Adaptive Formation Control of Multi-Quadrotors Cooperative Transportation

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***Abstract*—This paper presents a control system for cooperative multi-quadrotors formation transportation. The forces and moments between the multi-quadrotors and the payload are analyzed using the Udwadia-Kalaba method, and a multi-quadrotors transportation system model is established. An improved coefficient is introduced to address the rope length drift problem during the takeoff process. Based on consensus theory, the payload is considered a virtual leader, and a cooperative formation control system for multi-quadrotors is constructed. Ultimately, the cooperative formation system is controlled using the adaptive integral backstepping controller, alongside employing an adaptive law to estimate and counteract disturbances induced by the payload on the quadrotors. The control system is validated through simulation experiments to determine its effectiveness.**

***Keywords*—multiple-quadrotors, payload transportation, cooperative control, adaptive backstepping,**

I. Introduction

In recent years, propelled by the rapid advancements in quadrotor transportation technology [1]–[3], its applications have witnessed a continuous expansion, revealing immense potential across domains such as logistics transportation, emergency rescue operations, and construction endeavors [4], [5]. However, the limited payload capacity of individual quadrotors poses a significant challenge, rendering them inadequate for transporting large objects [6], [7]. To address this issue, the concept of multi-quadrotors cooperative transportation has emerged. This approach involves multiple quadrotors working in coordination to transport heavy or oversized objects [8], [9]. This technology holds promising prospects, significantly enhancing the payload capacity of aerial transportation and paving the way for diverse applications [10].

The multi-quadrotors cooperative transportation system represents a challenging underactuated, strongly coupled complex system [11], [12]. Concurrently, the interdependence among multiple quadrotors in the system introduces a significant coupling effect, where the motion states and control commands of each quadrotor mutually influence one another [13]. This coupling effect amplifies the complexity involved in system modeling and the design of coordinated control strategies. Consequently, the effective design and implementation of control strategies for multi-quadrotors cooperative transportation systems pose a formidable task. It necessitates a comprehensive consideration of various aspects including system dynamics, coordinated control, disturbance rejection, among others, to achieve stable and efficient execution of transportation tasks [14], [15].

The advancement has spurred significant interest in the development of multi-quadrotor cooperative transportation systems, presenting new challenges and opportunities in the field of control engineering. References [16] and [17] extensively modeled multi-quadrotors cooperative transportation systems using the Lagrangian method and devised nonlinear controllers to govern load positions. However, practical application of these methods necessitates additional sensors to measure the suspended load's angular displacement, thereby escalating system costs and complexities. Reference [18] employed centroid coordinates and Euler angle mathematical models, delineated the coupling between multiple quadrotors and liquid payloads. By formulating an energy-based control framework, they achieved positional and attitudinal tracking of liquid payload systems. Reference [19] introduced a novel adaptive constraint formation control architecture utilizing universal barrier functions to handle time-varying constraints. This approach dynamically adjusts the weight distribution among drones based on the urgency of each constraint, thereby enhancing formation control efficacy. In [20], considering the dynamics of payload and cables, a mathematical model was constructed for the entire system comprising multiple quadrotors and payload. They proposed a coordination control approach that integrates distributed optimization and sliding mode control to ensure system stability and trajectory tracking performance. Reference [21] established the dynamic model of a multi-quadrotors cooperative transportation system using Newton's equations. They employed PID controllers to manage quadrotor motion and PD controllers to regulate load swing, thereby maintaining quadrotor formation and suppressing load oscillations. Udwadia-Kalaba method was employed to derive the system's dynamic equations under constraints [22], making it applicable in the realm of multi-quadrotors cooperative transportation [23].

This work proposes a new control system designed to improve cooperative multi-quadrotors engaged in formation transportation. Main contributions are as follows:

- A comprehensive analysis of the forces and moments between the multi-quadrotors and the payload is conducted using the Udwadia-Kalaba method, resulting in the establishment of a detailed model for the multi-quadrotors transportation system. To address the rope length drift issue during takeoff, an innovative coefficient is proposed.
- The payload is designated as a virtual leader, leveraging consensus theory principles. This approach enables the multi-quadrotors to collectively maintain a desired formation around the payload.
- An adaptive algorithm is integrated to estimate and counteract disruptions induced by the payload's influence on the individual quadrotors. This notably enhances the stability and control efficacy of the overall system.

