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Collaborative Control Based on Payload- leading for the Multi-quadrotor Transportation Systems

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Abstract— **This paper presents a collaborative control method based on payload-leading for the multi-quadrotor transportation systems. The goal is to keep the relative distance between the quadrotors and the payload as constant as possible during the transportation, so as to ensure the stable attitude of the payload. The control mechanism consists of a guidance control law that generates the common desired velocity for the quadrotors, an internal feedback controller for each quadrotor, and a decentralized formation controller. The stability of the control structure is proved by Lyapunov theory. Finally, the experimental platform of the multi-quadrotor transportation system is built to verify the effectiveness of the control method. Experimental results show that the proposed method has an excellent control effect.**

I. INTRODUCTION

The quadrotor has attracted extensive attention in recent years because of its strong maneuverability and hovering ability in three-dimensional space, which can replace people to complete tasks such as information acquisition and operation in high-risk environments [1-3]. Quadrotors can carry out the transportation task by slinging the payload with cables, so it has more advantages without considering loading capacity and the matching of the load shape with the fuselage [4-6].

At present, there have been a lot of research achievements on single-quadrotor transport systems [7-10]. However, there are still some problems with this form, such as short endurance, limited transport capacity, and the swing of the payload will seriously affect the transport efficiency. Using multiple quadrotors to carry out cooperative suspension transport can restrain the violent swing of the payload, improve the load transport capacity, and improve the success rate of the transport task and the overall robustness [11-13]. However, the dynamics of the multi-quadrotor transport system is characterized by multi-constraints, multi-variables, dynamic coupling, and strong nonlinearity, which makes it more difficult than the simple multi-aircraft formation or single-quadrotor transport system to maintain collaborative control, unable to keep the payload's attitude stability very well during transportation, and has become a hotspot of current research [5, 14].


Figure 1. The multi-quadrotor transportation physical platform consists of four quadrotors. The payload is a rectangular aluminum frame connected to the quadrotors by cables.

In [15], the lifting process of a collaborative hanging load of four multi-rotors was studied, a position-based passive cooperative control method was proposed, and a geometric controller was designed to ensure that the multi-rotors could effectively track the desired trajectory. In [16], a nonlinear control strategy based on feedback linearization was proposed for the cooperative transportation system of three multi-rotors to maintain formation stability in the process of tracking the trajectory. In addition, the collective motion problem of the multi-rotors transportation system was also studied. The so-called collective motion is regarded as the continuous path given by homogeneous transformation, which avoids the accumulated displacement error, can realize the continuous transformation of formation, and can well avoid collision [17]. Most of the above research has studied the internal control of multi-rotor transportation systems, and these methods rely heavily on accurate system modeling and dynamic modeling. Moreover, the relevant studies are only verified by simulation.

There were also some studies on the formation control of multi-rotor systems. [18] investigated the task assignment and control problem. The main objective was to suppress the payload swing during transportation. The whole system adopts a distributed control strategy and was verified by simulation. The decentralized control strategy was adopted in references [19] and [20], and the cooperative control problem was studied under the condition of no suspension load measurement information feedback, so as to ensure the stable flight of a multi-aircraft formation. In [21], two drones were used to jointly lift a long rod. The overall system adopts a leader-follow control strategy, with the drone in front as the leader and the drone in the rear as the follower, so as to ensure the stable attitude of the hanging object through cooperation.

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Since the drones implement the leadership following a strategy through visual recognition, there is no communication topology interaction, so the number of drones cannot be expanded at will.

This paper presents a stable collaborative control method based on payload-leading for the multi-quadrotor transportation systems. Specifically, the guidance control law is designed by taking the payload as a virtual leader and using its position information. Then, an internal feedback controller is designed based on passivity to drive the multi-quadrotor. The proposed formation controller is decentralized in meaning and does not make any assumptions about the cables' state. This control structure can increase the number of drones at will.

The rest of this paper is organized as follows. Section II presents the model of the multi-quadrotor transportation system. Section III describes the process of the control development and stability analysis. Then, Section IV proves the experimental design scheme and analyzes the experimental results in detail. Finally, Section V summarizes the study.

