Bilateral Teleoperation of Multiple UAVs with Low-energy Coordinated Formation Control

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Abstract - This paper addresses the problem of the low-energy coordinated formation control of multiple unmanned aerial vehicles (UAVs) in a time-varying bilateral teleoperation system. To achieve the multi-UAV cooperative control with time-varying delays, a passive proportional velocity/position errors plus damping injection controller is proposed to enforce the coordinated formation and force tracking of the master haptic device and the slave UAVs. The stability of the controller is analysed by the Lyapunov-Krasovskii function and the delay-dependent stability criteria of system are obtained. Moreover, a min-weighted rigid graph is adopted to reduce the communication links and costs can be decreased. Finally, the human-in-the-loop simulations are performed to evaluate the effectiveness of the proposed control scheme.

Index Terms - bilateral teleoperation; coordinated formation; low-energy; time-varying delays; force feedback

I. INTRODUCTION

In recent years, the researches of the bilateral teleoperation control of multiple unmanned aerial vehicles (UAVs) have attracted the attention of numerous researchers. Groups of UAVs have proven to be very effective in solving complex tasks like surveillance, exploration and search and rescue [1, 2]. In the bilateral teleoperation system, the operator not only can manipulate a group of UAVs by the master device but receive the feedback force on the unknown environment to increase the situational awareness [3].

However, one problem of the multi-slave bilateral teleoperation system to be solved is the existence of time delays in the communication. For the constant or time-varying delays, the single-master-single-slave configuration of the teleoperation system has been studied for several decades. In [4], the concept of the wave variable was introduced to enforce the passivity of the delayed bilateral teleoperation system. However, the wave variable method brings about the position drifting problem that will degrade the stability of system. In [5], the damping injection method was put forward to overcome the position drifting problem while guarantee the passivity of the teleoperation system. Compared with the single slave configuration, there are fewer literatures about the single-master-multi-slaves configuration due to its complexities of model and coupling. In [6], a proportional-derivative controller was proposed to enforce the formation control and force tracking of the master and the slave UAVs with constant delays, but the time delays were constant. In [7], the time-varying delays were studied in the multi-slave teleoperation system, while the coordinated formation and the interaction with the environment were not considered. As far as we know, the coordinated formation control for the bilateral teleoperation system in the unknown environment while considering the time-varying delays has as yet little researches.

To achieve the multi-UAV cooperative control in the bilateral teleoperation system, the coordinated formation control where some states of the agent including attitude, position, and velocity reach an agreement can be adopted. In [8-10], the theoretical framework of the coordinated formation controller was developed. The basis of the coordinated formation control is that the velocities and positions of the neighbors are all in agreement. In these papers, the method of relative-position/velocity was applied to coordinate the agents in the multi-agent system, in which each agent was required to communicate with its neighbors. However, some interactions among the agents are not necessary. If consensus can be reached with less communication links, the energy dissipation can be decreased.

To solve the bilateral teleoperation control of multiple UAVs in a collaborative state, a coordinated formation controller is proposed. The stability of the controller is analyzed by the Lyapunov-Krasovskii function and the delay-independent stability criteria are given. Moreover, to achieve the coordinated formation with low energy constraints, a min-weighted rigid graph is adopted to simplify the slave topology. With the min-weighted topology, the communication links and energy dissipation can be decreased.

The remainder of this paper is organized as follows. Section 2 introduces the preliminaries of graph theory and rigid graph. The distributed coordinated formation controller for cooperative control is detailed proposed in Section 3. Section 4 develops the min-weighted rigid graph to decrease the energy dissipation of formation. The human-in-the-loop simulations that evaluate the effectiveness of the proposed formation control are performed in Section 5. Finally, concluding remarks are given in Section 6.

