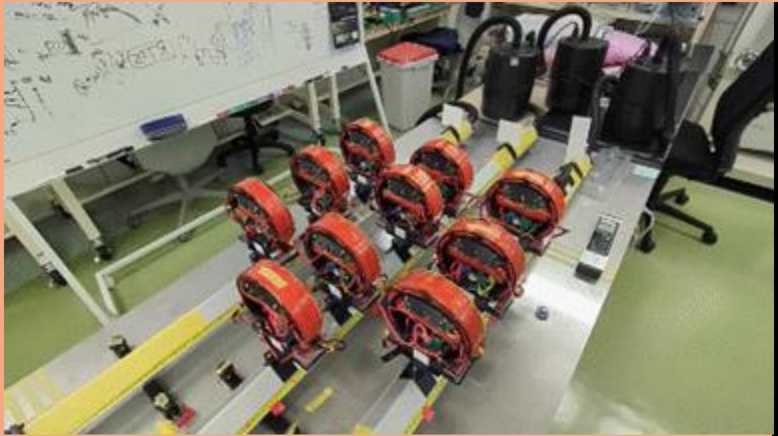
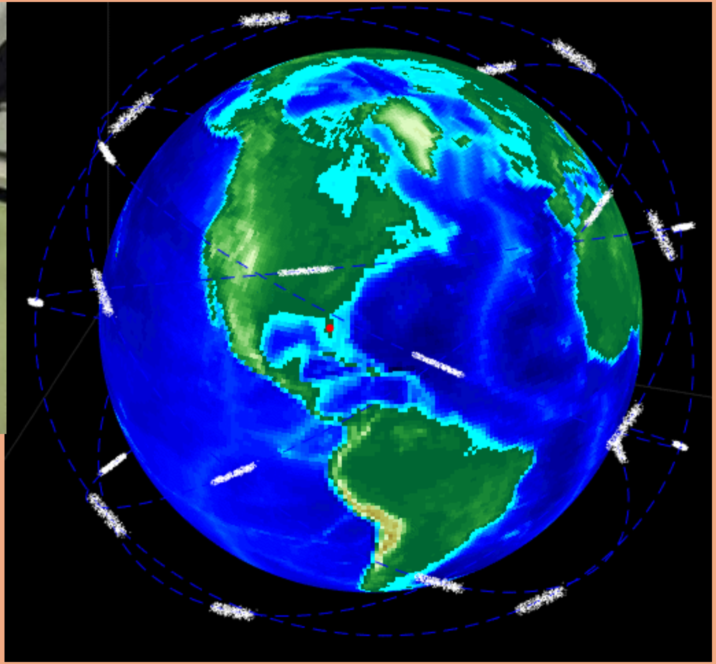
Experimental Study of Magnetically-Actuated Satellite Swarm: Controllability Extension via Time-Integrated Control with Geometry Learning





Coordinate transformation

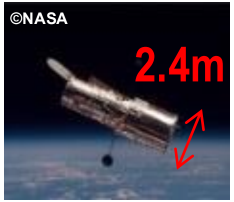
Yuta Takahashi (Institute of Science Tokyo, and Interstellar Technologies(IST)), Seang Shim, Yusuke Sawanishi, Hideki Yoshikado, Masaru Ishida, Noritsuna Imamura, Sumio Morioka (IST), Shin-ichiro Sakai (JAXA/ISAS), and Takahiro Inagawa (IST)

Background

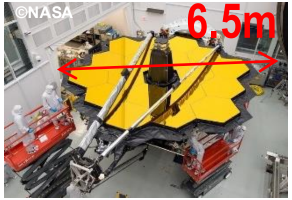
Large Space Structures for Science and Business

Array performance ∝ diameter

- Space telescopes (HST/JWST)

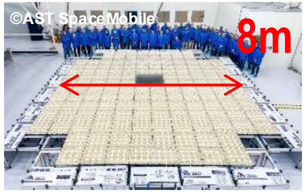


1990 → 2021



- Communication satellites (Iridium/BW3)