II. SYSTEM DYNAMICS

The schematic diagram of the multi-quadrotor transportation systems is shown in Figure 2. Assuming that there are *N* quadrotors in the system, let $i = \{1, 2, \ldots N\}$.

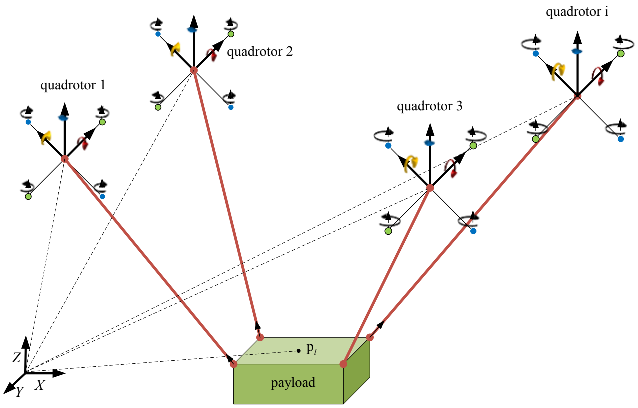


Figure 2. Schematic diagram of the multi-quadrotor cooperative transport with N = 4.

By applying the Newton-Euler method, the translational dynamics of the *ith* quadrotor can be obtained as [22].

$$m_i \ddot{p}_i(t) = F_i(t) + T_{cable,i}(t) - m_i g \tag{1}$$

where $p_i(t) \in \Re^3, F_i(t) \in \Re^3, g \in \Re^3, T_{cable,i}(t) \in \Re^3$, are defined as the position of the quadrotor, thrust forces, gravity acceleration, and the force applied by the payload to the *i*th quadrotor through the cable, respectively. m_i denotes the *i*th quadrotor's mass.

Similarly, the dynamics of the suspended payload can be modeled as

$$m_l \ddot{p}_l(t) = T_{cable,l}(t) - m_l g \tag{2}$$

where $p_l(t) \in \Re^3$ and m_l denote the position and the mass of the payload, respectively. $T_{cable,l}$ is the sum of the forces applied by the payload to the *N* quadrotor through cables. Since the control strategy proposed in this paper does not need to measure the payload tension states, the modeling of the suspension payload will not be introduced in detail here.

Next, consider *N* quadrotors and the suspension payload, a directed graph can be used to describe the interaction topology between quadrotors and the payload. We assume that each quadrotor can receive state information, such as the position of the payload, at the same time. According to the graph theory [23], we can define a communication topology incidence matrix as

$$d_{ik} = \begin{cases} -1 & \text{if } v_i \text{ is the tail of } \mathit{edge} \\ 1 & \text{if } v_i \text{ is the head of } \mathit{edge} \\ 0 & \mathit{otherwise} \end{cases} \tag{3}$$

Therefore, the distributed formation incidence matrix shown in Figure 1. is

$$M = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 1 & 1 & 1 \end{bmatrix}. \tag{4}$$

Since the quadrotors and suspension payload states are in three dimensions, we further defined the matrix $D := M \otimes I_3 \in \Re^{3(N+1)\times 3(N+1)}$ maps communication topology to the relative positions in Section III, where $\otimes$ is the Kronecker product.

III. CONTROL STRATEGY

In this section, to achieve the control objectives, a cooperative control strategy based on payload leadership is designed under the above-decentralized communication topology. First, a common mission velocity of the formation is generated by designing a guidance controller. Then, an internal feedback controller and a formation controller are designed to ensure that *N* quadrotors can converge quickly to the common desired speed and keep the relative distance between the quadrotor and the load stable, so as to ensure the stability of the suspension payload's attitude.

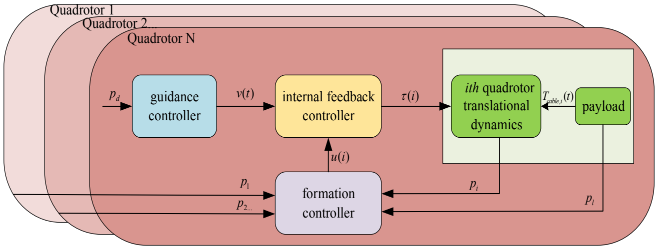


Figure 3. System control architecture of the multi-quadrotor transportation system.

