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# Formation Producing Control of Multi-Quadcopter Systems Under the Cloud Access

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**ABSTRACT** The use of cloud-connected UAV swarm plays an important role in the future of mobility. One of the challenges to address before realising this technology is achieving a formation producing control of quadcopter swarms under the cloud access. For this purpose, the problem of cloud-based formation control for a nonlinear 6-DOF under-actuated multi-quadcopter system is studied in this paper. This is different compared to the existing literature, studying the rendezvous problem for a second-order multi-agent system. As the first step, a hierarchical control structure is provided to derive the control laws and conditions for the stability of the nonlinear under-actuated multi-quadcopter system to guarantee the asymptotic consensus of the quads' positions to the biased average of the initial positions. Then, the control laws are extended and derived under the cloud access condition and the stability proofs are analysed for the quadcopters' dynamics. The results guarantee the practical consensus of the quadcopter system to the biased position of their initial values. Toward this, a scheduling rule for the access to the cloud is designed and it is shown that the rule avoids the Zeno behavior.For this purpose, upper bounds on the control laws of the cloud-connected neighboring agents between two consecutive connections of each agent are considered. The numerical results verify the efficacy of the proposed method.

**INDEX TERMS** Multi-Quadcopter Systems, Formation Control, Cloud Access, Consensus based Control.

## I. INTRODUCTION

Rapid growth of urban populations and the increasing complexity of transportation networks have created significant challenges in managing mobility efficiently and sustainably. Traditional ground-based transportation systems are reaching their limits, leading to congestion, increased emissions, and reduced quality of life in urban environments. To address these issues, there is a growing interest in exploring advanced technological solutions that can enhance mobility by improving efficiency, reducing environmental impact, and increasing safety [1], [2].

One such promising solution is the deployment of unmanned aerial vehicles (UAVs). Quadcopters as unmanned aerial vehicles have wide applications in many fields such as environmental monitoring [3] and navigation in extreme environments that are unaccessible to humans [4]. This may introduce various challenges in the control [5], [6] and navigation of quads [7], [8]. However, since quadcopters are resource-constrained vehicles with limited wireless communication and computing capabilities there exists an increasing need to use them in a coordinated group, often referred to as a UAV swarm. This results in a higher and more efficient performance for the overall system, especially when the quadcopters should accomplish a task in a large-scale environment.

These UAV swarms, when connected to cloud services, can revolutionize how we approach transportation and mobility. The term mobile cloud computing (MCC) is appropriately used for such multi-UAV systems [9]. By leveraging cloud connectivity, UAVs can cooperate in real-time, sharing data and optimizing their collective behavior to accomplish complex tasks more efficiently [10]. This collaborative approach not only improves the performance of the UAV operations, but also provides a scalable solution to modern mobility challenges [11], [12].

The integration of cloud services with UAV swarms enables several key capabilities. It allows UAVs to offload computationally intensive tasks, such as real-time data processing and decision-making, to the cloud. This reduces the onboard processing burden and enhances the UAVs' ability to perform complex operations [13], [14]. Quads can upload their own information to and download the information of the neighboring agents from the cloud which facilitates data sharing among UAVs. However, communication constraints, including limited bandwidth, intermittent links, and lack of energy resources when the UAVs are spread over a vast area, limit the overall performance of the system. It is known that asynchronous communication through the cloud server and using event-based control techniques can reduce the information exchange rate and make the communication more resilient against packet loss and cyber attacks in such scenarios, [15].

Autonomous operation of the quadcopters requires designing a control system paradigm, called formation control [16]. Depending on the mission purposes, two different types of formation control for multi-UAV systems are commonly used [17], [18]: formation tracking control and formation producing control. The main objective of the formation producing control is to bring the quadcopters into a predefined formation. Amongst all available techniques, a distributed consensus-based approach [19], [20] is the most popular one. For example, in [21], collaborative movements such as rendezvous, circular, and logarithmic spiral patterns are achieved using the coupling of existing consensus algorithms to Cartesian coordinate. The main goal of the current study is to position the quadcopters to the biased average of their initial positions. As such, a bias term is introduced to the consensus algorithm for producing a formation shape for the quadcopters.

For a could-connected formation control, as mentioned above, practical issues such as limited bandwidth, intermittent links, and lack of energy resources would limit the performance of the formation control systems. One approach to address these problems is introducing network protocols such as round-robin protocol (RRP) and try-once-discard protocol (TODP) [22]. Another technique proposed in the literature relies on event-triggered control methods, rooted in designing networked control systems [23]. In this method, the data exchange happens when a specific condition is satisfied [24]. In [25] a novel edge-event-triggered mechanism enables asynchronous intermittent communication between agents for observer design and fault-tolerant control of multi-agent-systems (MASs). However, in such methods agent to agent communication is required which is not applicable in many formation scenarios such as the ones when the quads are traveling a vast area. In such scenarios, it is necessary for the quads to share information via a cloud server. As long as the processing facilities are available onboard on each UAV, the storage capability of the cloud can only be used. Toward this, each quad upload its information to the cloud when it is connected and download the information of the neighboring agents from the cloud related to their last connection to the cloud. In other words, an asynchronous communication between agents should be considered. For formation control of multi-agent systems under cloud access, a specific scheduling rule to access the cloud server is proposed in [26]. Nonetheless, the paper used second-order dynamics for the analysis and synthesis of the scheduling rule, proposed for asynchronous access to the cloud. A similar problem for multi-agent systems with more general nonlinear dynamics is studied in [27]. However, the cloud access scheduling and the well-posedness of the closed-loop system are eventually derived for agents with first-order dynamics. Although in [28], the problem of cloud predictive control based formation of multi-agent systems with application in air bearing spacecraft simulator has been studied, the cloud is only used as a centralized processor. The communication between the agents and the cloud can be established continuously considering some communication delays. Although this reference is among a few research works in the field of cloud access based formation control of multi-agent systems, it is structurally different from our work. Similarly, in [29] continuous connections with delay but with multiple cloud nodes has been considered in which formation control of multi-agent systems is performed using distributed sliding mode predictive control approach with application in the air bearing spacecraft simulator.

In this study, however, we extend the methodology proposed in [26] for nonlinear 6-DOF under-actuated multi-quadcopter systems. For this purpose, the employed consensus algorithm is modified and generalised for the multi-quadcopter systems. The results guarantee the convergence of the quadcoptrs' positions to the biased average of the initial positions of the quadcopters, resulting in a formation producing control of quadcopters. The analyses and proofs provided for the stability of the control system are different compared to the one proposed in [26] in several ways. More specifically, the under-actuated problem of the quadcopter dynamic is addressed by proposing a hierarchical control structure. This involves separating the altitude subsystem in the $z$ direction from the translational subsystems in the $x$ and $y$ directions by employing a virtual control input. Then, the controllers under the cloud access are designed by following the approach proposed in [26], and after applying the modifications required to include the quadcopter dynamics. Moreover, the practical consensus of the biased positions is analyzed and the stability proof of the closed-loop system is provided. This is achieved by designing a new scheduling rule to access the cloud for three subsystemss of the quadcopters, i.e. altitude, and two translational subsystems in $x$ and $y$ directions. To guarantee the biased practical consensus of the quadcopters (formation producing control), upper bounds are considered on the control laws of the neighboring agents connected to the cloud between the consecutive connections of each agent. Furthermore, the scheduling rule is analyzed to prove the well-posedness of the closed-loop system and avoid the Zeno behavior.

To summarize, the novelties of the paper can be highlighted as follows:

- generalisaion and modification of the presented consensus problem in [26] for nonlinear 6-DOF under-actuated multi-quadcopter systems to guarantee the convergence of the quadcoptrs' positions to the biased average of the initial positions of the quadcopters with necessary proofs and in a hierarchical structure to address under-actuated quadcopter system.
- design of the controller under cloud access using the presented consensus problem in the previous step and following the proof approach presented in [26] with necessary changes for multi-quadcopter system to guarantee the practical consensus of the biased position.
- design of a scheduling rule for the access to the cloud guaranteeing the practical consensus of the quads.
- proving that the system does not show Zeno behavior by showing the presence of a time gap between two consecutive connections of each agent to the cloud.

The rest of the paper is organized as follows. In section II preliminaries on the graph theory and consensus control of the multi-agent systems are provided. Formation producing control using consensus-based control laws for a group of quadcopters is proposed and derived in section III. The problem is then extended to the case when the quadcopters are connected to the cloud in section IV. Simulation results are provided in section V. Finally, the paper is wrapped up in section VI.

## II. PRELIMINARIES

In this section, first some preliminary results on the graph theory are presented, and then the underlying consensus-based control theory on double-integrator systems is presented.

### A. GRAPH THEORY

Consider the graph $\mathrm{G} = (V, A, \epsilon)$ with the adjacency matrix of $A = [a_{ij}]$ representing the communication topology of the graph. Let $V = \{1, 2, \ldots, N\}$ denote the set of graph nodes represented by $\nu_i \in V$ or $i \in V$. Also, $e_l \in (\nu_i, \nu_j)$ or $e_l = ij$, $l = 1, \ldots, M$ refers to the edges of the graph and $\epsilon = \{e_1, e_2, \ldots, e_M\}$ is the set of all edges of the graph with size of $\epsilon$ equal to $M$. It is worth noting that in undirected graphs only one of the $ij$ or $ji$ edges is in the set $\epsilon$ while in the directed graphs both edges are a member of $\epsilon$.

