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Foes or Friends: Embracing Ground Effect for Edge Detection on Lightweight Drones

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Drone Motivated Low-Altitude Economy in China

16.7B
GDP in 2023
more than 10% of D.C.'s

1.26M
no. of drones
35 times airliner worldwide

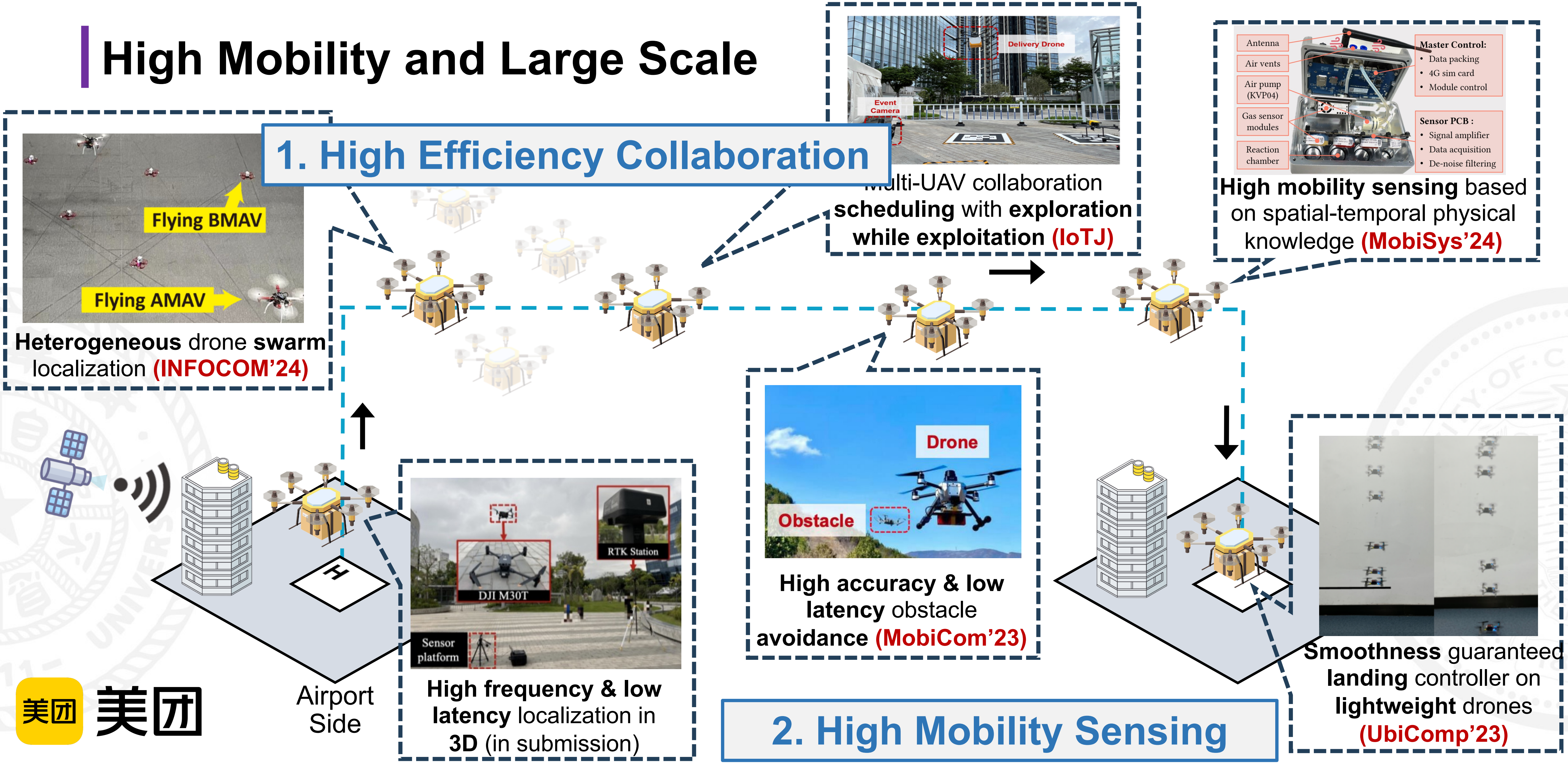
690
registered companies
2 new companies per day

100B
GDP at 2030
promising pillar industry

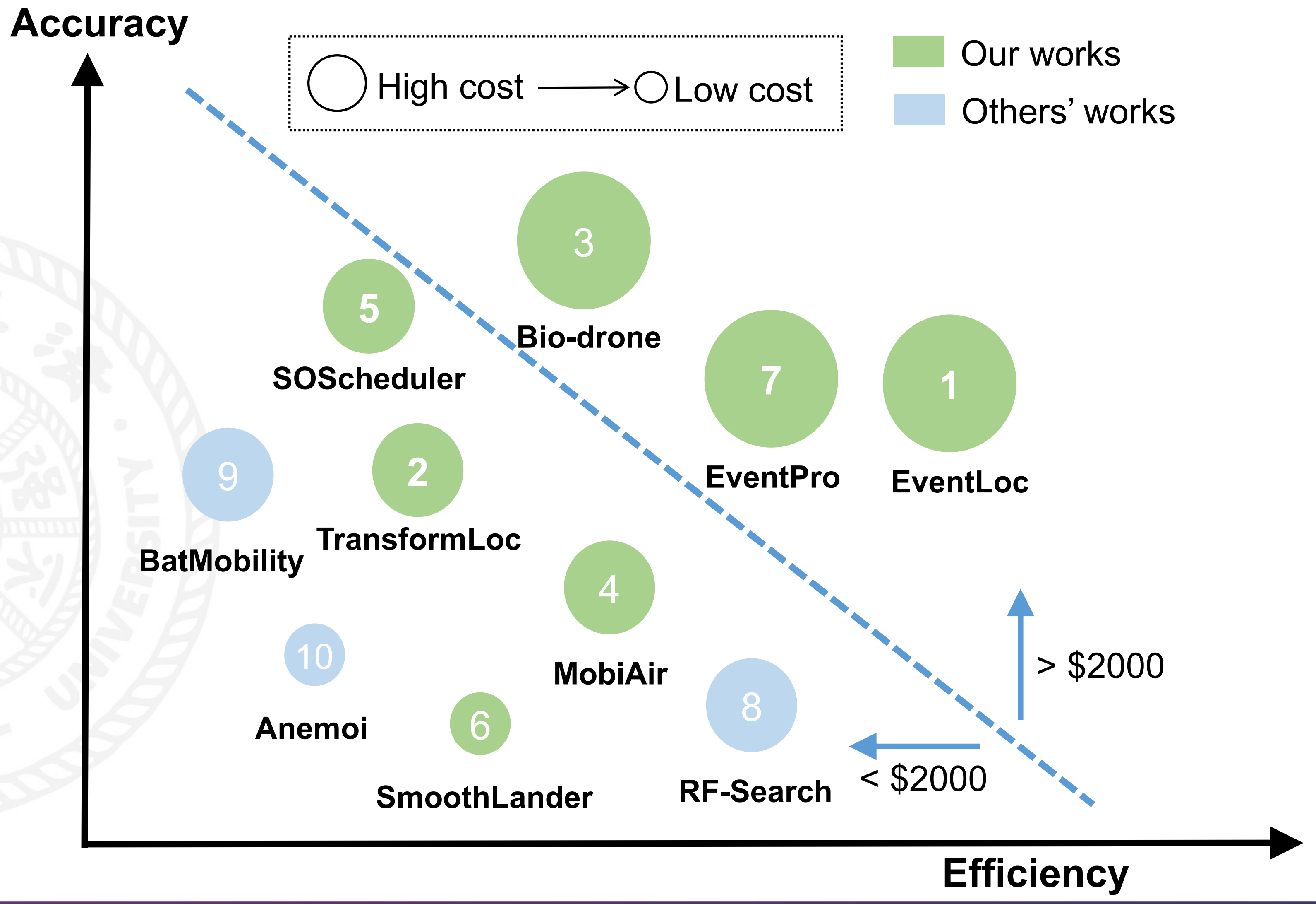
Applied in various fields

...