The subsequent structure of this paper is outlined as follows. Section II delineates the construction of the dynamics model for multi-quadrotors cooperative transportation. Section III elaborates on the design of cooperative formation algorithms and adaptive integral backstepping controllers. Section IV presents simulation experiments. Section V provides a conclusion.

II. Multi-quadrotors Transportation System Dynamics

This section establishes the dynamic model of multi-quadrotors cooperative transportation. First, the Newton-Euler method is used to model a single quadrotor. Then, the Udwadia–Kalaba method is utilized to model multi-quadrotors cooperative transportation, and the problem of rope length drift divergence is avoided through constraints.

A. Quadrotor Modeling

The figure shown in Fig. 1 is a common quadrotor with a cross-shaped configuration. The definition of parameters is seen in Table I.

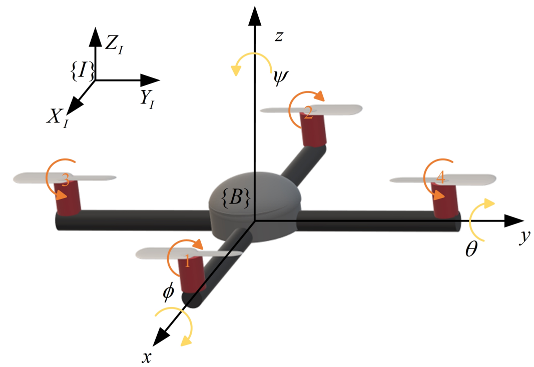

Fig. 1. Quadrotor model.

TABLE I
System parameters definition

Parameter	Definition
x, y, z	position of the quadrotor within the inertial frame
ϕ, θ, ψ	attitude angle roll, pitch, yaw
I_x, I_y, I_z	moment inertia of quadrotor
U_1, U_2, U_3, U_4	virtual control variables
l	quadrotor arm length
m	quadrotor mass
g	gravitational acceleration

According to Newton-Euler theorem, the quadrotor's dynamic model is

$$\begin{cases} \ddot{x} = \frac{U_x U_1}{m} \\ \ddot{y} = \frac{U_y U_1}{m} \\ \ddot{z} = \frac{(\cos\phi\cos\theta)U_1}{m_q} - g \\ \ddot{\phi} = \frac{lU_2 + \dot{\theta}\dot{\psi}(I_y - I_z)}{I_x} \\ \ddot{\theta} = \frac{lU_3 + \dot{\phi}\dot{\psi}(I_z - I_x)}{I_y} \\ \ddot{\psi} = \frac{U_4 + \dot{\phi}\dot{\theta}(I_x - I_y)}{I_z} \end{cases} \tag{1}$$

where $U_x = -(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi)$, $U_y = -(\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi)$.

B. Multi-quadrotors and Payload Modeling

Fig. 2 illustrates a model of a payload suspended by n ropes from n quadrotors. It is assumed that the ropes are massless, the payload represents a point mass, with the ropes linked to the center of mass of the quadrotors. The system's dynamic model is formulated employing the Udwadia-Kalaba method. This method allows for the consideration of the system's dynamic behavior under constraints, thus accurately describing the complex motion of the multi-quadrotors cooperative transportation system.

First define the distance from the payload to each quadrotor

$$\mathbf{L}_i^e = [x_i - x_L \quad y_i - y_L \quad z_i - z_L]^T \tag{2}$$

where x_i, y_i, and z_i denote the coordinates of the i-th quadrotor, while x_L, y_L, and z_L represent the coordinates of the payload.

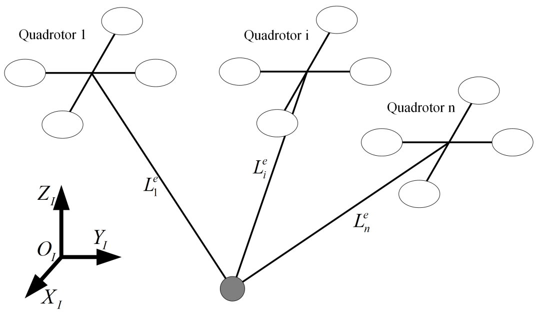

Fig. 2. Multi-quadrotors cooperative transportation model.