The incidence matrix $B = [b_{ij}]_{N\times M}$ is defined such that $b_{ij} = -1$ if the $i$-th node is tail and the $j$-th node is head and $b_{ij} = 1$ if the $i$-th node is head and the $j$-th node is tail, otherwise $b_{ij} = 0$. Besides, $\mathcal{N}_i = \{j \in V : a_{ij} \neq 0\}$ is the set of neighboring nodes of $i$-th node. $\mathcal{L}$ is used to define the Laplacian matrix of the graph G which satisfies $\mathcal{L} = BB^{\mathrm{T}}$. This property holds regardless of how the orientation of the graph G is chosen in undirected graphs. Moreover, for a graph which contains a spanning tree $\mathrm{G}_t$, the corresponding incidence matrix $B_t$ is a full column rank matrix such that $B = B_t T$ where $T = (B_t^{\mathrm{T}} B_t)^{-1} B_t^{\mathrm{T}} B$. Besides, the set of edges defining the spanning tree is $\tau \subseteq \epsilon = \{e_1, e_2, \ldots, e_{N-1}\}$ and $\mathrm{G} = \mathrm{G}_t \cup \mathrm{G}_c$ where $\mathrm{G}_c$ is the co-spanning tree. It is worth mentioning that $B_t$ is minor of $B$ containing the first $N-1$ columns and $B = [B_t \ B_c]$ where $B_c$ is the incidence matrix of $\mathrm{G}_c$.

The graph G is connected if there exists at least a path between any two distinct nodes of the graph. For a connected graph $rank(\mathcal{L}) = N - 1$. [19], [26], [30]

### B. CONSENSUS CONTROL OF MULTI-AGENTS SYSTEMS WITH DOUBLE INTEGRATOR DYNAMICS

Consider a multi-agent system described with the graph $G$ in which the $i$-th node represent the $i$-th agent with the following double-integrator dynamics:

$$\begin{aligned} \dot{\xi}_i(t) &= \zeta_i(t), \\ \dot{\zeta}_i(t) &= u_i(t). \end{aligned} \tag{1}$$

In (1), $\xi_i(t) \in \mathbb{R}$ and $\zeta_i(t) \in \mathbb{R}$ refer to the position and speed of the $i$-th agent, and $t$ refers to time. Also. $u_i(t)$ is the control input of the $i$-th agent. Now consider, the following controller for (1):

$$u_i(t) = \sum_{j\in\mathcal{N}_i} \big(\xi_j(t) - \xi_i(t)\big) + \gamma\big(\zeta_j(t) - \zeta_i(t)\big), \tag{2}$$

where $\gamma > 0$. Following [31], it can be guaranteed that $\lim\limits_{t\to\infty} |\xi_i(t) - \xi_j(t)| \to 0$ and $\lim\limits_{t\to\infty} |\zeta_i(t) - \zeta_j(t)| \to 0$. Moreover:

$$\begin{aligned} \lim_{t\to\infty} \xi_i(t) &= \frac{1}{N}\sum_{i=1}^{N} \big(\xi_i(0) + t\zeta_i(0)\big), \\ \lim_{t\to\infty} \zeta_i(t) &= \frac{1}{N}\sum_{i=1}^{N} \zeta_i(0), \end{aligned} \tag{3}$$

where $\xi_1(0)\ldots\xi_N(0)$ and $\zeta_1(0)\ldots\zeta_N(0)$ are initial positions and velocities of the agents. The consensus control presented in (2), solves the average consensus problem if $\zeta_1(0) = \cdots = \zeta_N(0)$.

## III. FORMATION PRODUCING IN MULTI-QUADCOPTER SYSTEMS

In this section, using the consensus-based control presented in II-B, appropriate controllers are introduced for the position subsystems of the quadcopters so that they guarantee the convergence of the agents' positions to the biased average consensus of their initial positions and the the convergence of the agents' velocities to the consensus value of zero (formation producing). To this end and as the first step, the controller for the altitude subsystem is developed and then through a hierarchical architecture, the control law is derived for the translational subsystems in $x$ and $y$ direction using the virtual control inputs. The virtual control inputs are introduced due to the under-actuated nature of the quadcopter system and they are used to produce the desired roll and pitch angles for the attitude control subsystem.

### A. THE ALTITUDE SUBSYSTEM

Consider the altitude dynamics of the $i$-th quadcopter subsystem as follows:

$$\ddot{z}_i(t) = \frac{u_{1i}(t)}{m_i}\big(\cos(\theta_i(t))\cos(\phi_i(t))\big) - g, \tag{4}$$

where $z_i(t)$, $\phi_i(t)$ and $\theta_i(t)$ are the altitude, roll, and pitch angles in the inertial frame and $u_{1i}(t)$ refers to the input signal which is the main thrust resulted from the combined forces of the rotors. Moreover, $m_i$ and $g$ are the quadcopter's mass and the gravity constants, respectively. Reformulating (4) in the state space form results in the following equation:

$$\begin{aligned}\dot{p}_{zi}(t) &= v_{zi}(t),\\ \dot{v}_{zi}(t) &= \Gamma_{zi}(t)u_{zi}(t) - g,\end{aligned} \tag{5}$$

where $p_{zi}(t) := z_i(t)$, $v_{zi}(t) := \dot{z}_i(t)$, $u_{zi}(t) := u_{1i}(t)$, and $\Gamma_{zi}(t) := \frac{\cos(\theta_i(t))\cos(\phi_i(t))}{m_i}$.

*Remark 1:* The singular orientation of $\cos(\phi_i(t))\cos(\theta_i(t)) = 0$ should be avoided in the attitude control as the altitude control of the quadcopter in this orientation is not possible.

Now, the main control objective is to bring the altitude of the agents to a formation defined by the bias terms $b_{z1} \dots b_{zN}$. In other words, the control objective for the altitude subsystem is formulated as follows:

$$\lim_{t\to\infty} p_{zi}(t) = \bar{p}_{zi}(0) + b_{zi}, \ \lim_{t\to\infty} v_{zi}(t) = 0, \tag{6}$$

where $\bar{.}$ here refers to average over $N$, i.e. $\bar{p}_{zi}(0) = \frac{1}{N}\sum_{i=1}^{N} p_{zi}(0)$.

*Assumption 1:* In this paper, it is assumed that $b_{zi}, i = 1 \dots N$ are selected such that $\bar{b}_{zi}(0) = 0$.

*Theorem 1:* For the altitude subsystem with the state space model presented in (5) and the consensus-based controller (7) below

$$u_{zi}(t) = \Gamma_{zi}^{-1}(t) \Big(\sum_{j\in\mathcal{N}_i} (p^*_{zj}(t) - p^*_{zi}(t)) + k_{vz}(v_{zj}(t) - v_{zi}(t)) + g\Big), \tag{7}$$

it is guaranteed that the control objective (6) is satisfied when Assumption 1 holds, $k_{vz} > 0$ and $v_{zi}(0) = 0, i, \dots, N$. Here $p^*_{zi}(t) := p_{zi}(t) - b_{zi}$,

*Proof.* Rewriting (5) in terms of $p^*_{zi}(t)$ with (7) as the controller, it can be concluded that:

$$\begin{aligned}\dot{p}^*_{zi}(t) &= v_{zi}(t),\\ \dot{v}_{zi}(t) &= u^*_{zi}(t),\end{aligned} \tag{8}$$

where

$$u^*_{zi}(t) = \sum_{j\in\mathcal{N}_i} \big(p^*_{zj}(t) - p^*_{zi}(t)\big) + k_{vz}\big(v_{zj}(t) - v_{zi}(t)\big), \tag{9}$$

Now comparing (8) and (9) with (1) and (2), one can conclude that $\lim_{t\to\infty} p^*_{zi}(t) = \bar{p}^*_{zi}(0)$. Also, $\lim_{t\to\infty} v_{zi}(t) = \bar{v}_{zi}(0) = 0$. $\lim_{t\to\infty} p^*_{zi}(t) = \bar{p}^*_{zi}(0)$ can be rewritten as $\lim_{t\to\infty} p_{zi}(t) - b_{zi} = \bar{p}_{zi}(0) - \bar{b}_{zi}$. Putting that along with Assumption 1, (6) completes the proof. □

### B. THE TRANSLATIONAL SUBSYSTEM

Consider the translational dynamic of $i$-th quadcopter in $x$ and $y$ direction as follows:

$$\ddot{x}_i(t) = \frac{u_{1i}(t)}{m_i} u_{xi}(t), \tag{10}$$

$$\ddot{y}_i(t) = \frac{u_{1i}(t)}{m_i} u_{yi}(t), \tag{11}$$

where $x_i(t)$ and $y_i(t)$ are the positions of the quad in $x$ and $y$ direction in the inertial frame and $u_{xi}(t) = \cos(\psi_i(t))\sin(\theta_i(t))\cos(\phi_i(t)) + \sin(\psi_i(t))\sin(\phi_i(t))$ and $u_{yi}(t) = \sin(\psi_i(t))\sin(\theta_i(t))\cos(\phi_i(t)) - \cos(\psi_i(t))\sin(\phi_i(t))$ with $\psi_i(t)$ is the yaw angle in the inertial frame. Therefore, the following state space models are obtained for the translational subsystems:

$$\begin{aligned}\dot{p}_{xi}(t) &= v_{xi}(t),\\ \dot{v}_{xi}(t) &= \Gamma_{xi}(t)u_{xi}(t),\end{aligned} \tag{12}$$

where $p_{xi}(t) := x_i(t)$, $v_{xi}(t) := \dot{x}_i(t)$, and $\Gamma_{xi}(t) := \frac{u_{zi}}{m_i}$.

$$\begin{aligned}\dot{p}_{yi}(t) &= v_{yi}(t),\\ \dot{v}_{yi}(t) &= \Gamma_{yi}(t)u_{yi}(t),\end{aligned} \tag{13}$$

where $p_{yi}(t) := y_i(t)$, $v_{yi}(t) := \dot{y}_i(t)$, and $\Gamma_{yi}(t) := \frac{u_{zi}}{m_i}$.

*Remark 2:* It is assumed that thrust should be generated for hovering, and hence $u_{1i}(t) \neq 0, \forall t \geq 0$.

