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Research Article

Leader-Follower Multimotor Speed Coordination via Adaptive Fuzzy Multiagent Consensus Scheme

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Coordinated speed of interconnected motors has vast application in the industry. Typically, the smooth operation of the system relies on the coordinated speed of the multiple motors such as the conveyer belt system. Thus, the problem to have coordinated speed in a network-connected motor is mostly dealt with wire-connected architectures such as cross coupling. The presented study suggests a unique design to deal with the said problem by proposing a network model consisting of a DC chopper drive, termed as an i_{th} agent of a network, while a leader-follower multiagent consensus algorithm is used, in a supervisory role, to ensure coordinated speed. Moreover, a hybrid controller (Fuzzy MRAC-RST), composed of Fuzzy logic controller, pole placement controller (F-RST), along with model reference adaptive controller (MRAC), is used to control the i_{th} agent. The proposed hybrid controller along with MAS consensus algorithm forms an adaptive tracking performance and ensure coordinated speed. The MATLAB platform is used for simulation purpose, and the obtained results validate the design concept.

1. Introduction

Recently, coordinated activities among distributed identical agents to achieve a global task are becoming a major area of focus in the control community. This problem of coordinated action is said to be a consensus problem or a multiagent system (MAS) consensus problem. It is obvious that coordination among agents requires communication among them, and thus they are modeled in a predefined network environment to perform the desired task and achieve consensus. Numerous authors use a consensus approach to address a variety of problems under different circumstances, such as those in [1–7]. Thus, it is obvious that the network control system (NCS) provides a basis for MAS, and therefore, NCS-based methods are adopted to model a variety of control problems, as addressed by [8–15].

On the other hand, the fuzzy logic-based multiagent approach is also gaining momentum to address numerous problems, not only in the control community but also in the related engineering domains due to their adaptive design of the controller, as well as system flexibility to the node (agent) malfunction. In [16], a distributed network of smart sensors is constructed for the purpose of information gathering about gas consumption. The author proposes MAS scheme, such that a fuzzy controller, smart sensor, gas volume, time, and temperature form i_{th} agent model. The author shows that the proposed model optimized the consumption of gas in urban areas. Similarly, in [17], a distributed MAS architecture is designed for energy management system (EMS), such that the hybrid energy systems (HES) are formed as a collection of interconnected elements (modeled as agents), to acquire a collective task. In the proposed design, the battery agent is governed by fuzzy logic and therefore called a fuzzy agent, which provides output power as per the fuzzy rules. Additionally, there are various researchers who had explored a different kind of MAS problem with fuzzy logic control, such as those in [18–21].

Moreover, as far as electric motors are concerned, they are one of the major inventions that change modern-day life. They are found almost everywhere in daily routine, from household hold application to larger power generation units and different electrical products. It is estimated that almost 50% of the world's electrical power is utilized by electric motors, such a huge consumption of electricity reveals the utilization of electric motor in our daily life. Moreover, synchronous speed systems with multiple interconnected motors already exist in the industry. There is a certain drawback of these systems such as they are greatly vulnerable to maintenance issues due to wire-connected architecture which ultimately increases system cost, not flexible in case of system malfunctioning. On the other side, a network-based system can effectively overcome these deficiencies due to the flexible nature of the network, i.e., it is easier to recognize and isolate the faulty agent while keep running the rest of the system at synchronous speed. The synchronous speed control problem with traditional wire-connected architecture is addressed by numerous authors, such as those in [22–25].

The multimotor speed synchronization found application in the areas of papermaking machines, differential drives, textile printing, offset printing, robotics, and so on [26]. In [27], the author presents a novel approach of using leader following MAS consensus control method to regulate and control the speed of vector controlled IM's. The author uses Simulink-based system design and observes the synchronous speed control not only in the presence of the disturbance delays but also with the sensor failure which leads to the agent dis-connectivity from the rest of the system. Similarly, in [28], the multimotor synchronization problem is addressed by utilizing the leader following MAS consistency theory, having undirected and switching topology by considering the delay in the network. The stability of the system is verified via the Lyapunov theorem with respect to the single agent such that if it is controllable and observable then the rest of the system reaches synchronous control of the motors. Similar problem is also addressed by the authors in [29, 30].