The behavior of the multi-quadrotor cooperative transportation is defined as follows [24]:

- Each quadrotor in the limit a common velocity vector $v(t) \in \Re^3$ prescribed for the group; that is

$$\lim_{t \to \infty} \left| \dot{p}_i - v(t) \right| = 0, \qquad i = 1, \ldots N. \tag{5}$$

- Each quadrotor keeps a relatively stable position with the payload, the difference variable r_k is defined as

$$r_k := \sum_{j=1}^{N} d_{jk} p_j = \begin{cases} p_i - p_l, & if \quad k \in \sigma_i^+ \\ p_l - p_i, & if \quad k \in \sigma_i^- \end{cases} \tag{6}$$

where σ^+ and σ^- denote the set of edges for which node v_i is the head and tail end, $p_l \in \Re^3$ is position of the payload.

A. Guidance Control

The purpose of the guidance controller is to generate a common mission expected velocity of the quadrotors formation and transport the payload to the desired position. In the decentralized communication topology structure, the payload is regarded as the virtual leader, and the expected mission speed of each quadrotor can be obtained based on the position information of the payload, which can keep the quadrotor formation highly consistent. The guidance control law is designed as follows.

Define an error vector $e_p \in \Re^3$

$$e_p = p_i - p_{ld} \tag{7}$$

where p_{ld} is the desired position of the payload.

The following guidance law is given:

$$v(t) = k_p (e_p - r_k) \tag{8}$$

where k_p is the controller gain.

B. Internal Feedback Control

Then, design an internal feedback controller based on passivity for each quadrotor $i = \{1, 2, \ldots N\}$. In this framework, a systematic design of scalable and decentralized cooperative control laws can be applicable [24].

$$\tau_i(t) = -k_i(\dot{p}_i - v(t)) + m_i \dot{v}(t) + m_i g + u_i \tag{9}$$

where $\tau_i(t) = F_i(t) + T_{cable,i}(t)$ is control input, $k_i > 0$ is the control gain, u_i is an external feedback signal from the formation controller. The internal feedback controller can guarantee quadrotor's dynamics passive from u_i to the velocity error

$$\delta_i = \dot{p}_i - v(t). \tag{10}$$

According to equations (9) and (10), the quadrotor dynamics (1) forms a subsystem χ_i with inputs u_i and output δ_i, which may be expressed as

$$\dot{p}_i = y_i + v(t) \tag{11}$$

$$\chi_i : \begin{cases} m_i \dot{\delta}_i = -k_i \delta_i + u_i \\ y_i = \delta_i \end{cases}. \tag{12}$$

C. Formation Control

Finally, a decentralized formation controller is presented, which can keep each drone stable at a relative position from the payload. The input signal u_i of the ith quadrotor subsystem is obtained

$$u_i = -\sum_{k=1}^{N} d_{ik} \zeta_k(r_k) \tag{13}$$

where

$$\zeta_k(r_k) = \kappa_k (r_k - r_k^d) \tag{14}$$

where κ_k is the control gain, r_k^d is the expected relative distance.

Next, the concatenated vectors are introduced as

$$p := \left[p_1^T, \cdots p_N^T \right]^T \in \Re^{3N} \qquad r := \left[r_1^T, \cdots r_k^T \right]^T \in \Re^{3k}$$

and concatenate r_k 's together, equation (13) can be rewritten as

$$u = -D^T \zeta(r). \tag{15}$$

D. Stability Analysis

In this section, we analyze the stability properties of the set of interconnected subsystems, which consist of the difference variable r_k and the velocity errors δ_i. The proposed formation controller and internal feedback controller can make the subsystem stable and convergent, so as to ensure the payload attitude is stable during transportation.