Similar to the altitude subsystem, the control objective is to bring the $x$ and $y$ positions of the agents to a formation defined by the bias terms $b_{x1} \dots b_{xN}$ and $b_{y1} \dots b_{yN}$, respectively. In other words:

$$\lim_{t\to\infty} p_{xi}(t) = \bar{p}_{xi}(0) + b_{xi}, \ \lim_{t\to\infty} v_{xi}(t) = 0. \tag{14}$$

$$\lim_{t\to\infty} p_{yi}(t) = \bar{p}_{yi}(0) + b_{yi}, \ \lim_{t\to\infty} v_{yi}(t) = 0. \tag{15}$$

*Assumption 2:* Throughout this paper it is assumed $b_{xi}, i = 1 \dots N$ and $b_{yi}, i = 1 \dots N$ are selected such that $\bar{b}_{xi} = 0$ and $\bar{b}_{yi} = 0$.

*Theorem 2:* For the translational subsystems with the state space model presented in (12) and (13) and the following virtual control laws:

$$u_{xi}(t) = \Gamma_{xi}^{-1}(t) \Big(\sum_{j\in\mathcal{N}_i} \big(p^*_{xj}(t) - p^*_{xi}(t)\big) + k_{vx}\big(v_{xj}(t) - v_{xi}(t)\big)\Big), \tag{16}$$

$$u_{yi}(t) = \Gamma_{yi}^{-1}(t) \Big(\sum_{j\in\mathcal{N}_i} \big(p^*_{yj}(t) - p^*_{yi}(t)\big) + k_{vy}\big(v_{yj}(t) - v_{yi}(t)\big)\Big), \tag{17}$$

it is guaranteed that the control objective (14) and (15) are satisfied when Assumption 2 holds, where $p^*_{xi}(t) := p_{xi}(t) - b_{xi}$ and $p^*_{yi}(t) := p_{yi}(t) - b_{yi}$, $k_{vx} > 0$, $k_{vy} > 0$, $v_{xi}(0) = 0, i, \ldots, N$, and $v_{yi}(0) = 0, i, \ldots, N$.

*Proof.* The proof is ommitted here due to similarity with the proof of Theorem 1.

## IV. CLOUD-CONNECTED FORMATION CONTROL OF QUADCOPTERS

As mentioned earlier, in this paper, it is assumed that the information between the quadcopters is transferred (uploaded) to the cloud storage at appropriate designed scheduling times and the agents also download the information from the neighboring agents from the cloud at the same times. Let $t_{i,k}$ be the $k$-th time that $i$-th agent accesses to the cloud and uploads its information packet including its own control signals, the states and the next access time to the cloud. Also, the agents download the information related to the neighboring agents from their last connections to the cloud, happening before $t_{i,k}$ at $t_{j,l_j(t_{i,k})}, j \in \mathcal{N}_i$ with $l_j(t) = \max\{k \in \mathbb{N} : t_{j,k} \le t\}$. It is worth mentioning that multiple accesses of the neighboring agents to the cloud is possible between $t_{i,k}$ and $t_{i,k+1}$, which are shown as $t_{j,l_j(t_{i,k})+1}, t_{j,l_j(t_{i,k})+2}, \ldots, j \in \mathcal{N}_i$. Here, these agents are shown with $\mathcal{N}'_{i,k} \in \mathcal{N}_i$. Since the neighboring agents' information is not available at time instant $t_{i,k}$, it is proposed to use their estimation.

### A. ALTITUDE SUBSYSTEM

According to the discussion above, the altitude controller in (7) is transformed to the following control law under the cloud access:

$$u_{zi,k}(t) = \Gamma^{-1}_{zi}(t_{i,k})\Big( \sum_{j\in\mathcal{N}_i} \big(\hat{p}^{*i,k}_{zj}(t_{i,k}) - p^*_{zi}(t_{i,k})\big) + k_{vz}\big(\hat{v}^{i,k}_{zj}(t_{i,k}) - v_{zi}(t_{i,k})\big) + g\Big), \tag{18}$$

where according to (5):

$$\begin{aligned} \hat{v}^{i,k}_{zj}(t) &= v_{zj}(t_{l_j(t_{i,k})}) + \\ &(t - t_{l_j(t_{i,k})})\big(\Gamma_{zj}(t_{l_j(t_{i,k})})u_{zj}(t_{l_j(t_{i,k})}) - g\big), \\ &t \in [t_{i,k}, t_{j,l_j(t_{i,k})+1}) \end{aligned} \tag{19a}$$

$$\hat{v}^{i,k}_{zj}(t) = \hat{v}^{i,k}_{zj}(t_{j,l_j(t_{i,k})+1}), t \ge t_{j,l_j(t_{i,k})+1} \tag{19b}$$

Besides:

$$\hat{p}^{*i,k}_{zj}(t) = p^*_{zj}(t_{l_j(t_{i,k})}) + \int_{t_{j,l_j(t_{i,k})}}^{t} \hat{v}^{i,k}_{zj}(\tau)d\tau. \tag{20}$$

Now, let define the difference between the real control signal and the one under cloud access as follows:

$$\tilde{u}_{zi}(t) = u_{zi,k}(t) - u_{zi}(t). \tag{21}$$

Moreover, let $\tilde{U}_z(t) = [\tilde{u}_{z1}(t) \ldots \tilde{u}_{zN}(t)]^{\mathrm{T}}$, $U_z(t) = [u_{z1}(t) \ldots u_{zN}(t)]^{\mathrm{T}}$ and $U_{z,k}(t) = [u_{z1,k}(t) \ldots u_{zN,k}(t)]^{\mathrm{T}}$. Therefore one can write:

$$U_{z,k}(t) = U_z(t) + \tilde{U}_z(t), \tag{22}$$

where according to (7), $U_{zi}(t)$ can be written as follows:

$$U_z(t) = \Gamma^{-1}_z(t)\Big(G - \mathcal{L}\big(P^*_z(t) + k_{vz}V_z(t)\big)\Big), \tag{23}$$

where $P^*_z(t) = [p^*_{z1}(t) \ldots p^*_{zN}(t)]^{\mathrm{T}}, V_z(t) = [v_{z1}(t) \ldots v_{zN}(t)]^{\mathrm{T}}$, $G = g1_N$ and $\Gamma_z(t) = \mathrm{diag}\big(\Gamma_{z1}(t) \ldots \Gamma_{zN}(t)\big)$. Besides, according to (5) and (8), the collective altitude state space model can be rewritten as follows:

$$\begin{aligned} \dot{P}^*_z(t) &= V_z(t), \\ \dot{V}_z(t) &= \Gamma_z(t)U_z(t) - G. \end{aligned} \tag{24}$$

Now, by replacing (23) into (22) and substituting $U_{zi,k}$ into (24) instead of $U_z(t)$ results in:

$$\begin{aligned} \dot{P}^*_z(t) &= V_z(t), \\ \dot{V}_z(t) &= -\mathcal{L}\big(P^*_z(t) + k_{vz}V_z(t)\big) + \Gamma_z(t)\tilde{U}_z(t). \end{aligned} \tag{25}$$

### B. TRANSLATIONAL SUBSYSTEMS

Similarly, according to (16), for the translational subsystem in $x$ direction, one can employ the following controller:

$$u_{xi,k}(t) = \Gamma^{-1}_{xi}(t_{i,k})\Big( \sum_{j\in\mathcal{N}_i} \big(\hat{p}^{*i,k}_{xj}(t_{i,k}) - p^*_{xi}(t_{i,k})\big) + k_{vx}\big(\hat{v}^{i,k}_{xj}(t_{i,k}) - v_{xi}(t_{i,k})\big)\Big), \tag{26}$$

where according to (12):

$$\begin{aligned} \hat{v}^{i,k}_{xj}(t) &= v_{xj}(t_{l_j(t_{i,k})}) + \\ &(t - t_{l_j(t_{i,k})})\big(\Gamma_{xj}(t_{l_j(t_{i,k})})u_{xj}(t_{l_j(t_{i,k})})\big), \\ &t \in [t_{i,k}, t_{j,l_j(t_{i,k})+1}) \end{aligned} \tag{27a}$$

$$\hat{v}^{i,k}_{xj}(t) = \hat{v}^{i,k}_{xj}(t_{j,l_j(t_{i,k})+1}), t \ge t_{j,l_j(t_{i,k})+1}. \tag{27b}$$

Besides:

$$\hat{p}^{*i,k}_{xj}(t) = p^*_{xj}(t_{l_j(t_{i,k})}) + \int_{t_{j,l_j(t_{i,k})}}^{t} \hat{v}^{i,k}_{xj}(\tau)d\tau. \tag{28}$$

Similar to (21), it can be written:

$$\tilde{u}_{xi}(t) = u_{xi,k}(t) - u_{xi}(t). \tag{29}$$

Besides, let $\tilde{U}_x(t) = [\tilde{u}_{x1}(t) \ldots \tilde{u}_{xN}(t)]^{\mathrm{T}}$, $U_x(t) = [u_{x1}(t) \ldots u_{xN}(t)]^{\mathrm{T}}$, $U_{x,k}(t) = [u_{x1,k}(t) \ldots u_{xN,k}(t)]^{\mathrm{T}}$, $P^*_x(t) = [p^*_{x1}(t) \ldots p^*_{xN}(t)]^{\mathrm{T}}$, $V_x(t) = [v_{x1}(t) \ldots v_{xN}(t)]^{\mathrm{T}}$, and $\Gamma_x(t) = \mathrm{diag}\big(\Gamma_{x1}(t) \ldots \Gamma_{xN}(t)\big)$. By following a procedure similar to the altitude subsystem, it can be written:

$$\begin{aligned} \dot{P}^*_x(t) &= V_x(t), \\ \dot{V}_x(t) &= -\mathcal{L}\big(P^*_x(t) + k_{vz}V_x(t)\big) + \Gamma_x(t)\tilde{U}_x(t). \end{aligned} \tag{30}$$