Thus, inspired by the abovementioned research, in this study, a new multimotor system is presented utilizing a predesigned fixed and undirected network to interconnect the agents in a leader following MAS architecture, which is, in this case, noninverting chopper-driven DC motor. Moreover, it is assumed that the speed sensors continuously provide the motor's speed data, which is available not only to the leading motor but also to the neighboring motors, via a network. Since the problem of distributed tracking requires only one leader, therefore, the leader following consensus problem is also said to be distributed tracking problem. Therefore, a robust Model Reference Adaptive Control (MRAC) with Fuzzy Regulation, Pole Placement & Tracking (F-RST) control is employed, not only to control the motors speed but also make the followers track the speed of the leading motor, such that they achieve a global task, i.e., synchronous speed aka consensus. Figure 1 depicts the concept of the proposed network scheme for the synchronous speed control of multiple DC motors such that the leader following multiagent consensus protocol plays a supervisory role. In the diagram, it is evident that the complete system is composed of three main entities, i.e., the DC motor and driving circuit, the local controller, and the MAS leader following coordination protocol. Moreover, it is noted that every motorized unit act as i_{th} following agent having its local controller, and thus regulating the following agent speed similar to that of the leader speed, which is available to all the network-connected followers in the consensus protocol communicated via a network.

Remark 1. The proposed work addresses the identical speed problem of the multimotor system in a novel way and overcomes the shortcomings of the existing methods which revolve around wired architecture. The proposed methodology offers greater flexibility for smoother operation, and the networked control loop also signifies the design novelty when compared with existing methodologies.

This paper is organized as follows. First of all, Section 1 presents the Introduction, followed by the preliminaries in Section 2. The state of the art for the proposed work is given in Section 3. Section 4 presents the proposed agent modeling, consensus, and control design schemes, followed by results and conclusion in Sections 5 and 6, respectively.

2. Preliminaries

In this study, R^n is Euclidean space with n dimensions $N(1,n) = \{1,2,\ldots,n\}$. The network is modeled via graph G such that graph node V represents an agent, while the connectivity among agents is represented by an edge E, which connects two or more nodes, written as $G = (V, E)$. The node-set is written as $V = \{V_i\}, i \in N(1,n)$, while the edge set is given as $E \subseteq V \times V$. In a communication network, if any two agents are connected, then it is written as $(V_i, V_j) \in E, i, j \in N(1,n)$ such that the set of neighbor for an i_{th} node is given as $N_i = \{j\colon (V_i, V_j) \in E, j \neq i\}$. Moreover, the total number of a neighbor of the i_{th} node is given by a Degree matrix $\mathfrak{D}(G)$ at its main diagonal. Furthermore, if any two nodes are connected via edge, their adjacency is said to be one, otherwise zero, and is given by an adjacency matrix $\mathscr{A}(G)$ as $(V_i, V_j) \in E = 1$. These matrices now conclude the most important matrix of the communication graph called Laplacian matrix $\mathscr{L}(G)$ and are given as $\mathscr{L}(G) = \mathfrak{D}(G) - \mathscr{A}(G)$. Following are some important lemmas, highlighting the significance of $\mathscr{L}(G)$, to achieve global consensus, i.e., synchronous speed.

Lemma 1 (see [31]). *If it is supposed that G is not only connected but also undirected, then $\mathscr{L}(G)$ possesses 0 and λ_2 as smallest and smallest positive eigenvalues, respectively.*

Lemma 2 (see [32]). *If the properties of $\mathscr{L}(G)$ in Lemma 1 holds, then $\lambda_2(G) > 0$, and holds* $\min_{x\neq 0, 1^T x=0} (x^T \mathscr{L} x / x^T x)$.

Remark 2. For communication graph having undirected fixed network topology, $\mathscr{L}(G) > 0$, i.e., $x^T \mathscr{L} x \geq 0, \forall x \in R^N$ and holds the sum of the square as $x^T \mathscr{L} x = (1/2) \sum_{i=1}^{N} \sum_{j=1}^{N} a_{ij} (x_i - x_j)^2$.