The length of the rope restricts the separation between the quadrotor and the payload

$$g_{c_i} = \|\mathbf{L}_i^e\|^2 - {L_i}^2 \tag{3}$$

where L_i represents the length of the i rope. Derive the constraint twice respectively

$$\frac{d}{dt} g_{c_i} = 2\mathbf{L}_i^{eT} \dot{\mathbf{L}}_i^e \tag{4}$$

$$\frac{d^2}{dt^2} g_{c_i} = 2\mathbf{L}_i^{eT} \ddot{\mathbf{L}}_i^e + 2\dot{\mathbf{L}}_i^{eT} \dot{\mathbf{L}}_i^e \tag{5}$$

Define the system acceleration before being constrained as

$$\ddot{\mathbf{q}}_u = \begin{bmatrix} u_{x_1} & u_{y_1} & u_{z_1} & \cdots & u_{x_n} & u_{y_n} & u_{z_n} & 0 & 0 & g \end{bmatrix}^T \tag{6}$$

The constrained system acceleration can be obtained by the Udwadia-Kalaba method

$$\ddot{\mathbf{q}}_c = \ddot{\mathbf{q}}_u + (\mathbf{M} \otimes \mathbf{I}_3)^{-1/2} \Big(\mathbf{V} (\mathbf{M} \otimes \mathbf{I}_3)^{-1/2} \Big)^{\dagger} (\mathbf{W} - \mathbf{V} \ddot{\mathbf{q}}_u) \tag{7}$$

where $\mathbf{V}_i = 2\mathbf{L}_i^{eT} \begin{bmatrix} 0_{3*3(i-1)} & \mathbf{I} & 0_{3*3(n-i)} & -\mathbf{I} \end{bmatrix}$, $\mathbf{W}_i = -2\dot{\mathbf{L}}_i^{eT} \dot{\mathbf{L}}_i^e$, $\mathbf{M} = diag(m_1, m_2, \cdots, m_n, m_L)$, and m_1, $\cdots$, m_n represent the mass of quadrotors, m_L represent the mass of the payload. $\otimes$ denotes the Kronecker product, and $(\boldsymbol{.})^{\dagger}$ represents the Moore-Penrose pseudoinverse.

Affected by the cumulative error of the integral and the error during take-off, the length of the rope has a drift problem, Udwadia-Kalaba equation can make $\ddot{g}_c = 0$, but $\dot{g}_c \neq 0$, $g_c \neq 0$, which will cause the rope length drifts with time, and it will tend to be infinite. The Baumgarte method mitigates the issue of infinite growth in rope length. This paper introduces an additional coefficient to address the problem of rope length drift during takeoff, thus providing improved control over rope length constraints.

$$\ddot{g}_c = -2\alpha \dot{g}_c - \beta^2 g_c - \gamma \tag{8}$$

where α, β, and γ are constants greater than zero. We can get the multi-quadrotors cooperative transportation system model with rope length constraints by substituting (8) in (7).

$$\begin{aligned} \ddot{\mathbf{q}}_c = \ddot{\mathbf{q}}_u + (\mathbf{M} \otimes \mathbf{I}_3)^{-1/2} \Big(\mathbf{V} (\mathbf{M} \otimes \mathbf{I}_3)^{-1/2} \Big)^{\dagger} * \\ \Big(\mathbf{W} - 2\alpha \dot{g}_c - \beta^2 g_c - \gamma - \mathbf{V} \ddot{\mathbf{q}}_u \Big) \end{aligned} \tag{9}$$

Let $\mathbf{F} = (\mathbf{M} \otimes \mathbf{I}_3)^{1/2} \Big(\mathbf{V} (\mathbf{M} \otimes \mathbf{I}_3)^{-1/2} \Big)^{\dagger} * \Big(\mathbf{W} - 2\alpha \dot{g}_c - \beta^2 g_c - \gamma - \mathbf{V} \ddot{\mathbf{q}}_u \Big)$, it is the force on the rope. We can get the final multi-quadrotors cooperative transport model.

$$\begin{cases} \ddot{x}_i = \frac{U_{x_i} U_{1_i} + \mathbf{F}_{3i-2}}{m_1} \\ \ddot{y}_i = \frac{U_{y_i} U_{1_i} + \mathbf{F}_{3i-1}}{m_1} \\ \ddot{z}_i = \frac{(\cos\phi_i \cos\theta_i) U_{1_i} + \mathbf{F}_{3i}}{m_1} - g \\ \ddot{x}_L = \mathbf{F}_{3n+1} \\ \ddot{y}_L = \mathbf{F}_{3n+2} \\ \ddot{z}_L = \mathbf{F}_{3n+3} \end{cases} \tag{10}$$

By placing the connection points at the centers of mass, the quadrotors' attitudes are decoupled, simplifying control.