1997 → 2022



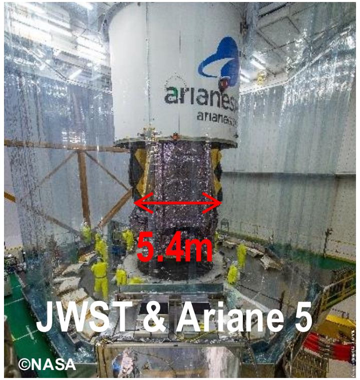
✓ Diameter grown 2-4x (30 years)

Problems

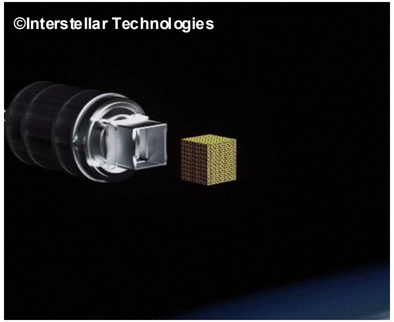
Δ Size constraints

Δ Difficulty of ground tests

Δ Single point of failure



Distributed space structure

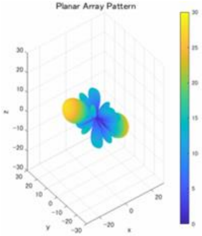


Scalability is driven by sensor progress outpacing material advancements.

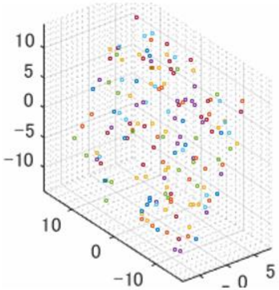
Motivation

Unstable Relative Orbital Dynamics and Magnetic Control

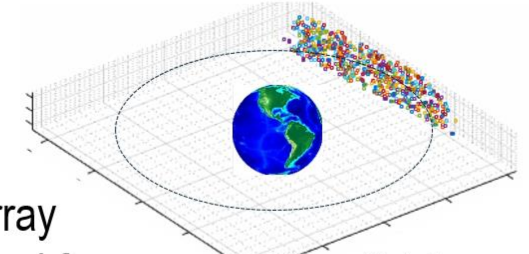
Ex) High-speed broadband communication ant.



The satellites of distributed space structure drifts without formation-keeping control.



Array fixed frame



Inertial frame

Electromagnetic formation flight [1,2,20-36]

✓ Long-term formation keeping actuation[1,2]

Prev. experiments: Position control (*N*=2)

3D experiment aboard the ISS under microgravity (Porter, A., K. et al., 2014)

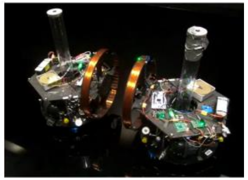
1D experiment (Sedwick, R. J. et al., 2014)

2D experiment by DC current (Kwon, D. W. et al., 2011)

2D experiment (Hariri, N. G., 2018)

AC current experiment for navigation and control (Nurge, M. Et al., 2016)

1D experiment by multi frequency AC current (Sunny, A. et al., 2019)

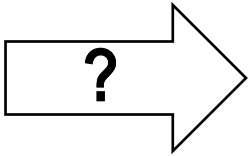


Docking experiment (Foust, R. C. et al., 2018)

[1] Yuta Takahashi, Hiraku Sakamoto, and Shin-ichiro Sakai, "Kinematics Control of Electromagnetic Formation Flight Using Angular-Momentum Conservation Constraint," AIAA JGCD, 2022.
[2] Seang Shim*, Yuta Takahashi* et al., "Feasibility Analysis of Distributed Space Antennas Using Electromagnetic Formation Flight," 2025 IEEE Aerospace Conference, * co-first.