High Mobility and Large Scale

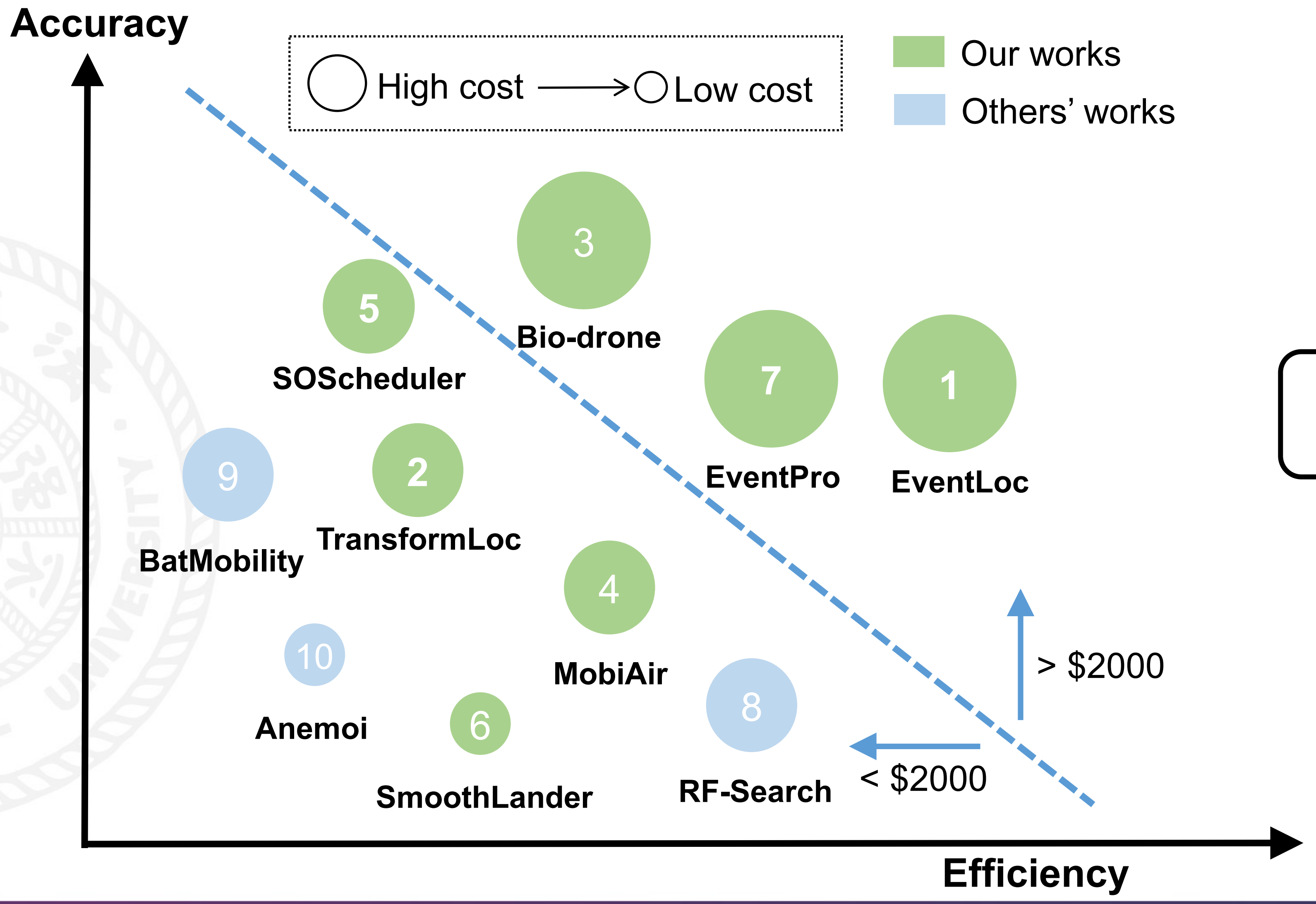


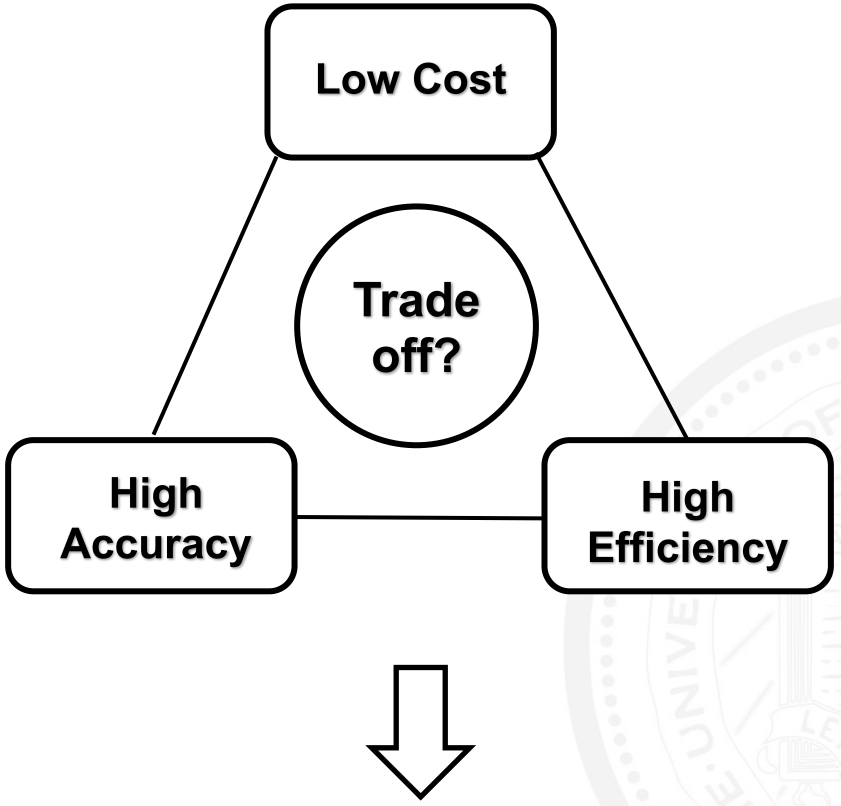
High Mobility Sensing



[1] Wang H, et.al. EventLoc.
[2] Wang H, et al. TransformLoc: Transforming MAVs into Mobile Localization Infrastructures in Heterogeneous Swarms. INFOCOM'24.
[3] Xu J, et al. Taming event cameras with bio-inspired architecture and algorithm: A case for drone obstacle avoidance. MobiCom'23.
[4] Liu Y, et al. MobiAir: Unleashing Sensor Mobility for City-scale and Fine-grained Air-Quality Monitoring with AirBERT. MobiSys'24.
[5] Chen X, et al. SOScheduler: Toward Proactive and Adaptive Wildfire Suppression via Multi-UAV Collaborative Scheduling. IoTJ.
[6] Zhao C, et al. SmoothLander: A Quadrotor Landing Control System with Smooth Trajectory Guarantee Based on Reinforcement Learning. UbiComp'23.
[7] Chen X, et.al. EventPro.