III. Cooperative Formation Controller Design

For successful cooperative transportation, it's essential to achieve stable coordination among the multi-quadrotors, it is imperative to devise a robust and dependable formation control system for multiple quadrotors. Additionally, the development of a nonlinear controller with strong disturbance rejection capabilities and high robustness is essential. Based on the consistency theory, where the formation system employs a virtual leader concept, defined as the expected position of the payload. Utilizing a first-order consistency cooperative formation algorithm, we derive the desired trajectories for each quadrotor. Subsequently, we devise an adaptive integral back-stepping controller to precisely govern the quadrotors, thereby ensuring the stability of the formation system and promoting coordinated motion among them. Moreover, leveraging adaptive laws enables us to effectively estimate and compensate for disturbances induced by the payload on the quadrotors, further enhancing the robustness and disturbance rejection capability of the system. The designed control structure is shown in Fig 3, and the attitude solution is $\begin{cases} \phi_{di} = U_{yi} \cos\psi_i - U_{xi} \sin\psi_i \\ \theta_{di} = -U_{yi} \sin\psi_i - U_{xi} \cos\psi_i \end{cases}$.

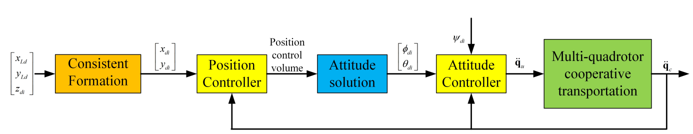

Fig. 3. Control structure.

A. Collaborative Trajectory Generation

Develop a communication topology for the collaborative formation depicted in Fig. 4. As depicted in Fig. 4, the communication graph exhibits strong connectivity. Additionally, it integrates a directed spanning tree, which optimizes message routing within the network. The adjacency matrix $\mathbf{A}$ is defined as $\mathbf{A} = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$, and the Laplacian matrix $\mathbf{L}$ is given by $\mathbf{L} = \begin{bmatrix} 6 & -1 & -1 & -1 & -1 & -1 & -1 \\ 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & -1 & 0 & -1 & 0 \\ 0 & -1 & 0 & 2 & 0 & -1 & 0 \\ 0 & 0 & -1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 2 & -1 \\ 0 & 0 & 0 & -1 & 0 & 0 & 1 \end{bmatrix}$.

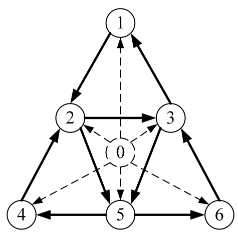

Fig. 4. Communication topology diagram.

The designed consistent collaborative formation algorithm is as follows

$$u_i = -h\left(\xi_i - \xi_i^* - \xi_0\right) - \left(\sum_{j=1}^{n} a_{ij}\left[\left(\xi_i - \xi_i^*\right) - \left(\xi_j - \xi_j^*\right)\right]\right) \quad (11)$$

We use h to represent this link, with a value of 1 indicating the follower can receive information from the leader. This describes the communication between the virtual leader and the follower drones. ξ^* (which is a matrix of real numbers) represents the deviation of the quadrotorss from the planned formation. ξ_0 (also a vector of real numbers) represents the current position of the virtual leader.

B. Controller Design

To achieve smooth and coordinated movement of the multi-quadrotors during cooperative transport, collaborative operation among the quadrotors under payload constraints is crucial. Additionally, the system must maintain stability when facing external disturbances and variations. Employing the adaptive integral backstepping approach, this paper presents the design of a highly efficient and reliable nonlinear controller to fulfill these requirements. This method combines the characteristics of adaptive control and integral backstepping control to estimate and provide feedback on the payload influence online, thus achieving system stability and robustness.

