Multi-UAV scalable platform for heavy load transportation

○ Pongsakorn SONGSUROJ, Student Member, Tohoku University, songsuroj.pongsakorn@rm.is.tohoku.ac.jp
Yoshito OKADA, RIKEN AIP, Tohoku University, okada@rm.is.tohoku.ac.jp
Kazunori OHNO, Member, Tohoku University, RIKEN AIP
Satoshi TADOKORO, Member, Tohoku University

In transporting a heavy load, instead of utilizing a conventional unmanned aerial vehicle (UAV), this research introduces the new scalable UAV design for lifting and transporting applications. The main concept focuses on reconfigurable control layers with multiple UAVs arranged in hierarchical order. Data transmission across layers is responsible for sending desired actuator outputs to the mixer located in the low-layer UAV units. Moreover, in this scalable UAV platform, each layer has different control methods for each unique controlling task. With several small propeller configurations, it gains flight safety, stability and mobility while achieving high thrust for heavy load lifting application.

Key Words: Unmanned Aerial Vehicle, Drone, Multicopter, Scalable UAV Platform, Heavy load lifting

1 Introduction

Recently, the popularity of unmanned aerial vehicles (UAV) has continuously increased in many sectors, not only for hobby purposes. The UAV can be mainly divided into two categories, fixed-wing, and multicopter, based on lifting mechanism. Many researchers utilize various designs of multicopter for their applications such as tricopter, quadrotor, hexacopter, and octocopter. However, in lifting and transporting applications, the main design of a multicopter can be separated into two types, a large propeller multicopter, and a small propeller multicopter. To generate the same amount of thrust, the large propeller multicopter utilizes few numbers of large propellers while the small propeller multicopter uses several numbers of small propellers. Moreover, another advantage of a small propeller over a large propeller is that it generates less torque, bringing more safety in operation.

In the paper [1], the author introduces the use of hexacopter for heavy payload lifting. Although the result shows that it is capable of reaching 15-minute flight time while carrying 15 kilograms of water, the multicopter with few propellers cannot effectively handle the unpredictable situation when some propellers are broken during flight. On the other hand, with a large number of propellers, the small propeller multicopter can act as substitutes when one stops moving.

[2] applies this concept by installing four quadrotors with 16 propellers located in different corners and connecting them with quadrotor X airframe structure in the center. This configuration achieves enough thrust for high payload lifting and proves the idea of multi-UAV integration, based on one main single airframe.

Similarly, [3] presents the same UAV configuration, distributing roll, pitch, yaw commands from the central controller to four quadrotors without modification. Transmitting the same commands continuously to different UAVs does not always provide good results. High variance in angular velocity between left-side rotors and right-side rotors of each quadrotor unit can cause instability to the whole system. Furthermore, both [2] [3] only focus on fixed structural airframes with unscalable configurations. Different types of airframes cannot be applied to these platforms without revising control methods.

Thus, our proposed research aims to provide scalability and reconfigurability for the UAV platform by utilizing multi-layer data transmission and centralized control methods.

2 Methodology

2.1 System Architecture

This research proposes the hierarchical system architecture of the UAV platform based on different flying tasks. Multiple layers can be configured to satisfy different flight requirements.

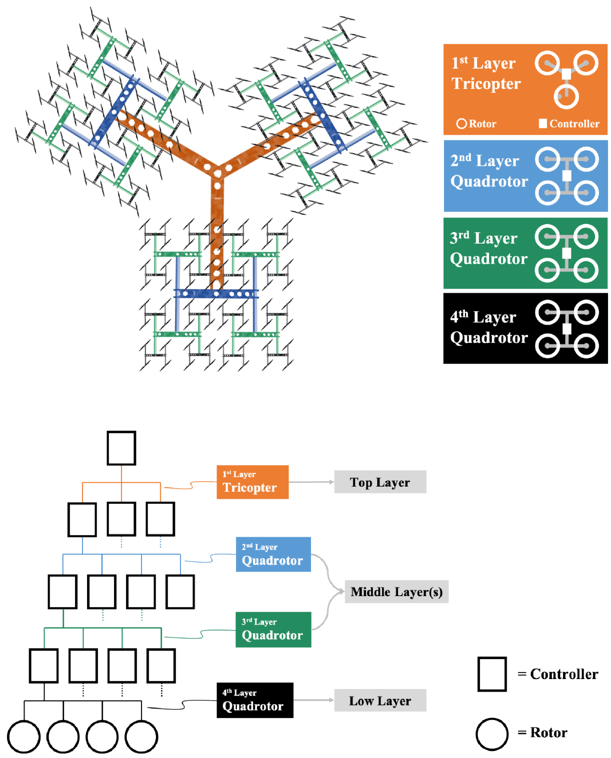

Fig.1 Platform System Architecture

Of all layers, they are categorized into three groups. The top layer group is where the main UAV is located. With the centralized control concept, the main UAV should contain only one unit for computation and data transmission. The overall structure of the UAV platform depends on this layer since the main UAV chooses its base airframe as a core structure.