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II. PRELIMINARIES

A. Graph theory

Algebraic graph theory [11] can be used to describe the topology of the multi-robot system including N UAVs. Each UAV is regarded as a node, and the topology of UAVs can be described as a weighted graph $G = (V, E, A)$, where $V = \{1, 2, \cdots, N\}$ is the set of nodes, $E \subseteq V \times V$ is the set of edges and $A = [a_{ij}]$ is the weighted adjacency matrix. If the UAV $i$ is within the communication range of the UAV $j$, the elements $a_{ij} = 1$ otherwise $a_{ij} = 0$. The neighbour set of UAV $i$ is denoted as $N_i = \{j \in V : (i, j) \in E\}$. The Laplacian matrix is denoted by $L = [l_{ij}]$ with $l_{ii} = \sum_{j \neq i} a_{ij}$, $l_{ij} = -w_{ij}$ where $w_{ij} > 0$ if $j \in N_i$.

B. Rigid graph

The theory of rigid graph [12] can achieve better effectiveness in the cooperative applications which require the UAVs keep rigid topology. A graph is said to be rigid if and only if the relative distances between every pair $||x(t) - x(t)||$ is constant for all $(i, j) \in E$.

For a graph $G \subseteq R^c$ ($c \in \{2, 3\}$), the rigid matrix $M$ is

$$M = (i, j) = \begin{bmatrix} 0 & 0 & x_i^1 - x_j^1 & 0 & \cdots & 0 & x_i^{c-1} - x_j^{c-1} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & x_i^1 - x_j^1 & 0 & \cdots & 0 & x_i^{c-1} - x_j^{c-1} \\ \end{bmatrix}$$

where each row $[0 \cdots 0 x_i^1 - x_j^1 \cdots 0 x_i^{c-1} - x_j^{c-1} \cdots 0]$ corresponds to an edge $(i, j) \in E$ and the columns correspond to the coordinates of the nodes.

L1: $G = (V, E, A)$ with $N (N \geq c)$ nodes in $R^c$ is minimally rigid if the topology is infinitesimally rigid. A frame is said to be infinitesimally rigid if and only if rank($M$) = $cN - c(c+1)/2$ and the weighted sum of the topology edges in all infinitesimally rigid graphs is minimal.

III. COORDINATED FORMATION CONTROL

In this section, the coordinated formation algorithm is designed for the multi-UAV bilateral teleoperation system. In the slave site, only UAV1 is selected as the leader to connect to the master haptic device and the others are the followers which are required to communicate with the neighbours to form a rigid formation. The overall teleoperation system is shown in Fig.1.

A. The protocol of coordinated formation

In bilateral teleoperation, the operator is incorporated into the system and manipulates the formation by the master haptic device. The dynamics of the master haptic device is

$$M_m(q_m)\dot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m = f_m + f_k$$

where $q_m, \dot{q}_m, \ddot{q}_m$ are the joint position, velocity and acceleration, respectively. $M_m$ is the inertia matrix. $C_m$ is the Coriolis and centripetal matrix. $f_k$ is the human force applied on the device. $f_m$ is the haptic force feedback to the master.

The UAV can be regarded as a second-order system. The dynamics of UAV $i (i \in V)$ can be defined as

$$\begin{cases} \dot{x}_i = v_i \\ m_i \ddot{v}_i = f^*_i + f^*_T, \psi_i = w_i \end{cases}$$

where $x_i, v_i, m_i$ is the position, velocity and mass of the UAV $i$, respectively. $\psi_i$ is yaw angle and $w_i$ is the yaw-rate input. $f_i^*$ is the control force applied on UAV $i$, $f^*_T$ is the force caused by the interaction of UAV $i$ with the environment.

Defining the acceleration of the UAV $i$ as

$$\ddot{v}_i = \rho_i \dot{v}_i + \gamma_i$$

where $\gamma \rightarrow 0^+$, $\rho_i$ represents the acceleration at an infinitesimal time instant before $t$ so it can be assumed $\rho_i \approx \ddot{v}_i$.

The following properties, assumptions and lemmas will be used in this paper [13, 14].

P1: The matrix $M_m(q_m) - 2C_m(q_m, \dot{q}_m)$ is skew-symmetric.

