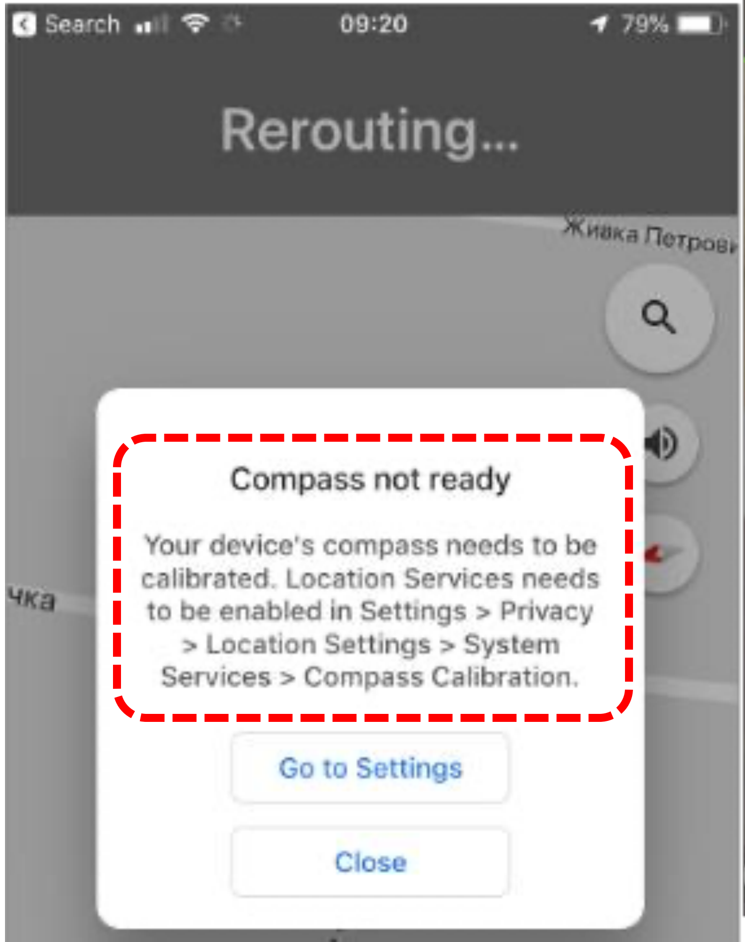
Tactile sensing

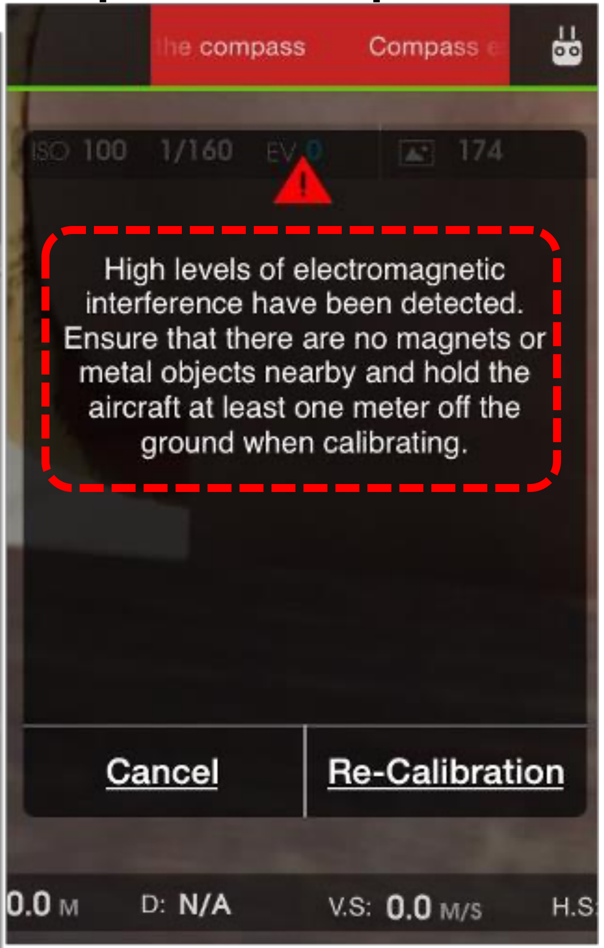


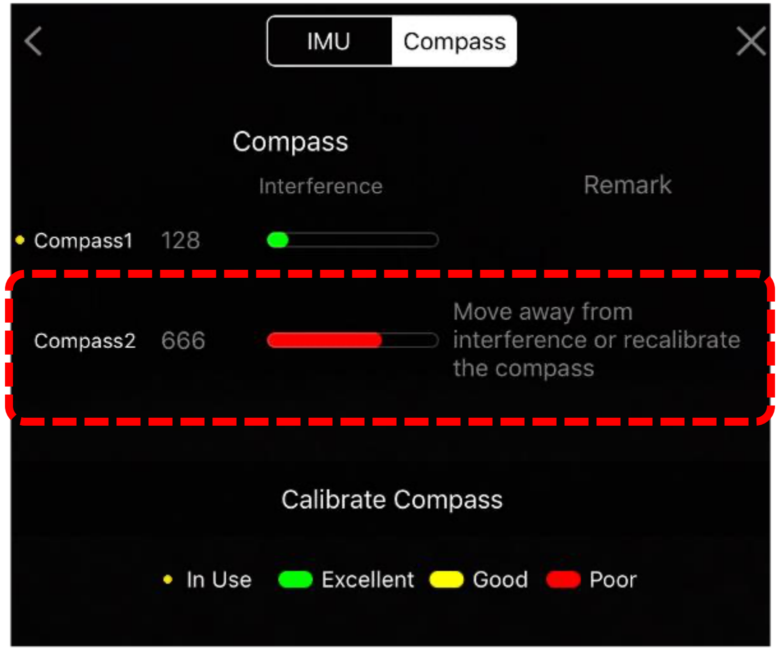
https://reskin.dev/

Wait...