Theorem 1: The proposed control strategy can ensure that the common velocity vector error and the relative position error vector converge to zero, if the following conditions are satisfied

$$\begin{cases} \lim_{t \to \infty} \left| \dot{p}_i - v(t) \right| = 0 \\ \lim_{t \to \infty} \left| r_k - r_k^d \right| = 0 \end{cases}. \tag{16}$$

Proof: Consider a positive definite Lyapunov function V_f based on equations (14) and (15)

$$V_f(r) = \sum_{k=1}^{N} \zeta_k(r_k). \tag{17}$$

By taking the derivative of equation (17), we obtain

$$\dot{V}_f(r) = \zeta^T \dot{r} = \zeta^T D^T \dot{p} = (\zeta D)^T \dot{p} = -u^T y \le 0. \tag{18}$$

Next, according to the subsystem (12), the corresponding storage function V_b is given as

$$V_b(\delta) = \sum_{i=1}^{N} \frac{1}{2} m_i \delta_i^T \delta_i. \tag{19}$$

By taking the derivative of equation (19), we obtain

$$\dot{V}_b(\delta)=\sum_{i=1}^{N}-k_i\delta_i^T\delta_i+u^Ty=-\delta^T\mathrm{K}\delta+u^Ty \tag{20}$$

where $\mathrm{K}=(k_i\otimes I_3)\otimes I_N$.

Thus, the final Lyapunov function of the system is defined as

$$V(r,\delta)=V_f(r)+V_b(\delta) \tag{21}$$

where $V(r,\delta)$ is a positive definite function.

Further, by taking the derivative of equation (21), it yields

$$\dot{V}(r,\delta)=\dot{V}_f(r)+\dot{V}_b(\delta)=-\delta^T\mathrm{K}\delta\le 0 \tag{22}$$

From equations (21) and (22), it can be seen that the closed-loop system is stable in the Lyapunov sense. Then apply the Invariance principle, $V(r,\delta)$ is radially unbounded and satisfies $V(0,0)=0$. Theorem 1 is proved.

IV. EXPERIMENTAL PLATFORM DESIGN

In this section, the multi-quadrotor transportation system platform is introduced in detail, which is used to demonstrate the theoretical results acquired in Section III.

The architecture of the multi-quadrotor transportation platform is presented in Figure 4. Each quadrotor is mainly composed of a positioning module, communication module, flight control system (FCS), and a single board computer (SBC). There is a ground control station (GCS) to monitor the states of quadrotors and send necessary commands such as take-off, return, and start to transport. We design a redundant communication network with WiFi and a 4G module where the communication base station is composed of a wireless access point (WAP) and a router. The payload is a rectangular aluminum frame with a flight control system at its center, connected to the same communications network as the quadrotor. In this way, the payload is connected to the distributed system, and the payload is regarded as the virtual leader. Each quadrotor can obtain the position information of the payload to further realize the formation control. the interaction topology between quadrotors and the payload is illustrated in Figure 5. where, p_{ld} is the transport target position and r_d is the expected relative distance between quadrotors and the payload are given.

The key parameters of the quadrotor and payload are shown in TABLE I.

TABLE I. KEY PARAMETERS OF THE QUADROTOR AND PAYLOAD

Parameters	*Value*
Diagonal Wheelbase	350mm
Quadrotor Weight	1460g
Maximum Takeoff Weight	1800g
Battery Life	30min
Payload Weight	1.5kg

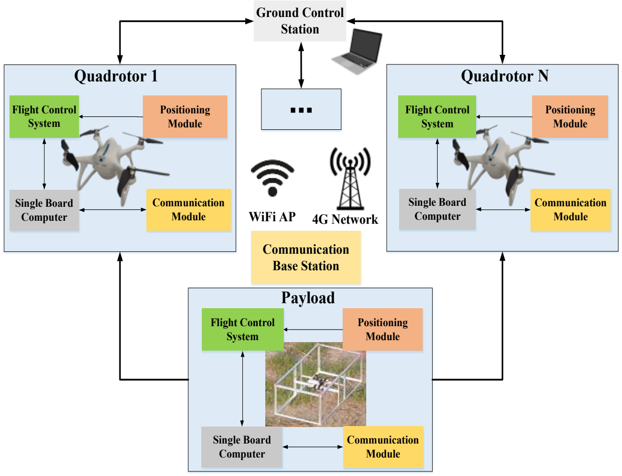


Figure 4. The architecture of the multi-quadrotor transportation platform, with N = 4.