[8] Zhang, et al. RF-Search: Searching Unconscious Victim in Smoke Scenes with RF-enabled Drone MobiCom'23.
[9] Emerson Sie, et.al. BatMobility: Towards Flying Without Seeing for Autonomous Drones. MobiCom'23.
[10] Xia S, et.al. Anemoi: A Low-cost Sensorless Indoor Drone System for Automatic Mapping of 3D Airflow Fields

High Mobility Sensing





Any chance to jump out of such **tradeoff**?

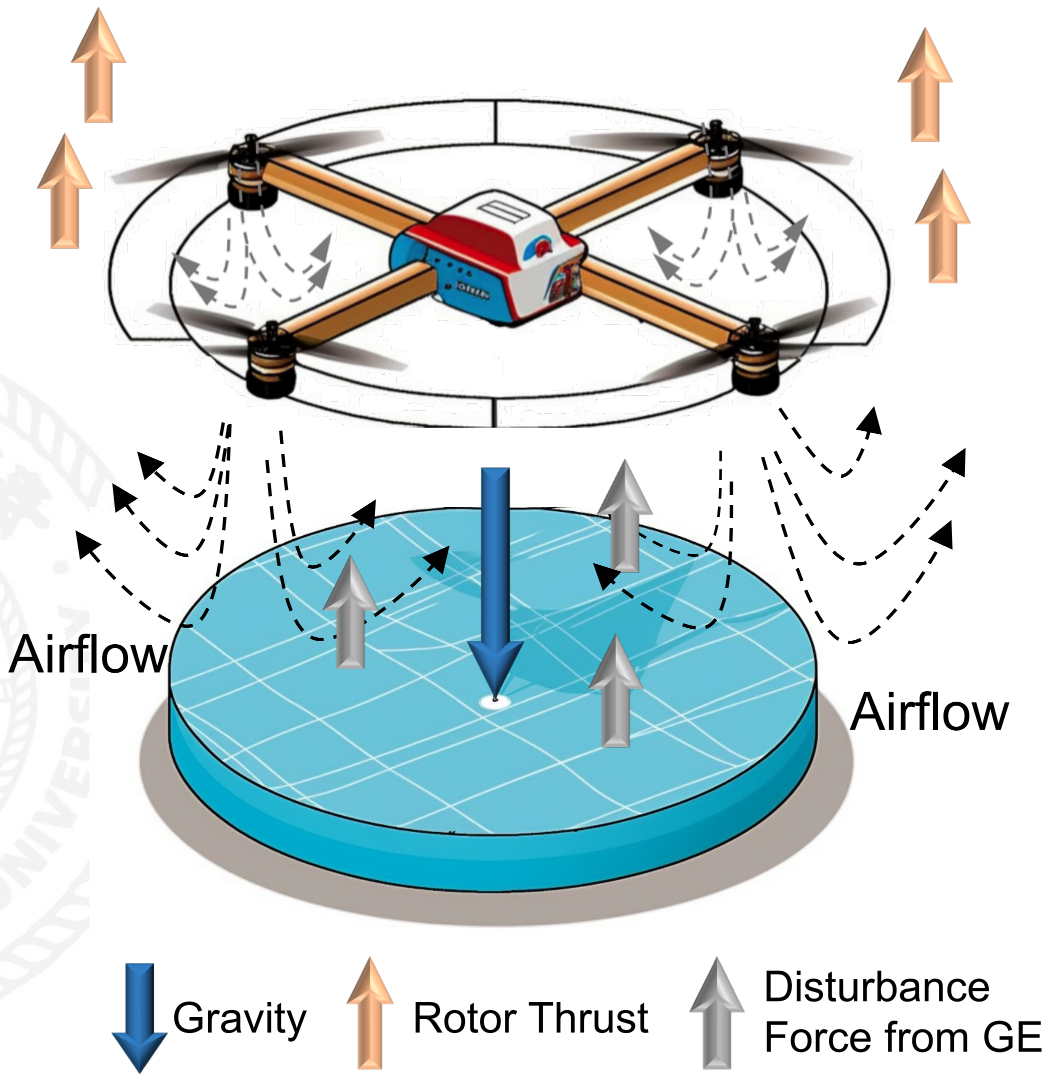
How to avoid the paradigam to continually add **sophisticated** sensors and/or design **sophisticated** algorithms?

行有不得，反求诸己 -- 《孟子 · 离娄上》

If things do not work out, look within yourself for solutions

Drone itself is a **sophisticated** machine with Flight Control.
Is there some opportunities to unlock additional sensing capabilities within these **sophisticated** machines？

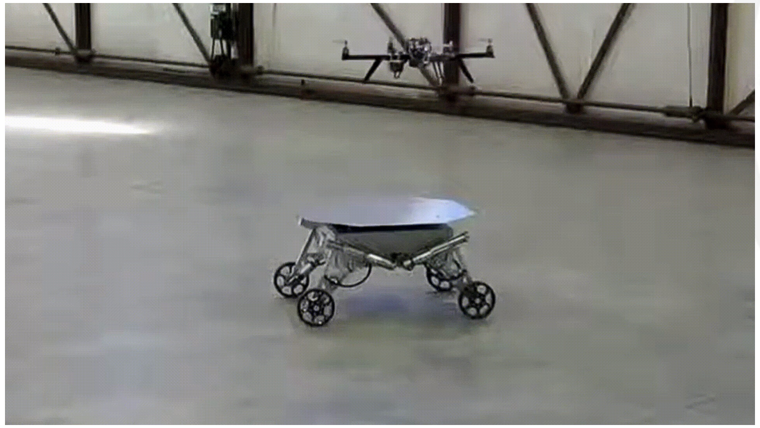
Ground Effect (GE): Foe or Friend?



Foe?

- Landing Crash! Low Altitude Jittering! ......

