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科研費 KAKENHI

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研究課題名（和文）Glocal Motion Control for Multi-rotor Flying Vehicles

研究課題名（英文）Glocal Motion Control for Multi-rotor Flying Vehicles

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交付決定額（研究期間全体）：（直接経費）　　1,800,000円

研究成果の概要（和文）：本研究は、マルチローター(MRFV)のグローカル運動制御の基礎を開発する。MRFV をマルチエージェントシステムとしてモデル化し、各プロペラが機体を経由して物理的相互作用を示すのに対して、ロバストフォールトトレラント制御を研究している。一般化周波数変数理論を用いて着陸制御システムの安定性条件を提案した。非線形的な推力特性を考慮した絶対安定解析によりロバスト高度制御システムを実現した。ノミナルモデル集合に基づくグローバル性能（姿勢制御）とローカル性能（プロペラ速度制御）のトレードオフを検討した。提案手法検証及び高度な運動制御教育のために、デュアルプロペラテストベンチを開発した。

研究成果の学術的意義や社会的意義
This research can be seen as a transdisciplinary study that establishes a bridge between multi-agent control theory and motion control of multi-rotor.
Besides, it contributes a brick to the development of flying vehicle society, international collaboration, and education in Japan.

研究成果の概要（英文）：This study has been established the background for glocal motion control of multi-rotor flying vehicles (MRFVs). This study shows that to properly design the controller, the MRFV should be modelled as a multi-agent system, in which each propeller physically interacts with each other via the MRFV body. Based on this philosophy, several approaches have been developed with disturbance observer and fault tolerant control. A generalized frequency variable approach was proposed to guarantee the stability of the landing control system. A robust altitude control system was designed with absolute stability analysis considering the nonlinear thrust characteristic. The trade-off between the global performance (attitude control) and local performance (propeller speed control) was clarified based on a nominal model set to be shared between the upper- and lower-layers. A dual-propeller test-bench was developed for not only proposed method validation but also advanced motion control education.

研究分野：制御およびシステム工学関連

キーワード：glocal control　multi-rotor　multi-agent-system　altitude control　attitude control　disturbance observer　loss of effectiveness　hierarchical control

１．研究開始当初の背景

Flying vehicles (FVs) have always been a dream for research and commercialization. In recent years, this concept is expected to speed up a mobility revolution by covering the gap between aircrafts and on-road vehicles. In Japan, the Ministry of Economy, Trade, and Industry has proposed the road map towards FV in 2030s. FV has various advantages and merits for the society. It reduces the cost to develop infrastructure such as tunnels through the mountains. It reduces the traffic jam and hence, improving the social welfare. It makes the travel to be seamless, since the requirement to change the means of transportation is reduced.　As can be seen from Fig. 1, FVs are multi-rotor mechatronics systems with the capability of vertical take-off and landing.

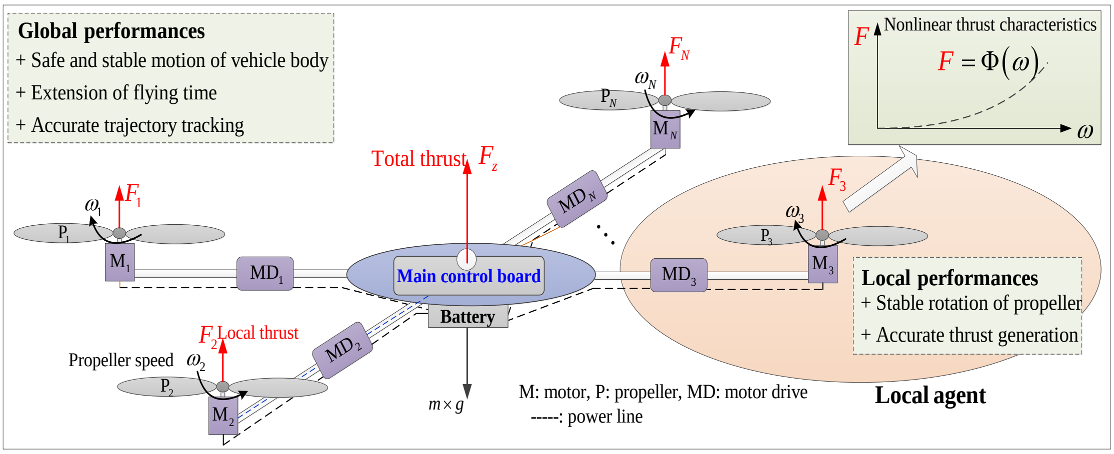

Figure 1. Multi-rotor flying vehicle as a multi-agent system.