A1: The human operator and the environment are passive for $i \in V$, i.e.,

$$\int_0^T q_i^T(t)d\dot{q}_i(t)dt \geq 0, -\int_0^T v_i^T(t)f_i^*(t)dt \geq 0$$

L2: For any vector function $a(t)$ and $b(t)$ and any time-varying delay $0 \leq T(t) \leq \bar{T}$, there exists a positive-definite matrix $\Gamma$ such that the following inequality holds

$$-2a^T(t)\int_{-T(t)}^0 b(\xi)d\xi - \int_{-T(t)}^0 b^T(\xi)\Gamma b(\xi)d\xi \leq \bar{T}a^T(t)\Gamma^{-1}a(t)$$

L3: For any vector function $f(t)$ and $g(t)$ and any time-varying delay $0 \leq T(t) \leq \infty$, there exists a constant $\alpha$ such that the following inequality holds,

$$-2\int_0^T f^T(\sigma)d\sigma \int_{-T}^0 g(\sigma + \theta)d\sigma d\theta \leq \alpha \left\| f \right\|^2 + \frac{T^2}{\alpha} \left\| g \right\|^2$$

It is well known that the damping injection method can guarantee the stability of the bilateral teleoperation system with time-varying delays. Therefore, the coordinated formation controller is designed as

$$\begin{align*}
  f_m &= -k_m (k_m q_m - v_i (t - T_m) - \alpha_m \ddot{q}_m) \\
  f_i^* &= -k_i (v_i - k_i q_{m,i}(t - T_m)) - \alpha_i \dot{v}_i \\
  f_i^* &= -k \sum_{j \neq i} (v_j - v_i (t - T_j)) \\
  -k \sum_{j \neq i} (x_j - x_i (t - T_j) - d_j) - \beta_i \dot{x}_i
\end{align*}$$

where $f_m$ is the force feedback to the master. $f_i^*$ the control force applied on UAV1. $f_i^*$ the control force applied on UAV $i$ with $i \in V$. $\alpha_m, \alpha_i$ and $\beta_i$ are damping coefficients. $k_m, k_i, k$ and $\beta$ are positive coefficients. $T_m = k_m q_m$ is the master reference speed that maps the master’s position to the UAV’s velocity to solve the dissimilarity between master device and slave UAV. $T_m/T_{m,1}$ is the time-varying delay between
UAV1/master and master/UAV1, \(T_m\) is the time-varying delay between UAV i and UAV j.

**Theorem 1:** For the single-master-multi-UAVs teleoperation system with the coordinated formation controller in Eq. (4), if there exist positive-definite matrices \(P, Q\) and positive constants \(\alpha_m, \beta\) such that the following inequalities hold
\[
-\alpha_m I + \frac{\sum_{i,j=1}^{n} k_{ij} \rho_{ij}}{2} \rho_{ij} + \frac{1}{2\alpha_m} \sum_{i,j=1}^{n} N_{ij} w_i T^2, \forall i \in V, j \in N_i
\]
then the overall teleoperation system is stable, the variables \([k_q, qa_n - \dot{v}_i], \dot{v}_i, \dot{v}_j\) are bounded.

**B. Stability analysis**

The total control force for UAV \(i\) is linearly mixed as \(f_i^a\) and \(f_i^f\). In the first part, the velocity of the leader is required to converge to the velocity of the master. In the second part, the UAVs are required to keep consensus with the neighbours with a desired relative position and equal velocity. In the following, the stability of the closed-loop system is analysed.

First, the relation of the master and the leader UAV by using \(f_i^a\) is investigated. The following Lyapunov function is constructed as
\[
V^a = \frac{1}{2} \dot{q}_m^T M \dot{q}_m + \frac{m_n v_n^T k_q}{2} \rho_{ij} + \frac{k_n}{2k_n} (k_q, q_n - v_i)^T
\]
(5)

With \(P\), the time derivative of \(V^a\) is
\[
\dot{V}^a = \dot{q}_m^T f_m + \dot{q}_m^T f_f + \frac{k_n}{k_n} \rho_{ij} (f_i^a + f_i^f) - \frac{m_n v_n^T k_q}{2k_n} \rho_{ij} \cdot \rho_{ij}
\]
(6)

With the controller Eq. (4), \(V^a\) can be rewritten as
\[
\dot{V}^a = \dot{q}_m^T (k_q (\dot{v}_i (t - T_m) - \dot{k}_q a_n) + \dot{q}_m^T \cdot f_f
\]
(7)

where \(T_m\) is the maximum time-varying delay between UAV1/master and master/UAV1.