[1]



[2]

[1] https://www.youtube.com/watch?app=desktop&v=66PmaluCvbU
[2] https://www.youtube.com/watch?v=6UZjfsy1fJo

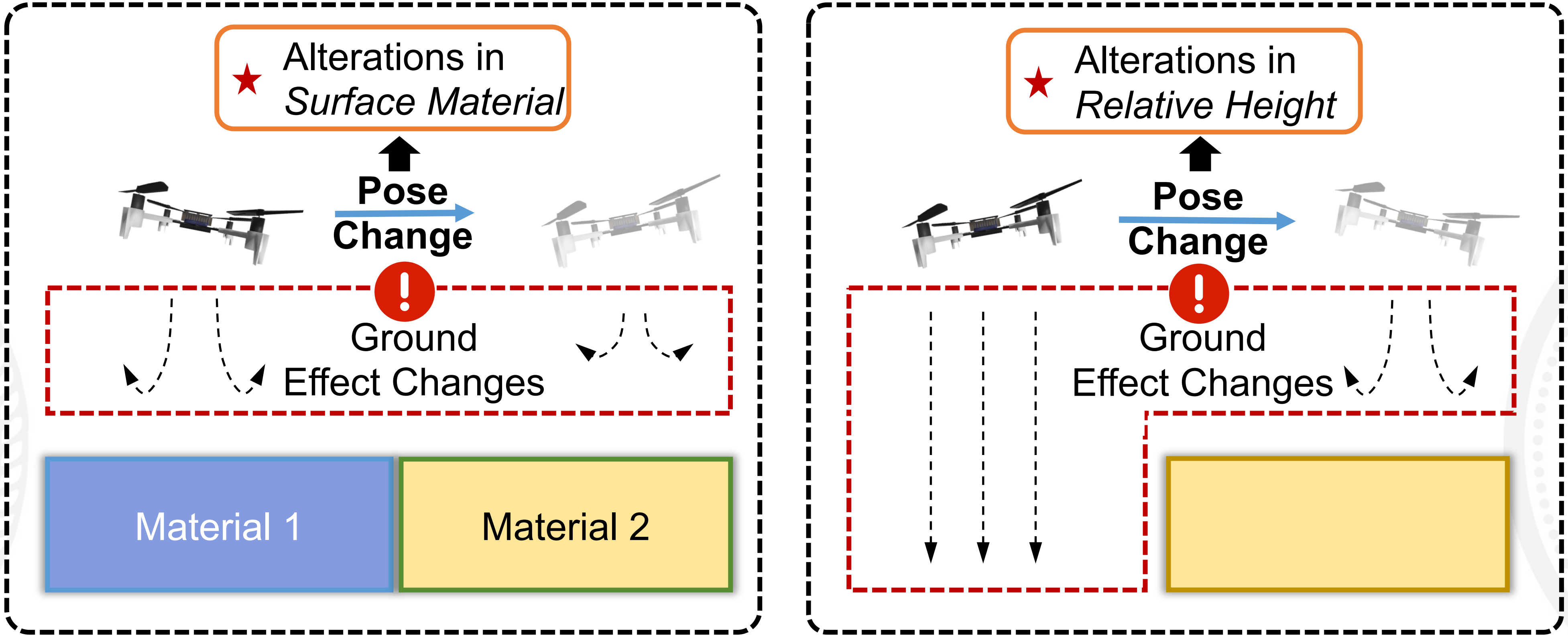
Ground Effect As a For or a Friend?

Ground Effect seems to reflect information of ground surface, especially the edge of a surface

As a Friend for Sensing?

Ground Effect As a Friend!

- New sensing modality for **Edge Detection**!



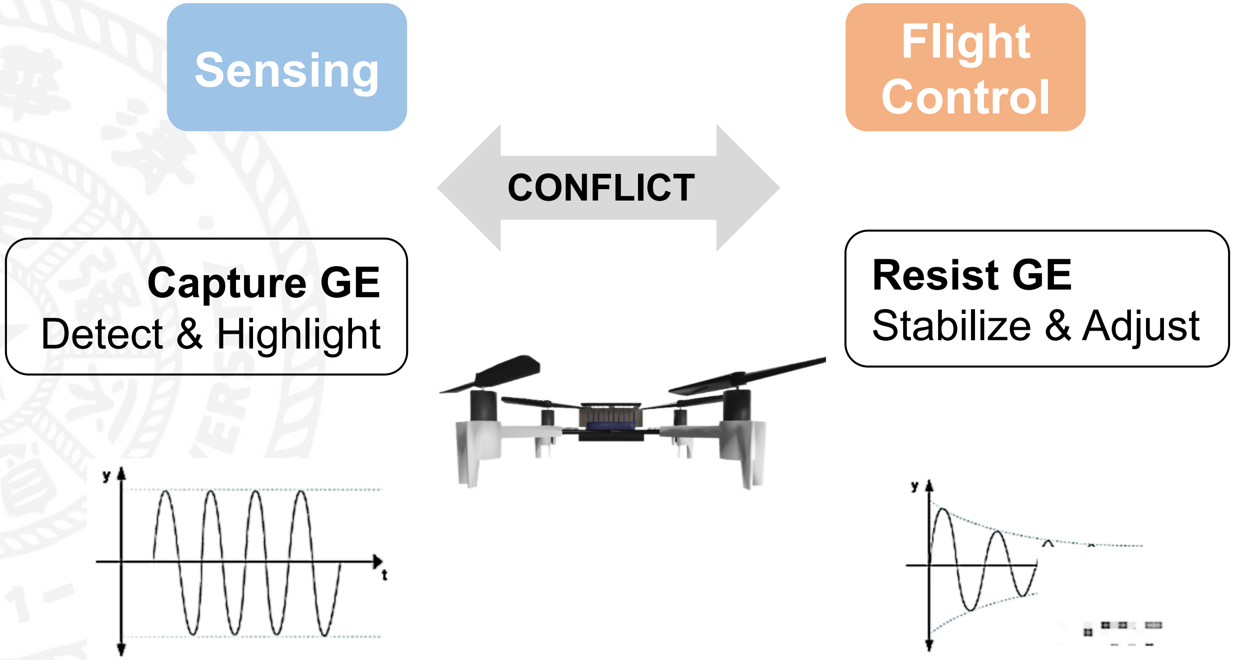
Leveraging Control information for Sensing
(Without Additional Sensors!)

Ground Effect As a Friend!

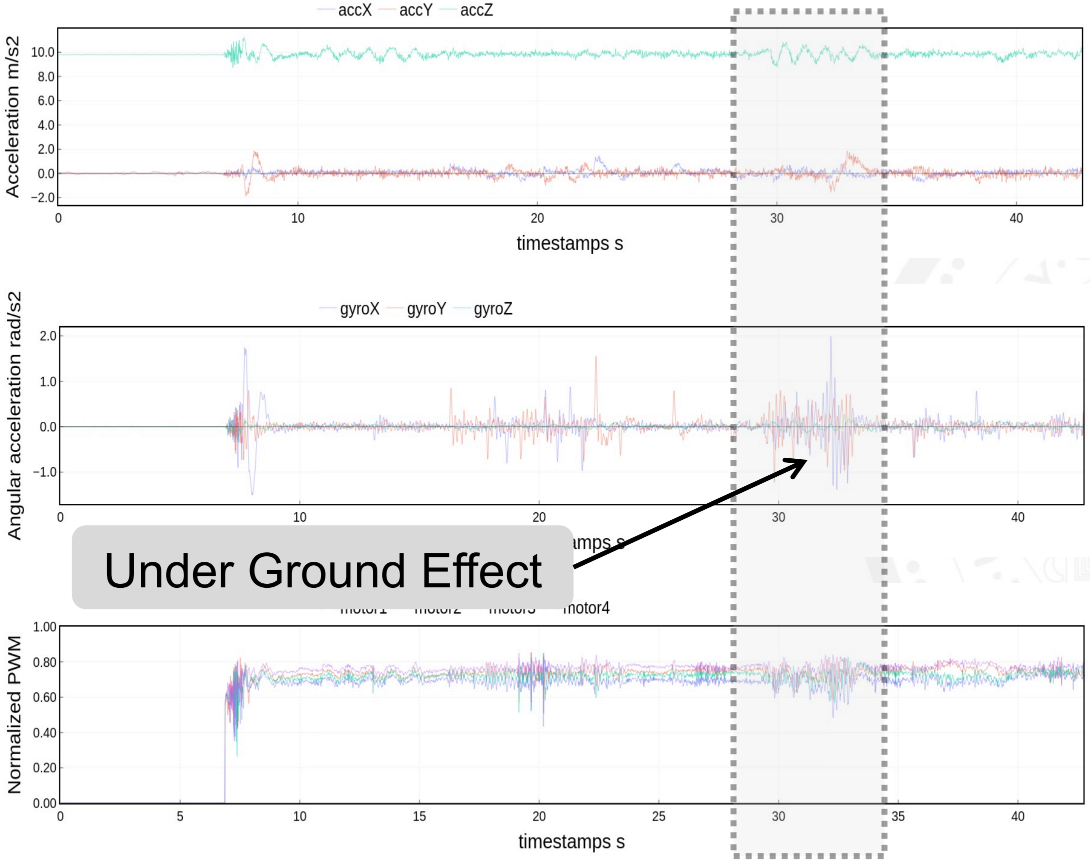
But how to turn this idea into reality?