As shown in Fig. 1, MFV is actually a multi-agent system (MAS), in which each agent is a locally controlled propeller. The agents physically interact with each other to generate the global motion of the vehicle body. Note that, the thrust force has a nonlinear relationship with the rotational speed of the propeller. In addition, the propeller thrust has a certain saturation value. In long-term operation, this value reduces in accordance with the battery voltage, which depends on the battery state-of-charge. It turns out that: First, controlling MFV is to control a complex MAS with physical interaction and nonlinearity. Moreover, MFV always suffers unknown disturbances, actuator faults and time-delay in sensor measurements. Consequently, stabilization of MFV control system is a theoretical challenge. Second, controlling MFV is to simultaneously attain several global performances and several local performances. For instance, the global performance is to maintain the accurate trajectory tracking, while the local performance is to guarantee accurate thrust generation.

２．研究の目的

Studies on MFVs, including drones and unmanned aerial vehicles (UAVs), has been conducted by researcher worldwide [R1]. However, almost the previous works neglected the propeller actuators and their interaction. For instance, Lyu et al. applied a robust control tool, namely disturbance observer (DOB) to hovering control of UAV [R2]. Unfortunately, they merely treated the MFV as a mass point moving in the three-dimensional Euclidean space, and the nonlinearity are treated as norm-bounded perturbation. Recently, Tran et al. introduced negative imaginary theory to position control of drones [R3]. To utilize the theory, it is required to obtain nominal transfer function of the drone dynamics via parametric identification. As pointed out by Sariyildiz et al. [R4], the aforementioned approaches, which do not capture the real nonlinear dynamics of the controlled plant, cannot guarantee system stability rigorously. To the best of the applicant’s knowledge, there is still a lack of theoretical results and motion control approaches to deal with the complex MAS in Fig. 1.

With respect to the above discussion, this study is to propose a novel framework to design and analyze the motion control methods for multi-rotor flying vehicles (MFVs) 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 source’ voltage in long time operation.

３．研究の方法

The research methodology of this study can be summarized as follows:

Research questions: With respect to the complexity of the MFV dynamics, it is necessary to consider the following questions. First, how to rigorously guarantee the stability and robust stability of the control system by a practical procedure? Second, does the trade-off exist between the *global* and *local* performances?

Modeling: The MFV is modelled as a multi-agent system, in which each local agent is a locally controlled propeller. This model is named “global/local model,” as it can describes both the global behavior of the MFV body dynamics, and the local behavior of the propeller dynamics.

Control design and system analysis: This study utilizes the robust control techniques to design the controller. Disturbance observer is used to deal with the external disturbances, including the global disturbance to the MFV body and local disturbance to the propeller. Besides, multi-rate state observer is used to implement state estimation by the fusion of different sensors (GPS, onboard vision system, inertia measurement unit). The control system is designed with the hierarchical decentralized configuration, including the upper-layer controller to attain the global objective, and lower-layer controller to attain the local objective of the propeller. The system is analyzed in term of robust stability performance. Besides, this study performs absolute stability analysis with respect to some nonlinearities in the MFV dynamics, especially the nonlinear characteristics of the relationship between propeller thrust and propeller speed.

Validation: The proposed methods are evaluated by both simulation and experiment. To this end, the simulator that captures the global/local behavior and nonlinearity of the MFV is established. For the sake of safety, a multi-rotor-test-bench is developed to perform the control algorithms. The wind tunnel is utilized to imitate the strong disturbance in real operation scenario.