Notice \(v_i (t - T_m) - \dot{v}_i = -\int_{-T_m}^t \dot{v}_i (\xi) d\xi, \quad q_m (t - T_m) - \dot{q}_m = -\int_{-T_m}^t \dot{q}_m (\xi) d\xi\), one has
\[
\dot{V}^a = \int_{-T_m}^t \dot{v}_i (\xi) d\xi + \int_{-T_m}^t \dot{q}_m (\xi) d\xi
\]
(8)

With Theorem 1, one has \(\dot{V}^a < 0\) and the stability of the closed system is guaranteed. Therefore, for master and leader UAV, the velocity \(\dot{q}_m\), the acceleration \(\rho_1\) and the velocity track error \(k_q, q_n - v_i\) are bounded.

For the follower UAVs, the Lyapunov function is
\[
V^a = \frac{1}{2} \dot{q}_m^T M \dot{q}_m - \int_{-T_m}^t (\dot{v}_i, \dot{f}_i) dt
\]
(9)

The time derivative of \(V^a\) is
\[
\dot{V}^a = \dot{v}_i^T (f_i^a + f_i^f) - \dot{v}_i^T f_i^f
\]
(10)

The following total scaled energy function is defined as
\[
V^a = \frac{1}{2} \dot{v}_i^T (L \otimes I_N) \dot{v}_i + \sum_{i=1}^{N} V^a_i
\]
(11)

where \(x = (x_1, \cdots, x_N), \quad v = (v_1, \cdots, v_N), \quad I_N\) is an identity matrix of size \(N, R\) is the relative distance matrix, \(\otimes\) is the standard Kronecker product.
In the coordinated formation control, each UAV is required to communicate with its neighbors to keep a fully connected topology. However, the connections among some UAVs seem not necessary and they may make the communication much more complex. If consensus can be reached with minimal neighbour information, the communication links and energy dissipation can be decreased. Therefore, the min-weighted rigid graph is adopted to simplify the slave formation topology. The flowchart for the min-weighted rigid graph is shown in Fig.2.

\begin{align}
V' &\leq -\sum_{i=1}^{N} \frac{\beta_i + k_i}{k_i} \left| \dot{x}_i \right|^2 - \sum_{i=1}^{N} \left( \sum_{j=1}^{N} \int_{t_i}^{t} \sum_{j=1}^{N} \sum_{j \neq i} v_j^i \dot{x}_i(\xi) d\xi \right) \\
&\quad + \sum_{i=1}^{N} \sum_{j=1}^{N} \left( \frac{\delta_{ij} + \epsilon_{ij}}{2} \right) \left| v_i \right|^2 + \frac{T_i}{2} \left| \dot{v}_i \right|^2 \tag{13}
\end{align}

Integrate Eq.(13) from zero to $t$, and the derivative is

\begin{align}
V' - V(0) &\leq -\sum_{i=1}^{N} \frac{\beta_i + k_i}{k_i} \left| \dot{x}_i \right|^2 + \sum_{i=1}^{N} \sum_{j=1}^{N} \left( \frac{\delta_{ij} + \epsilon_{ij}}{2} \right) \left| v_i \right|^2 + \frac{T_i}{2} \left| \dot{v}_i \right|^2 \tag{14}
\end{align}

where $\delta_{ij} > 0$ and $\epsilon_{ij} > 0$. Using the fact that $V' > 0$,

\begin{align}
V(0) &\geq \sum_{i=1}^{N} \sum_{j=1}^{N} \left[ \frac{\beta_i + k_i - \delta_{ij} - \epsilon_{ij}}{2} \right] \left| v_i \right|^2 + \frac{T_i}{2} \left| \dot{v}_i \right|^2 \tag{15}
\end{align}

Therefore, setting the damping injection $\beta_i$

\begin{align}
\beta_i > \frac{\left( \delta_{ij} + \epsilon_{ij} \right) k_i}{2} - k_i + \frac{1}{2\delta_{ij}} \sum_{j \neq i} w_{ij} T_j \tag{16}
\end{align}

for each slave UAV ensures that $v_i \in L_2$ and $V' \in L_\infty$, which in turn implies that $x_i - x_j - d_{ij} \in L_\infty$ for all $i \in V$, $j \in N_i$.