Throughout this work, $k_\bullet$,$\lambda_\bullet$ and $\gamma_\bullet$ represent constants that are all positive. Taking the quadrotor height as an example, the tracking error is

$$e_{zi} = z_{di} - z_i \quad (12)$$

where z_{di} is desired height. Take the derivative of (12)

$$\dot{e}_{zi} = \dot{z}_{di} - \dot{z}_i = \dot{z}_{di} - w_{zi} \quad (13)$$

where w_{zi} is the actual height speed. Design the Lyapunov function of e_{zi}

$$V_1 = \frac{1}{2}{e_{zi}}^2 \quad (14)$$

Derive it

$$\dot{V}_1 = e_{zi}\dot{e}_{zi} = e_{zi}\left(\dot{z}_{di} - w_{zi}\right) \quad (15)$$

Take w_{zi} as the virtual control input, we set the expected value to w_{zdi} to satisfy the condition $\dot{V}_1 \leq 0$, let $w_{zdi} = k_{zi}e_{zi} + \dot{z}_{di}$. To enhance robustness and diminish error, introduce an integral component within the desired virtual input for enhanced system behavior.

$$w_{zdi} = k_{zi}e_{zi} + \dot{z}_{di} + \lambda_{zi}\chi_{zi} \quad (16)$$

Let the virtual input error be

$$e_{w_{zi}} = w_{zdi} - w_{zi} \quad (17)$$

Substituting in (16), we obtain

$$w_{zi} = k_{zi}e_{zi} + \dot{z}_{di} + \lambda_{zi}\chi_{zi} - e_{w_{zi}} \quad (18)$$

Derive (17)

$$\dot{e}_{w_{zi}} = \dot{w}_{zdi} - \dot{w}_{zi} = k_{zi}\dot{e}_{zi} + \ddot{z}_{di} + \lambda_{zi}e_{zi} - \ddot{z}_i \quad (19)$$

$\ddot{z}_i$ signifies the height acceleration model, as derived in (18)

$$\dot{V}_1 = -k_{zi}e_{zi}^2 - e_{zi}\lambda_{zi}\chi_{zi} + e_{zi}e_{w_{zi}} \quad (20)$$

In order to satisfy the condition $\dot{V}_1 \leq 0$, it is necessary to have both $e_{w_{zi}}$ and χ_{zi} converge to zero. Design Lyapunov functions for e_{zi}, $e_{w_{zi}}$, χ_{zi}

$$V_2 = \frac{1}{2}e_{zi}^2 + \frac{1}{2}e_{w_{zi}}^2 + \frac{1}{2}\lambda_{zi}\chi_{zi}^2 \quad (21)$$

Differentiate (21)

$$\dot{V}_2 = e_{zi}\dot{e}_{zi} + e_{w_{zi}}\dot{e}_{w_{zi}} + \lambda_{zi}\chi_{zi}\dot{\chi}_{zi} \quad (22)$$

Substitute (19) and (20) into (22)

$$\begin{aligned} \dot{V}_2 = & -k_{zi}e_{zi}^2 + e_{zi}e_{w_{zi}} \\ & + e_{w_{zi}}\begin{bmatrix} k_{zi}\dot{e}_{zi} + \ddot{z}_{di} + \lambda_{zi}e_{zi} + g \\ -\dfrac{\left(\cos\phi_i\cos\theta_i\right)U_{1_i} + \mathbf{F}_{3i}}{m_i} \end{bmatrix} \end{aligned} \quad (23)$$

To guarantee stability (i.e., $\dot{V}_2 \leq 0$), the control variable U_{1_i} should be designed as

$$U_{1_i} = \frac{m_i}{\left(\cos\phi_i\cos\theta_i\right)}\begin{bmatrix} \left(1 - k_{zi}^2 + \lambda_{zi}\right)e_{zi} - k_{zi}\lambda_{zi}\chi_{zi} + \\ \left(k_{zi} + k_{w_{zi}}\right)e_{w_{zi}} + \ddot{z}_{di} + g - D_{zi} \end{bmatrix} \quad (24)$$

where $D_{zi} = \frac{\mathbf{F}_{3i}}{m_i}$ is the disturbance caused by the payload on the height of the quadrotors, which is unknown. Therefore, we design an adaptive law (25) to estimate and compensate for it.

