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2023 年度　永守財団　研究助成　研究報告書

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1. 研究題目

Glocal Motion Control for Multi-rotor Flying Vehicles
マルチローターのグローカル運動制御

2. 研究目的

Scientific purpose: This study proposes a novel framework to design and analyze the motion control methods for multi-rotor flying vehicles to simultaneously attain several global and local performances, and robustly operate under strict conditions, such as unknown disturbance, actuator fault, sensor delay, and the reduction of energy in long time operation.

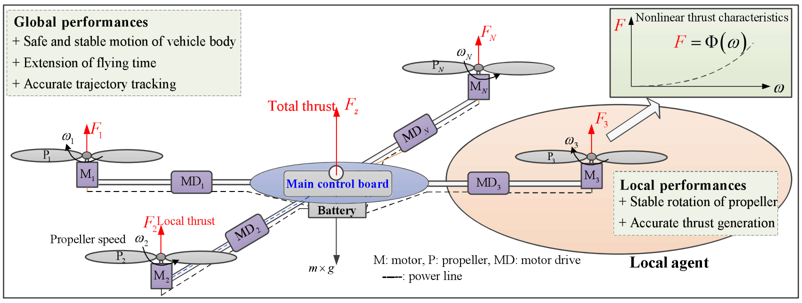


Fig. 1.　Multi-rotor as a global/local multi-agent system.

Education purpose: This study is to develop a set of several multi-rotor-systems for the motion control education at both undergraduate and graduate levels, to promote the students' experimental skill and their understanding on advanced control theory.

科学的目的:本研究は、将来の空飛ぶクルマの時代に貢献するために、電動モータと制御工学の知見に基づいて、マルチローターのグローカル運動制御システムを開発しています。マルチローターのシステムでは、グローバルの目標もローカル目標も同時に達成することが不可欠です(図1)。例えば、機体のグローバル目標は位置・姿勢制御とエネルギー最適ですが、ローカルプロペラの目標は回転速度制御や推力制御及び故障診断です。グローバルとローカルの両方の目標を達成するため、階層分散制御システムを設計するのは一つの研究課題です。もう一つの課題は、システム解析の複雑さを軽減するための実践的なアプローチを提案したいと考えています。

教育目的:本研究は、学生の実験スキルと高度な制御理論の理解を促進するために、学部レベルおよび大学院レベルのモーション制御教育用のマルチローターのテストベンチを開発しています。

3. 研究内容及び成果

3.1. Problem statement (問題設定)

This study is to examine a fairly general framework to design hierarchically decentralized disturbance observer (HD-DOB) for multi-rotor systems. The system consists of a global DOB based controller (DOBC) which controls the global motion of the multi-rotor body, and a bunch of local DOBCs which control the rotational motions of the propellers [1]. It is expected that the HD-DOB effectively rejects both global and local disturbances and model uncertainties, thereby enhancing the motion control performance. With respect to the high dimension of the multi-rotor system, we aim at strategy that alleviates the burden of controller design.

3.2. Testbench (テストベンチ)

The testbench was placed at the wind tunnel room at Hongo Campus of the University of Tokyo (Fig. 2). The wind tunnel can blow the wind at 20 m/s. In this test, the pitch motion is locked, and we only considered the yaw motion. The global objective is yaw angle control, and the local objective is propeller speed control. Each propeller is installed with a motor drive and an encoder. The yaw angle and yaw-rate are measured by the yaw axis encoder and inertial measurement unit. Using the QUARC platform provided by Quanser, the control system is implemented in Matlab/Simulink.

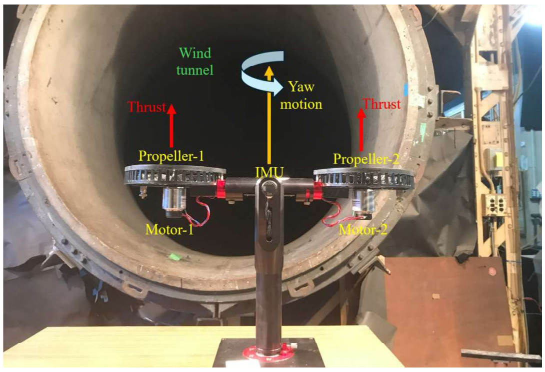


Fig. 2. Testbench system with wind tunnel.