The proposed UAV platform supports more than one layer for the middle layer. The UAVs installed at this layer are called parent UAVs, which link between a top-layer UAV and low-layer UAVs with customizable configuration. The number of middle layers and parent UAVs can be adjusted to meet application requirements.

The low layer is the layer where child UAVs reside. Since this layer is the last layer where rotors and propellers are attached to child UAVs, the number of layers is limited to one.

In Fig.1, it illustrates the proposed multi-UAV platform with a four-layer configuration. The orange tricopter is as-

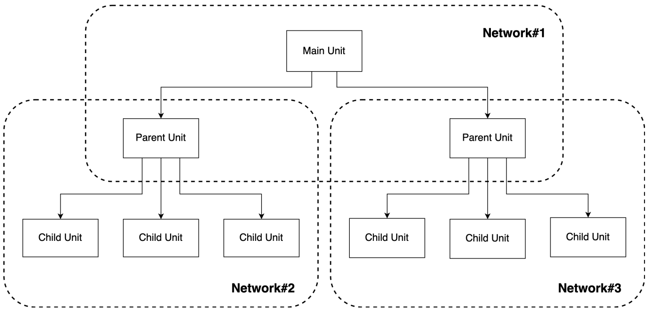

Fig.2 Network Grouping System

signed as the main unit in the top layer while blue quadrotors and green quadrotors play a role in the middle layer. Lastly, the low layer is where 48 black quadrotors and 144 propellers are installed.

Due to unique flight tasks in each layer, this research presents the new method, using three different firmware. The firmware from the top layer is responsible for retrieving sensor measurements and computing actuator outputs. In the middle layer, its firmware transfers actuator outputs obtained from the top layer to the low layer. Finally, child UAVs spin their propellers according to the value of received actuator outputs.

2.2 Data Transmission

To send data across multiple layers, this UAV platform concentrates on hierarchical order and network grouping systems as shown in Fig. 2. Therefore, the UAV unit in the top layer can only exchange data with middle layer units. In the same way, low-layer units are not allowed to retrieve any messages directly from the top layer unit. Furthermore, UAV units in different network groups cannot view any messages in other network groups. From this aspect, it substantially reduces workload from transferring many messages across layers and also improves network stability.

3 Platform Modelling

Our presented model comprises three layers, top layer, middle layer, and low layer, according to the proposed UAV platform architecture. In the top layer, one main UAV using a quadrotor H airframe is selected as the core structure. Next, instead of installing rotors on the main unit, four quadrotor airframes are placed on its different corners. On top of each parent unit airframe, four conventional quadrotors are set with four propellers attached. In total, there are one main unit, four parent units, and 16 child units with 64 propellers as displayed in Fig.3.

However, conveying actuator outputs from the top-layer unit to low-layer units without modification can have a negative impact on UAV stability. The torque generated from front-left child UAVs will cancel one generated from the front-right child UAV. Similarly, rear-right UAV torque will get deducted with rear-left UAV torque, causing the total torque of the child units to be equal to zero due to Newton's third law of motion. From this point, this research proposes a new method to make the total torque of child UAVs non-zero by applying a coaxial airframe to the main unit. Types of the coaxial airframe depend on the selected main airframe. In this model, the main UAV uses quadrotor H as the main airframe. Hence, the coaxial airframe which should be deployed to the model is an octa-coaxial H airframe as depicted in Fig.4., comprising eight actuator outputs in total.

The octa-coaxial H airframe is partially similar to the quadrotor H airframe, but it can support up to eight rotors.