$$\dot{\hat{D}}_{zi} = -\gamma_{zi}e_{wzi} \quad (25)$$

Expand the new Lyapunov function

$$V_3 = \frac{1}{2}e_{zi}^2 + \frac{1}{2}\lambda_{zi}\chi_{zi}^2 + \frac{1}{2}e_{wzi}^2 + \frac{1}{2\gamma_{zi}}\tilde{D}_{zi}^2 \quad (26)$$

where $\tilde{D}_{zi} = \hat{D}_{zi} - D_{zi}$ is the estimation error of adaptive law. Differentiate (26)

$$\dot{V}_3 = \frac{1}{2}e_{zi}\dot{e}_{zi} + \frac{1}{2}\lambda_{zi}\chi_{zi}e_{zi} + \frac{1}{2}e_{wzi}\dot{e}_{wzi} + \frac{1}{\gamma_{zi}}\tilde{D}_{zi}\dot{\tilde{D}}_{zi} \quad (27)$$

The variation of disturbance caused by the payload is considered to be relatively small, that's $\dot{D}_{zi} = 0$. Substitute (23), (24) and (25) into (27), we can get

$$\dot{V}_3 = -k_{zi}e_{zi}^2 - k_{wzi}e_{wzi}^2 \leq 0 \quad (28)$$

The effectiveness of the proposed adaptive integral backstepping controller in achieving asymptotic stability of the closed-loop system is rigorously proven through Lyapunov analysis. For the sake of brevity, the design of the remaining controllers, which follows a similar procedure, is not elaborated upon.

IV. Simulation

The multi-quadcopter cooperative transport system model designed in this paper adopts the QBall2 quadrotor as the subject, with the parameters of the model listed in Table II.

TABLE II
SYSTEM PARAMETERS

Parameter	Vaule
m_i	1.8 kg
m_L	1 kg
l	0.2 m
I_{xi}	0.03 kg·m^2
I_{yi}	0.03 kg·m^2
I_{zi}	0.04 kg·m^2
g	9.81 m/(s^2)
L_i	3 m

Let the horizontal initial position matrix and position deviation matrix of the six quadrotors be $\xi_0 = \xi^* = \begin{bmatrix} -1 & 1 & 0 & 1 & -1 & 0 \\ \sqrt{3} & \sqrt{3} & 2 & -\sqrt{3} & -\sqrt{3} & -2 \end{bmatrix}^T$, and the desired heights are 5m. After 10 seconds, let the expected trajectory of the virtual leader be $\begin{bmatrix} x_{leader} \\ y_{leader} \end{bmatrix} = \begin{bmatrix} 0.3(t-10) \\ -4\cos(0.1t-1)+4 \end{bmatrix}$. The parameters of the nonlinear cooperative formation control controller designed are listed in Table III. The results of the simulation experiments are as follows.

TABLE III
PARAMETERS OF THE CONTROLLER

	x	y	z	ϕ	θ	ψ
k_i	1.45	1.45	7.8	53.3	53.3	5.8
k_{wi}	0.8	0.8	20	5.5	5.5	3.5
λ_i	2	2	20.55	8.5	8.5	0.01
γ_i	2	2	10	10	10	5
h	1					
α, β, γ	40,36,0.76					

Fig. 5 provides a 3D visualization of the trajectory tracking performance by the multi-quadrotors during cooperative transport, revealing its commendable stability and precision in operation. The trajectory tracking outcomes distinctly illustrate the motion paths of multiple quadrotors in three-dimensional space, thereby substantiating the efficacy of the designed control algorithm. Observably, the system adheres to the trajectories prescribed by the cooperative formation algorithm, ensuring precise flight execution during tasks. Moreover, the system exhibits real-time responsiveness to payload influences, maintaining a stable flight posture throughout the operation, thereby ensuring the safety and reliability of cargo transportation missions. This underscores the robustness and reliability of the designed control system, enabling effective task completion in practical application scenarios.

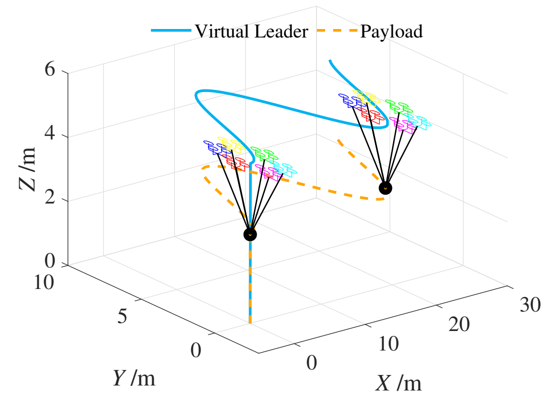

Fig. 5. 3-D trajectory results of the multi-quadrotors cooperative transportation system.