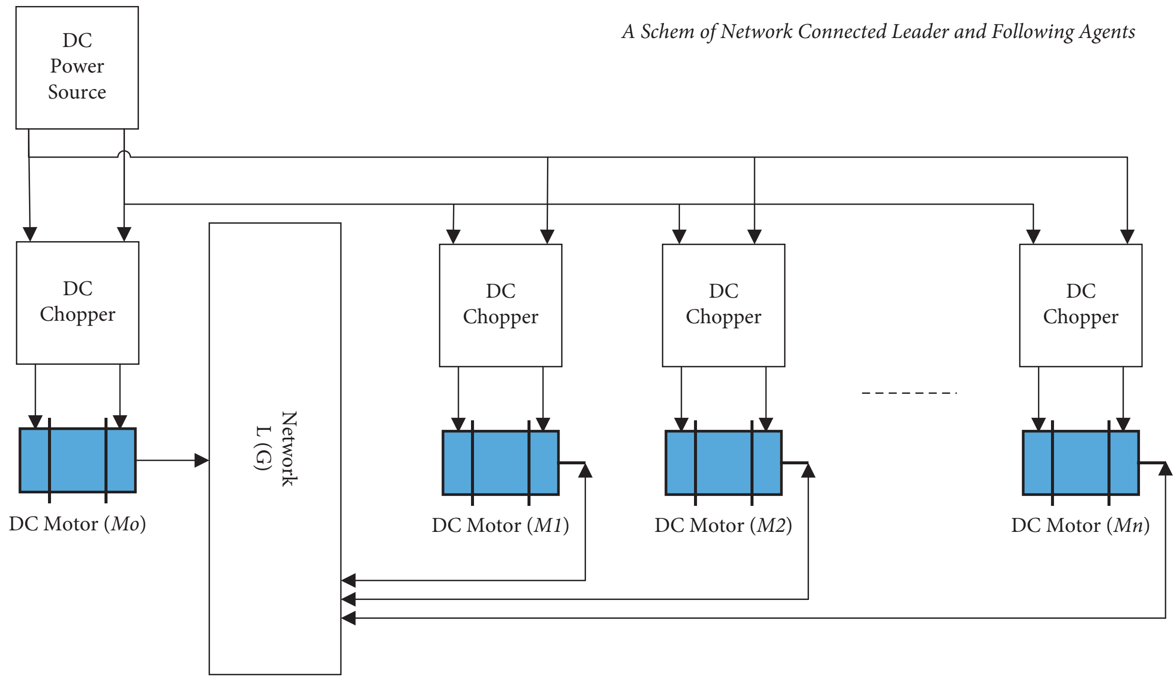


Figure 1: Conceptual block diagram of the proposed study.

2.1. Problem Definition. A global consensus, i.e., synchronous speed is said to be reached among the network-connected motors, as long as there exists a control input $u_i(t)$ which regulates the control signals to the agents such that $\lim_{t\longrightarrow\infty}\|W_i(t) - W_j(t)\| = 0$ for $i, j \in N(1, n)$ holds. Since the proposed study uses a leader following consensus approach; therefore, it is necessary to utilize lemmas that play an important role to analyze the leader following behavior with the communication network graph.

Lemma 3 (see [33, 34]). *If Lemma 1 holds, then for leader following architecture, there exists a subgraph* $\overline{G}$, *such that there will be a positive definite matrix* $\mathscr{H}(G)$ *holding* $\mathscr{H}(G) = \mathscr{L}(G) + d$. *The matrix* $\mathscr{H}(G)$ *must be symmetric, real eigenvalues* μ, *and comprises of orthogonal matrix property* $\mathbb{W}\mathscr{H}\mathbb{W}^T = \rho = diag\{\mu_1, \ldots, \mu_N\}$, *as well. Whereas* d *is said to be leader adjacency.*

Remark 3. $\mathscr{H}(G) = \mathscr{H}(G)^T$ when the leader is reachable in $\overline{G}$. A symmetric $\mathscr{H}(G)$ also holds an orthogonal $\mathbb{W}$ matrix, given as $\rho = \mathbb{W}\mathscr{H}\mathbb{W}^T$.

$$\rho = \mathbb{W}\mathscr{H}\mathbb{W}^T = \begin{bmatrix} w_1 & w_2 & \cdots & w_n \end{bmatrix} \begin{bmatrix} \mu_1 & & & \\ & \mu_2 & & \\ & & \ddots & \\ & & & \mu_n \end{bmatrix} \begin{bmatrix} w_1^T \\ w_2^T \\ \vdots \\ w_n^T \end{bmatrix}. \quad (1)$$

Moreover, the following assumption is used throughout this study.

Assumption 1. It is assumed that the system matrices A_σ and B_σ are stable and controllable.

3. State of the Art

Since the network connectivity enables the sharing of data, i.e., speed, between the agents, the speed consensus problem is solved by using the proposed speed consensus algorithm $u_i(t)$, which regulates the input to the agents such that the norm L_2 of speed between the neighboring agents becomes zero, thus consensus on speed is said to be reached. Essentially, the hybrid MRAC-FRST controller enables the proposed system to reach a consensus such that the consensus algorithm keeps on overseeing the agent's speed and regulates the hybrid controller's inputs for the agents. Any disturbance in the speed causes error to generate, which not only violates the L_2 norm condition but also causes the MIT cost function to be raised.