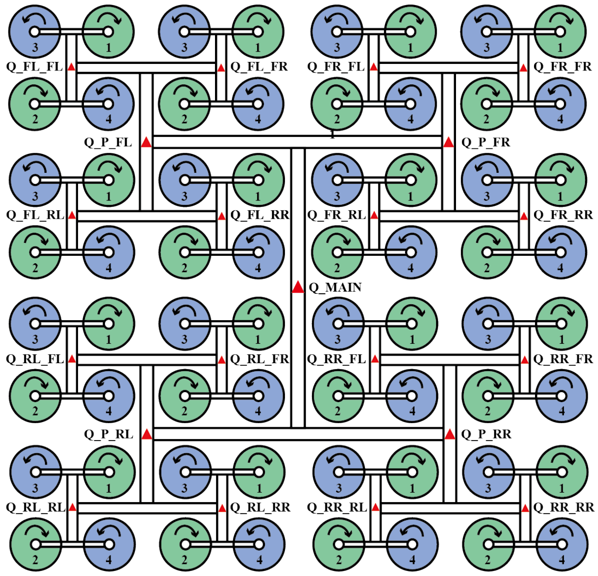

Fig.3 3-Layer Assembled UAV

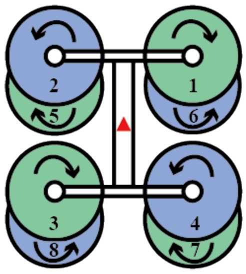

Fig.4 Octa-coaxial H Airframe

Additionally, propellers on the same side are vertically divided into the upper part and the lower part, rotating in opposite directions. Under the experimental environment, the specifications of all rotors and propellers are similar. To calculate actuator outputs of the octa-coaxial H airframe, this research uses the pseudo-inverse method because the number of installed propellers is higher than degrees of freedom. According to [6], the actuator effectiveness matrix (B) can be obtained by the layout position of the rotors. The complete actuator effectiveness matrix of the Octa-coaxial airframe is displayed in Eq. (1).

$$B = \begin{bmatrix} -d\sin(\theta) & d\cos(\theta) & iC_Q & C_T \\ d\sin(\theta) & -d\cos(\theta) & iC_Q & C_T \\ -d\sin(\theta) & d\cos(\theta) & iC_Q & C_T \\ d\sin(\theta) & -d\cos(\theta) & iC_Q & C_T \\ d\sin(\theta) & -d\cos(\theta) & iC_Q & C_T \\ -d\sin(\theta) & d\cos(\theta) & iC_Q & C_T \\ d\sin(\theta) & -d\cos(\theta) & iC_Q & C_T \\ -d\sin(\theta) & d\cos(\theta) & iC_Q & C_T \end{bmatrix}^T \tag{1}$$

Where d is the distance between the rotor and the center of mass and θ is an angular position of the rotor in degree. i is equal to +1 when the rotor moves in clockwise and equal to -1 when the rotor moves in counterclockwise. C_Q stands for torque coefficient whereas C_T is thrust coefficient

Then, find control allocation matrix by computing pseudo inverse as given in Eq. (2).

$$B^+ = B^*(BB^*)^{-1} \tag{2}$$

In this simulation, we applied the Octo-coaxial H airframe with $d = 1$ and assumed that C_Q and C_T are equal to 1 and 0.05, respectively. As a result, the control allocation can be found in Ep. (3).

$$P = B^+ = \begin{bmatrix} -0.1768 & 0.1768 & -2.5 & 0.125 \\ 0.1768 & 0.1768 & 2.5 & 0.125 \\ 0.1768 & -0.1768 & -2.5 & 0.125 \\ -0.1768 & -0.1768 & 2.5 & 0.125 \\ 0.1768 & 0.1768 & -2.5 & 0.125 \\ -0.1768 & 0.1768 & 2.5 & 0.125 \\ -0.1768 & -0.1768 & -2.5 & 0.125 \\ 0.1768 & -0.1768 & 2.5 & 0.125 \end{bmatrix} \tag{3}$$

Next, the actuator outputs can be derived from Eq. (4)

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \\ U_6 \\ U_7 \\ U_8 \end{bmatrix} = \begin{bmatrix} -0.1768 & 0.1768 & -2.5 & 0.125 \\ 0.1768 & 0.1768 & 2.5 & 0.125 \\ 0.1768 & -0.1768 & -2.5 & 0.125 \\ -0.1768 & -0.1768 & 2.5 & 0.125 \\ 0.1768 & 0.1768 & -2.5 & 0.125 \\ -0.1768 & 0.1768 & 2.5 & 0.125 \\ -0.1768 & -0.1768 & -2.5 & 0.125 \\ 0.1768 & -0.1768 & 2.5 & 0.125 \end{bmatrix} \begin{bmatrix} Q_R \\ Q_P \\ Q_Y \\ T \end{bmatrix} \tag{4}$$

Where U_i is an actuator output at i^{th} rotor. Q_R is roll torque. Q_P is pitch torque. Q_Y is yaw torque and T is thrust.

Finally, actuator outputs (Ui) will be converted into uORB messages before transferring to destinations in the form of MAVLink messages.