For the translational subsystem in $y$ direction, similar to (26) to (28) the following controller under the cloud access can be proposed:

$$u_{yi,k}(t) = \Gamma^{-1}_{yi}(t_{i,k})\Big( \sum_{j\in\mathcal{N}_i} \big(\hat{p}^{*i,k}_{yj}(t_{i,k}) - p^*_{yi}(t_{i,k})\big) + k_{vx}\big(\hat{v}^{i,k}_{yj}(t_{i,k}) - v_{yi}(t_{i,k})\big)\Big), \tag{31}$$

According to (13):

$$\begin{aligned}\hat{v}_{yj}^{i,k}(t) &= v_{yj}(t_{l_j(t_{i,k})})+\\ &(t-t_{l_j(t_{i,k})})\big(\Gamma_{yj}(t_{l_j(t_{i,k})})u_{yj}(t_{l_j(t_{i,k})})\big),\\ &t\in[t_{i,k},t_{j,l_j(t_{i,k})+1})\end{aligned} \tag{32a}$$

$$\hat{v}_{yj}^{i,k}(t) = \hat{v}_{yj}^{i,k}(t_{j,l_j(t_{i,k})+1}), t \geq t_{j,l_j(t_{i,k})+1}. \tag{32b}$$

Besides

$$\hat{p}_{yj}^{*i,k}(t) = p_{yj}^*(t_{l_j(t_{i,k})}) + \int_{t_{j,l_j(t_{i,k})}}^{t} \hat{v}_{yj}^{i,k}(\tau)d\tau. \tag{33}$$

Similar to (21), it can be written:

$$\tilde{u}_{yi}(t) = u_{yi,k}(t) - u_{yi}(t). \tag{34}$$

Besides, let $\tilde{U}_y(t) = [\tilde{u}_{y1}(t)\dots\tilde{u}_{yN}(t)]^{\mathrm{T}}$, $U_y(t) = [u_{y1}(t)\dots u_{yN}(t)]^{\mathrm{T}}$, $U_{y,k}(t) = [u_{y1,k}(t)\dots u_{yN,k}(t)]^{\mathrm{T}}$, $P_y^*(t) = [p_{x1}^*(t)\dots p_{yN}^*(t)]^{\mathrm{T}}$, $V_y(t) = [v_{y1}(t)\dots v_{yN}(t)]^{\mathrm{T}}$, and $\Gamma_y(t) = \mathrm{diag}(\Gamma_{y1}(t)\dots\Gamma_{yN}(t))$. By following a procedure similar to the altitude subsystem, the following is obtained:

$$\begin{aligned}\dot{P}_y^*(t) &= V_y(t),\\ \dot{V}_y(t) &= -\mathcal{L}\big(P_y^*(t) + k_{vy}V_y(t)\big) + \Gamma_y(t)\tilde{U}_y(t).\end{aligned} \tag{35}$$

### C. CLOUD-CONNECTED PRACTICAL CONSENSUS OF THE QUADCOPTER SYSTEMS

Now, let define the edge states ( [26]) which represents the difference between the agents' states with the assumption that the connectivity graph contains a spanning tree with the corresponding incidence matrix $B_t$. For the altitude subsystem let $X_z(t) := B_t^{\mathrm{T}}P_z^*$, $Y_z(t) := B_t^{\mathrm{T}}V_z$ and $\mu_z(t) = [X_z^{\mathrm{T}}(t)\ \ Y_z^{\mathrm{T}}(t)]^{\mathrm{T}}$. For the translational subsystem in $x$ direction let $X_x(t) := B_t^{\mathrm{T}}P_x^*$, $Y_x(t) := B_t^{\mathrm{T}}V_x$, $\mu_x(t) = [X_x^{\mathrm{T}}(t)\ \ Y_x^{\mathrm{T}}(t)]^{\mathrm{T}}$ and in $y$ direction let $X_y(t) := B_t^{\mathrm{T}}P_y^*$, $Y_y(t) := B_t^{\mathrm{T}}V_y$ and $\mu_y(t) = [X_y^{\mathrm{T}}(t)\ Y_y^{\mathrm{T}}(t)]^{\mathrm{T}}$.

*Definition 1:* [26] The multi-quadcopter system achieves practical consensus if there exists $\chi_z \geq 0$, $\chi_x \geq 0$ and $\chi_y \geq 0$ such that $\lim_{t\to\infty}\|\mu_z(t)\| \leq \chi_z$, $\lim_{t\to\infty}\|\mu_x(t)\| \leq \chi_x$, and $\lim_{t\to\infty}\|\mu_y(t)\| \leq \chi_y$.

*Theorem 3:* For a multi-quadcopter system formulated in (5), (12), and (13) with the controllers under cloud access presented in (18), (26) and (31), respectively, if $|\tilde{u}_{zi}(t)| \leq \zeta_z$, $|\tilde{u}_{xi}(t)| \leq \zeta_x$ and $|\tilde{u}_{yi}(t)| \leq \zeta_y$ where $\zeta_z$, $\zeta_x$ and $\zeta_y$ are positive values, then the practical consensus is solved with the following $\chi_z$, $\chi_x$ and $\chi_y$:

$$\chi_z = \frac{\sqrt{N}}{m_{min}}\|B_t\|\frac{\zeta_z}{\lambda_z}, \tag{36}$$

where $\lambda_z = -\max\{Re(\lambda_{H_z}) : \lambda_{H_z} \in eig(H_z)\}$ where $H_z = \begin{bmatrix}\mathbf{0}_{(N-1)} & \mathbf{I}_{(N-1)}\\ -B_t^{\mathrm{T}}BT^{\mathrm{T}} & -k_{vz}B_t^{\mathrm{T}}BT^{\mathrm{T}}\end{bmatrix}$, $m_{min}$ is the minimum weights of the quadcopters and:

$$\chi_x = \frac{\sqrt{N}}{m_{min}}\|B_t\|\frac{\zeta_x u_{zmax}}{\lambda_x}, \tag{37}$$

where $\lambda_x = -\max\{Re(\lambda_{H_x}) : \lambda_{H_x} \in eig(H_x)\}$ where $H_x = \begin{bmatrix}\mathbf{0}_{(N-1)} & \mathbf{I}_{(N-1)}\\ -B_t^{\mathrm{T}}BT^{\mathrm{T}} & -k_{vx}B_t^{\mathrm{T}}BT^{\mathrm{T}}\end{bmatrix}$ and $u_{zmax}$ is the maximum value of $u_{zi,k}(t)$ as $t\to\infty$ (see appendix B) and:

$$\chi_y = \frac{\sqrt{N}}{m_{min}}\|B_t\|\frac{\zeta_y u_{zmax}}{\lambda_y}, \tag{38}$$

where $\lambda_y = -\max\{Re(\lambda_{H_y}) : \lambda_{H_y} \in eig(H_y)\}$ where $H_y = \begin{bmatrix}\mathbf{0}_{(N-1)} & \mathbf{I}_{(N-1)}\\ -B_t^{\mathrm{T}}BT^{\mathrm{T}} & -k_{vy}B_t^{\mathrm{T}}BT^{\mathrm{T}}\end{bmatrix}$.

*Proof.* First consider the altitude subsystem as presented in (25) and multiply the model by $B_t^{\mathrm{T}}$ from the left side. Using the fact that $\mathcal{L} = BT^{\mathrm{T}}B_t^{\mathrm{T}}$ , it can be concluded that:

$$\begin{aligned}\dot{X}_z(t) &= Y_z(t),\\ \dot{Y}_z(t) &= -B_t^{\mathrm{T}}BT^{\mathrm{T}}\big(X_z(t) + k_{vz}Y_z(t)\big) + B_t^{\mathrm{T}}\Gamma_z(t)\tilde{U}_z(t).\end{aligned} \tag{39}$$

Therefore:

$$\dot{\mu}_z(t) = H_z(t)\mu_z(t) + F_z(t)\tilde{U}_z(t), \tag{40}$$

where $H_z(t)$ is presented in (36) and $F_z(t) = B_t^{\mathrm{T}}\Gamma_z(t)$. The solution of (40) can be written as:

$$\mu_z(t) = e^{H_z(t)t} + \int_0^t e^{H_z(\tau)(t-\tau)}F_z(\tau)\tilde{U}_z(\tau)d\tau. \tag{41}$$

It can be proved that $H_z(t)$ is Hurwitz (see appendix A). Using the property that $\|e^{H_z(\tau)(t-\tau)}\| \leq e^{-\lambda_z(t-\tau)}$ ( [26]), $\|F_z(t)\| \leq \|B_t\|\|\Gamma_z(t)\| \leq \frac{\|B_t\|}{m_{min}}$, $\|\mu_z(0)\| \leq \mu_{z0}$ and the triangular inequality, the following is given:

$$\|\mu_z(t)\| \leq \alpha_z(t), \tag{42}$$

where

$$\alpha_z(t) = e^{-\lambda_z t}\mu_{z0} + \sqrt{N}\zeta_z\frac{\|B_t\|}{m_{min}}\int_0^t e^{-\lambda_z(t-\tau)}d\tau. \tag{43}$$

Therefore, $\lim_{t\to\infty}\|\mu_z(t)\| \leq \chi_z$ where $\chi_z$ is presented in (36). Multiplying the translational subsystem (30) in $x$ direction by $B_t^{\mathrm{T}}$ from the left side, and following something similar to (40) yields

$$\dot{\mu}_x(t) = H_x(t)\mu_x(t) + F_x(t)\tilde{U}_x(t), \tag{44}$$

where $H_x(t)$ is presented in (37) and $F_x(t) = B_t^{\mathrm{T}}\Gamma_x(t_{i,k})$. Solving (44) similar to (41) and using the properties of $\|e^{H_x(\tau)(t-\tau)}\| \leq e^{-\lambda_x(t-\tau)}$, $\|F_x(t)\| \leq \|B_t\|\|\Gamma_x(t_{i,k})\| \leq \frac{\|B_t\|u_{zmax}}{m_{min}}$, $\|\mu_x(0)\| \leq \mu_{x0}$ and the triangular inequality, the similar inequality as (42) is obtained as follows:

$$\|\mu_x(t)\| \leq \alpha_x(t), \tag{45}$$

where

$$\alpha_x(t) = e^{-\lambda_x t}\mu_{x0} + \sqrt{N}\zeta_x\frac{\|B_t\|u_{zmax}}{m_{min}}\int_0^t e^{-\lambda_x(t-\tau)}d\tau. \tag{46}$$

Thus, $\lim_{t\to\infty} \|\mu_x(t)\| \leq \chi_x$ where $\chi_x$ is presented in (37). A similar proof can be provided for $\lim_{t\to\infty} \|\mu_y(t)\| \leq \chi_y$ with $\chi_y$ presented in (38). It is worth noting that $H_x(t)$ and $H_y(t)$ are Hurwitz with a similar proof provided in appendix A for $H_z(t)$ . □

### D. DESIGN OF THE SCHEDULING RULE

In this subsection, the scheduling rule determining the next time that each agent accesses to cloud is designed.