Challenges

C1: **Target Discrepancy** between sensing & flight control complicates GE profiling

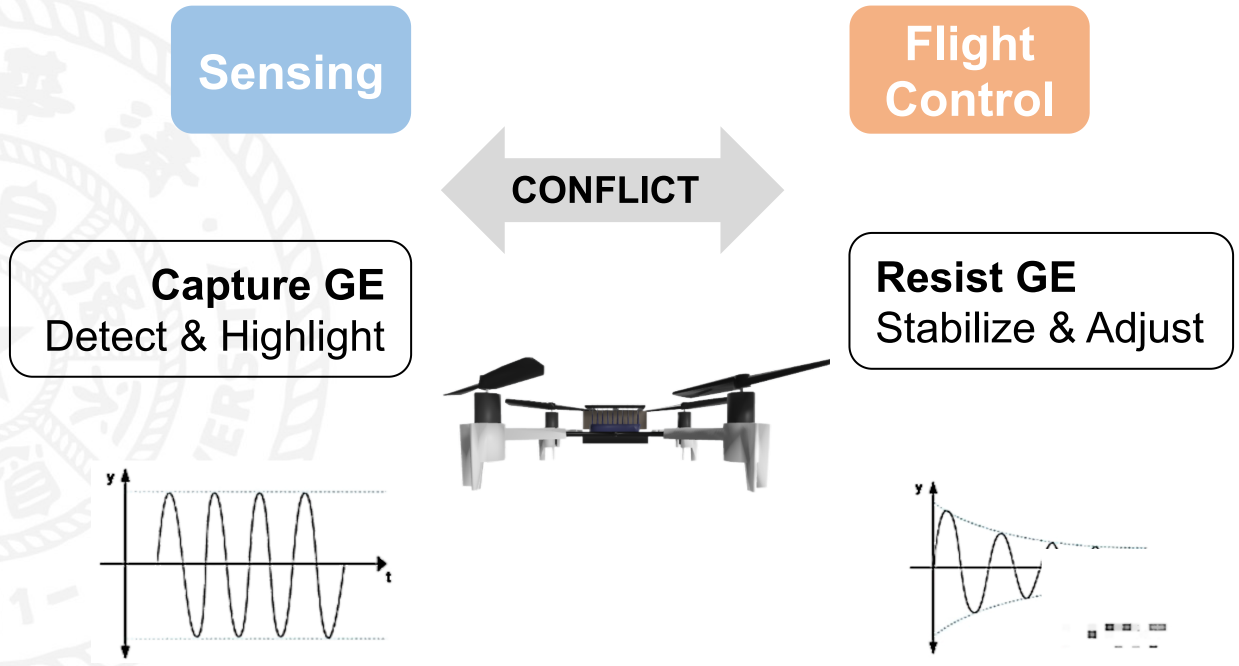


C2: **Noisy** sensing data hinders accurate GE detection



Challenges

C1: **Target Discrepancy** between sensing & flight control complicates GE profiling



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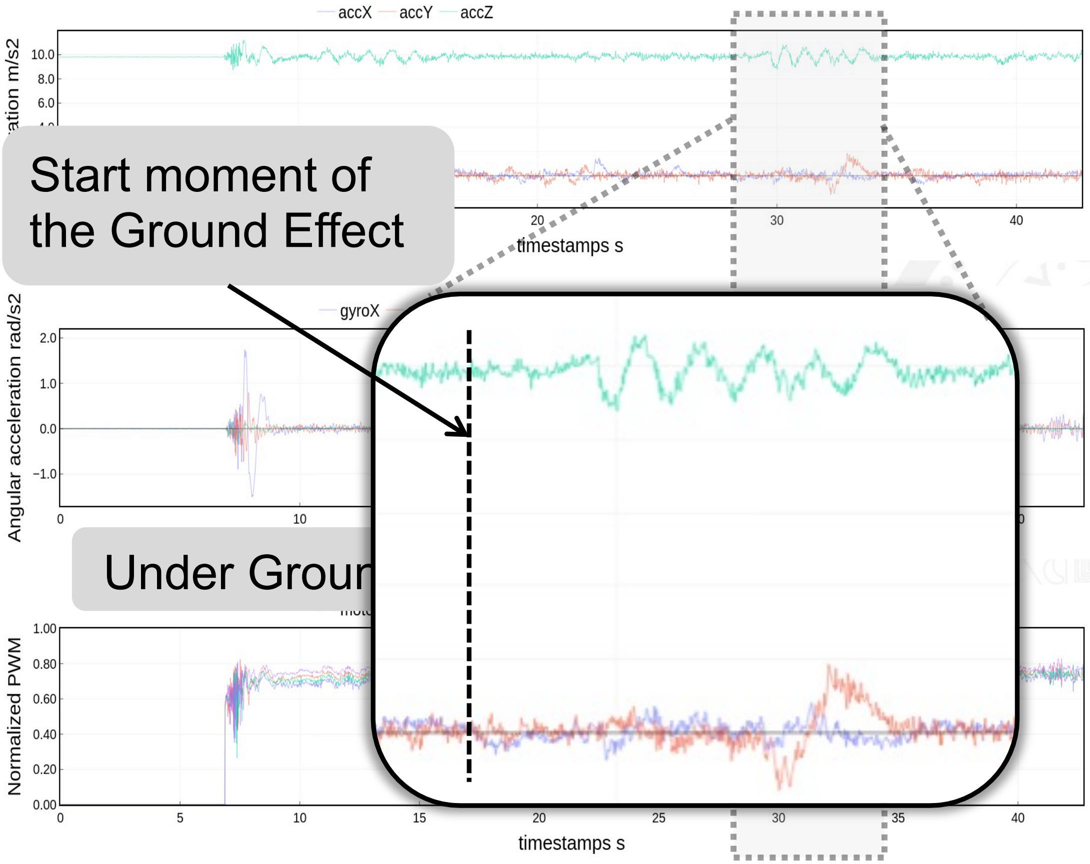