The analysis of the trajectory tracking results depicted in Figs. 6 to 8 for the quadrotors and payload along all axes (x, y, and z) demonstrates the impressive performance of the designed adaptive integral backstepping control in achieving precise tracking of both entities. The figures clearly illustrate the motion trajectories of the quadrotors and payload along each axis, demonstrating excellent tracking performance. This further validates the effectiveness of the controller, indicating its capability to adeptly handle system dynamics and maintain stable transportation of the quadrotors and payload. Moreover, the cooperative formation algorithm, designed based on consensus theory, plays a pivotal role in practical tracking scenarios. The figures distinctly exhibit the coherent trend of the quadrotors' horizontal positions, facilitating the maintenance of stable relative positions among multiple quadrotors and ensuring the stability of payload transportation. The application of the cooperative formation algorithm enables multiple quadrotors to perform transportation tasks in a coordinated manner, thereby enhancing the overall operational efficiency and stability of the system. Furthermore, the limitation on rope length plays a crucial role in ensuring stable payload transportation. It prevents the payload from diverging from its intended position.

Fig. 9 depicts the positional tracking errors experienced by the quadrotors. It is evident that upon initial takeoff, significant errors occur along each axis due to the influence of the payload tension. This phenomenon arises as the presence of

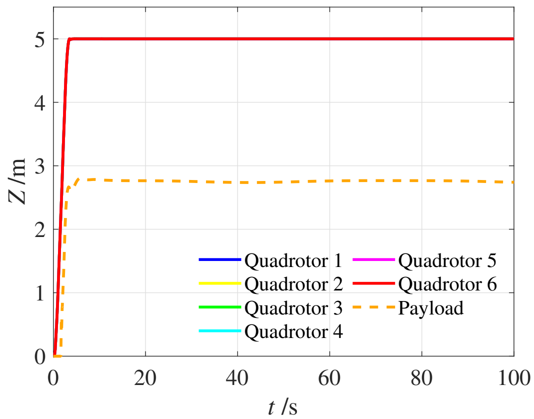

Fig. 6. The heights of the quadrotors and the payload.

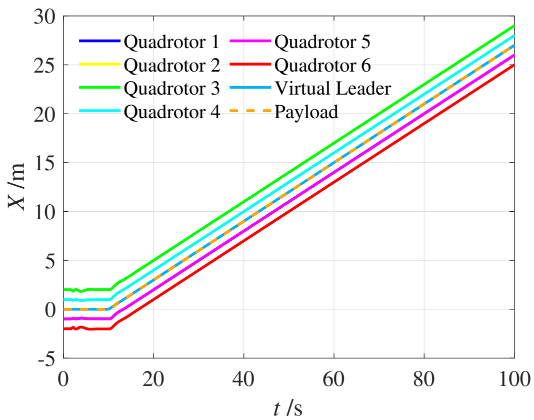

Fig. 7. x axes of the quadrotors and the payload.

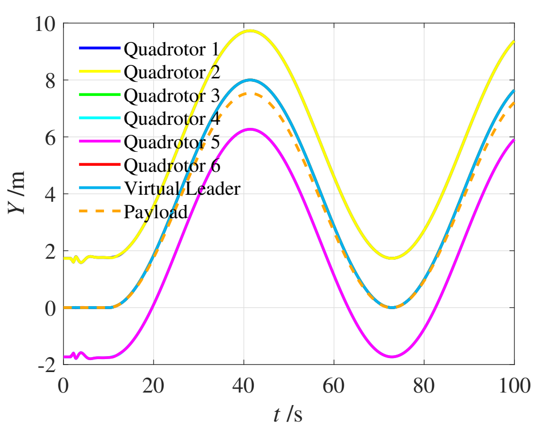

Fig. 8. y axes of the quadrotors and the payload.

the payload induces dynamic variations in the multi-quadrotors cooperative transportation system, consequently leading to an amplification of control errors. However, it is noteworthy that under the influence of the designed adaptive laws, the errors swiftly diminish, facilitating rapid system stabilization. The implementation of adaptive laws enables the system to dynamically adjust in response to the system's dynamic variations, effectively counteracting external disturbances and payload changes, thereby maintaining robust tracking performance. Thus, despite the potential for significant errors during liftoff, the rapid responsiveness and adjustment capabilities of the adaptive laws facilitate the swift reduction of errors, allowing the system to attain stability within a short timeframe.