- Compasses usually require frequent recalibration



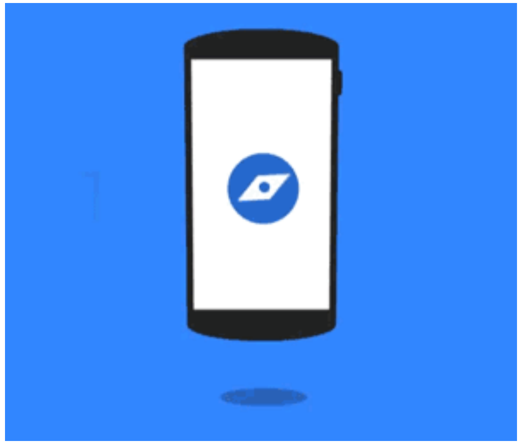




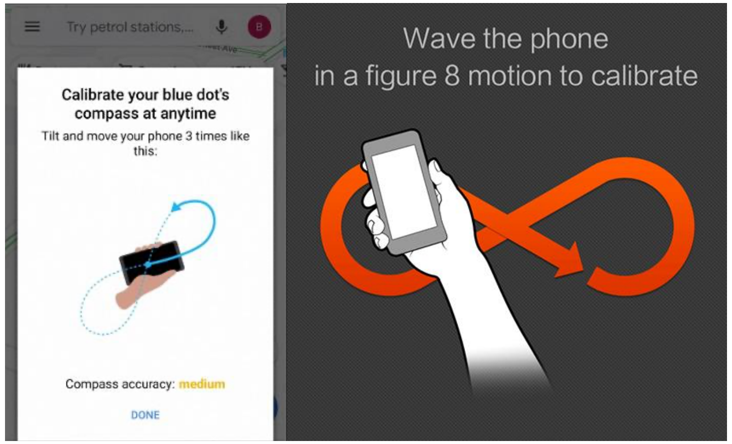
Calibration is not a Trivial Task

- These calibration methods are tedious

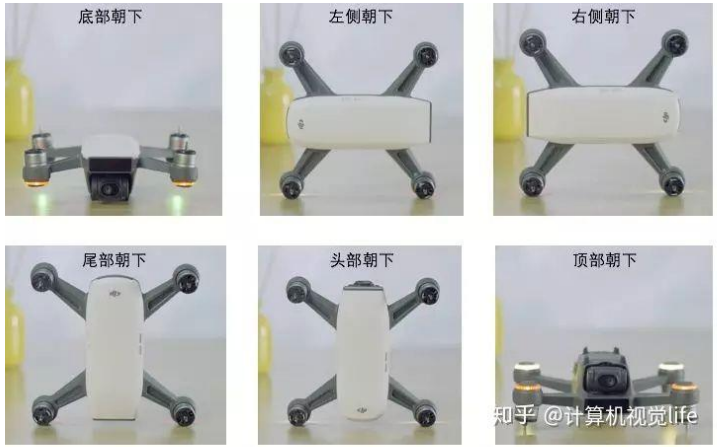
Tilt calibration



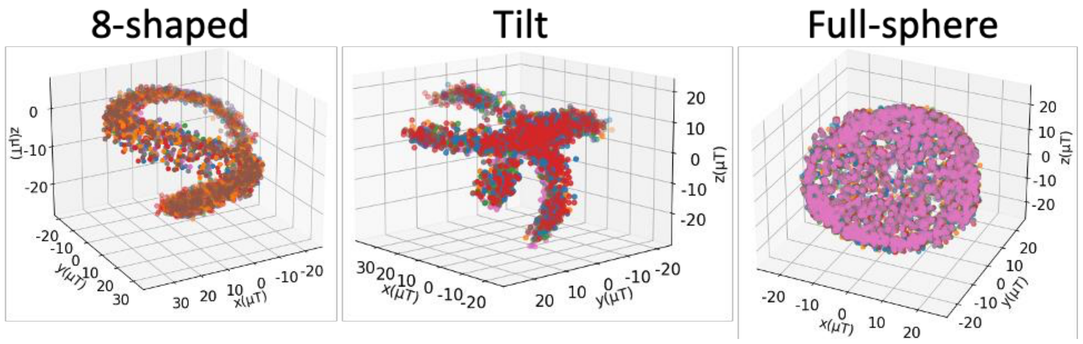
8-shaped calibration

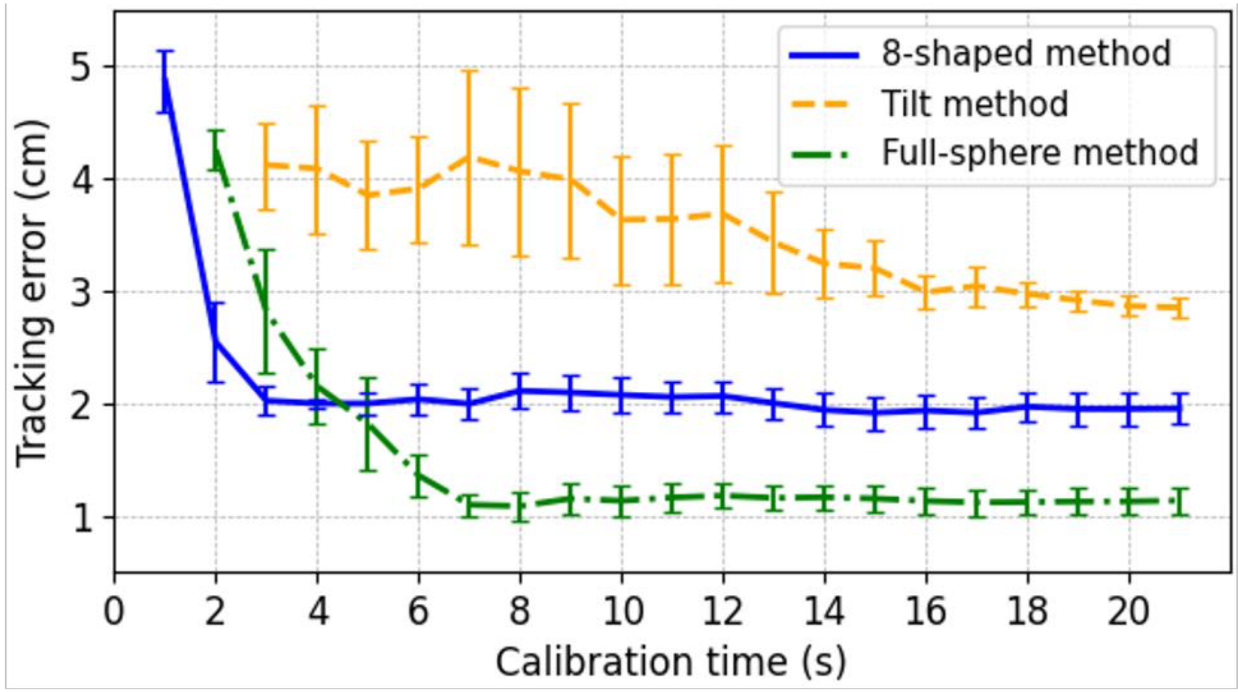


Six-sided calibration for UAVs



Calibration can also be Time-consuming



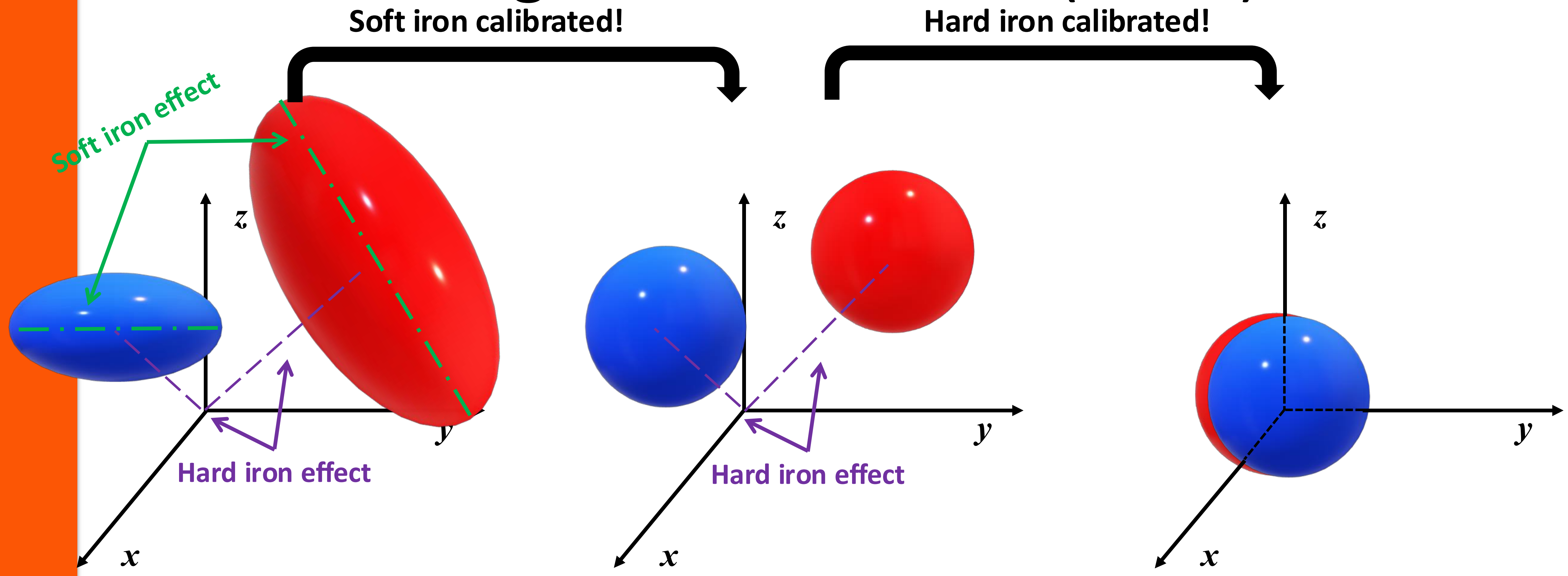


An extensive calibration is necessary for calibration performance

Understanding the Disturbance

- Magnetic disturbances
  - Hard-iron effect
  - Soft-iron effect

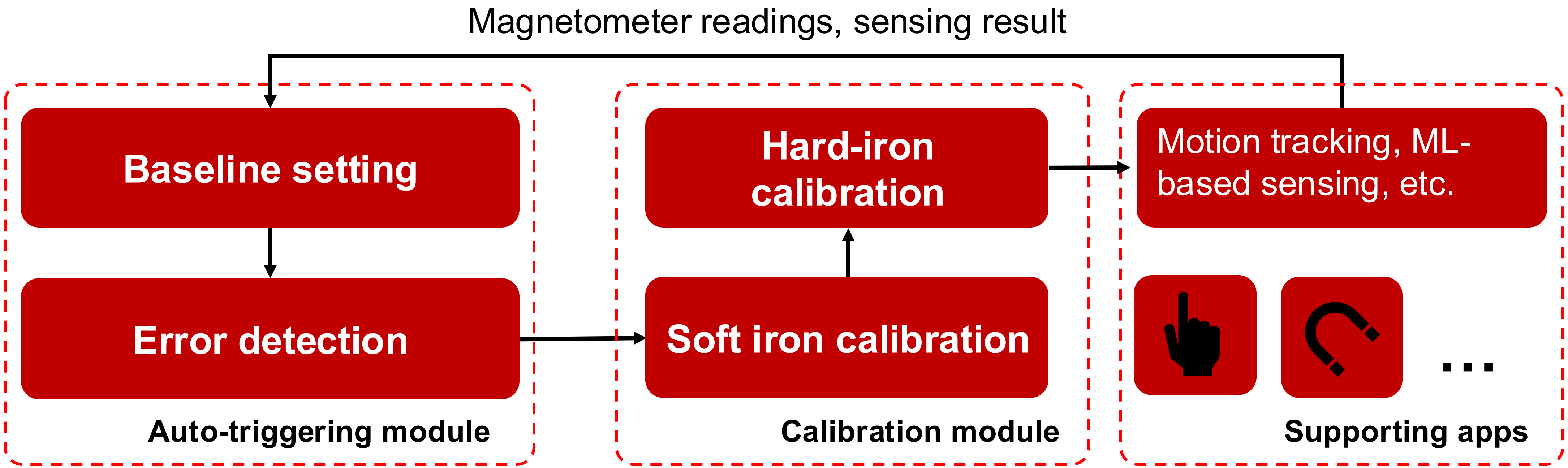
Understanding the Disturbance (Cont.)