Our Objective
Testbed Design of Magnetically-Actuated Satellite Swarm

Our objective:



Our contribution:

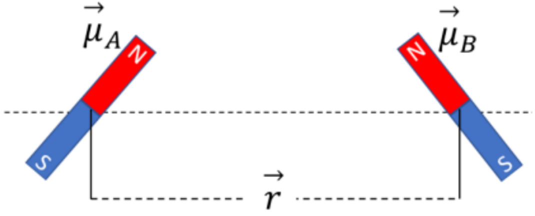
1. Survey: the challenges in magnetically formation and attitude control for N≥3 satellites
    1) Nonholonomic constraints
    2) Underactuation
    3) Scalability
    4) Computational cost

    ⇒ **Our solution: Time-Integrated Control**
2. Testbed design for proof-of-concept and evaluation criteria
3. Coil geometry learning based on the results of initial experiments

1) Survey of the challenges in formation and attitude control
Tip: Underactuation in Magnetic Control

Magnetic swarm control: △The number of constraints: 6N > The number of variable: 3N [1]

1) *N* satellite × 6-DoF control (force & torque) = constraints: 6*N*



2) *N* satellite × 3-axis magnetic coil = variable: 3*N*

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$\mathcal{OPT}_{\mathrm{DC}}$: **DC-based Optimal Dipole Allocation Problem**

$$\text{min.}\ J(\mu_{1(x,y,z)}, \dots, \mu_{n(x,y,z)}, \chi)$$

$$\text{s.t.}\ \begin{cases} \underbrace{f_{cj(x,y,z)}, \tau_{cj(x,y,z)}}_{=\text{ Command input}} = \sum_{k \neq j} \{f_{j \leftarrow k(x,y,z)}, \tau_{j \leftarrow k(x,y,z)}\} \\ = \sum_{k=1}^{3} \sum_{\substack{l=1 \\ (l \neq j)}}^{n} \sum_{m=1}^{3} \underbrace{\mu_{jk}}_{\text{Variable}} \underbrace{C_{jklm}}_{\text{Const.}} \underbrace{\mu_{lm}}_{\text{Variable}} \end{cases}$$

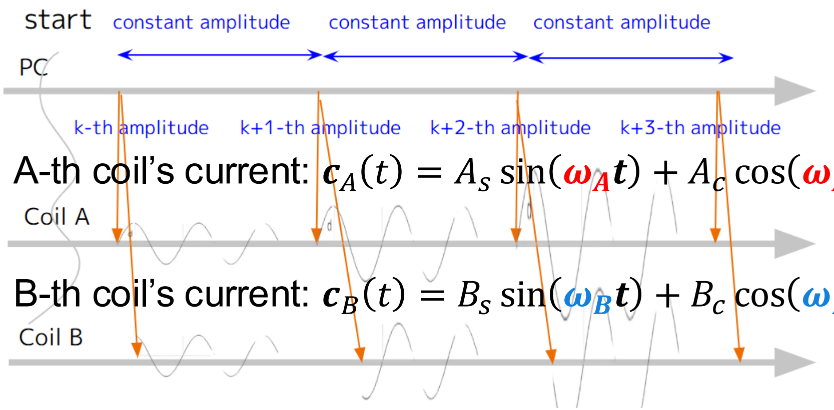
Fewer variables than constraints
→ possibly no solution

[1] Yuta Takahashi, Hiraku Sakamoto, and Shin-ichiro Sakai, "Kinematics Control of Electromagnetic Formation Flight Using Angular-Momentum Conservation Constraint," AIAA JGCD, 2022.