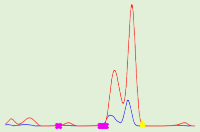
Solutions: Theories, and Formulas

S1: Integrating **IMU data** and **Motor commands** for GE profiling

$$X(n) = \sum_{m=m1}^{m2} \sum_{k=0}^{N-1} x(k) \cdot w(k-m) e^{-j2\pi kn/N}$$

Fluctuation Components Feature Extraction

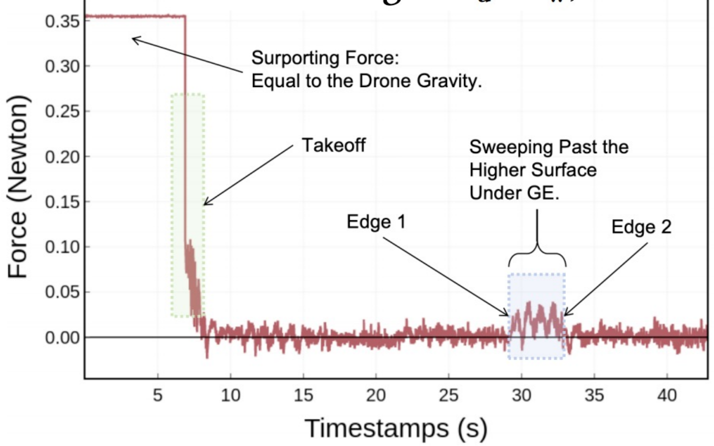
Cascaded Cross-Spectrum Feature Fusion



$$G_{xy}(f) = X(f)Y^*(f).$$
$$G_{xx}(f) = X(f)X^*(f).$$
$$|G_{xy}(f)|^2 = |G_{xx}(f)||G_{yy}(f)|.$$
$$|P_{ccs}(f)| = |X_1(f)X_2^*(f)X_3(f)\ldots X_n^*(f)|$$
$$= \sqrt{|G_{x_1x_1}(f)||G_{x_2x_2}(f)|\ldots|G_{x_nx_n}(f)|}.$$

Disturbance Force $\mathbf{f}_\mathbf{w}$

$$ma = mg + R\mathbf{f}_\mathbf{u} + \mathbf{f}_\mathbf{w},$$



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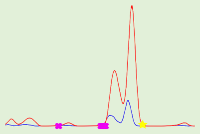

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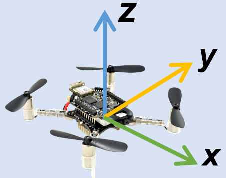
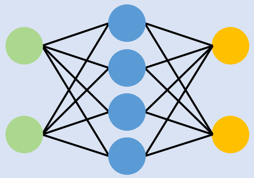
$$|G_{xy}(f)|^2 = |G_{xx}(f)||G_{yy}(f)|.$$
$$|P_{ccs}(f)| = |X_1(f)X_2^*(f)X_3(f)...X_n^*(f)| = \sqrt{|G_{x_1x_1}(f)||G_{x_2x_2}(f)|...|G_{x_nx_n}(f)|}.$$

$$ma = mg + R\mathrm{f_u} + \mathrm{f_w},$$
$$\mathrm{a} = \dot{\mathrm{v}}, \mathrm{v} = \dot{\mathrm{p}},$$
$$J\dot{\omega} = J\omega \times \omega + \tau_u + \tau_w,$$
$$\dot{R} = RM(\omega),$$
$$H_0 = \begin{bmatrix} k_T & k_T & k_T & k_T \\ 0 & k_T l_r & 0 & -k_T l_r \\ -k_T l_r & 0 & k_T l_r & 0 \\ -c_Q & c_Q & -c_Q & c_Q \end{bmatrix},$$

Aerodynamics-Informed Double Phase Physical Filter



Physical Knowledge-aided Network



Loss Functions:

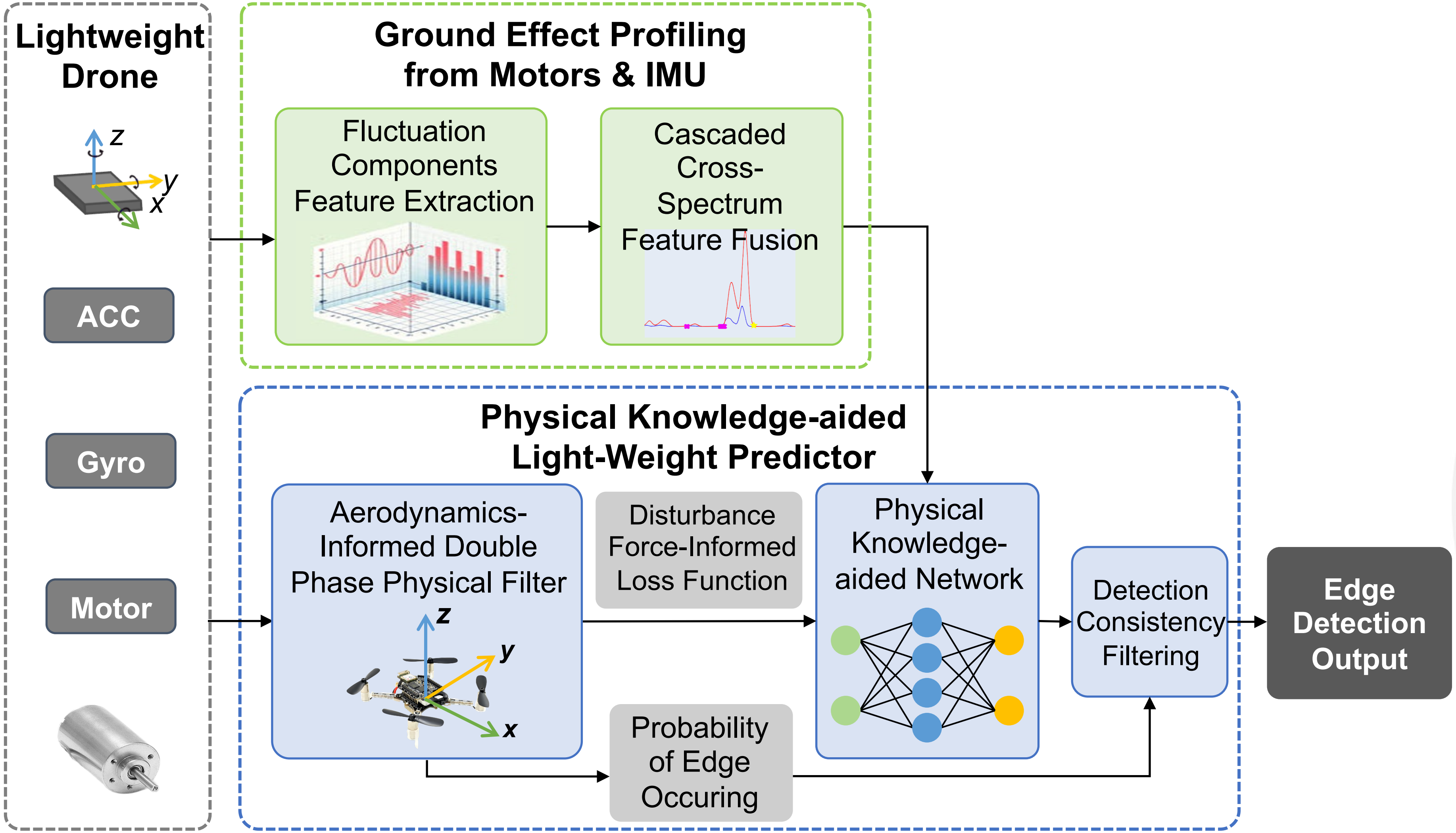
$$\mathcal{L}_F = \begin{cases} e^{|\hat{y}-1|} - 1, & ||f_w|| \geqslant T. \\ e^{|\hat{y}|} - 1, & \text{others}. \end{cases},$$ ← Disturbance Force-Informed Loss Function