V. MIN-WEIGHTED RIGID GRAPH

In the coordinated formation control, each UAV is required to communicate with its neighbors to keep a fully connected topology. However, the connections among some UAVs seem not necessary and they may make the communication much more complex. If consensus can be reached with minimal neighbour information, the communication links and energy dissipation can be decreased. Therefore, the min-weighted rigid graph is adopted to simplify the slave formation topology. The flowchart for the min-weighted rigid graph is shown in Fig.2.

Then, to calculate the communication cost in the slave site, a low-energy radio model [15] which is usually used in the wireless sensor network is introduced. It is assumed that the UAVs are all equipped with the transmitter and the receiver. The communication cost depends on the distance between the transmitter and the receiver. Thus, to transmit an $l$-bit message a distance $d$, the communication cost is

\begin{align}
E_{el}(l,d) = E_{elec} + l \epsilon_{fris} d^2, d < d_0
\end{align}

and to receive this message, the communication cost is

\begin{align}
E_{el}(l,d) = E_{elec} + l \epsilon_{fris} d^2, d \geq d_0
\end{align}

where $E_{elec}$ is the electronic energy which depends on many factors such as the digital coding, modulation, and spreading of the signal. $d_0$ is the distance threshold, $\epsilon_{fris}$ and $\epsilon_{fris}$ depend on the acceptable intensity and bit-error rate.

VI. HUMAN-IN-THE-LOOP SIMULATIONS

In this section, the human-in-the-loop simulations are presented to verify the effectiveness of the main results. The simulations are performed on Ubuntu12.04/ROS. The PHANTOM Omni haptic device is choose as the master device. The five quadrators Parrot AR.Drone2.0 are selected as the slave robots. The initial conditions for devices are: $x_{0m} = (0, 0, 0)^T$, $q_1 = (6, 4, 2)^T$, $q_2 = (5, 0, 1)^T$, $q_3 = (0, 0, 2)^T$, $q_4 = (0, 6, 1)^T$, $q_5 = (3, 3, 3.5)^T$ and $q_{in} = v_i = (0,0,0)^T$ for $i = 1, \cdots, 5$.

The desired relative distance matrix of formation is

\begin{align}
\begin{bmatrix}
2 & 0 & 2 \\
0 & 2 & 0 \\
2 & 0 & 2
\end{bmatrix}, \begin{bmatrix}
0 & 2 & 0 \\
2 & 0 & 2 \\
0 & 2 & 0
\end{bmatrix}, \begin{bmatrix}
0 & 2 & 0 \\
2 & 0 & 2 \\
0 & 2 & 0
\end{bmatrix}, \begin{bmatrix}
0 & 2 & 0 \\
2 & 0 & 2 \\
0 & 2 & 0
\end{bmatrix}
\end{align}

where $T_{med}$ and $T_{med}$ are the communication delays.

The parameters of the communication energy are: $E_{elec}=30nJ/bit$, $\epsilon_{fris}=10pJ/bit/m^2$, $\epsilon_{fris}=0.001 pJ/bit/m^2$, $E_{amp}=1 m$. The control parameters for the coordinated formation are: $m_{0}=0.45kg$, $k_{0}=10$, $K_{0}=1$, $k_{0}=0.005$, $k_{0}=0.5$, $\alpha_{0}=1$, $\alpha_{0}=8$, $\beta_{0}=1$ for $i=2, 3, 4, 5$.