Can we enable a seamless calibration process that can

1. Fully calibrate electromagnetic disturbances;
2. Incur minimum user disturbances.

System Overview of MAGIC

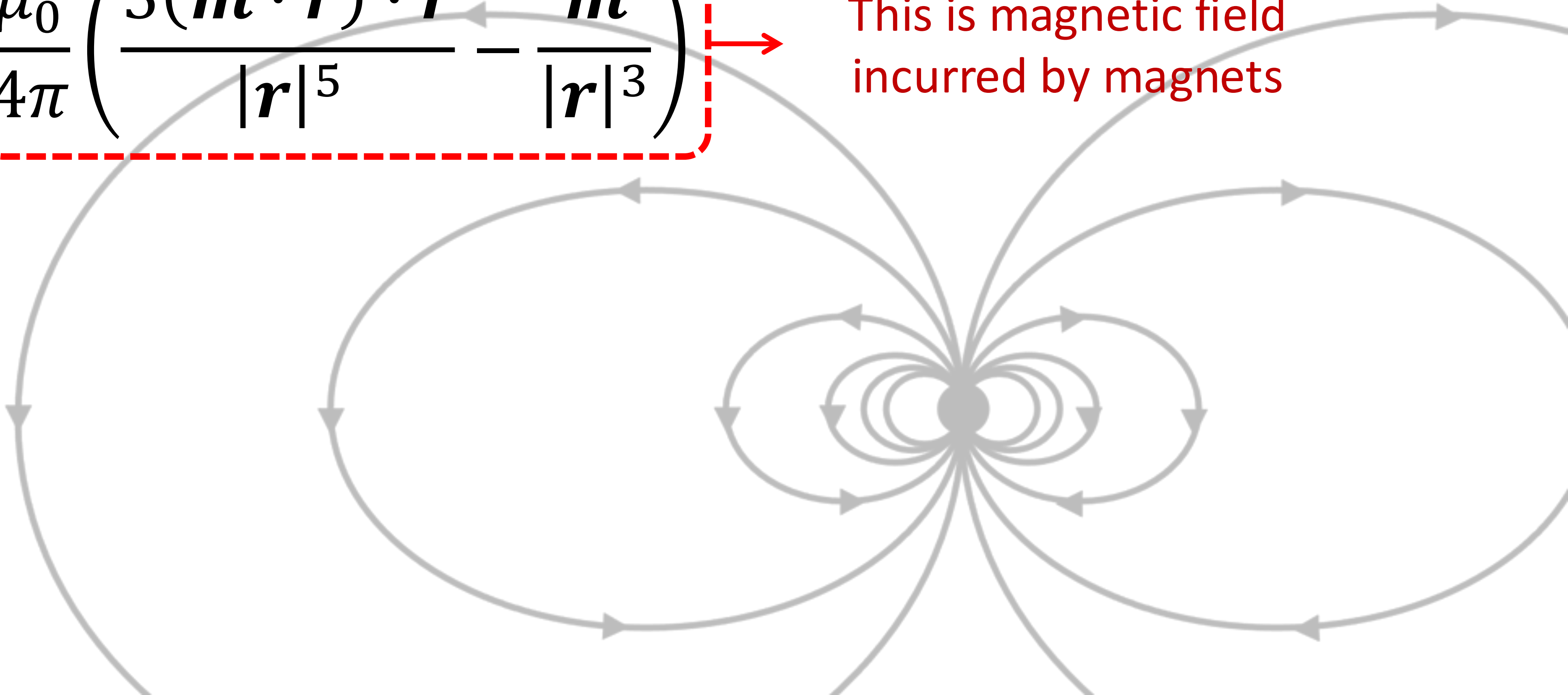


Soft-iron Calibration

- Know the soft-iron parameters

$$\boldsymbol{B} = \boldsymbol{G} + \boxed{\frac{\mu_0}{4\pi}\left(\frac{3(\boldsymbol{m}\cdot\boldsymbol{r})\cdot\boldsymbol{r}}{|\boldsymbol{r}|^5} - \frac{\boldsymbol{m}}{|\boldsymbol{r}|^3}\right)}$$

This is magnetic field incurred by magnets



Soft-iron Calibration (Cont.)

- Know the soft-iron parameters

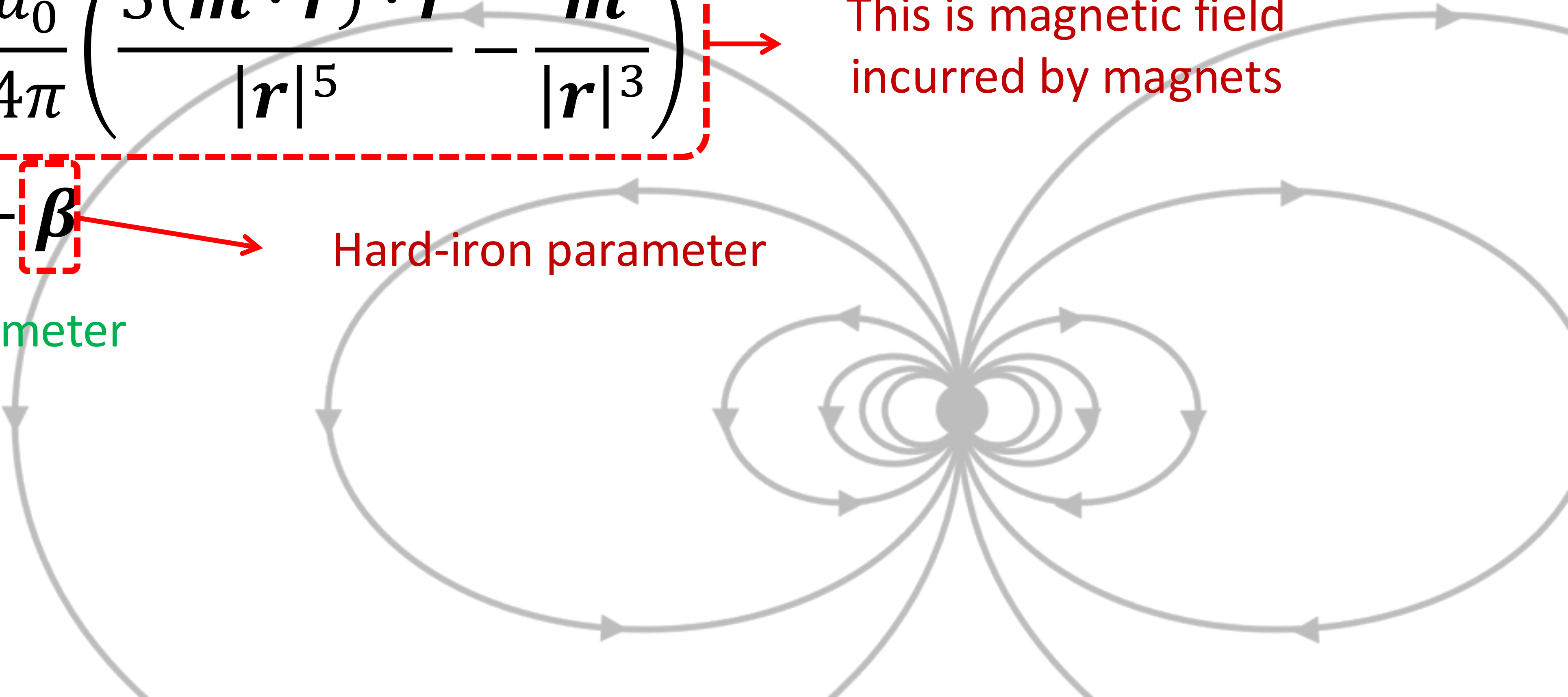
$$\boldsymbol{B} = \boldsymbol{G} + \boxed{\frac{\mu_0}{4\pi}\left(\frac{3(\boldsymbol{m}\cdot\boldsymbol{r})\cdot\boldsymbol{r}}{|\boldsymbol{r}|^5} - \frac{\boldsymbol{m}}{|\boldsymbol{r}|^3}\right)}$$

This is magnetic field incurred by magnets

$$\widehat{\boldsymbol{B}} = \boxed{\boldsymbol{\alpha}}\boldsymbol{B} + \boxed{\boldsymbol{\beta}}$$

Hard-iron parameter

Soft-iron parameter



Soft-iron Calibration (Cont.)

- Know the soft-iron parameters

$$\boldsymbol{B} = \boldsymbol{G} + \frac{\mu_0}{4\pi}\left(\frac{3(\boldsymbol{m}\cdot\boldsymbol{r})\cdot\boldsymbol{r}}{|\boldsymbol{r}|^5} - \frac{\boldsymbol{m}}{|\boldsymbol{r}|^3}\right)$$

This is magnetic field incurred by magnets

$$\widehat{\boldsymbol{B}} = \boldsymbol{\alpha}\boldsymbol{B} + \boldsymbol{\beta}$$

Can we replace this arbitrary magnetic field with a known magnetic field?