$$\mathcal{L}_S = -y \log \hat{y} - (1-y)\log(1-\hat{y}),$$

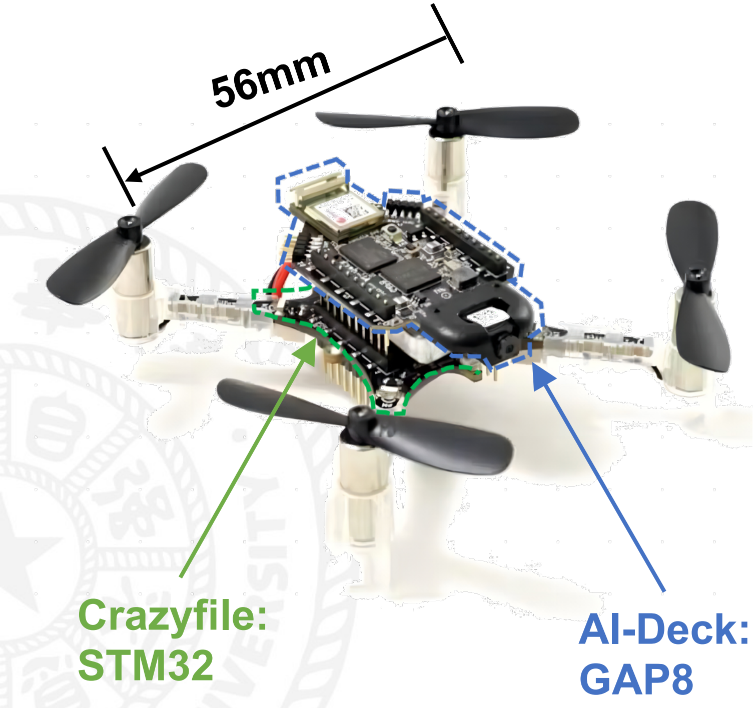
$$\mathcal{L} = \mathcal{L}_S + \lambda \cdot \mathcal{L}_F,$$ ← Total Loss

S2: **Physical Knowledge** embedded neural network for noise cancellation

AirTouch: Driven by Physical Knowledge & Data

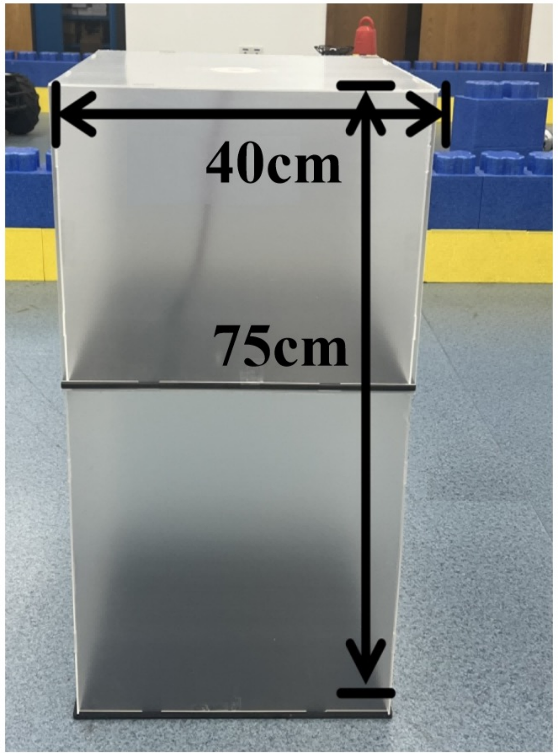


Experimental Setup and Performance

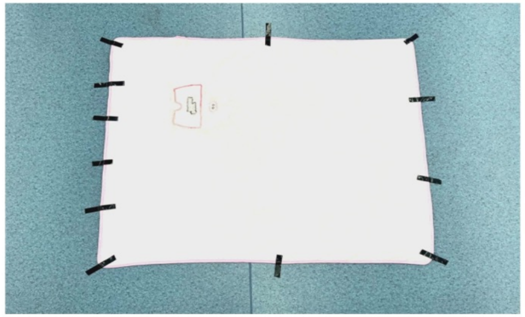


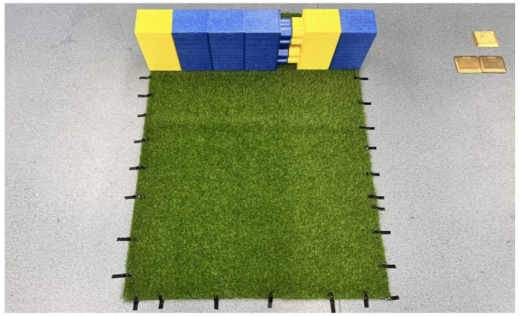
Weight:	Only **36 g**
Processor:	22.65 GOPS
Memory:	512KB
Sensors:	IMU, Baro