\begin{table}[h]
\centering
\caption{The features of the rigid matrix at initial}
\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|}
\hline
\textbf{Edges} & $M_{d1}$ & $M_{d2}$ & $M_{d3}$ & $M_{d4}$ & $M_{d5}$ & $M_{d6}$ & $M_{d7}$ & $M_{d8}$ & $M_{d9}$ \\
\hline
(L-F1) & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ \\
(L-F2) & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ \\
(L-F3) & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ \\
(L-F4) & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ \\
(F1-F2) & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ \\
(F1-F3) & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ \\
(F1-F4) & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ \\
(F2-F3) & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ \\
(F2-F4) & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ \\
(F2-F4) & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ & $\times$ \\
Rank & 9 & 9 & 9 & 9 & 9 & 9 & 9 & 9 & 9 \\
Weight & 50 & 47 & 48 & 49 & 46 & 48 & 48 & 48 & 48 \\
\hline
\end{tabular}
\end{table}

Notation: L: Leader, F1: Folollwer1, F2: Folollwer2, F3: Folollwer3, F4: Folollwer4, $\times$: Including edge, $\times$: Not includes edge, $\times$: The corresponding matrix is not infinitesimally rigid matrix.
At time $t = 0$, the initial rigid matrix $M(0)$ is firstly constructed. Then, constructing the infinitesimally rigid matrix $M_c$ until the rank of the matrix satisfies $cN - c(c+1)/2 = 3 \times 5 - 3 \times 4/2 = 9$. There are six infinitesimally rigid matrixes that can be seen in Table I. Finally, the weighted sum of the topology edges in all infinitesimally rigid graphs is calculated. From Table I we can see that the rigid matrix $M_{c6}$ is the min-weighted rigid matrix. The topology relationships of slave UAVs at initial are shown in Fig.3. Moreover, the optimal topology is constantly updated with the coordinated formation.

![Fig. 3 Optimal rigid topology at initial.](image)

In Fig.4, the coordinated formation flight with fully connected topology and optimal rigid topology are shown. The topology relationships of slave UAVs are marked by the black solid lines. Obviously, the communication links of the optimal topology are decreased. The formation tracks the motion of the master haptic device and avoids the obstacle. Fig.5 shows the communication cost and the trajectory in two modes. We can see that there is a greater difference between the fully connected topology and the optimal topology. In optimized mode, each UAV can communicate with the neighbours in the min-weighted rigid graph and the communication edges can be fixed during the coordinated formation process. The communication energy dissipation with the optimal topology is decreased and the trajectory is farther.

The velocity information is shown in Fig.6 (a), (b) and (c). $v_{mx}$, $v_{my}$ and $v_{mz}$ are components of the master velocity sent to the leader UAV. $v_i$, $v_y$, and $v_z$ are the components of the velocities of the slave UAVs for $i=1,\ldots,5$. It can be seen that the velocities of the slave UAVs $v_1$, $\ldots$, $v_5$ are converged to the master velocity. At time $t = 32s$, the velocities of the slave UAVs are decreased to prevent collisions with the obstacle. At time $t = 63s$, the formation flies away the obstacle and the velocities re-track the master one. Yaw angles for the slave UAVs are shown in Fig.6 (d). In Fig.6 (e), the relative distances among the UAVs satisfy the desired one. The coordinated formation can be achieved because all states approximately converge to the desired values. In the meanwhile, the operator can perceive the feedback force generated by the obstacle when the formation reaches the obstacle that can be seen in Fig.6 (f).

VII. CONCLUSIONS

In this paper, the low-energy coordinated formation control of multiple UAVs in the bilateral teleoperation system with time-varying delays has been proposed. Firstly, the coordinated formation control is designed for the task with tracking the master haptic device, and the stability analysis is given. Moreover, the min-weighted rigid graph is adopted to minimized the communication energy dissipation. The control combining coordinated formation control and optimal topology is applied in the multi-UAV system with obstacle. The human-in-the-loop simulation results show that the slave UAVs can form a low-energy rigid formation in the obstacle environment with time-varying delays while track the motion of the master device. With the min-weighted topology, the communication links and costs are significantly decreased.

![Fig. 4 3D coordinated formation. (a) Fully connected topology. (b) Optimal rigid topology](image)

![Fig. 5 Communication cost and trajectory.](image)
The movement of the optimized formation is farther during the same time. The interactions of the slave UAVs with the environment are presented to the operator by force rendering. The proposed control scheme is able to improve the manoeuvrability of multi-UAV formation.

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