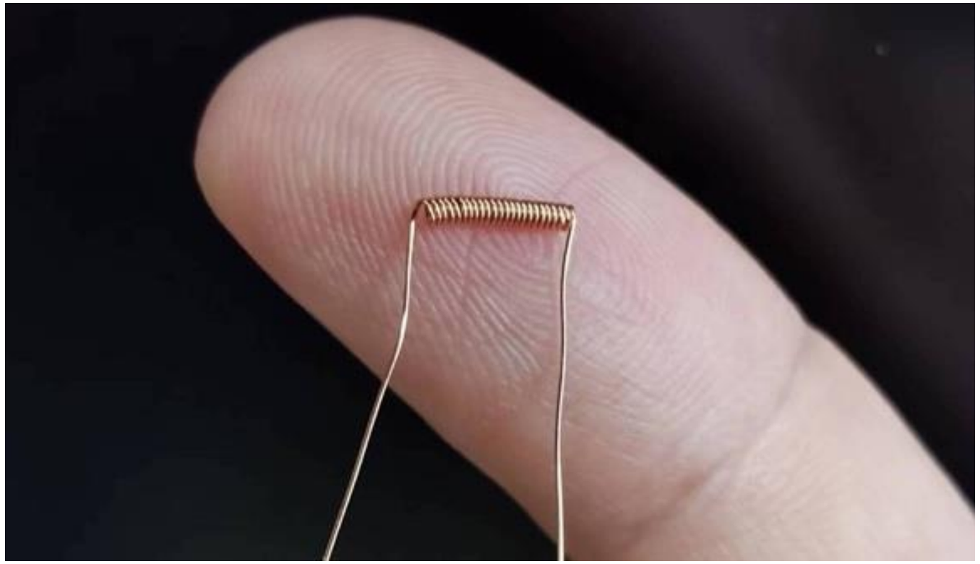
r

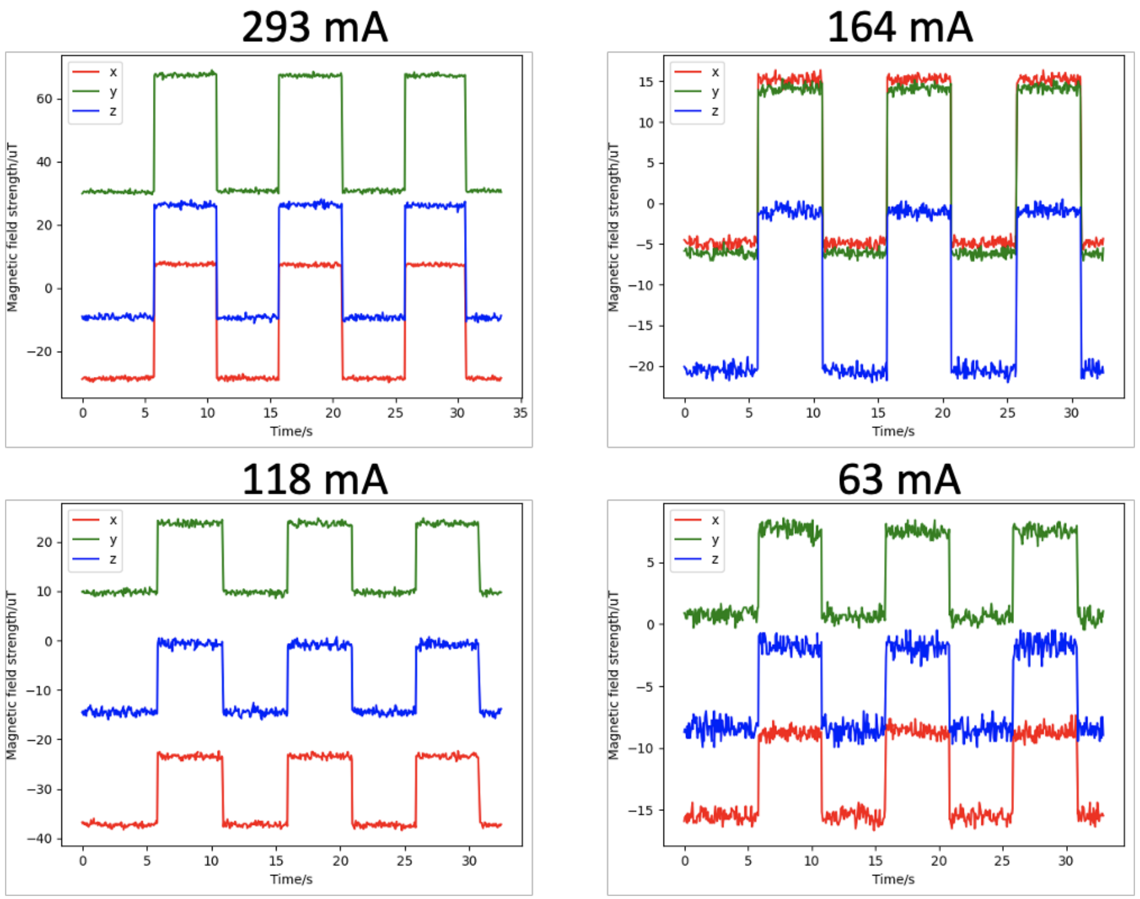
Soft-iron parameter

$$\boldsymbol{\gamma}\widehat{\boldsymbol{B}} + \boldsymbol{\omega} = \frac{\mu_0}{4\pi}\left(\frac{3(\boldsymbol{m}\cdot\boldsymbol{r})\cdot\boldsymbol{r}}{|\boldsymbol{r}|^5} - \frac{\boldsymbol{m}}{|\boldsymbol{r}|^3}\right)$$

$$\boldsymbol{\omega} = -\boldsymbol{\beta}\cdot\boldsymbol{\alpha}^{-1} - G$$

Solution: Using Electromagnets





Hard-iron Calibration

$$\boxed{\text{Hard-iron parameter}}$$

$$\widehat{\boldsymbol{B}} = \boxed{\boldsymbol{\alpha}}\boldsymbol{B} + \boxed{\boldsymbol{\beta}}$$

Soft-iron parameter

Hard-iron Calibration

$$\widehat{\boldsymbol{B}} = \quad \boldsymbol{B} + \boxed{\boldsymbol{\beta}}$$

Hard-iron parameter, it is an intrinsic feature with the sensor, it cannot be decoupled from ***G*** without extensive movement

Hard-iron Calibration

$$\widehat{\boldsymbol{B}} = \boldsymbol{B} + \boxed{\boldsymbol{\beta}}$$

Hard-iron parameter, it is an intrinsic feature with the sensor, it cannot be decoupled from ***G*** without extensive movement

$$\widehat{\boldsymbol{B}} = \boldsymbol{B}^{signal} + \boxed{\boldsymbol{G}} + \boldsymbol{\beta}$$

Constant feature with the environment

Here, $\boldsymbol{B}^{signal} = \frac{\mu_0}{4\pi}\left(\frac{3(\boldsymbol{m}\cdot\boldsymbol{r})\cdot\boldsymbol{r}}{|\boldsymbol{r}|^5} - \frac{\boldsymbol{m}}{|\boldsymbol{r}|^3}\right)$

Hard-iron Calibration

$$\widehat{\boldsymbol{B}} = \boldsymbol{B} + \boxed{\boldsymbol{\beta}}$$

Hard-iron parameter, it is an intrinsic feature with the sensor, it cannot be decoupled from ***G*** without extensive movement

$$\widehat{\boldsymbol{B}} = \boldsymbol{B}^{signal} + \boxed{\boldsymbol{G}} + \boldsymbol{\beta}$$

Constant feature with the environment

Now we introduce, $\boldsymbol{B}^{cali} = \boldsymbol{G}_{\boldsymbol{0}} + \boldsymbol{\beta}$

$$\widehat{\boldsymbol{B}} - \boldsymbol{B}^{cali} = \boldsymbol{B}^{signal} + \boxed{\boldsymbol{G} - \boldsymbol{G}_{\boldsymbol{0}}}$$

We removed $\boldsymbol{\beta}$, now we only need to address constant, solvable environmental constants

Auto-triggering Scheme

- Design goal: automatically determine whether calibration is needed

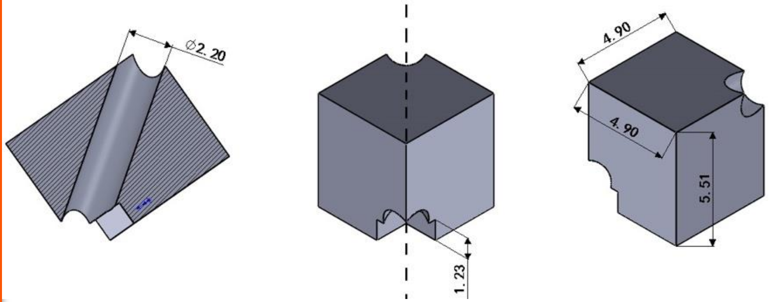
- The key idea: a two-step approach
    1. Determine a baseline of the current magnetic status
    2. Periodically monitor the magnetic status with a novel feature set