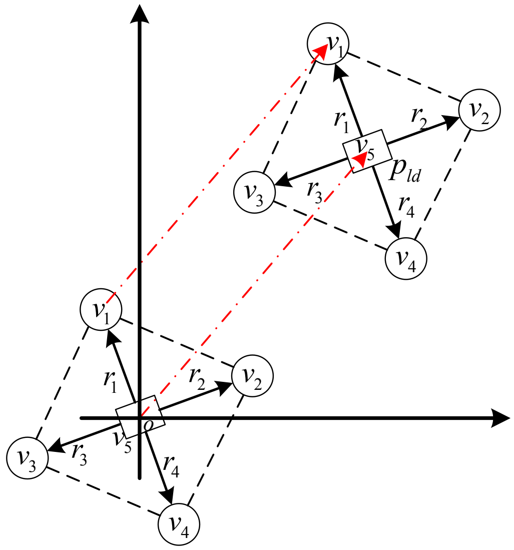
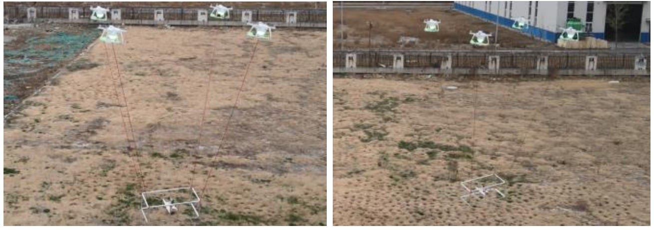


Figure 5. The Interaction topology of the multi-quadrotor transportation system. v_1, v_2, v_3 and, v_4 are quadrotors and v_5 is payload.

V. EXPERIMENT RESULTS

In the experiment, we set the quadrotors to take off from point A and transport the payload to point B. To ensure the attitude stability of the payload, the four quadrotors maintain a stable relative distance from the suspension payload by tracking the commonly expected velocity effectively. To verify the effectiveness of the proposed method, it is compared with the decentralized control method in [20] which does not consider the payload states. Figure 6 shows the images of different phases of the experiment. Figures 7-10 show the comparative experimental results.

(a) Initial state (b) Taking-off



(c) Lifting (d) Transporting

(e) Reach location (f) Landing

Figure 6. Images of different phases of the experiment

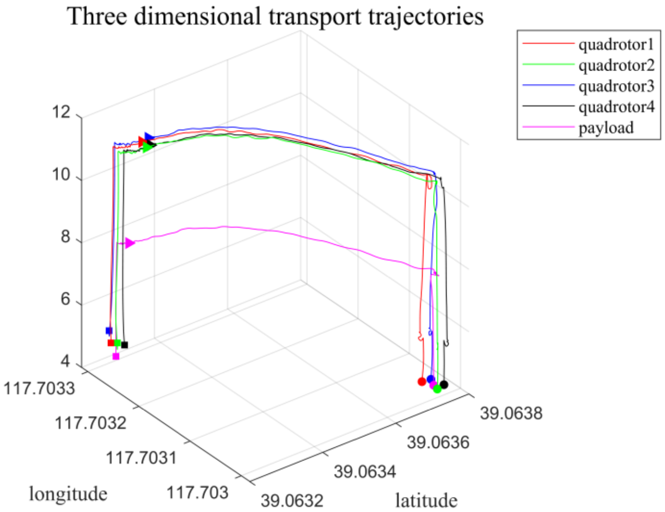


Figure 7. Three dimensional trajectories of the multi-quadrotor transportation system

Figure 7 shows the trajectories of the four quadrotors in the three-dimensional space during the whole process of cooperating to carry the load. It can be seen that quadrotors can maintain a good formation and transport the payload to the target point.

Figure 8 and Figure 9 show the experimental results of the proposed method and the method in [20], respectively. The shaded area is the relative distance error distribution of the quadrotors to the payload center and the velocities distribution of quadrotors, and the solid line represents the mean.