４．研究成果

This research can be seen as a transdisciplinary study that establishes a bridge between multi-agent control theory and motion control of multi-rotor. Besides, it contributes a brick to the development of flying vehicle society, international collaboration, and education in Japan. The main achievements are summarized as follows.

Scientific contribution: This study has been established the background for glocal motion control of MFVs. This study shows that to properly design the controller, the MRFV should be modelled as a multi-agent system, in which each propeller physically interacts with each other via the MRFV body. Based on this philosophy, several approaches have been developed with disturbance observer and fault tolerant

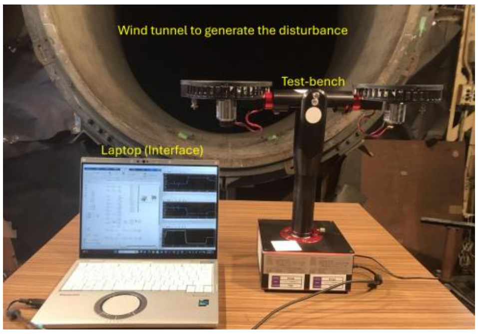

Figure 2. Propeller test-bench developed under the project.

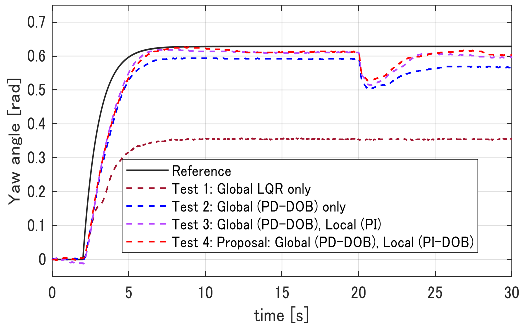

Figure3. Experimental results obtained by the test-bench.

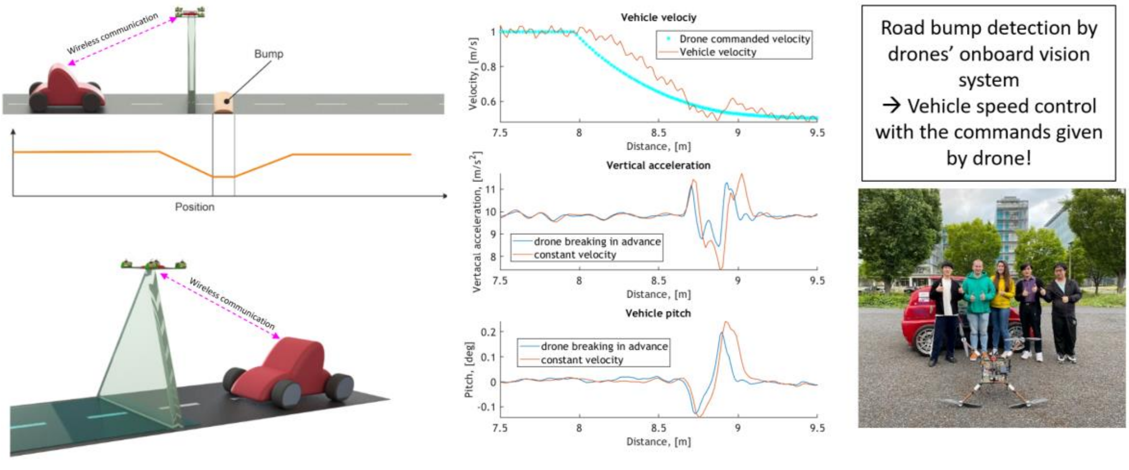

Figure 4. International education-research collaboration (Drone-to-vehicle data integration for enhancing vehicle motion control).

control [1]. A generalized frequency variable approach was proposed to guarantee the stability of the landing control system [3]. A robust altitude control system was designed with absolute stability analysis considering the nonlinear thrust characteristic [2]. The trade-off between the global performance (attitude control) and local performance (propeller speed control) was clarified based on a nominal model set to be shared between the upper- and lower-layers. A dual-propeller test-bench was developed for not only proposed method validation but also advanced motion control education (see Fig. 2 and Fig. 3).