Put Everything Together

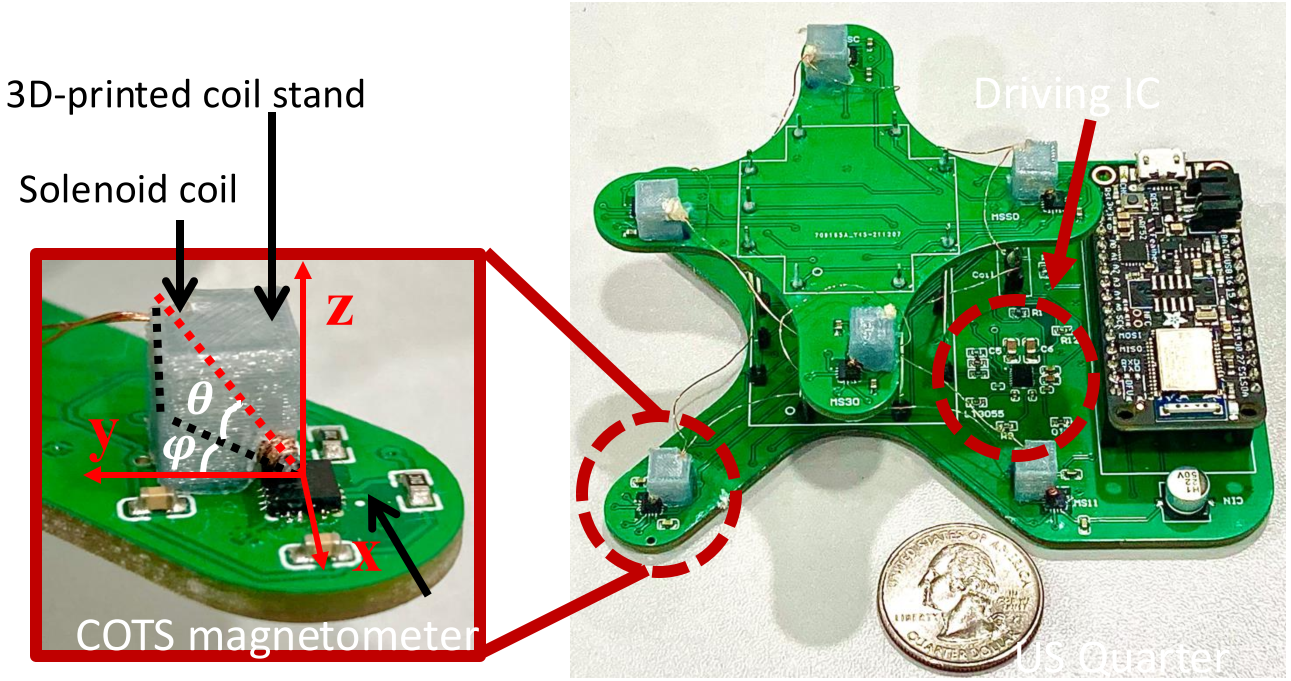
Design of the coil and stand

Medium coil

Compact coil

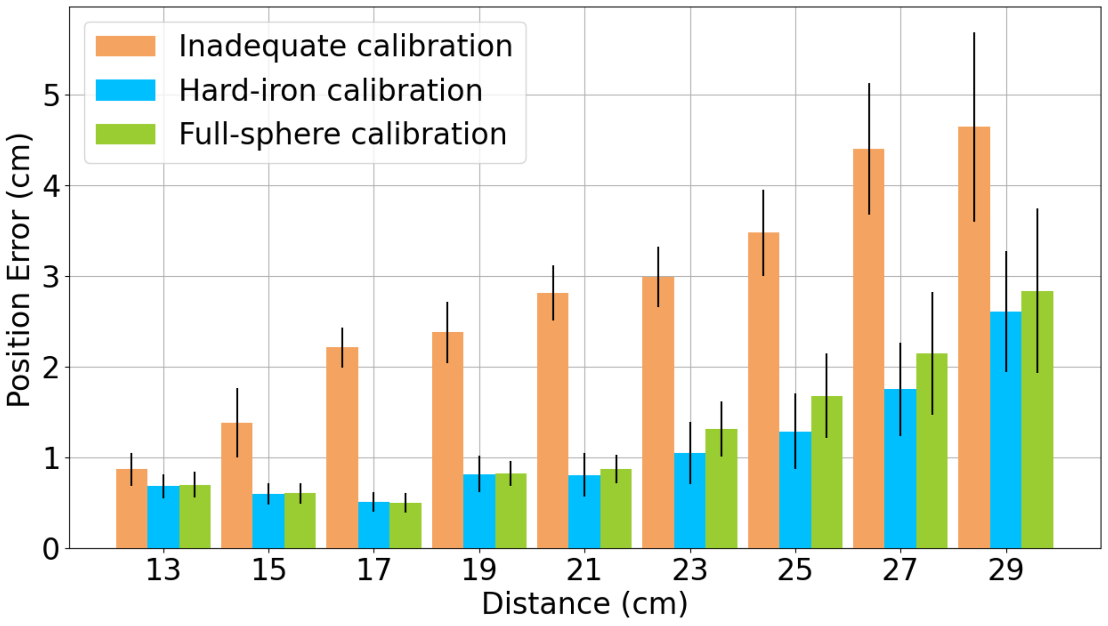


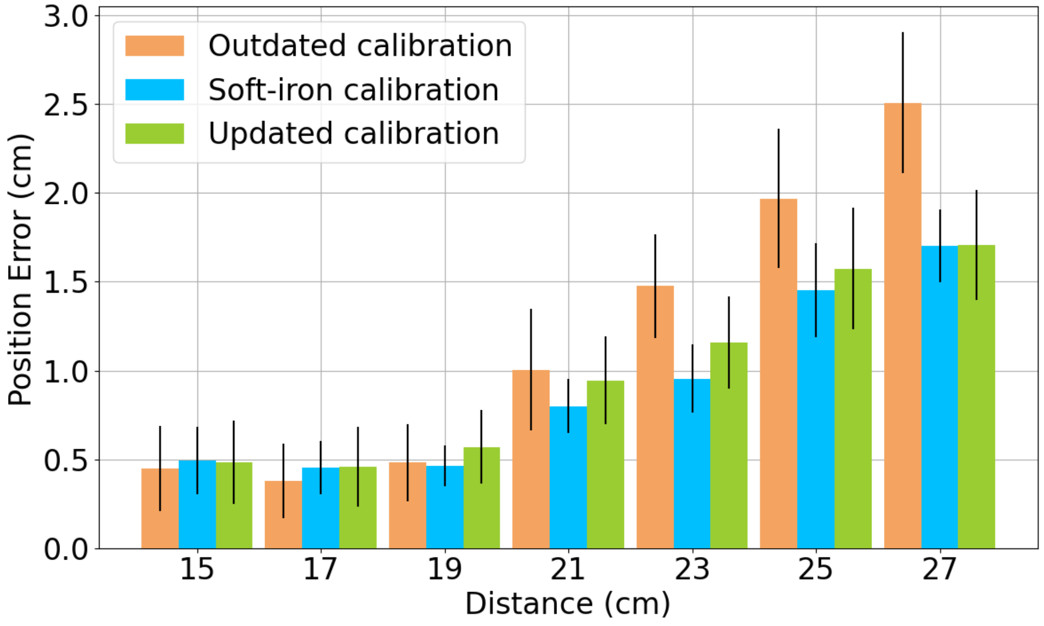
MAGIC's assembly on MagX system



Performance Evaluation

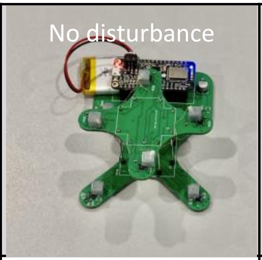
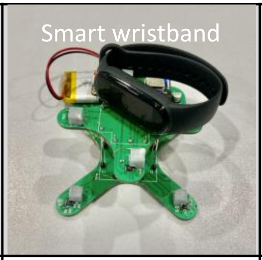
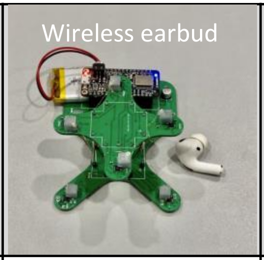
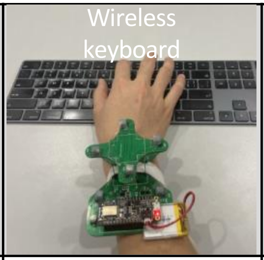
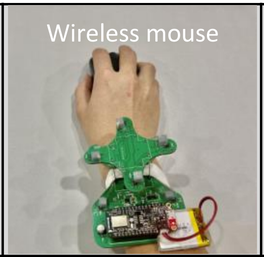
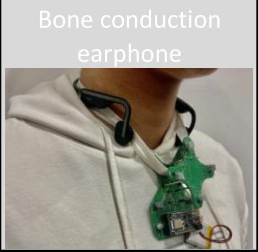
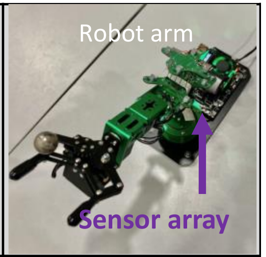
- Hard iron and soft iron calibration