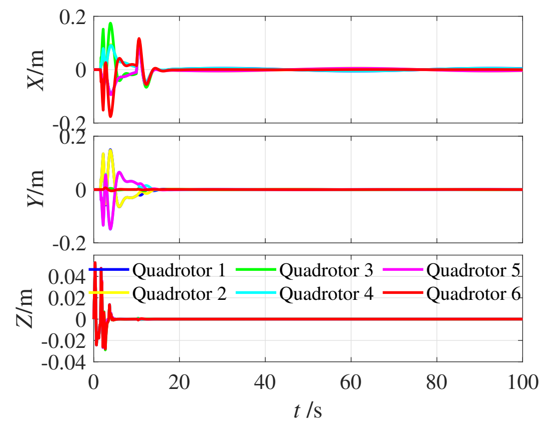

Fig. 9. Quadrotor position tracking error.

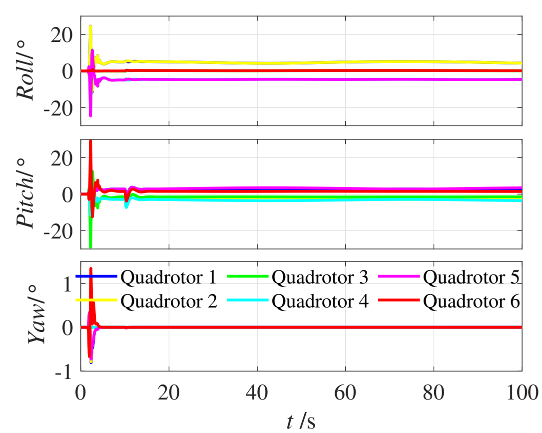

Fig. 10. Quadrotor attitude tracking results.

Fig. 10 presents the attitude tracking results of the quadrotors. It can be observed that during takeoff, there are significant oscillations in the attitude angles due to the influence of payload tension. However, it is noteworthy that these oscillations are rapidly stabilized under the influence of the nonlinear controller. This indicates the effective ability of the nonlinear controller to counteract disturbances induced by the payload, enabling the quadrotors to swiftly attain a stable state. In order to maintain the balance of the payload, once the system reaches a stable state, the roll and pitch angles of the quadrotors will be maintained at constant values. This maintenance of stability is crucial for achieving dynamic equilibrium in the multi-quadrotors collaborative transportation system. By maintaining stable attitude angles, the system can effectively preserve the balance of the payload, ensuring the safety and stability of the entire transportation process.

V. Conclusion

This work addresses the challenge of controlling multiple quadrotors for cooperative transportation by introducing a comprehensive control system that ensures stable formation and precise trajectory tracking. Through the application of the Udwadia-Kalaba method, forces and moments between the multi-quadrotors and the payload are thoroughly analyzed, leading to the establishment of a detailed transportation system model. Additionally, an innovative coefficient is introduced to mitigate the rope length drift issue during takeoff. This constraint effectively ensures the stable transportation of the payload, preventing excessive movement of the payload. Utilizing consensus theory principles, the payload is treated as a virtual leader, facilitating the construction of a cooperative formation control system for the multi-quadrotors. The cooperative formation algorithm enables multiple quadrotors to perform transportation tasks in a coordinated manner, this significantly improves the system's stability and contributes to its overall efficiency. Moreover, the adaptive integral backstepping method is employed to achieve control of the cooperative formation system. This method effectively handles system dynamics and disturbances caused by the payload, leading to improved stability and control performance of the entire system. Simulations confirm that the proposed control system is both effective in achieving its goals and robust to different conditions. The results demonstrate significant improvements in stability and control precision, underscoring the practical applicability of the developed control framework for cooperative multi-quadrotors formation transportation, and lay a solid foundation for the advancement of autonomous aerial transportation systems.

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