1) Survey of the challenges in formation and attitude control
Controllability Extension via Time-Integrated Control

Time-Integrated control [1,2,31]

- AC magnetic field of multiple frequencies



A-th coil's current: $\boldsymbol{c}_A(t) = A_s \sin(\boldsymbol{\omega_A t}) + A_c \cos(\boldsymbol{\omega_A t})$

B-th coil's current: $\boldsymbol{c}_B(t) = B_s \sin(\boldsymbol{\omega_B t}) + B_c \cos(\boldsymbol{\omega_B t})$

- Different frequency interactions → 0

$$\int_T \sin(\boldsymbol{\omega_A}\tau)\sin(\boldsymbol{\omega_B}\tau)\mathrm{d}\tau = 0$$

if $\boldsymbol{\omega_A} \neq \boldsymbol{\omega_B}$

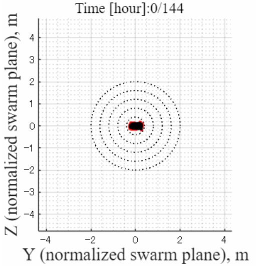
- Controllability extension on average

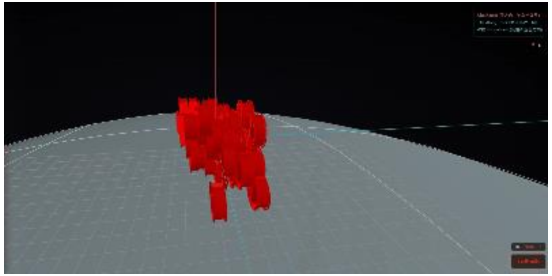
$$\int_0^T f_{A\leftarrow B}(t)\mathrm{d}\tau \approx \frac{1}{2}\left(f\left(A_s, B_s\right) + f\left(A_c, B_c\right)\right)$$

✓The num. of const. : 6N = The num. of var. : 6N

→Simultaneous control of electromagnetic force and torque on average dynamics [1]

Distance-based swarm control strategy [3]



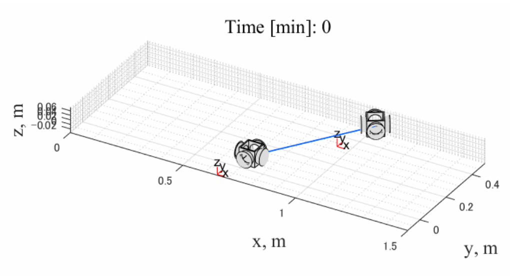


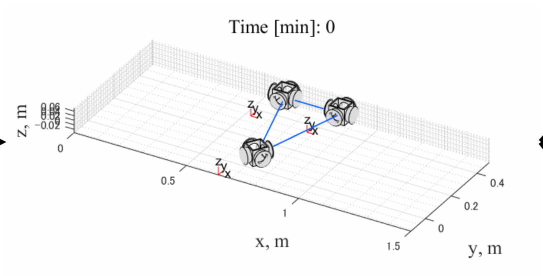
[3] Takahashi, Yuta, Seang Shim, and Shin-ichiro Sakai. "Distance-Based Relative Orbital Transition for Palm-Sized Satellite Swarm With Guaranteed Escape-Avoidance." In AIAA Scitech 2025 Forum, 2025, selected as a Finalist for the Best Student Paper Award of the GNC graduate student paper competition at the AIAA SciTech Forum 2025.

1) Survey of the challenges in formation and attitude control
Sequential Ground Experiments

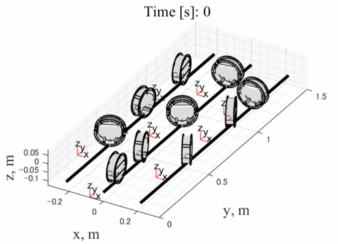
Ground experiments to verify controllability extension by time-integrated control
that enables evaluation of control accuracy under orbital formation dynamics.