Performance Evaluation

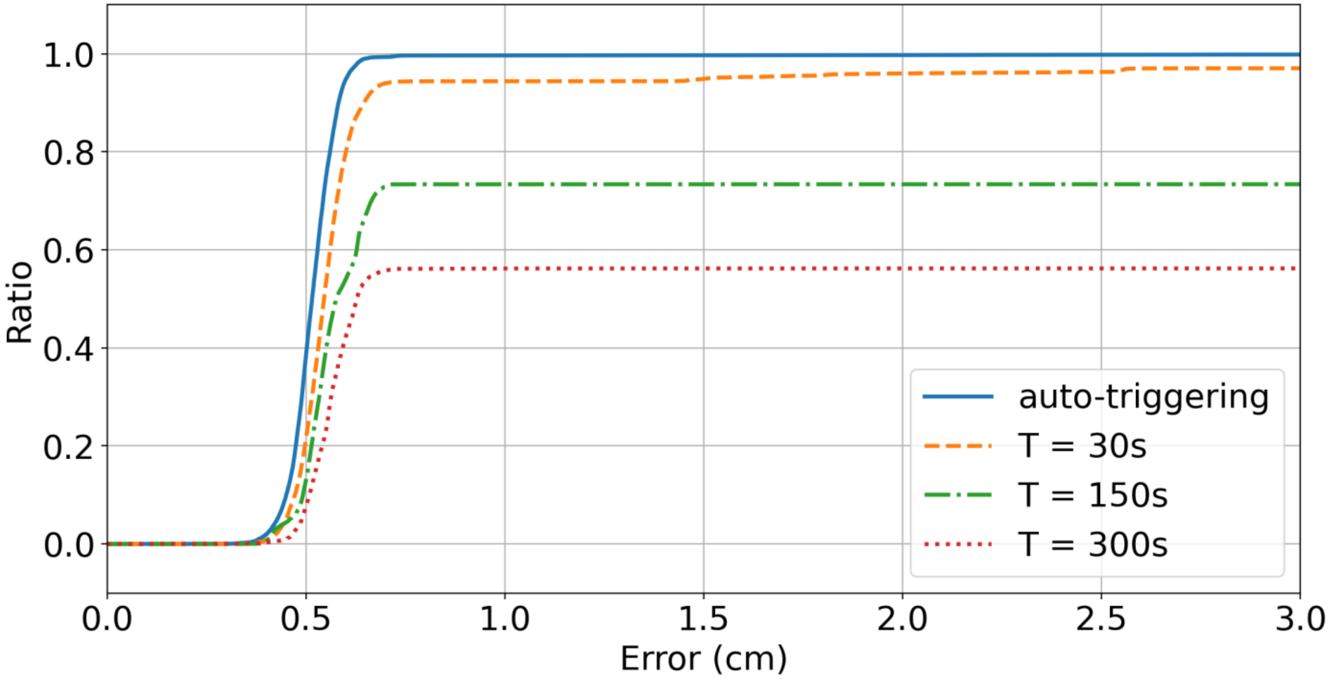
- Auto-triggering scheme

Electronic devices tested in experiments	No disturbance 	Smart wristband 	Charging case of wireless earbuds 	Wireless earbud 	Wireless keyboard 	Wireless mouse 	Bone conduction earphone 	Robot arm 
Need calib.?	**NO**	**YES**	**YES**	**NO**	**NO**	**NO**	**YES**	**NO**
Err. (mean, std)	(0.98, 0.04)	(6.52, 0.78)	(6.76, 0.46)	(2.73, 0.11)	(0.98, 0.03)	(1.01, 0.04)	(9.11, 6.88)	(1.11, 0.13)

With MAGIC's baseline setting and status monitoring
We can accurately connect the calibration status with system performance, and trigger calibration ONLY when NEEDED

Performance Evaluation

- Auto-triggering vs. periodic calibration methods



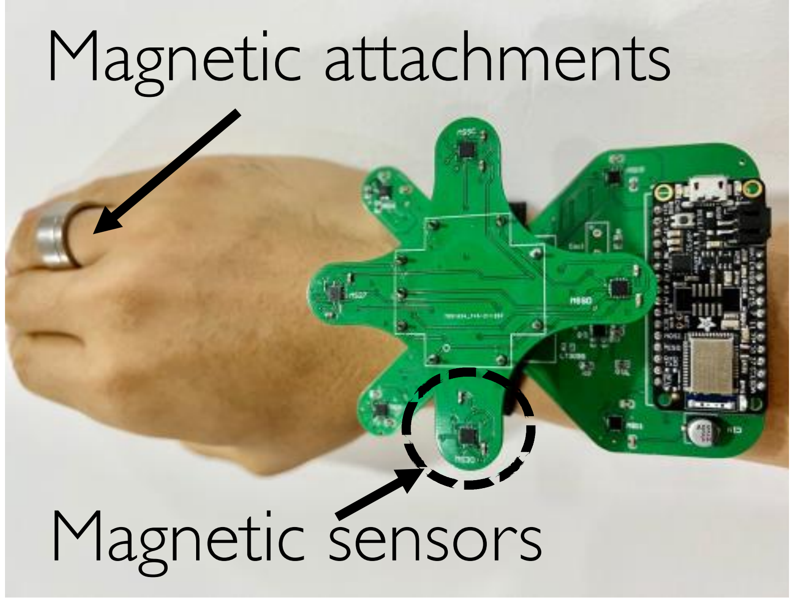
The Energy Cost of MAGIC

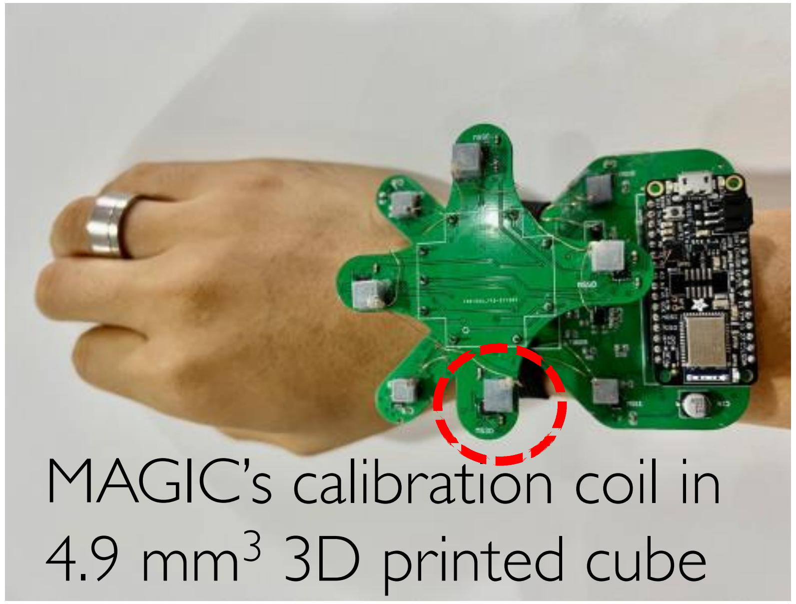
- We compared MAGIC's energy cost with different time intervals'

Interval	Auto-triggering	300 s	150 s	30 s
Energy cost (J)	270.82	270.82	275.24	310.59
Occurrences	3	3	6	30

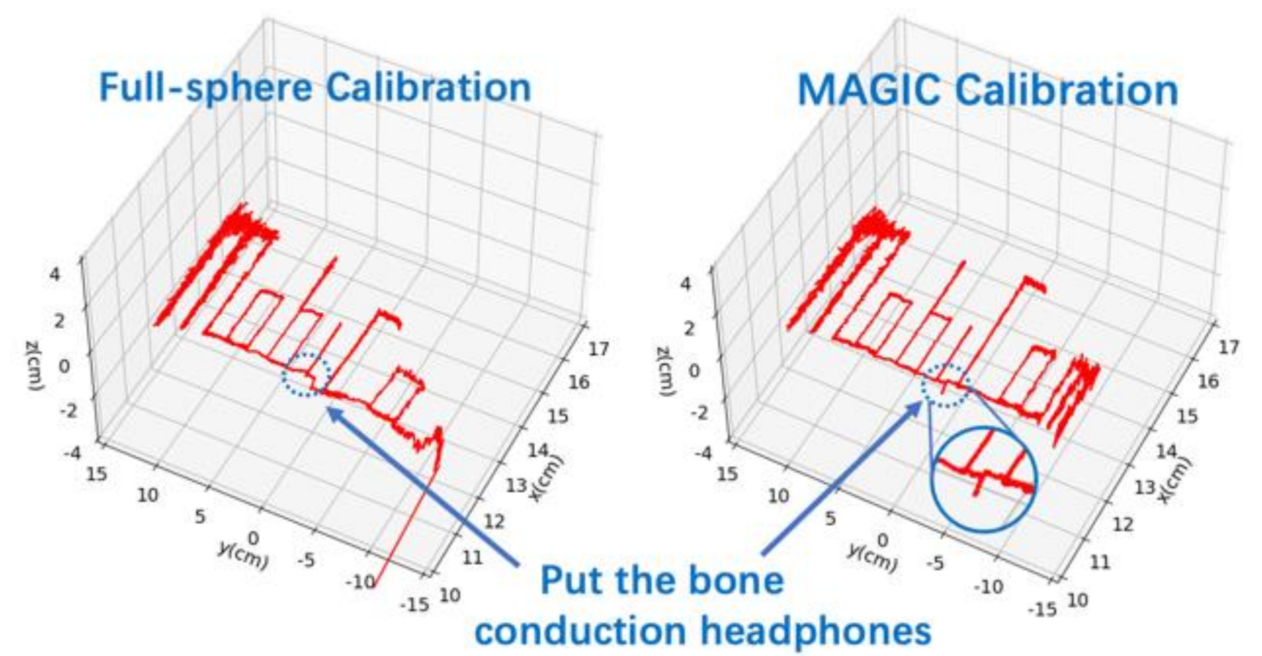
What can We Achieve with MAGIC?