4. Modeling, Consensus, and Control Design

In this study, the agents are made of a noninverting DC to DC chopper to drive the DC motor. Whereas it is assumed that the speed sensors are providing continuous feedback about the present speed of the respective motor via a network. Now, the state-space model of the i_{th} agent is written as

$$\dot{x} = A_\rho x_i + B_\rho U_i,$$

$$y = C x_i,$$

$$[\dot{W}] = \begin{bmatrix} 0 & -\dfrac{1}{l} & 0 & 0 \\ \dfrac{1}{c} & -\dfrac{1}{r_a c} & 0 & 0 \\ 0 & \dfrac{1}{l_a} & -\dfrac{r_a}{l_a} & \dfrac{\kappa_e}{l_a} \\ 0 & 0 & \dfrac{\kappa_e}{j} & 0 \end{bmatrix} \begin{bmatrix} i_l \\ v_c \\ i_a \\ W \end{bmatrix} + \begin{bmatrix} \dfrac{s}{l} \\ 0 \\ 0 \\ 0 \end{bmatrix} U_i, \tag{2}$$

$$W = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_l \\ v_c \\ i_a \\ W \end{bmatrix},$$

where s is either 0 or 1 with respect to switch position, and switching order is given as $\sigma = 0$ to ∞ with $(1, \ldots, n)$ arrangements, A is the system matrix, B is the input matrix, U is the i_{th} controller input, C is the output matrix, v is the main power supply for the circuit, l is the chopper inductance, i_l is the current flowing through chopper inductor, c is the chopper capacitance, v_c is the voltage across the chopper capacitor, i_a is the current flowing through the motor armature, r_a is the resistance of motor armature, l_a is the inductance of the motor armature, W is the motor speed, κ_e is the back e.m.f constant of the motor, j is the inertia of the motor, and $\mathbb{T}_L$ is the motor torque. The proposed model of the i_{th} agent motor and driver circuit is given in Figure 2, whereas Table 1 provides system parameters.

Now, to develop a suitable controller for the proposed system, the entire system is simulated for two scenarios, namely, the system without network-induced communication delays and with the communication delays. Furthermore, Figure 3 shows the insight of the i_{th} follower and its connectivity with the leader. It is seen that the motorized follower is connected with the leader, via a network, so that it can continuously regulate its speed as per the leader speed, which is providing the reference speed data.

Figure 4 shows the controller design, and it is evident that the fuzzy controller uses error and its derivative as an input to control the chopper circuit which eventually controls the power delivered to the motor. The error is generated whenever the follower speed has deviated from the leader speed, which is readily available due to network connectivity. Furthermore, the control input to the i_{th} follower is the error system, in the form as given in equations (4) and (5), respectively.

Thus far, it is established that consensus is reached, once all the following motors reach the speed of the leading motor, thus attaining the synchronous speed, so reducing the error dynamics to zero, i.e., $\lim_{t\longrightarrow\infty}\varepsilon(t) = 0$, where $\varepsilon = [\varepsilon_i^T, \ldots, \varepsilon_N^T]^T$. The dynamics of the leading motor is unaffected by the following motors, but influences the following motors, and thus, the leading motor dynamics is written as

$$\dot{x} = A_\rho x_0. \tag{3}$$

Therefore, the error between the i_{th} agent and the leading motor can be written as $\varepsilon_{\text{i}} = W_{\text{i}} - W_0$. Thus, the i_{th} agent leader following consensus protocol, aiming motor speed, without delay, is written as

$$U_i(t) = \sum_{j\in N_i} \left(W_i - W_j\right) + d_i\left(W_0 - W_i\right). \tag{4}$$

However, the consensus protocol with network-induced delays is given as

$$U_i(t) = \sum_{j\in N_i} \left(W_i(t-\tau) - W_j(t-\tau)\right) + d_{\text{i}}\left(W_0(t-\tau) - W_i(t-\tau)\right). \tag{5}$$

For the case of delay, the author in [35] presents a bound for the delay, that it has to be under $\pi/2\lambda_{\max}$ range or there should be zero encirclements of $-1/\lambda_k, \forall k > 1$ by system Nyquist plot.