2D pos. & angle control

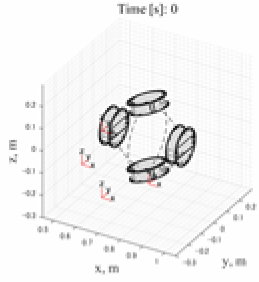




2D formation & angle control



3D formation & attitude control



2) Testbed design for proof-of-concept of Time-Integrated Control

Testbed Design for Proof-of-Concept

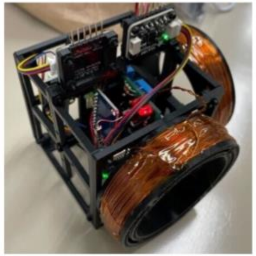
Opti. for maximizing acceleration

$$D^*_{\text{coil}}, \overline{V}^*_{\text{cir}} = \underset{D_{\text{coil}}, V_{\text{cir}} \in \mathbb{R}}{\arg\max} \; \frac{\overline{\mu}^2}{m_{\text{coil}}}$$

$$\text{s.t.} \begin{cases} m_{\text{coil}} = \dfrac{\Omega_{\text{coil}}(V, \overline{c}_{\text{wire}}, k_{\Omega/kg}, \overline{m}_{\text{coil}})}{k_{\Omega/kg}} \leq \overline{m}_{\text{coil}} \\ F(d_0) = \dfrac{1}{2}\dfrac{3\mu_0}{2\pi}\dfrac{\mu^2}{d^4} \geq a_d \\ t_{\text{coil}} \leq \dfrac{D_{\text{coil}}}{6} \end{cases}$$

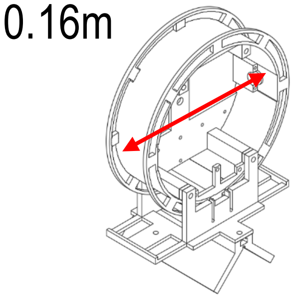
- mass, acceleration, size constraints

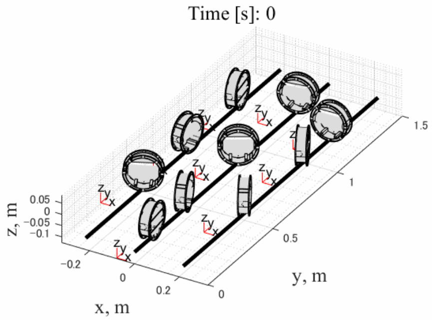
1) 1U satellite model



Linear air track: μ-gravity~1e-3N

2) 2-axis coil & time-integrated control





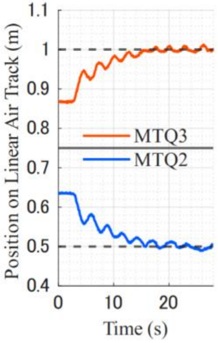
Coordinate transformation $\begin{bmatrix} e_1 \\ e_4 \end{bmatrix} \triangleq \Theta \begin{bmatrix} e_{v_e} \\ e_{p_e} \end{bmatrix}$ between orbital dynamics $\begin{bmatrix} e_1 \\ e_4 \end{bmatrix}$ and experimental dynamics $\begin{bmatrix} e_{v_e} \\ e_{p_e} \end{bmatrix}$ under closed-loop control with input u

$$u = -\frac{\beta k_A}{2}\left(k_v - \frac{\beta k_A}{2}\right) L^2 (p - p_d) - k_v L (v - v_d)$$

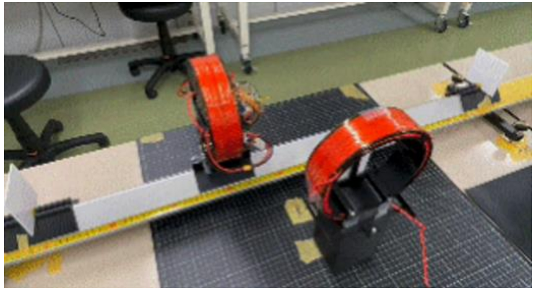
↳ Evaluation criteria

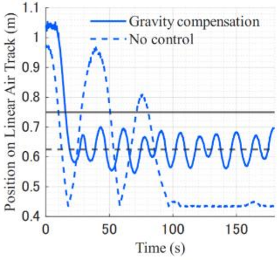
2) Testbed design for proof-of-concept of Time-Integrated Control
Testbed Design for Proof-of-Concept