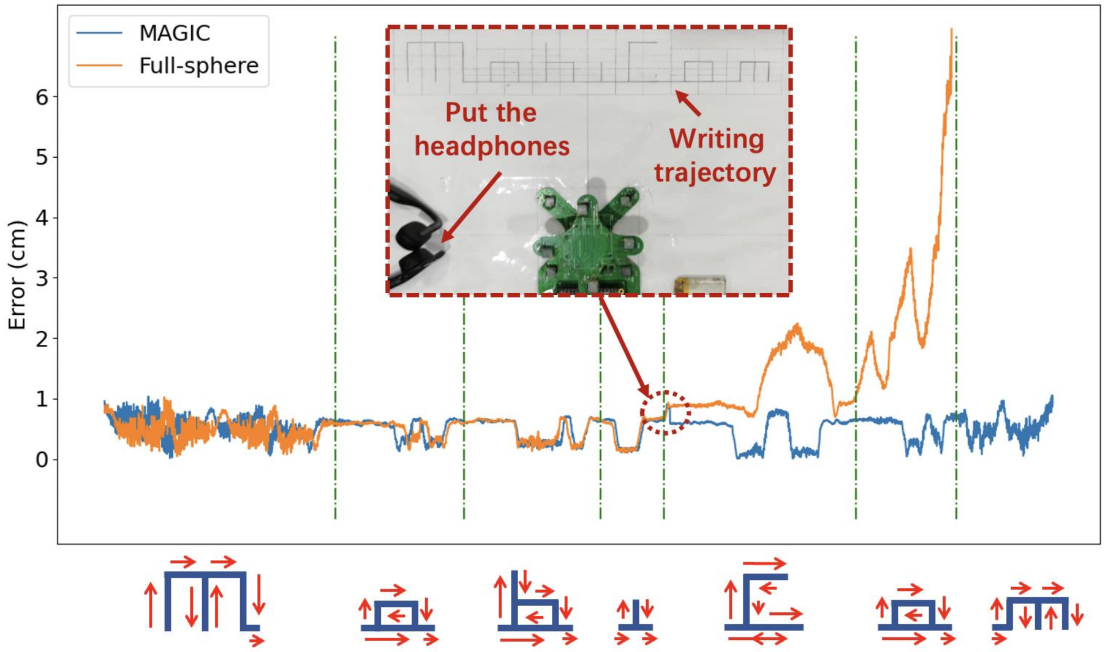
A workable, wearable, and efficient **essential** for magnetic tracking technology