*Theorem 4:* For a multi-quadcopter system formulated in (5), (12) and (13) with the controllers under the cloud access presented in (18), (26) and (31), and the scheduling rules below:

$$t_{i,k+1} = \min\{t > t_{i,k} : \sigma_{zi}(t) \geq \zeta_z, \sigma_{xi}(t) \geq \zeta_x, \sigma_{yi}(t) \geq \zeta_y\}, \quad (47)$$

where

$$\sigma_{zi}(t) = \theta_{zi}(t) + \phi_{zi}(t), \quad (48a)$$

$$\theta_{zi}(t) = \|u_{zi,k} - \Gamma_{zi}^{-1}(t_{i,k})\Big(\sum_{j\in\mathcal{N}_i} \big(\hat{p}_{zj}^{*i,k}(t) - \hat{p}_{zi}^{*i,k}(t)\big) + k_{vz}\big(\hat{v}_{zj}^{i,k}(t) - \hat{v}_{zi}^{i,k}(t)\big) + g\Big)\|, \quad (48b)$$

$$\phi_{zi}(t) = \gamma_z \sum_{j\in\mathcal{N}'_{i,k}} \Big( \int_{t_{j,l(t_{i,k})+1}}^{t} \int_{t_{j,l(t_{i,k})+1}}^{\tau} \big(\frac{\eta_{zj}(\theta)}{m_{min}} + g\big) d\theta + k_{vz} \int_{t_{j,l(t_{i,k})+1}}^{t} \big(\frac{\eta_{zj}(\tau)}{m_{min}} + g\big) d\tau \Big), \quad (48c)$$

and $\gamma_z$ and $\eta_{zj}(t)$ are defined in appendix B and

$$\sigma_{xi}(t) = \theta_{xi}(t) + \phi_{xi}(t), \quad (49a)$$

$$\theta_{xi}(t) = \|u_{xi,k} - \Gamma_{xi}^{-1}(t_{i,k})\Big(\sum_{j\in\mathcal{N}_i} \big(\hat{p}_{xj}^{*i,k}(t) - \hat{p}_{xi}^{*i,k}(t)\big) + k_{vx}\big(\hat{v}_{xj}^{i,k}(t) - \hat{v}_{xi}^{i,k}(t)\big)\Big)\|, \quad (49b)$$

$$\phi_{xi}(t) = \frac{\gamma_x \bar{\eta}_z}{m_{min}} \sum_{j\in\mathcal{N}'_{i,k}} \Big( \int_{t_{j,l(t_{i,k})+1}}^{t} \int_{t_{j,l(t_{i,k})+1}}^{\tau} \eta_{xj}(\theta) d\theta d\tau + k_{vx} \int_{t_{j,l(t_{i,k})+1}}^{t} \eta_{xj}(\tau) d\tau \Big), \quad (49c)$$

where $\bar{\eta}_z$ is the maximum value for $\eta_{zj}(t)$ and $\gamma_x$ defined in appendix B and

$$\sigma_{yi}(t) = \theta_{yi}(t) + \phi_{yi}(t), \quad (50a)$$

$$\theta_{yi}(t) = \|u_{yi,k} - \Gamma_{yi}^{-1}(t_{i,k})\Big(\sum_{j\in\mathcal{N}_i} \big(\hat{p}_{yj}^{*i,k}(t) - \hat{p}_{yi}^{*i,k}(t)\big) + k_{vy}\big(\hat{v}_{yj}^{i,k}(t) - \hat{v}_{yi}^{i,k}(t)\big)\Big)\|, \quad (50b)$$

$$\phi_{yi}(t) = \frac{\gamma_y \bar{\eta}_z}{m_{min}} \sum_{j\in\mathcal{N}'_{i,k}} \Big( \int_{t_{j,l(t_{i,k})+1}}^{t} \int_{t_{j,l(t_{i,k})+1}}^{\tau} \eta_{yj}(\theta) d\theta d\tau + k_{vy} \int_{t_{j,l(t_{i,k})+1}}^{t} \eta_{yj}(\tau) d\tau \Big), \quad (50c)$$

where $\gamma_y = \gamma_x$.

Then the practical consensus presented in Theorem 3 is guaranteed.

*Proof.* First we consider the altitude subsystem. The main goal is to compute the next access time to the cloud such that the condition $|\tilde{u}_{zi}(t)| \leq \zeta_z$ is contradicted. By using (7), (18) and (21), $\tilde{u}_{zi}(t)$ is computed. For this purpose, we consider two different kinds of neighboring agents. The first ones have no access to the cloud in $t \in [t_{i,k}, t_{i,k+1})$ and the second ones have access to the cloud during this period of time. The second kind is shown with the set $\mathcal{N}'_{i,k}$ or the agents $j \in \mathcal{N}'_{i,k}$ and their first access time during this period is shown by $t_{j,l(t_{i,k})+1}$. For the first kind of agents it is possible to approximate $v_{zj}(t)$ and $p^*_{zj}(t)$ with (19a) and (20) respectively, for $t \in [t_{i,k}, t_{i,k+1})$. However, for the second one since $j \in \mathcal{N}'_{i,k}$ this approximation is written as

$$v_{zj}(t) \approx \hat{v}_{zj}^{i,k}(t) + \int_{t_{j,l(t_{i,k})+1}}^{t} \big(\Gamma_{zj}(\tau) u_{zj}(\tau) - g\big) d\tau. \quad (51)$$

and

$$p^*_{zj}(t) \approx \hat{p}_{zj}^{*i,k}(t) + \int_{t_{j,l(t_{i,k})+1}}^{t} \int_{t_{j,l(t_{i,k})+1}}^{\tau} \big(\Gamma_{zj}(\theta) u_{zj}(\theta) - g\big) d\theta d\tau. \quad (52)$$

Besides, $v_{zi}(t)$ and $p^*_{zi}(t)$ in $u_i(t)$ are approximated for $t \in [t_{i,k}, t_{i,k+1})$ as $v_{zi}(t) \approx \hat{v}_{zi}^{i,k}(t)$ and $p^*_{zi}(t) \approx \hat{p}_{zi}^{*i,k}(t)$, respectively.

Therefore, after approximating $\Gamma_{zi}(t)$ with $\Gamma_{zi}(t_{i,k})$ for $t \in [t_{i,k}, t_{j,l(t_{i,k})+1})$ and with $\Gamma_{zi}(t_{j,l(t_{i,k})+1})$ for $t \in$

$[t_{j,l(t_{i,k})+1}, t_{i,k+1})$ we arrive (53) as follows:

$$\tilde{u}_{zi}(t) = u_{zi,k} - \Gamma_{zi}^{-1}(t_{i,k})\Big(\sum_{j\in\mathcal{N}_i}((\hat{p}_{zj}^{*i,k}(t) - \hat{p}_{zi}^{*i,k}(t)) + k_{vz}(\hat{v}_{zj}^{i,k}(t) - \hat{v}_{zi}^{i,k}(t))) + g\Big) - \Gamma_{zi}^{-1}(t_{j,l(t_{i,k})+1}) \Big(\sum_{j\in\mathcal{N}'_{i,k}}\Big(\int_{t_{j,l(t_{i,k})+1}}^{t}\int_{t_{j,l(t_{i,k})+1}}^{\tau}(\Gamma_{zj}(t_{j,l(t_{i,k})+1})u_{zj}(\theta) - g)d\theta d\tau + k_{vz}\int_{t_{j,l(t_{i,k})+1}}^{t}(\Gamma_{zj}(t_{j,l(t_{i,k})+1})u_{zj}(\tau) - g)d\tau\Big)\Big). \quad (53)$$

Now according to appendix B, stating $|\Gamma_{zi}^{-1}(t)| \le \gamma_z$ and $|u_{zi}(t)| < \eta_{zi}(t)$ in (82) and by using triangular inequality and the fact that $|\Gamma_{zj}(t)| \le \frac{1}{m_{min}}$, it can be concluded that $|\tilde{u}_{zi}(t)| \le \sigma_{zi}(t) = \theta_{zi}(t) + \phi_{zi}(t)$, where $\theta_{zi}(t)$ and $\phi_{zi}(t)$ are defined in (48a) according to (53) and (82).
For the translational subsystem in $x$ direction, the main goal is to compute the next access time to the cloud such that the condition $|\tilde{u}_{xi}(t)| \le \zeta_x$ is contradicted. Now by using (16), (26) and (29), we can compute $\tilde{u}_{xi}(t)$. For this purpose, similar to the previous step we consider two different kinds of neighboring agents. For the first one there is no access to the cloud in $t \in [t_{i,k}, t_{i,k+1})$ and the second one has access to the cloud during this time at $t_{j,l(t_{i,k})+1}$ and for the agents $j \in \mathcal{N}'_{i,k}$. For the first kind of agents it is possible to approximate $v_{xj}(t)$ and $p_{xj}^*(t)$ with (27a) and (28) for $t \in [t_{i,k}, t_{i,k+1})$. However, for the second one $j \in \mathcal{N}'_{i,k}$ and according to (12) this approximation can be written as:

$$v_{xj}(t) \approx \hat{v}_{xj}^{i,k}(t) + \int_{t_{j,l(t_{i,k})+1}}^{t}(\Gamma_{xj}(\tau)u_{xj}(\tau))d\tau. \quad (54)$$

and

$$p_{xj}^*(t) \approx \hat{p}_{xj}^{*i,k}(t) + \int_{t_{j,l(t_{i,k})+1}}^{t}\int_{t_{j,l(t_{i,k})+1}}^{\tau}(\Gamma_{xj}(\theta)u_{xj}(\theta))d\theta d\tau. \quad (55)$$