1D positional control under μ-gravity



2D positional control under μ-gravity

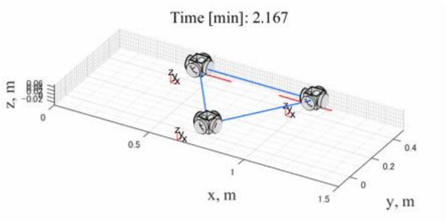




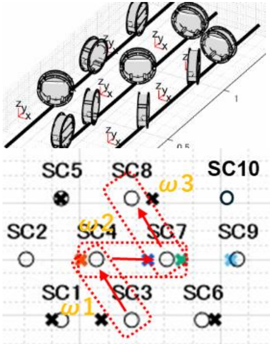
(c) Position control result.

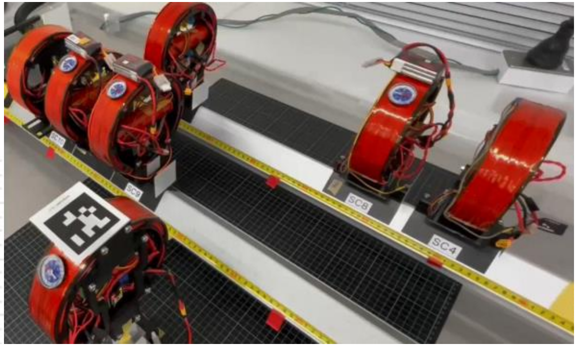
✓ On-going experiments under μ-gravity

2D pos. & angle control



2D formation & angle control

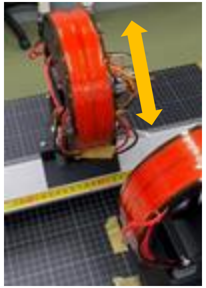




3) Coil geometry learning based on the results of initial experiments
High-Accuracy Magnetic-Field Interaction Control

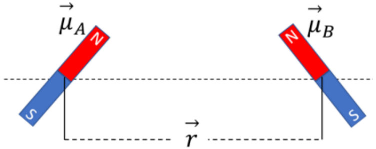
Unintended vibration due to dipole approximation error

(neglecting computationally intensive coil geometry)



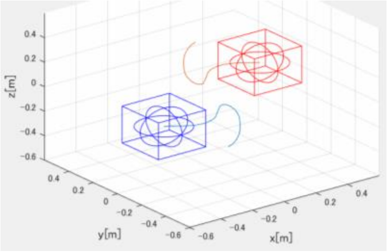
Docking simulation comparison

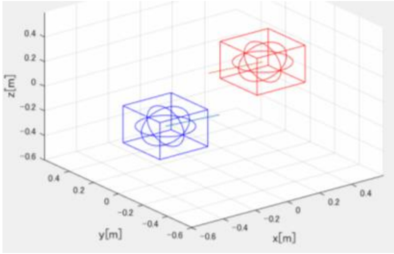
1) Dipole approximation, 2) Coil geometry-based



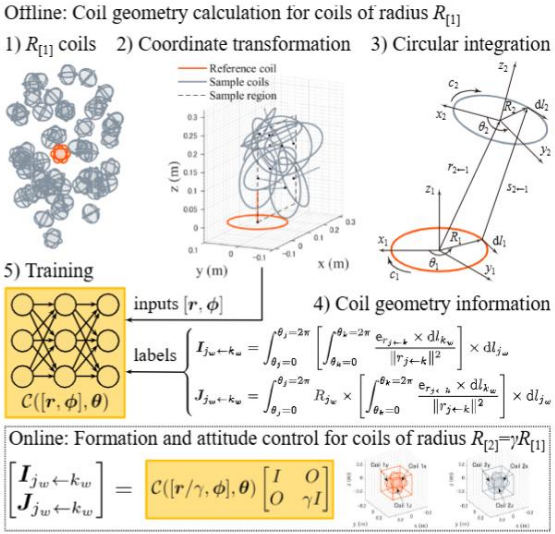
$$\begin{bmatrix} {}^a f_{j\leftarrow k} \\ {}^a \tau_{j\leftarrow k}\end{bmatrix} = \frac{\mu_0}{4\pi A^2}\begin{bmatrix} {}^a I_{j\leftarrow k_x} & {}^a I_{j\leftarrow k_y} & {}^a I_{j\leftarrow k_z} \\ {}^a J_{j\leftarrow k_x} & {}^a J_{j\leftarrow k_y} & {}^a J_{j\leftarrow k_z}\end{bmatrix} ({}^a\mu_k \otimes {}^a\mu_j)$$