Now, to design a suitable digital controller, a Z-transform of the continuous-time transfer function, with a sampling interval of 0.2 sec, for the proposed agent model is obtained as

$$G(z) = \frac{z^3 - 1.372\times10^{-8}z^2 - 1.078\times10^{-16}z - 4.487\times10^{-40}}{z^4 - 1.869\times10^{-8}z^3 + 3.388\times10^{-16}z^2 + 1.212\times10^{-39}z - 1.141\times10^{-62}}. \tag{6}$$

Thus, the above equation reveals the degrees of the numerator and denominator to be 0 and 4, respectively,

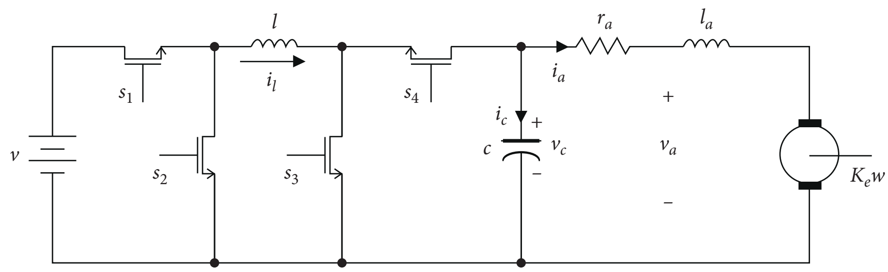


Figure 2: Proposed noninverting buck-boost chopper fed DC motor.

Table 1: System parameters.

Variable	Value (unit)
c	400 μF
l	1.5 mH
v	160 V
j	7×10^{-6} kg · m^2
l_a	7 mH
r_a	1 Ω
κ_e	0.04 V/rad/s
$\mathbb{T}_L$	0 Nm
W	250 rpm

concluding a third-order RST controller, having values $\deg A_c = 7$, $\deg R = S = 3$. For simplicity, $\deg T = \deg S$, and thus, RST polynomials constitute as

$$\begin{aligned} \mathrm{FR}\left(z^{-1}\right) &= 1 + r_1 z^{-1} + r_2 z^{-2} + r_3 z^{-3}, \\ \mathrm{FS}\left(z^{-1}\right) &= s_0 + s_1 z^{-1} + s_2 z^{-2} + s_3 z^{-3}, \\ \mathrm{FT}\left(z^{-1}\right) &= \left(t_0 + t_1 z^{-1} + t_2 z^{-2} + t_3 z^{-3}\right) A_0. \end{aligned} \tag{7}$$

The generalized response of the RST controller is written as

$$\begin{aligned} R\mathcal{U}(t) &= T\mathcal{U}_c(t) - S\mathcal{Y}_a(t), \\ \mathcal{U}(t) &= \frac{T}{R}\mathcal{U}_c(t) - \frac{S}{R}\mathcal{Y}_a(t). \end{aligned} \tag{8}$$

Here

$$\begin{aligned} \mathcal{Y}_a(t) &= \frac{BT}{\mathrm{AR} + \mathrm{BS}}\mathcal{U}_c(t), \\ \mathrm{AR} + \mathrm{BS} &= A_c. \end{aligned} \tag{9}$$

Let the reference system be written as

$$G_r = \frac{B_r}{A_r} = \mathcal{Y}_r, \tag{10}$$

where $A_c = A_0 A_r$. In RST control design, a compatibility $A_0 = 1$ holds, and thus, $\mathrm{AR} + \mathrm{BS} = A_r$. Now, for the proposed system to work properly, it is desirable to obtain a reference output using the MRAC control approach, such that the MRAC controller enables the F-RST controller to fine-tune its parameters so that the error remains minimum and thereby the differences between actual and desired output are eliminated. Thus, the error is written as $\varepsilon = \mathcal{Y}_a - \mathcal{Y}_r$.

$$\varepsilon = \left(\frac{\mathrm{BT}}{\mathrm{AR} + \mathrm{BS}}\right)\mathcal{U}_c(t) - \mathcal{Y}_r. \tag{11}$$

To penalize the F-RST polynomials, they are introduced in the error dynamics, and thereafter, an MRAC-centered MIT cost function is introduced subsequently in the error dynamics, to guarantee stable system performance. Thus, first, taking on polynomial FR as

$$\varepsilon = \left(\frac{\mathrm{BT}}{A\left(1 + r_1 z^{-1} + r_2 z^{-2} + r_3 z^{-3}\right) + \mathrm{BS}}\right)\mathcal{U}_c(t) - \mathcal{Y}_r. \tag{12}$$