4 Result and Discussion

To evaluate the stability of this UAV platform, the UAV model in Fig.5 was set to move along a square trajectory in Gazebo simulated environment without wind and magnetic force acting on the UAV. In Fig.6, the result displays in x y z coordinate with the red line representing the target local position of the UAV, whereas the blue one illustrating the actual local position of the UAV. The 3D graph shows that the UAV model using this multi-layer platform can successfully follow the square waypoints. Even though there were slight differences in position error due to its large amount of inertia, it managed to reach the given destination.

5 Conclusion

With this proposed UAV platform concept, it breaks scalability and reconfigurability limitations from the conventional UAV. More UAVs can be installed to increase thrust and torque to support higher payloads in lifting and transporting applications. Different types of airframe structures can be customized and reconfigured to match different work scenarios. In this research, we demonstrated the multi-UAV scalable platform with one main unit, four parent units, 16 child units with 64 propellers. A centralized control method was utilized by retrieving estimated data from the main unit and obtaining actuator outputs in the last process to be sent to lower layer units. According to the result, it successfully achieves flight stability and provides safety redundancy.

In the next chapter, other configurations and various types of airframes will be applied to this UAV platform to increase functional diversity. In addition, the adaptive control method [7] will be implemented to provide automatic adaptability when UAV configuration changes.

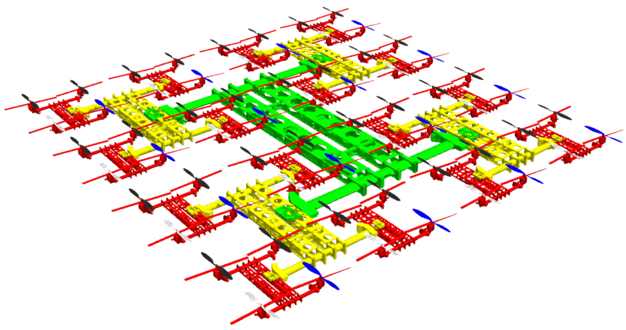

Fig.5 Multi-UAV model

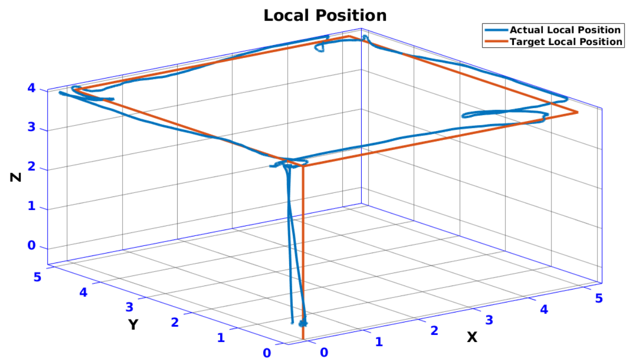

Fig.6 Local position

References

[1] B. Y. Suprapto, M. A. Heryanto, H. Suprijono, J. Muliadi and B. Kusumoputro, "Design and development of heavy-lift hexacopter for heavy payload," International Seminar on Application for Technology of Information and Communication (iSemantic), pp. 242-247, 2017

[2] Masataka Nakamura, Masafumi Miwa, "Study of multicopter for heavy load carrying," System Integration Division (SI2019), pp. 3079-3082, 2019

[3] R. Lalantha and R. Munasinghe, "Feasibility Study of a Novel Cross Assembled Multi-quadrotor Unmanned Aerial Vehicle," IEEE International Conference on Information and Automation for Sustainability (ICIAfS), pp. 1-6, 2018

[4] B. W. McCormick, "Aerodynamics, Aeronautics and Flight Mechanics," John Wiley and Sons, 1979.

[5] Gilar Budi Raharja, Kim Gyou Beom and Yoon Kwangjoon, "Design and implementation of coaxial quadrotor for an autonomous outdoor flight," 8th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI), pp. 61-63, 2011

[6] Kunpeng Li, Ziwei Song, Zhihao Cai, and Yingxun Wang, "Multi-rotor pseudo-inverse method research based on kernel space," IEEE Chinese Guidance, Navigation and Control Conference (CGNCC), pp. 1418-1422, 2016

[7] Toshiaki Kami, Yoshito Okada, Kazunori Ohno, Satoshi Tadokoro, "Rolling Flight of Passive Rotating Spherical Shell Quadcopter UAV by Adaptive Control," The 37th annual conference of the Robotics Society of Japan (RSJ2019), 2019

[8] "PX4/PX4-Autopilot", PX4 Autopilot, [Online]. Available: https://docs.px4.io/master/en/development/development.html