Besides, $v_{xi}(t)$ and $p_{xi}^*(t)$ in $u_{xi}(t)$ for $t \in [t_{i,k}, t_{i,k+1})$ are approximated as $v_{xi}(t) \approx \hat{v}_{xi}^{i,k}(t)$ and $p_{zi}^*(t) \approx \hat{p}_{xi}^{*i,k}(t)$, respectively. Therefore, after approximating $\Gamma_{xi}(t)$ with $\Gamma_{xi}(t_{i,k})$ for $t \in [t_{i,k}, t_{j,l(t_{i,k})+1})$ and with $\Gamma_{xi}(t_{j,l(t_{i,k})+1})$ for $t \in [t_{j,l(t_{i,k})+1}, t_{i,k+1})$, the following is obtained:

$$\tilde{u}_{xi}(t) = u_{xi,k} - \Gamma_{xi}^{-1}(t_{i,k})\Big(\sum_{j\in\mathcal{N}_i}((\hat{p}_{xj}^{*i,k}(t) - \hat{p}_{xi}^{*i,k}(t)) + k_{vx}(\hat{v}_{xj}^{i,k}(t) - \hat{v}_{xi}^{i,k}(t)))\Big) - \Gamma_{(}^{-1}t_{j,l(t_{i,k})+1}) \Big(\sum_{j\in\mathcal{N}'_{i,k}}\Big(\int_{t_{j,l(t_{i,k})+1}}^{t}\int_{t_{j,l(t_{i,k})+1}}^{\tau}(\Gamma_{xj}(t_{j,l(t_{i,k})+1})u_{xj}(\theta))d\theta d\tau + k_{vx}\int_{t_{j,l(t_{i,k})+1}}^{t}(\Gamma_{xj}(t_{j,l(t_{i,k})+1})u_{xj}(\tau))d\tau\Big)\Big) \quad (56)$$

Now, according to appendix B, stating $|\Gamma_{xi}^{-1}(t)| \le \gamma_x$ and by using triangular inequality, and the fact that $|\Gamma_{xj}(t)| \le \frac{\bar{\eta}_z}{m_{min}}$, it can be concluded that $|\tilde{u}_{xi}(t)| \le \sigma_{xi}(t) = \theta_{xi}(t) + \phi_{xi}(t)$, where $\theta_{xi}(t)$ and $\phi_{xi}(t)$ are defined in (49a) according to (56) and appendix B.
A similar proof can be provided for the translational subsystem in the $y$ direction resulting in (50a). $\square$

### E. ZENO BEHAVIOR ANALYSIS

*Theorem 5:* For the multi-quadcopter system with the state space model presented in (5), (12) and (13) and the control laws presented in (18), (26), (31), under the cloud access with the scheduling rule introduced in (47), the system does not show Zeno behavior.

*Proof.* First, we consider the altitude subsystem. Then, $\hat{v}_{zi}^{i,k}(t)$, $\hat{v}_{zj}^{i,k}(t)$, $\hat{p}_{zi}^{*i,k}(t)$ and $\hat{p}_{zj}^{*i,k}(t)$ are defined as follows:

$$\hat{v}_{zi}^{i,k}(t) = v_{zi}(t_{i,k}) + \int_{t_{i,k}}^{t}(\Gamma_{zi}(\tau)u_{zi}(\tau) - g)d\tau. \quad (57)$$

$$\hat{v}_{zj}^{i,k}(t) = \hat{v}_{zj}^{i,k}(t_{i,k}) + \int_{t_{i,k}}^{t'}(\Gamma_{zj}(\tau)u_{zj}(\tau) - g)d\tau, \quad (58)$$

where $t' = \min\{t, t_{j,l_j(t_{i,k})+1}\}$. Also

$$\hat{p}_{zi}^{*i,k}(t) = p_{zi}^*(t_{i,k}) + \int_{t_{i,k}}^{t}\int_{t_{i,k}}^{\tau}(\Gamma_{zi}(\theta)u_{zi}(\theta) - g)d\theta d\tau. \quad (59)$$

$$\hat{p}_{zj}^{*i,k}(t) = \hat{p}_{zj}^{*i,k}(t_{i,k}) + \int_{t_{i,k}}^{t'}\int_{t_{i,k}}^{\tau}(\Gamma_{zj}(\theta)u_{zj}(\theta) - g)d\theta d\tau. \quad (60)$$

Therefore, substituting (18) and (57)-(60) into (48b) yields:

$$\theta_{zi}(t) = \|\Gamma_{zi}^{-1}(t_{i,k})\Big( \sum_{j\in\mathcal{N}_i} \int_{t_{i,k}}^{t}\int_{t_{i,k}}^{\tau} \big(\Gamma_{zi}(\theta)u_{zi}(\theta) - g\big)d\theta d\tau - \int_{t_{i,k}}^{t'}\int_{t_{i,k}}^{\tau} \big(\Gamma_{zj}(\theta)u_{zj}(\theta) - g\big)d\theta d\tau + k_{vz} \Big(\int_{t_{i,k}}^{t'} \big(\Gamma_{zj}(\tau)u_{zj}(\tau) - g\big)d\tau - \int_{t_{i,k}}^{t} \big(\Gamma_{zi}(\tau)u_{zi}(\tau) - g\big)d\tau\Big)\Big)\|. \tag{61}$$

According to appendix B, we have $|\Gamma_{zi}^{-1}| \leq \gamma_z$ and $|u_{zi}(t)| \leq \eta_{zi}(t)$. Besides, since $\eta_{zi}(t) := \gamma_z g + \gamma_z\beta_{zi}\alpha_z(t)$ it can be concluded that $|\eta_{zi}(t)| \leq \eta_{z,max}$. Moreover, $\Gamma_{zi}(t) \leq \frac{1}{m_{min}}$. By using these results in (61) and applying the triangular inequality and using (48a) and (48c) it can be concluded that:

$$\sigma_{zi}(t) \leq \gamma_z(\frac{\eta_{z,max}}{m_{min}} + g)N_i\big((t - t_{i,k})^2 + 2k_{vz}(t - t_{i,k})\big), \tag{62}$$

where $N_i$ refers to the number of neighboring agents of the $i$-th agent. Using (62) and condition $\sigma_{zi}(t) \geq \zeta_z$ in (47) the following quadratic inequality is achieved:

$$\gamma_z(\frac{\eta_{z,max}}{m_{min}} + g)N_i\big((t - t_{i,k})^2 + 2k_{vz}(t - t_{i,k})\big) \geq \zeta_z. \tag{63}$$

The solutions for (63) are such that $t_{i,k+1} - t_{i,k} \geq \tau_{z1} > 0$ or $t_{i,k+1} - t_{i,k} \leq \tau_{z2} < 0$ where the later is unacceptable. Therefore:

$$t_{i,k+1} \geq t_{i,k} + \tau_{z1}. \tag{64}$$

Similarly, for the translational subsystem in the $x$ direction, $\hat{v}_{xi}^{i,k}(t)$, $\hat{v}_{xj}^{i,k}(t)$, $\hat{p}_{xi}^{*i,k}(t)$ and $\hat{p}_{xj}^{*i,k}(t)$ can be calculated as:

$$\hat{v}_{xi}^{i,k}(t) = v_{xi}^{i,k}(t_{i,k}) + \int_{t_{i,k}}^{t} \Gamma_{xi}(\tau)u_{xi}(\tau)d\tau. \tag{65}$$

$$\hat{v}_{xj}^{i,k}(t) = \hat{v}_{xj}^{i,k}(t_{i,k}) + \int_{t_{i,k}}^{t'} \Gamma_{xj}(\tau)u_{zj}(\tau)d\tau, \tag{66}$$

$$\hat{p}_{xi}^{*i,k}(t) = p_{xi}^{*}(t_{i,k}) + \int_{t_{i,k}}^{t}\int_{t_{i,k}}^{\tau} \Gamma_{xi}(\theta)u_{xi}(\theta)d\theta d\tau. \tag{67}$$

$$\hat{p}_{xj}^{*i,k}(t) = \hat{p}_{xj}^{*i,k}(t_{i,k}) + \int_{t_{i,k}}^{t'}\int_{t_{i,k}}^{\tau} \Gamma_{xj}(\theta)u_{xj}(\theta)d\theta d\tau. \tag{68}$$

Now substituting (26) and (65)-(68) into (49b) results in

$$\theta_{xi}(t) = \|\Gamma_{xi}^{-1}(t_{i,k})\Big( \sum_{j\in\mathcal{N}_i} \int_{t_{i,k}}^{t}\int_{t_{i,k}}^{\tau} \Gamma_{xi}(\theta)u_{xi}(\theta)d\theta d\tau - \int_{t_{i,k}}^{t'}\int_{t_{i,k}}^{\tau} \Gamma_{xj}(\theta)u_{xj}(\theta)d\theta d\tau + k_{vx}\Big( \int_{t_{i,k}}^{t'} \Gamma_{xj}(\tau)u_{xj}(\tau)d\tau - \int_{t_{i,k}}^{t} \Gamma_{xi}(\tau)u_{xi}(\tau)d\tau\Big)\Big)\|. \tag{69}$$