3.3. Research content (研究の内容)

This study presents a systematic approach to design the HD-DOB control system in Fig. 3. The role-sharing between the global controller $\{C_g, Q_g, P_{gn}\}$ and local controller $\{C_{l,i}, Q_{l,i}, P_{ln,i}\}$ is introduced via a "global/local shared model set" which should be taken in both layers [1]. Consequently, we setup a two-stage-procedure that allows the controllers to be designed separately via standard robust control problem.

Stage 1: Select a nominal model P_o with volume δ_o.

Stage 2-L: For each local subsystem, $\{C_{l,i}, Q_{l,i}, P_{ln,i}\}$ is designed to: (i) maximize the local performance, (ii) guarantee that the multiplicative error between the local subsystem and P_o is norm bounded by δ_o.

Stage 2-G: $\{C_g, Q_g, P_{gn}\}$ is designed to maximize the global performance. To perform this optimization, the transfer function of the lower-layer from r_g to v_g is normalized to be P_o with perturbation bounded by δ_o.

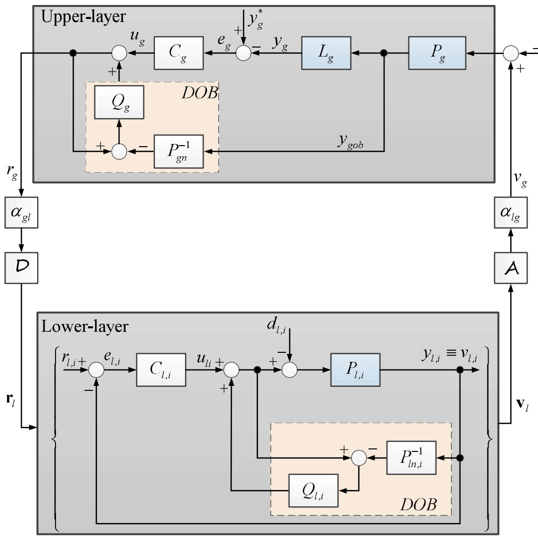


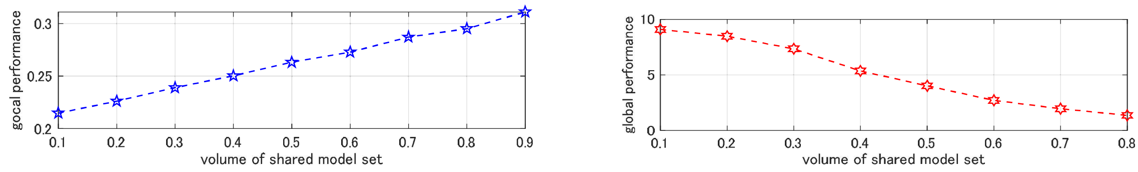
Fig. 3. HD-DOB control system.

Using the above procedure, we designed the HD-DOB to control the yaw angle of the testbench. Notably, the design burden is independent of the number of propeller actuators. Furthermore, the trade-off between the global performance (yaw angle control) and local performance (propeller speed control) can be theoretically and numerically analyzed via the volume δ_o (Fig. 4). Increasing δ_o is to reduce the global performance but increase the local performance. Therefore, selecting a "medium" δ_o is an idea to compromise the trade-off.

As shown in Fig. 5, experiments were conducted with different control methods. The wind tunnel introduced a strong wind of 10 m/s. From 20 seconds, the system suffered software disturbances to the motor drives. Test results showed that the HD-DOB (Method 4) successfully reduced the yaw angle tracking error. The RMSE of yaw angle tracking was reduced by 33% in comparison with the conventional control system that only utilized DOB in the upper-layer (Method 2).

