2022 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:
"Development of multi-motor test-bench for motion control education and research"

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 (Fig. 1) 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.

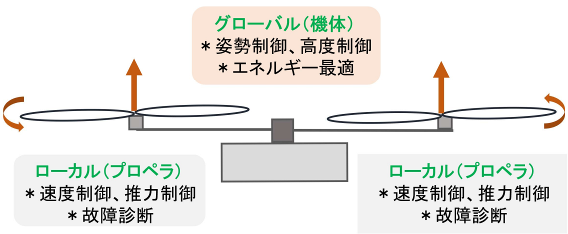


Fig. 1.　Multi-rotor as a global/local multi-agent system.

Education purpose: This study develops a multi-motor testbench 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 setting of the theoretical framework (制御理論のフレームワークの問題設定)

We show that, although the multi-rotor flying vehicle dynamics is quite complex, it can be generally modeled as a multi-agent system, as can be seen in Fig. 2. Especially, the local actuator dynamics and the body dynamics physically interact via the aggregation and distribution. Thanks to this model, we can develop various control approaches in a hierarchically decentralized way. In addition, we can provide several methodologies to analyze and design the system.

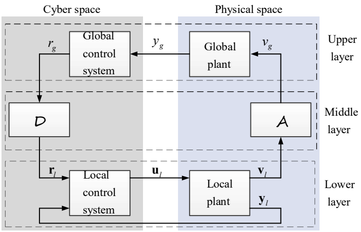


Fig. 2. General model of multi-rotors.

Fig. 3. Test-bench.

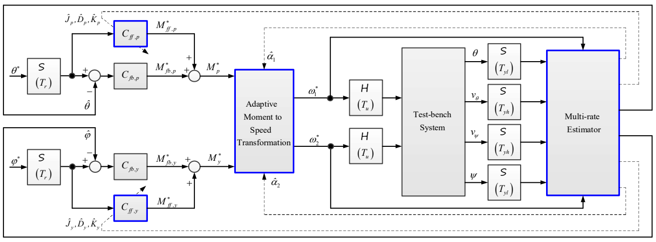


Fig. 4. Multirate altitude control system of dual-propeller testbench.

3.2. Test-bench system (テストベンチシステム)

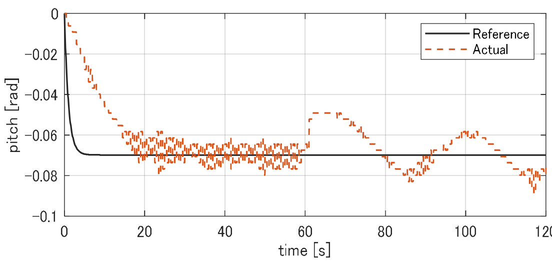
To evaluate the proposed theory and methodologies, we have utilized the dual-propeller test bench shown in Fig. 3. The test-bench was installed with encoders to measure the rotational speeds of the propellers, motor current sensors, inertia measurement unit, and the encoders to obtain the attitude angles of the test-bench. By using the QUARC platform provided by Quanser, the control system is implemented conveniently in Matlab/Simulink. Remarkably, the position of the propeller can be adjustable. This allows the test-bench to imitate the motion of drones and helicopters. The students can use test-bench to study various control engineering methods, such as state observer, Kalman filter, pole-placement based controller design, linear quadratic regulator, disturbance observer and other robust control techniques.

3.3. Research content (研究の内容)

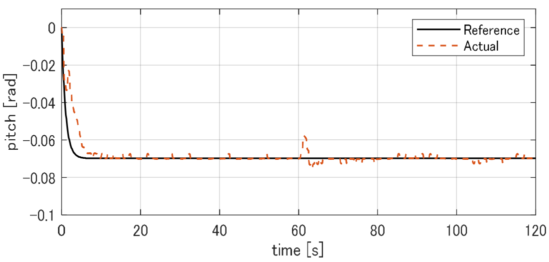
① With respect to the aggregation and distribution in the control system, we proposed a control configuration to integrate the energy management and motion control for multi-motor system. In addition, passivity theory was utilized to reduce the burden in system stability analysis. The method has been applied to on-road electric vehicle to optimize the energy consumption even if the vehicle runs on the low friction surface [1]. Its application to flying vehicle will be examined in the future.

② We investigated the landing control system of the flying vehicle. The control system is very complex, as it includes the vertical speed controller, and the pitch-(yaw-, roll-)rate controllers. To reduce the effort to guarantee system stability, we modelled the system as a multi-agent system in Fig. 2, and utilized a theory named "generalized frequency variable" [2].