International collaboration: The project investigator conducted joint study with the researchers from Technical University of Ilmenau (Germany) to develop a drone-to-vehicle data integration to enhance vehicle motion control by accurately estimating the road condition. The joint study is a project under the support of the OWHEEL project (Marie Sklodowska-Curie Actions RISE) (see Fig. 4 and [6]). Besides, another joint-study was conducted with the researcher from Conservatoire National des Arts et Métiers (CNAM, France) to develop a state observer for nonlinear systems [7]. The application of the state observer to drone and multi-rotor has been considered as a future work.

Education: The project investigator has participated into the supervising and teaching of the students at Toyota Technological Institute and The University of Tokyo. The investigator has advised some students to do research on multi-rotor motion control ([8], [9], [10]) as well as multi-motor vehicle motion control ([11], [12]). Especially, the absolute stability analysis, which was originally developed for altitude control of multi-rotor [2], has been extended to driving force control of in-wheel-motor vehicle [11]. The multi-rate Kalman filter developed for drone position control [10] was also utilized for electric vehicle position control [12].

Main publications of this study:

[1] B.-M. Nguyen, "Disturbance Observer Based Control for Passive Multi-actuator Systems with Aggregation and Distribution," Asian Journal of Control (2024) [DOI: https://doi.org/10.1002/asjc.3333].

[2] B.-M. Nguyen, T. Kobayashi, K. Sekitani, M. Michihiro, and T. Narikiyo, "Altitude Control of Quadcopter Flying Vehicles with Absolute Stability Analysis," IEEJ Transactions on Industry Applications, Vol. 11, No. 4 (2022).

[3] B-M. Nguyen, S. Nagai, and H. Fujimoto, "Multi-rate Attitude Control of Dual-rotor System Considering Propeller Loss of Effectiveness", 49th Annual Conference of the IEEE Industrial Electronics Society (2023).

[4] 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).

Related study on multi-motor vehicles

[5] 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 (2023).

International collaboration

[6] B.-M. Nguyen, "Multi-Actuated Electrical Vehicle Control," OWHEEL International Workshop on Modelling, Control, Navigation of Electrical Multi-Actuated Vehicles," UTC, France (2024).

[7] T.-N. Dinh, B.-M. Nguyen, F. Zhu, and T. Raissi, "Functional Interval Observer for Discrete-Time Nonlinear Lipschitz Systems," IFAC Paper Online, Vol. 56, Iss. 2, pp. 8476-8481 (2023).

Education

[8] Y. Sato, 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).

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５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　3件／うち国際共著　2件／うちオープンアクセス　0件）

１．著者名 Nguyen Binh-Minh	４．巻 Early Access
２．論文標題 Disturbance observer based control for passive multi‐actuator systems with aggregation and distribution	５．発行年 2024年
３．雑誌名 Asian Journal of Control	６．最初と最後の頁 1~16
掲載論文のDOI（デジタルオブジェクト識別子） 10.1002/asjc.3333	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Nguyen Binh-Minh、Kobayashi Tetsuya、Sekitani Kazuhiro、Kawanishi Michihiro、Narikiyo Tatsuo	４．巻 11
２．論文標題 Altitude Control of Quadcopters with Absolute Stability Analysis	５．発行年 2022年
３．雑誌名 IEEJ Journal of Industry Applications	６．最初と最後の頁 562～572
掲載論文のDOI（デジタルオブジェクト識別子） 10.1541/ieejjia.21010314	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

１．著者名 Nguyen Binh-Minh、Trovao Joao Pedro F.、Ta Cao-Minh	４．巻 72
２．論文標題 Double-Layer Energy Management for Multi-Motor Electric Vehicles	５．発行年 2023年
３．雑誌名 IEEE Transactions on Vehicular Technology	６．最初と最後の頁 8623～8635
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TVT.2023.3244808	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計9件（うち招待講演　1件／うち国際学会　9件）