Now following appendix B we have $|\eta_{xi}(t)| \leq \eta_{x,max}$. Also, $|\Gamma_{xi}^{-1}| \leq \gamma_x$, and $|u_{xi}(t)| \leq \eta_{xi}(t) = \gamma_x\beta_{xi}\alpha_x(t)$, and $\Gamma_{xi}(t) \leq \frac{\eta_{z,max}}{m_{min}}$. By using these limits and the triangular inequality and putting them along with (49a) and (49c), it can be concluded that:

$$\sigma_{xi}(t) \leq \gamma_x(\frac{\eta_{z,max}\eta_{x,max}}{m_{min}})N_i\big((t - t_{i,k})^2 + 2k_{vx}(t - t_{i,k})\big). \tag{70}$$

Moreover, by using (70) and condition $\sigma_{xi}(t) \geq \zeta_x$ in (47), the following quadratic inequality is achieved:

$$\gamma_x(\frac{\eta_{z,max}\eta_{x,max}}{m_{min}})N_i\big((t - t_{i,k})^2 + 2k_{vx}(t - t_{i,k})\big) \geq \zeta_x. \tag{71}$$

The solutions for inequality (70) are $t_{i,k+1} - t_{i,k} \geq \tau_{x1} > 0$ or $t_{i,k+1} - t_{i,k} \leq \tau_{x2} < 0$. Since the later solution is we have:

$$t_{i,k+1} \geq t_{i,k} + \tau_{x1}. \tag{72}$$

Following a similar approach for the translational subsystem in $y$ direction results in:

$$t_{i,k+1} \geq t_{i,k} + \tau_{y1}, \tag{73}$$

where $\tau_{y1} > 0$. Combining (64), (72) and (73) and according to (47) one can conclude that:

$$t_{i,k+1} \geq t_{i,k} + \tau, \tag{74}$$

where $\tau = \min\{\tau_{z1}, \tau_{x1}, \tau_{y1}\} > 0$ and this proves that the system does not show Zeno behavior. □

*Remark 3:* It is worth mentioning that the values of $k_{vz}$, $k_{vx}$ affect the roots of quadratic inequalities in (63) and (71), and hence the values of $\tau_{z1}$, $\tau_{x1}$ and also $\tau_{y1}$. This affects the time interval between two consecutive connections of each agent to the cloud. It is obvious that an increase in $k_{vz}$ leads to increase in $\eta_{z,max}$ which which results in a smaller time interval $\tau_{z1}$, according to (63). A similar result can be inferred for $\tau_{x1}$ and $\tau_{y1}$ as result of increase in $k_{vx}$ and $k_{vy}$, respectively.

## V. SIMULATION RESULTS

In this section, the efficiency of the proposed controllers is evaluated numerically using a simulation environment created in MATLAB/SIMULINK. For this purpose, three homogeneous quadcopters with a similar mass of $m_i$ =

$1.47\{kg\}, i = 1, 2, 3$ are connected to the cloud with the storage capability. Other physical parameters of the quads such as the moments of inertia are similar to the ones used in [16]. The initial conditions are considered as $p_{zi}(0) = 0$, $v_{zi}(0) = 0$, $v_{yi}(0) = v_{xi}(0) = 0$, $\phi_i(0) = 0$, $\theta_i(0) = 0$, $\psi_i(0) = 0$ for $i = 1, 2, 3$. Moreover, $p_{y1}(0) = 0$, $p_{y2}(0) = 0.2$, $p_{y3}(0) = 0.4$, $p_{x1}(0) = 0$, $p_{x2}(0) = 0.2$, $p_{x3}(0) = 0.4$. Besides, $b_{z1} = 0$, $b_{z2} = -0.5$, $b_{z3} = 0.5$, $b_{xi} = b_{yi} = 0$ for $i = 1, 2, 3$. Moreover, $k_{vx} = k_{vy} = k_{vz} = 0.8$.
The simulation results are depicted in Figs. 1 and 2 for $\zeta_z = 5$, $\zeta_x = 0.1$ and $\zeta_y = 0.1$. Fig. 1 shows the positions of the agents in $x$, $y$, and $z$ directions. As can be seen from the figures, the agents reached an average consensus plus the bias terms and the quads have reached a line formation due to the defined bias terms. However, an undesirable ramp is seen in the figures which is due to a nonzero initial speed condition. The employed consensus-based controller guarantees the convergence to the average of agents' initial positions only if the initial speeds are zero, otherwise, the consensus value will be a ramp with a gradient of the initial speeds' average. This causes, the ramp behavior to appear due to intermittent connections to the cloud which causes the change in the speeds' initial values in every connection. The times that agents are connected to the cloud are illustrated in Fig. 2. This plot confirms that the closed-loop system does not show the Zeno behavior.

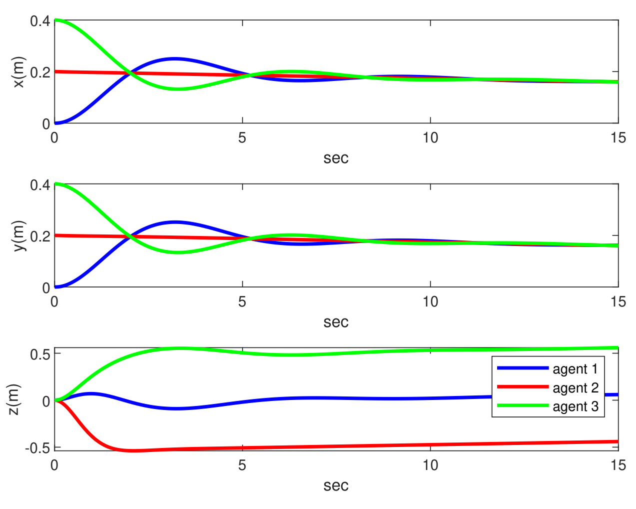


FIGURE 1: Position of the agents ( $\zeta_z = 5$, $\zeta_x = 0.1$, $\zeta_y = 0.1$).

As can be inferred from (47) in Theorem 4, different values in $\zeta_x$, $\zeta_y$, and $\zeta_z$ result in different cloud access connection frequency, and hence different performances. Table 1 provides a comprehensive comparisons for different values of $\zeta_x$, $\zeta_y$ and $\zeta_z$. Comparing the parameters $\|\mu_x(t)\|$, $\|\mu_y(t)\|$ and $\|\mu_z(t)\|$ in their steady state time (simulation has been running for 15 sec) is shown in the table. It is obvious that as $\zeta_x$, $\zeta_y$ and $\zeta_z$ increase, the values of $\|\mu_x(t)\|$, $\|\mu_y(t)\|$

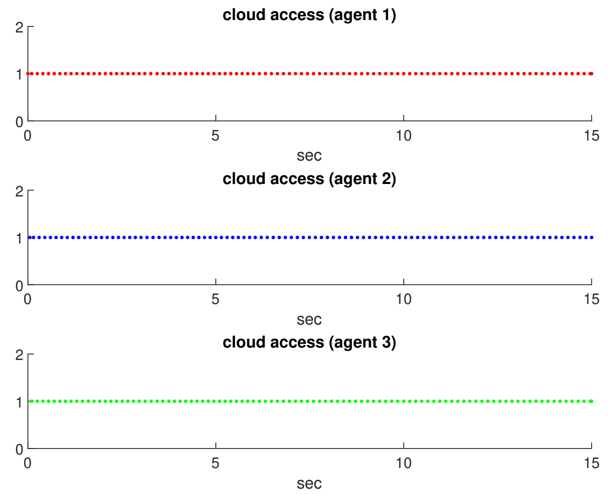


FIGURE 2: Accesses to the cloud ( $\zeta_z = 5$, $\zeta_x = 0.1$, $\zeta_y = 0.1$).

and $\|\mu_z(t)\|$ in the steady state time almost increase as it was expected according to (36) to (38) and Definition 1. The average value for the cloud access time interval is computed by computing the time intervals between two successive connections to the cloud for all agents and the average value of all elements is computed. It is also obvious from the table that as $\zeta_x$, $\zeta_y$ and $\zeta_z$ are increasing, the time interval between connections to the cloud increases, and therefore the average number of accesses to the cloud decreases. This is a desirable outcome as the main goal of the control under cloud access. The settling time is also computed as the next index for the comparative study. To compute the settling time, the $\|\chi_x(t)\|$, $\|\chi_y(t)\|$ and $\|\chi_z(t)\|$ plots are considered and the average settling time in both plots are computed. The result shows a bit increase in the settling times as $\zeta_x$, $\zeta_y$, and $\zeta_z$ are increasing. According to the Table 1, the degradation in the system performance is not remarkable compared to the significant decrease in the number of accesses to the cloud. However, looking at Fig. 3, illustrating the quad position for $\zeta_z = 8$, $\zeta_x = 0.25$ and $\zeta_y = 0.25$, it can be seen that the ramp behavior is more severe when the number of accesses to the cloud is decreased.
It is worth mentioning that according to Remark 3 when $k_{vx} = k_{vy} = k_{vz} = 8$, the cloud access time interval is reduced to $0.1091$ sec with the increased average number of connections to $138.3333$ as it was expected.