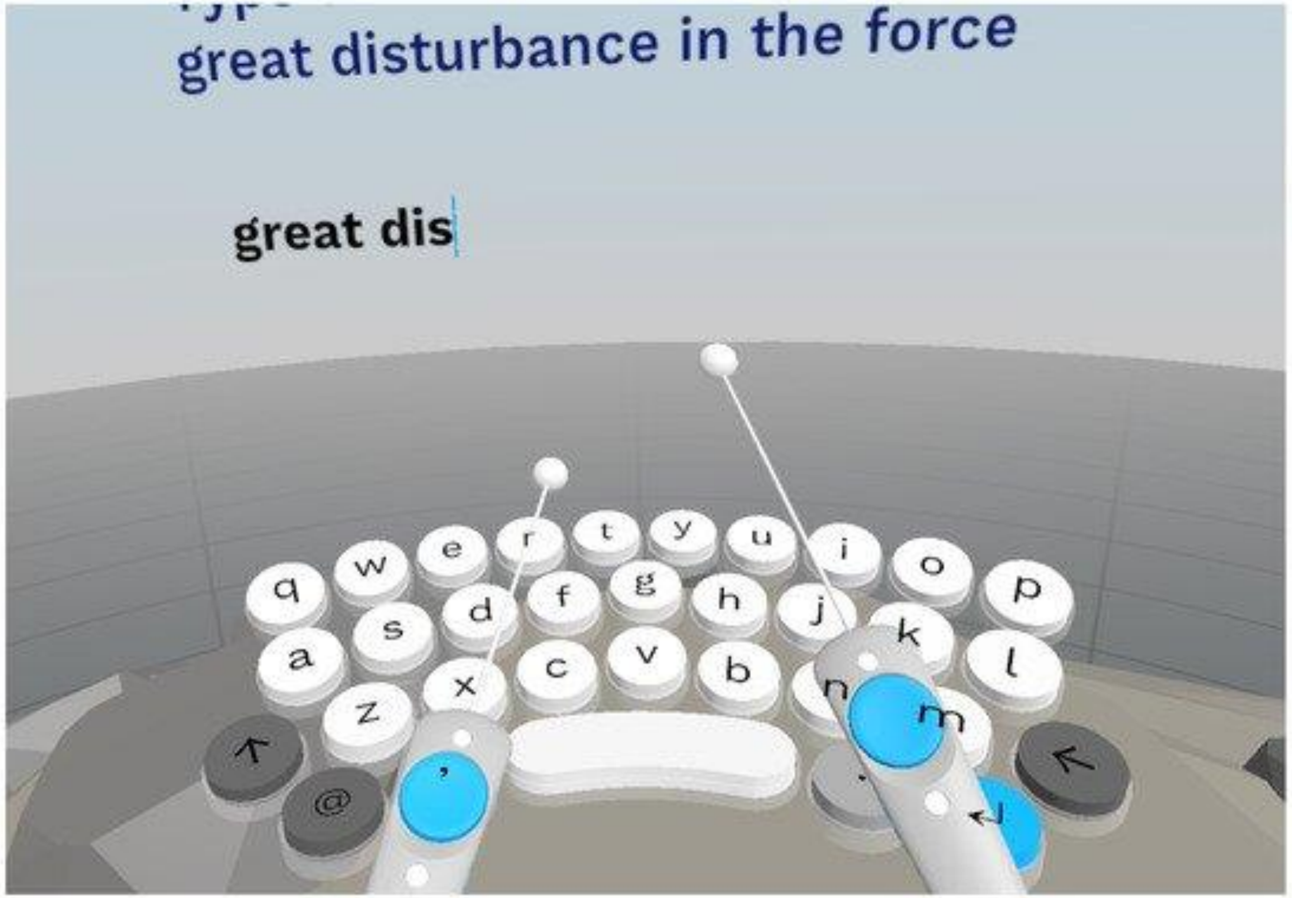


Hand-writing Experiment





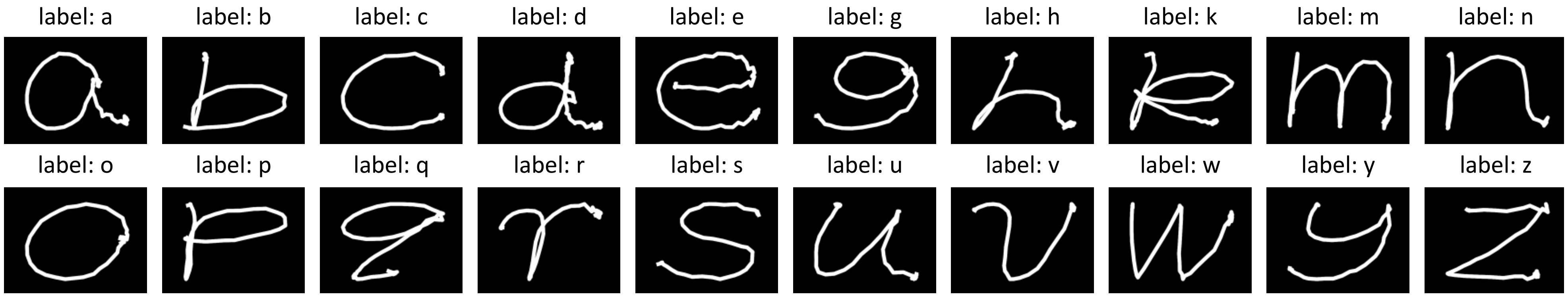
Text Entry in VR is a Nightmare …



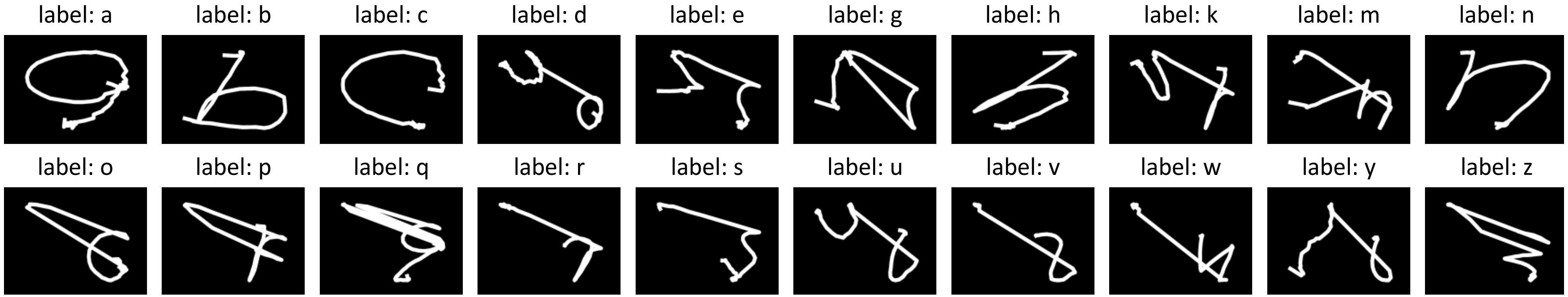
https://www.mdpi.com/2227-7080/7/2/31

3D Handwriting, Made into Reality

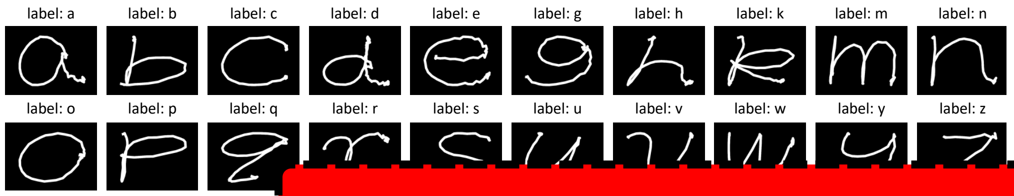
Calibrated with MAGIC

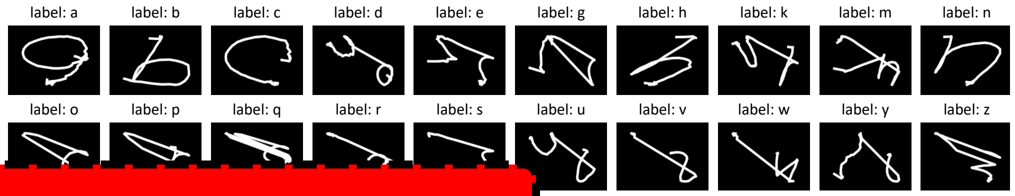


Calibrated with full-sphere method

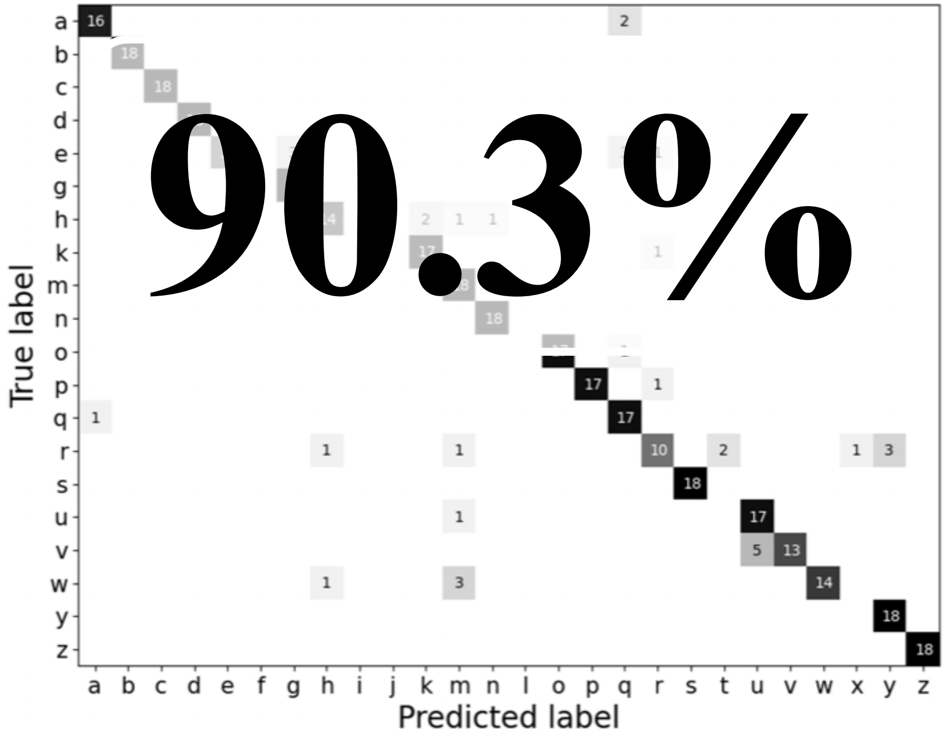


3D Handwriting, Made into Reality

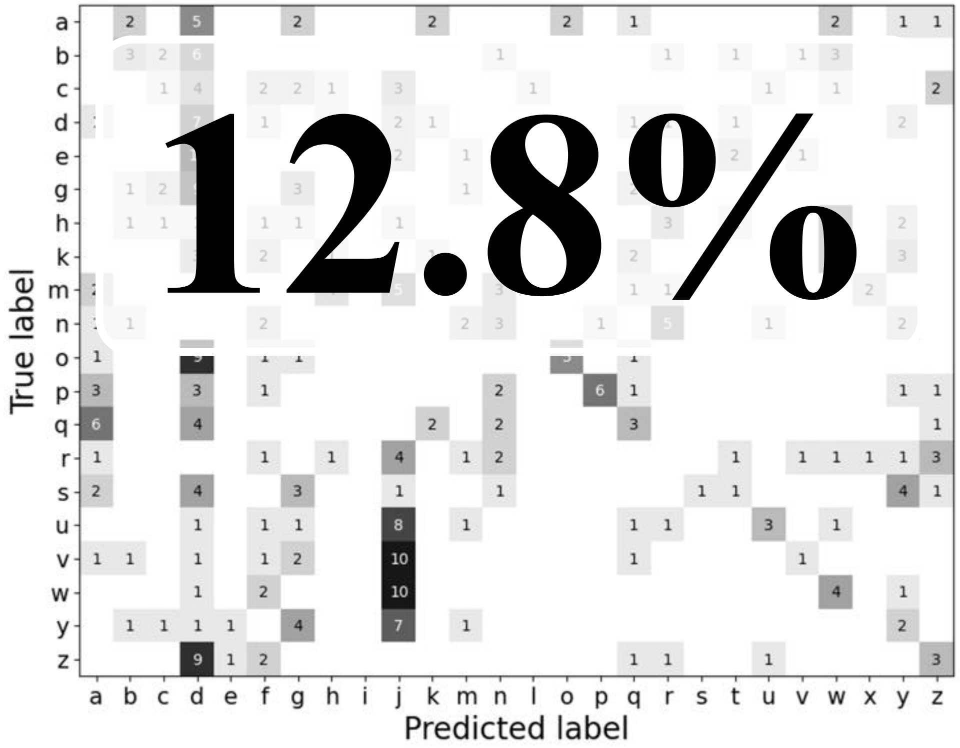




The classifier was trained with MNIST Letters dataset

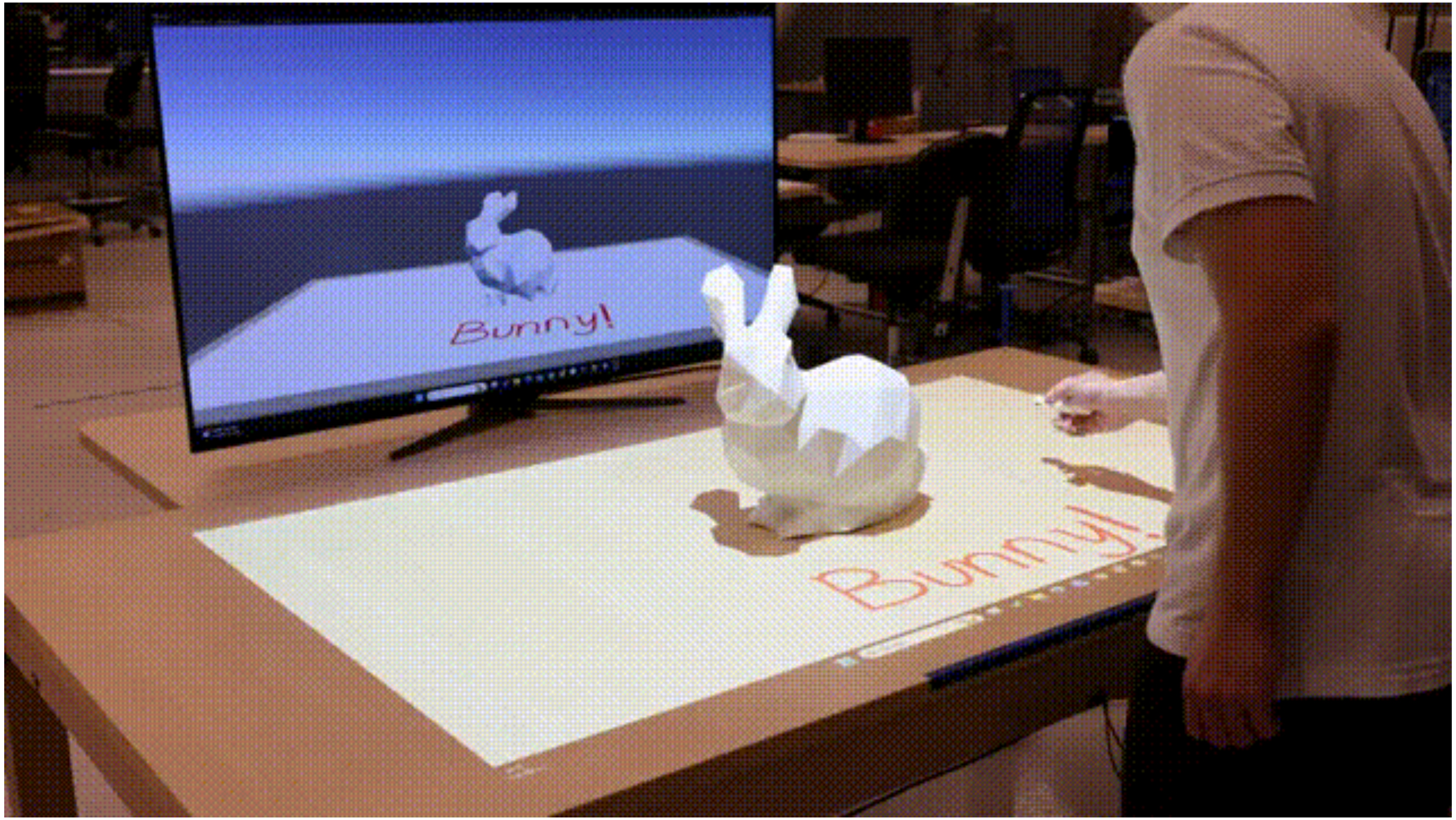


90.3%



12.8%

Magnetic Sensing for Smart Office



MagDesk: Interactive Tabletop Workspace Based on Passive Magnetic Tracking
UbiComp 2025, Kunpeng Huang, Yasha Iravantchi, Dongyao Chen, and Alanson Sample

Conclusion

- MAGIC is a practical and easy-to-use calibration system for magnetic sensing apps
  - MAGIC handles notorious soft- and hard-iron disturbances
  - MAGIC enables end-to-end automatic calibration by using a lightweight auto- triggering scheme

Final Thoughts of Magnetic Tracking

- Magnetic sensing can accurately detect the relative location

Final Thoughts of Magnetic Tracking

- Magnetic sensing can accurately detect the relative location
- Three **key challenges**
  - Limited sensing distance
  - Hard to differentiate passive magnets
  - Requires a separated framework, i.e., sensor array + magnet