③ We recently proposed a multirate control system to improve the altitude control of the dual-propeller test-bench. The control system includes a multirate estimator, which can provide in real-time the estimation of the pitch and yaw angles, the inertia and damping terms of the pitch and yaw dynamics, and the loss of effectiveness (LoE) of the propeller. Then, we established a two-degree-of freedom control configuration with adaptive feedforward controller and LoE



(a) Singlerate control without LoE compensation.



(b) Proposed multirate control with LoE compensation.

Fig. 5. Experimental results of pitch angle control using the propeller test-bench.

compensator, as shown in Fig. 4. As a result, attitude control performance is remarkably improved (Fig. 5). In comparison with a conventional singlerate control system without fault tolerance, the proposed system can reduce the pitch angle and yaw angle tracking errors by 69.3 % and 39.6 %, respectively [3].

3.4. Joint research activities (共同研究)

We also conducted joint-research with the colleagues from the other countries. Recently, we worked with Dr. Thach Ngoc Dinh, who is an Associate Professor with Conservatoire National des Arts et Métiers (France) to propose a Functional Interval Observer for Discrete-Time Nonlinear Lipschitz Systems. The work was presented at IFAC World Congress 2023 [4]. The application of this theoretical result in multi-motor systems will be investigated in future study.

3.5. Educational activities (教育活動)

We frequently discussed with the students at e-Mobility and Control Lab (The University of Tokyo). The discussions range from theoretical issues to technical issues and experimental issues. Some of the students' works on drone control have been presented at the international conferences [5], [6]. Besides, by using the dual-propeller test-bench, we support Master student at Toyota Technological Institute to conduct research on fault detection for drones (拡張カルマンフィルタによるドローンのプロペラ故障検知).

4. 今後の研究の見通し

In the next step, we focus on the following two objectives: First, we plan to develop a drone which is driven by six propellers (hexarotor). This experimental system is to evaluate the control methods which have been proposed and developed using the test-bench. Second, we deal with hierarchically decentralized configuration for disturbance-observer-based control of large-scaled dynamical systems. In particular, we examine the systems in Fig. 2, with the aggregation in the physical space, and the distribution in the cyber space. To reduce the complexity of system design and analysis, our main idea is to clarify the role-sharing of the global and local controllers via a "Global/Local Shared Model Set," which should be taken in both the global and local sides. We setup a fairly general framework and derive the global and local control problems based on μ-synthesis. The effectiveness of the proposed approach is demonstrated via the yaw motion control of a dual-propeller system with experimental verification.

5. 助成研究による主な発表論文，著書名

学術論文(査読付)

[1] B. -M. Nguyen, J. P. F. Trovão and M. C. Ta, "Double-Layer Energy Management for Multi-Motor Electric Vehicles," IEEE Transactions on Vehicular Technology, Vol. 72, No. 7, pp. 8623-8635, July 2023.

国際会議(査読付)

[2] B. -M. Nguyen, S. Nagai and H. Fujimoto, "Multirate Attitude Control of Dual-Rotor System Considering Propeller Loss of Effectiveness," 49th Annual Conference of the IEEE Industrial Electronics Society, 2023.

[3] B. -M. Nguyen, S. Hara and V. P. Tran, "A Multi-Agent Approach to Landing Speed Control with Angular Rate Stabilization for Multirotors," IEEE Vehicle Power and Propulsion Conference, 2022.

[4] T. -N. Dinh, B. -M. Nguyen, F. Zhu and T. Raïssi, "Functional Interval Observer for Discrete-Time Nonlinear Lipschitz Systems, IFAC-Papers On Line,Vol. 56, Iss. 2, pp. 8476-8481, 2023.

[5] K. Fujimoto, S. Nagai, B. -M. Nguyen and H. Fujimoto, "Test Bench Study on Attitude Estimation in Ground Effect Region Based on Motor Current for In-Flight Inductive Power Transfer of Drones," 49th Annual Conference of the IEEE Industrial Electronics Society, 2023.

[6] Y. Satoh, K. Fujimoto, R. Matsumoto, B. -M. Nguyen, S. Nagai and H. Fujimoto, "Basic Study on Received Power Control of In-Flight Inductive Power Transfer for Drones by Active Rectifier Switching and Altitude Regulation," 49th Annual Conference of the IEEE Industrial Electronics Society, 2023.