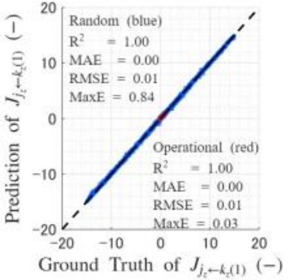
$$\begin{cases} I_{j_w\leftarrow k_w} = \displaystyle\int_{\theta_j=0}^{\theta_j=2\pi}\left[\int_{\theta_k=0}^{\theta_k=2\pi}\frac{e_{r_{j\leftarrow k}}\times dl_{k_w}}{\|r_{j\leftarrow k}\|^2}\right]\times dl_{j_w} \\ J_{j_w\leftarrow k_w} = \displaystyle\int_{\theta_j=0}^{\theta_j=2\pi} R_{j_w}\times\left[\int_{\theta_k=0}^{\theta_k=2\pi}\frac{e_{r_{j\leftarrow k}}\times dl_{k_w}}{\|r_{j\leftarrow k}\|^2}\right]\times dl_{j_w}\end{cases}$$

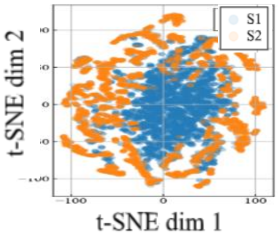




Coil Geometry Learning by MLP: 146 KB





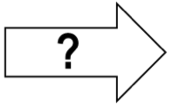


- Average calculation time: 0.36 s → 0.03s
- Standard deviation: 0.53 s → 0.01 s (**stable**)

✓ High-accuracy magnetic-field control

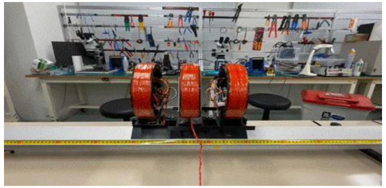
Research Objective and Presentation Summary

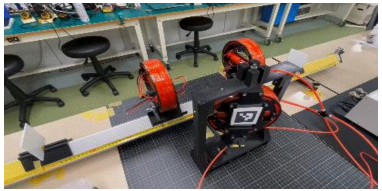
Our objective: magnetically formation and attitude control for $N \geq 3$ satellites

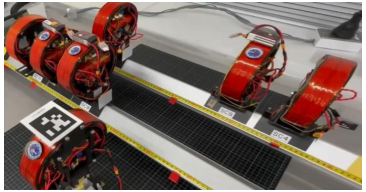


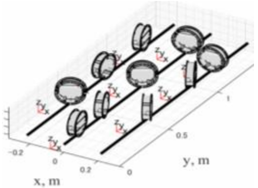
Our contribution:

1. Survey of the challenges and solution
   1) Challenges: Nonholonomic constraints, Underactuation, Scalability, Computational cost
   2) Solution: Time-integrated control
2. Testbed design for time-integrated control and evaluation criteria

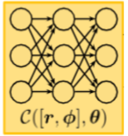








3. Coil geometry learning based on the results of initial experiments



Reference

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[2] Takahashi, Y., "Study on Guidance and Control of Large-Scale Electromagnetic Formation Flight," Master's Thesis, Tokyo Institute of Technology, Tokyo, 2021.
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Thank you for your time and attention!