## VI. CONCLUSION

In this paper the problem of formation producing control using consensus based control approach under the cloud access is studied for multi-quadcopter systems. To this end, the method proposed in [26] has been extended for multi-quadcoptr systems. In [26] multi-agent systems with second-order dynamics are considered, however, this study focuses

TABLE 1: Comparison of the results in different scenarios of $\zeta_z$, $\zeta_x$ and $\zeta_y$ changes.

| $\zeta_z, \zeta_x, \zeta_y$ | $\|\mu_x(15)\|$ | $\|\mu_y(15)\|$ | $\|\mu_z(15)\|$ | Cloud access time interval (sec) (Average) | Settling time 5%(sec) | Number of accesses to the cloud (Average) |
|---|---|---|---|---|---|---|
| $\zeta_z = 8$, $\zeta_x = 0.25$, $\zeta_y = 0.25$ | 0.0025 | 0.0025 | 0.0015 | 0.2465 | 5.11 | 61.6667 |
| $\zeta_z = 5$, $\zeta_x = 0.1$, $\zeta_y = 0.1$ | 0.0020 | 0.0020 | 0.0013 | 0.1555 | 5.08 | 97.3333 |
| $\zeta_z = 3$, $\zeta_x = 0.06$, $\zeta_y = 0.06$ | 0.0019 | 0.0019 | 0.0012 | 0.0897 | 5.06 | 167.6667 |
| $\zeta_z = 0$, $\zeta_x = 0$, $\zeta_y = 0$ (No cloud access) | 0.0008 | 0.0008 | 0.0005 | continuous connection | 4.92 | $\infty$ |

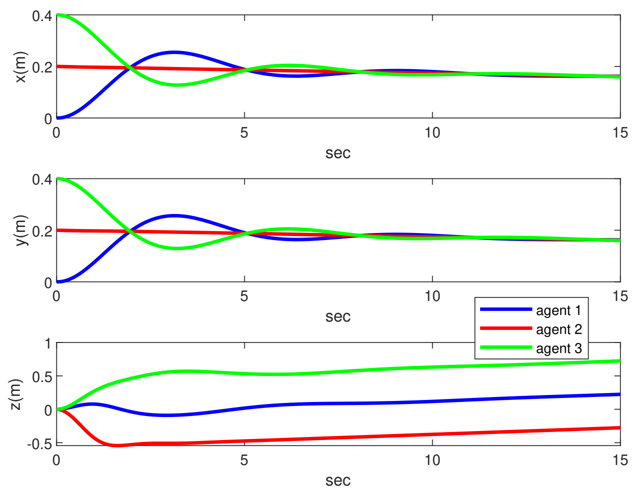


FIGURE 3: The agents' position for $\zeta_z = 8$, $\zeta_x = 0.25$, $\zeta_y = 0.25$.

on the nonlinear agents with under-actuated quadcopter dynamics. Although the rendezvous problem is addressed in [26], the method proposed in this paper modifies the consensus based controller to guarantee convergence to the average of the initial quad positions plus a predefined bias term. Then, the controller is extended to the case where communication amongst the quads is under the cloud access and the practical consensus of the proposed controller is proved. For this purpose, a scheduling rule for the agents to access the cloud is designed and it is shown that the closed loop system with the proposed scheduling rule is Zeno behavior free. The effectiveness of the method has been analyzed through extensive numerical results and different scenarios for the cloud access. However, due to the specific type of the employed consensus filter, the ramp behavior can be seen in the convergence of the quad positions. Therefore, it is proposed to use an alternative consensus filter as the future work.

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## APPENDIX A PROOF THAT $H_Z$ IS HURWITZ:

With the assumption that the connectivity graph of the multi-quadcopter system, $G$, contains a spanning tree $G_t$, it is concluded that $B_t$ is full column rank $N\times(N-1)$ matrix. To show that $H_z(t)$ is Hurwitz, one can compute its eigenvalues through $\det(\lambda\mathbf{I} - H_z(t)) = 0$.

$$\det(\lambda\mathbf{I}-H_z(t)) = \det\left(\begin{bmatrix}\lambda\mathbf{I}_{(N-1)} & -\mathbf{I}_{(N-1)} \\ B_t^{\mathrm{T}}BT^{\mathrm{T}} & \lambda\mathbf{I}_{(N-1)} + k_{vz}B_t^{\mathrm{T}}BT^{\mathrm{T}}\end{bmatrix}\right) \tag{75}$$

*Remark 4:* For a block matrix with the same size square matrix blocks $A$, $B$, $C$ and $D$, $\det\begin{bmatrix}A & B\\ C & D\end{bmatrix} = \det(AD-BC)$ if $C$ and $D$ commute [32].

According to Remark 4 and (75) one can conclude:

$$\det(\lambda\mathbf{I}-H_z(t)) = \det\left(\lambda^2\mathbf{I}_{(N-1)} + (\lambda k_{vz}+1)B_t^{\mathrm{T}}BT^{\mathrm{T}}\right) = (\lambda k_{vz}+1)^{N-1}\det\left(\frac{\lambda^2}{(\lambda k_{vz}+1)}\mathbf{I}_{(N-1)} + B_t^{\mathrm{T}}BT^{\mathrm{T}}\right) \tag{76}$$

*Remark 5:* For any invertible $X_{m\times m}$ with $A_{m\times n}$ and $B_{n\times m}$ [33]:

$$\det(X+AB) = \det(X)\det(\mathbf{I}_n + BX^{-1}A). \tag{77}$$

Using (77) if one let $X = \frac{\lambda^2}{(\lambda k_{vz}+1)}\mathbf{I}_{(N-1)}$, $A = B_t^{\mathrm{T}}$ and $B = BT^{\mathrm{T}}$, (76) can be transformed to:

$$\det(\lambda\mathbf{I}-H_z(t)) = \lambda^{2N-2}\det\left(\mathbf{I}_N + \frac{(k_{vz}\lambda+1)}{\lambda^2}\mathcal{L}\right) = \frac{(k_{vz}\lambda+1)^N}{\lambda^2}\det\left(\frac{\lambda^2}{(\lambda k_{vz}+1)}\mathbf{I}_N + \mathcal{L}\right), \tag{78}$$

where $\mathcal{L} = BT^{\mathrm{T}}B_t^{\mathrm{T}}$. If one let $\lambda' = \frac{\lambda^2}{(k_{vz}\lambda+1)}$, then the solutions of $\lambda'$ are eigenvalues of $-\mathcal{L}$ which are negative and one eigenvalue is zero. Therefore, the solutions of $\lambda$ are negative and $H_z(t)$ is Hurwitz.

## APPENDIX B PROOF OF BOUNDNESS OF INPUT SIGNALS:

If one replace $\mathcal{L}$ with $BT^{\mathrm{T}}B_t^{\mathrm{T}}$ in (23), the following is obtained:

$$U_z(t) = \Gamma_z^{-1}(t)\left(G - BT^{\mathrm{T}}K_{vz}\mu_z(t)\right), \tag{79}$$

where $K_{vz} = \mathbf{I}_{(N-1)} \otimes [1\ k_{vz}]$ where $\otimes$ refers to Kronecker product and therefore:

$$u_{zi}(t) = \Gamma_{zi}^{-1}(t)\big(g - B_i T^{\mathrm{T}} K_{vz}\mu_z(t)\big), \tag{80}$$

where $B_i$ is $i$-th row of $B$. Using the triangular inequality one can conclude:

$$|u_{zi}(t)| \leq |\Gamma_{zi}^{-1}(t)|g + \|\Gamma_{zi}^{-1}(t)B_i T^{\mathrm{T}} K_{vz}\|\|\mu_z(t)\|. \tag{81}$$

If one considers $|\Gamma_{zi}^{-1}(t)| \leq \gamma_z$ according to Remark 1, and let $\|B_i T^{\mathrm{T}} K_{vz}\| = \beta_{zi}$, then:

$$|u_{zi}(t)| \leq \eta_{zi}(t), \tag{82}$$

where $\eta_{zi}(t) := \gamma_z g + \gamma_z \beta_{zi}\alpha_z(t)$ with $\alpha_z(t)$ defined in (43). According to (21) one can conclude $|u_{zi,k}(t)| \leq |\tilde{u}_{zi}(t)| + |u_{zi}(t)|$ and if the condition $|\tilde{u}_{zi}(t)| \leq \zeta_z$ holds, then:

$$|u_{zi,k}(t)| \leq u_{zi,max}(t), \tag{83}$$

where $u_{zi,max}(t) := \zeta_z + \eta_{zi}(t)$.
According to Theorem 3, since $\lim\limits_{t\to\infty} \|\mu_z(t)\| \leq \chi_z$ holds, $\lim\limits_{t\to\infty} |u_{zi,k}(t)| \leq u_{zi,max,k}$ where $u_{zi,max,k} = \gamma_z(g + \beta_{zi}\chi_z) + \zeta_z$.

For translational subsystem in $x$-axis consider the proposed controller in (16), the collective input controller $U_x(t)$ is as follows:

$$U_x(t) = -\Gamma_x^{-1}(t)\Big(\mathcal{L}\big(P_x^*(t) + k_{vx}V_x(t)\big)\Big). \tag{84}$$

Now, if $\mathcal{L}$ is replaced with $BT^{\mathrm{T}}B_t^{\mathrm{T}}$ in (84), it yields:

$$U_x(t) = -\Gamma_x^{-1}(t)\Big(BT^{\mathrm{T}}\big(X_x(t) + k_{vx}Y_x(t)\big)\Big). \tag{85}$$

Therefore:

$$U_x(t) = -\Gamma_x^{-1}(t)BT^{\mathrm{T}}K_{vx}\mu_z(t), \tag{86}$$

where $K_{vx} = \mathbf{I}_{(N-1)} \otimes [1\ k_{vx}]$. Thus:

$$u_{xi}(t) = -\Gamma_{xi}^{-1}(t)B_i T^{\mathrm{T}} K_{vx}\mu_x(t). \tag{87}$$

According to Remark 2 one can consider a minimum value for $|u_{zi}(t)|$ and therefore $|\Gamma_{xi}^{-1}(t)| \leq \gamma_x$. Now let $\beta_{zi} := B_i T^{\mathrm{T}} K_{vx}$ which gives:

$$|u_{xi}(t)| \leq \eta_{xi}(t), \tag{88}$$

where $\eta_{xi}(t) = \gamma_x\beta_{xi}\alpha_x(t)$ where $\alpha_x(t)$ is defined in (46). A similar bound can be defined for $|u_{yi}(t)|$.

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