It can be seen that the average relative distance error of the proposed method is about 0.5m, which is smaller than that of the comparison method. The velocity fluctuations in the x and y directions are very small. Generally speaking, compared with the results in [20], the proposed method can better maintain the formation of quadrotors and transport the payload at a relatively stable speed. The formation control effect is excellent.

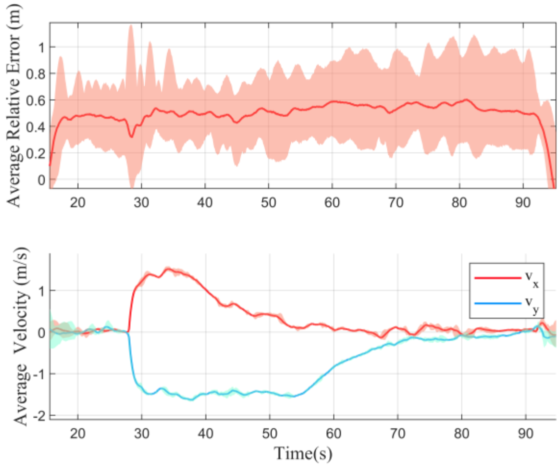


Figure 8. Experimental results for the proposed approach

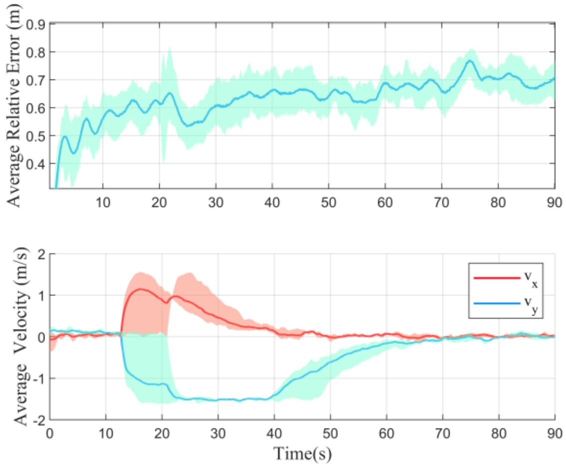


Figure 9. Experimental results for the method in [20];

In Figure 10, the attitude angles of the payload during transportation are shown. Since the suspension payload is a rectangular aluminum frame, the triaxial angle measurement results are given. It is clearly seen from Figure 10 that the proposed approach can suppress the payload attitude fluctuations into a smaller range during transportation. Overall, the payload attitude remained very stable and achieved the expected goal.

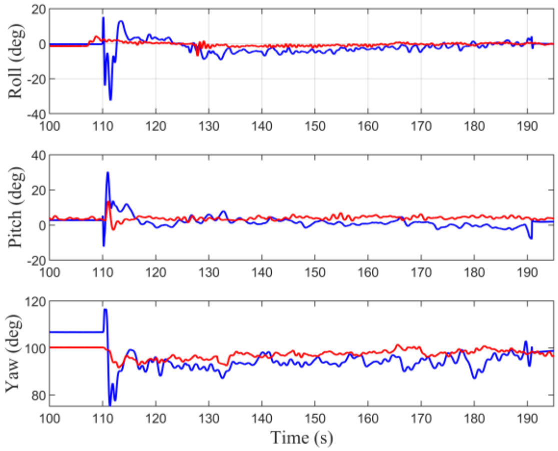


Figure 10. The attitude angles of the payload during transportation (Red solid line, the proposed approach; Blue solid line, the method in [20])

VI. CONCLUSION

In this paper, we present a collaborative control strategy based on payload-leading for multiple quadrotors to realize collaborative transport. With a cascade control scheme and a multi-quadrotor transportation system platform, the proposed control strategy has been verified with flight experiments. It is shown that the proposed guidance control law with the payload as the virtual leader can successfully transport the payload to the target position. Under the action of the internal feedback controller and the formation controller, we achieved the collaborative effect and ensured the stability of the payload during transportation.

The proposed method has verified the collaborative performance, but it will produce a large fluctuation at the start and stop of quadrotors, which will affect the safety. To this end, immediate future work will focus on smooth start and stop during transportation.

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