１．発表者名 Nguyen Binh-Minh, Hara Shinji, Tran Vu Phi
２．発表標題 A Multi-Agent Approach to Landing Speed Control with Angular Rate Stabilization for Multirotors
３．学会等名 2022 IEEE Vehicle Power and Propulsion Conference (VPPC)（国際学会）
４．発表年 2022年

1．発表者名
Nguyen Binh-Minh, Nagai Sakahisa, Fujimoto Hiroshi

2．発表標題
Multirate Attitude Control of Dual-Rotor System Considering Propeller Loss of Effectiveness

3．学会等名
IECON 2023- 49th Annual Conference of the IEEE Industrial Electronics Society（国際学会）

4．発表年
2023年

1．発表者名
Nguyen Binh-Minh

2．発表標題
Multi-Actuated Electrical Vehicle Control

3．学会等名
OWHEEL International Workshop on Modelling, Control, Navigation of Electrical Multi-Actuated Vehicles（招待講演）（国際学会）

4．発表年
2023年

1．発表者名
Dinh Thach Ngoc, Nguyen Binh-Minh, Zhu Fanglai, Raissi Tarek

2．発表標題
Functional Interval Observer for Discrete-Time Nonlinear Lipschitz Systems

3．学会等名
22nd World Congress of the International Federation of Automatic Control (IFAC)（国際学会）

4．発表年
2023年

1．発表者名
Yoshimura Kazuma, Nguyen Binh-Minh, Fujimoto Hiroshi, Kawanishi Michihiro, Narikiyo Tatsuo

2．発表標題
Dual-Rate Altitude Control of Drones Based on Double-Layer Kalman Filter

3．学会等名
8th IEEJ international workshop on Sensing, Actuation, Motion Control, and Optimization (SAMCON2022)（国際学会）

4．発表年
2022年

1．発表者名 Satoh Yusuke, Fujimoto Kota, Matsumoto Ryo, Nguyen Binh-Minh, Nagai Sakahisa, Fujimoto Hiroshi
2．発表標題 Basic Study on Received Power Control of In-Flight Inductive Power Transfer for Drones by Active Rectifier Switching and Altitude Regulation
3．学会等名 IECON 2023- 49th Annual Conference of the IEEE Industrial Electronics Society（国際学会）
4．発表年 2023年

1．発表者名 Fujimoto Kota, Nagai Sakahisa, Nguyen Binh-Minh, Fujimoto Hiroshi
2．発表標題 Test Bench Study on Attitude Estimation in Ground Effect Region Based on Motor Current for In-Flight Inductive Power Transfer of Drones
3．学会等名 IECON 2023- 49th Annual Conference of the IEEE Industrial Electronics Society（国際学会）
4．発表年 2023年

1．発表者名 Ueno Takumi, Nguyen Binh-Minh Nagai Sakahisa, Fujimoto Hiroshi
2．発表標題 Driving Force Control for In-Wheel Motor Electric Vehicles with Wheel Speed Limiter and Absolute Stability Analysis
3．学会等名 IECON 2023- 49th Annual Conference of the IEEE Industrial Electronics Society（国際学会）
4．発表年 2023年

1．発表者名 Koishi Tomoaki, Nguyen Binh-Minh, Shimizu Osamu, Yamada Shota, Fujimoto Hiroshi
2．発表標題 Lateral Misalignment and Yaw Angle Control Considering Vehicle Dynamics Based on Receiving Energy in Dynamic Wireless Power Transfer
3．学会等名 22nd World Congress of the International Federation of Automatic Control (IFAC)（国際学会）
4．発表年 2023年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計5件

国際研究集会	開催年
39th Vietnam Power Electronics Community Webinar: On the Prospects of EV	2023年～2023年
国際研究集会	開催年
Vietnamese Control Systems and Robotics Group: Young Talents Seminars	2023年～2023年
国際研究集会	開催年
Vietnamese Control Systems and Robotics Groups Workshop	2022年～2022年
国際研究集会	開催年
Vietnamese Academic Network in Japan Conference	2022年～2022年
国際研究集会	開催年
OWHEEL International Workshop on Modelling, Control, Navigation of Electrical Multi-Actuated Vehicles	2023年～2023年

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関