- Height change

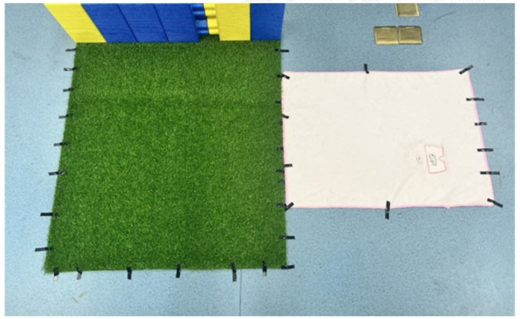


- Material variation


a. Mat & Cement

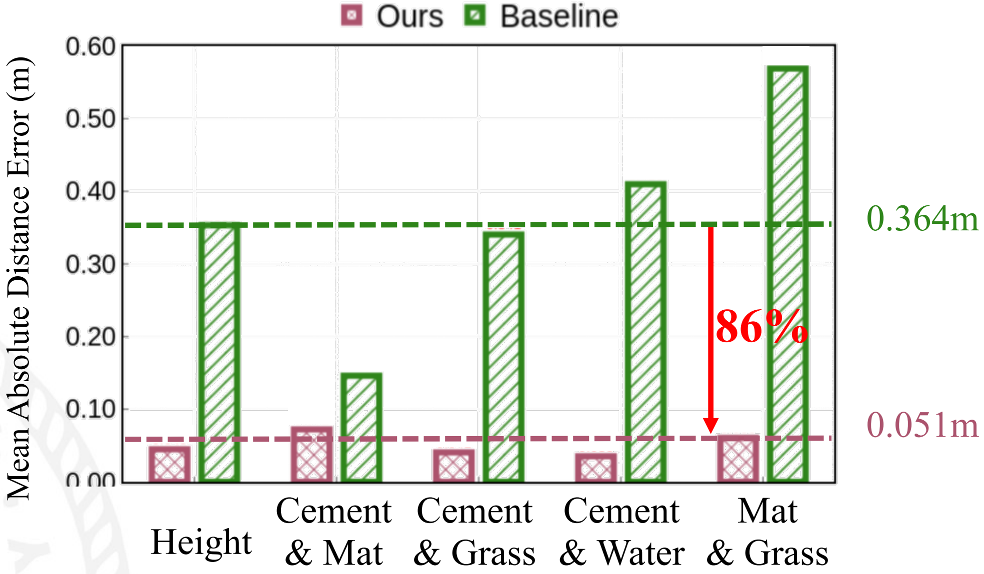

b. Grass & Cement


c. Water & Cement

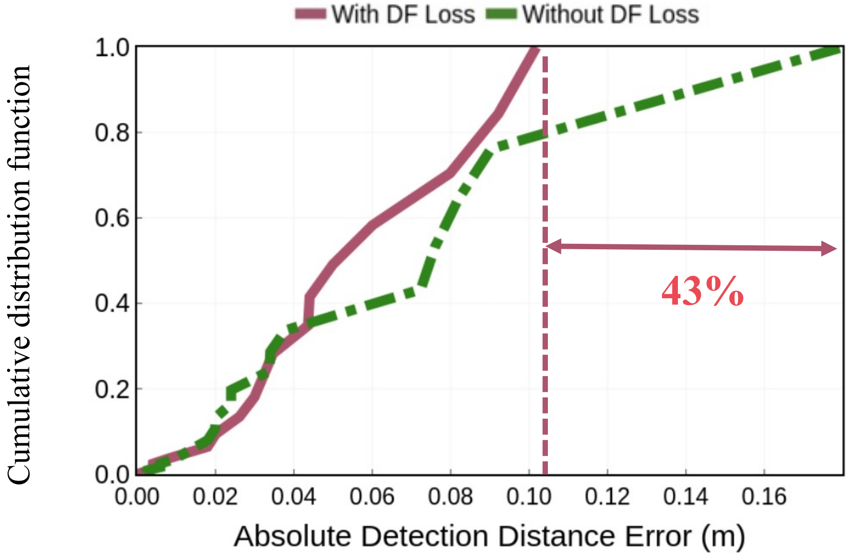

d. Grass & Mat

Performance

(1) Overall MAE reduces



(2) DF loss provides improvement

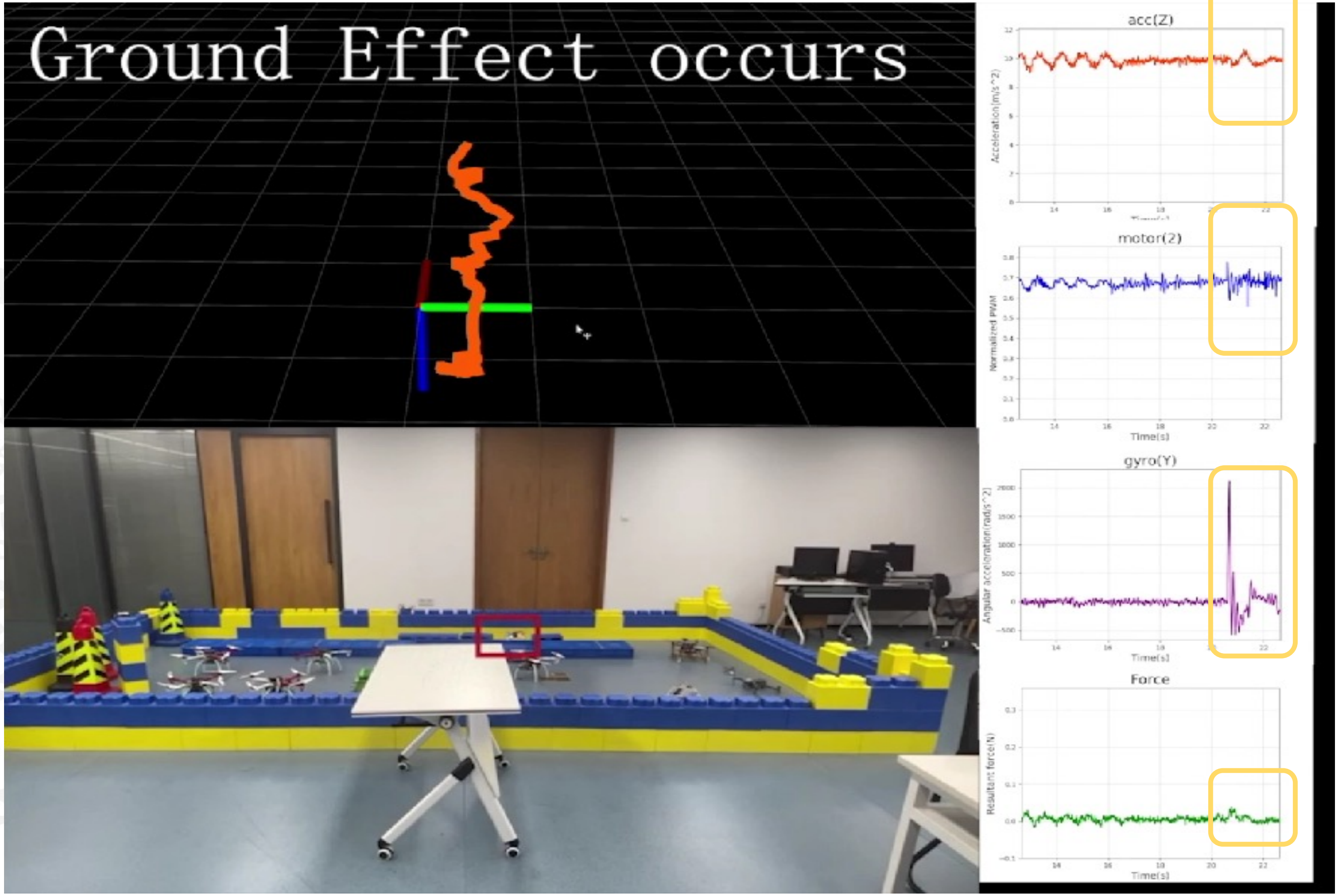


(3) Lightweight design

Items	**Vision-based**	**AirTouch**
FLOPs	3900 million	0.28 million — **0.007%**
NN param size	58 KB	13KB — **22%**
Memory per frame	Millions of bits	32K bits — **Substantially less**
Capability	Vulnerable in poor visual conditions	Works in **low-light**, **similar texture**

Demo and Conclusion

Variation in signals



Conclusion

- **AirTouch System:**
  Ground Effect ->
  Sensing Modality
- **Technical Points:**
  GE profiling module;
  Noise cancellation NN
  with physical knowledge.
- **Evaluation:**
  Error: 5.1cm (↓86%).
  Power: 43mW.

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Unify Sensing and Control for Lightweight Drones!

*These authors contributed equally to this research.
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