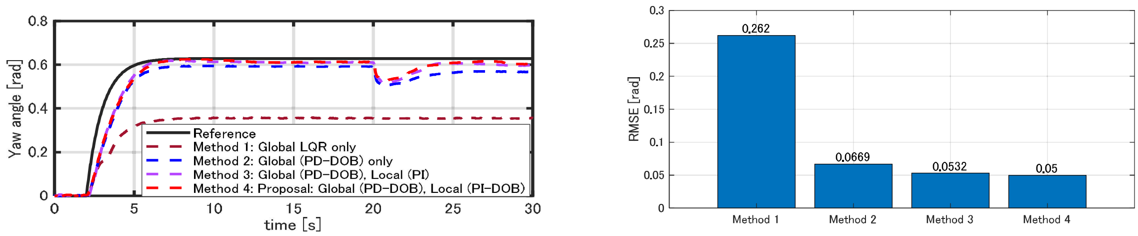
3.4. Joint research activities (共同研究)

We conducted joint with researchers at Ilmenau University of Technology (Germany) on the collaboration between electric vehicle and drones. The result has been under review at an academic journal [2]. Other international



(a) Local performance index.　　(b) Global performance index.

Fig. 4.　Trade-off between global and local control performance of the testbench.



(a) Experimental results.　　(b) Root-mean-square-deviation (RMSE) comparison.

Fig. 5.　Yaw angle control under strong wind (10 m/s) and software disturbance from 20 seconds.

collaborations with researchers worldwide were reported in our recent article [3].

3.5. Education activities (教育活動)

At e-Mobility & Control Lab (The University of Tokyo), the educational activities were conducted in many ways: theoretical discussion, technical support, experiment supervision, academic paper writing and submission [5], [6], [9]. The testbench has been used to support a PhD student at Centre Automatique et Systém of Mines Paris (France) to study unknown input disturbance observer. The outcome of this study will be published in 2025.

4. 今後の研究の見通し

In the next step we consider the following objectives:

(1) Theoretical development: We extend the HD-DOBC to control both the yaw and pitch motion of the testbench. The result will be further extended to the full motion control system of the real multi-rotors. Besides, we are pursuing the unified glocal control framework for multi-actuator systems [4], [7], [8].

(2) Application development: We will complete the basic study on how to implement the multi-rotor control system using Pixhawk flight controller. Especially, we focus on how to generate the control algorithm from Matlab/Simulink to reduce the burden of system implementation. Besides, the communication between the electric vehicle and multi-rotor will be realized.

5. 助成研究による主な発表論文，著書名

[1] **B.-M. Nguyen**, S. Hara, H. Fujimoto: "Disturbance Observer Based Global/Local Control using Shared Model Set: Design Concept with Practical Application to Multi-rotors," IEEJ Journal of Industry Applications (2024, To be Accepted After Minor Revision).

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[3] **B.-M. Nguyen**, J. P. Trovao: "Advancing Automotive Electronics: The Role of Collaborative Education and Project Development," IEEE Vehicular Technology Magazine, Vol. 19, Iss. 3, pp. 116-127, doi: 10.1109/MVT.2024.3414068 (2024).

[4] **B.-M. Nguyen**: "Disturbance Observer Based Control for Passive Multi-Actuator Systems with Aggregation and Distribution," Asian Journal of Control, Vol. 26, Iss. 5, pp. 2308-2323, doi: 10.1002/asjc.3333 (2024).

[5] T. Ueno, **B.-M. Nguyen**, S. Nagai, H. Fujimoto: "Wheel Velocity Based Cascade Driving Force Control for Electric Vehicles," IEEE/ASME Transactions on Mechatronics, doi: 10.1109/TMECH.2024.3456151 (2024).

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[9] 藤本浩太，永井栄寿，**阮平明**，藤本博志："ドローンへの飛行中給電のための地面効果領域におけるモータ電流を用いた姿勢推定のベンチ検証，" 2024年電気学会産業応用部門大会，水戸 （2024）.