Partial derivative with respect to r_1, r_2, and r_3 yields

$$\begin{aligned} \frac{\delta\varepsilon}{\delta r_1} &= \left(\frac{\mathrm{BT}}{A\left(1 + r_1 z^{-1} + r_2 z^{-2} + r_3 z^{-3}\right) + \mathrm{BS}}\right)\mathcal{U}_c(t) - \mathcal{Y}_r, \\ \frac{\delta e}{\delta r_1} &= -\frac{Az^{-1}}{A_r}\mathcal{Y}_a, \\ \frac{\delta\varepsilon}{\delta r_2} &= -\frac{Az^{-2}}{A_r}\mathcal{Y}_a, \\ \frac{\delta\varepsilon}{\delta r_3} &= -\frac{Az^{-3}}{A_r}\mathcal{Y}_a. \end{aligned} \tag{13}$$

Performing the same procedure, the polynomial's FS and FT yield

$$\begin{aligned} \frac{\delta\varepsilon}{\delta s_0} &= -\frac{B}{A_r}\mathcal{Y}_a, \\ \frac{\delta\varepsilon}{\delta s_1} &= -\frac{Bz^{-1}}{A_r}\mathcal{Y}_a, \\ \frac{\delta\varepsilon}{\delta s_2} &= -\frac{Bz^{-2}}{A_r}\mathcal{Y}_a, \\ \frac{\delta\varepsilon}{\delta s_3} &= -\frac{Bz^{-3}}{A_r}\mathcal{Y}_a. \end{aligned} \tag{14}$$

For polynomial FT,

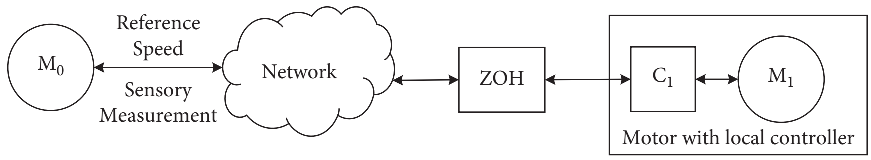


Figure 3: Model of the i_{th} follower and the leader in the proposed multimotor system.

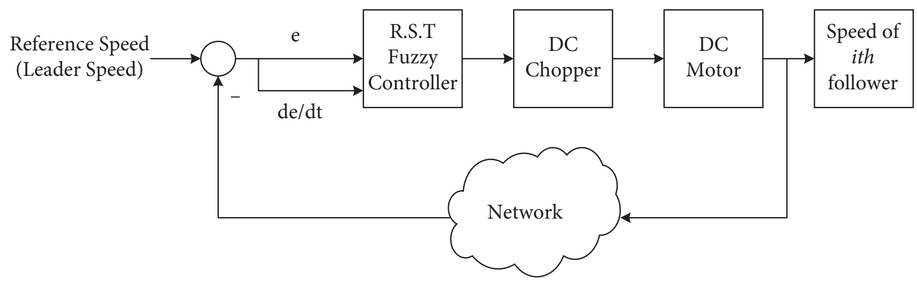


Figure 4: The controller design scheme of the i_{th} follower depicting its speed control.

Table 2: If-then rule of fuzzy controller for "KR."

$\overrightarrow{(\mathrm{d}\varepsilon/\mathrm{d}t)}$	BN	SN	ZR	SP	BP
Error ↓					
BN	ZR	ZR	SP	BP	BP
SN	ZR	SP	SP	SP	BP
ZR	ZR	SP	SP	SP	BP
SP	ZR	SP	SP	SP	BP
BP	ZR	ZR	SP	SP	BP

$$\begin{aligned}
\frac{\delta\varepsilon}{\delta t_0} &= \frac{A_0}{T}\mathcal{Y}_a,\\
\frac{\delta\varepsilon}{\delta t_1} &= \frac{A_0 z^{-1}}{T}\mathcal{Y}_a,\\
\frac{\delta\varepsilon}{\delta t_2} &= \frac{A_0 z^{-2}}{T}\mathcal{Y}_a,\\
\frac{\delta\varepsilon}{\delta t_3} &= \frac{A_0 z^{-3}}{T}\mathcal{Y}_a.
\end{aligned} \tag{15}$$

To ensure stability, the MIT cost function is coupled with the error signal, such that the cost function reduces as error goes to zero, thus penalizing F-RST polynomials, and it is concluded that the FRST-MRAC controllers are conducting the desired tracking performance. The cost function is given as

$$\begin{aligned}
\hat{j}(\phi) &= \frac{1}{2}\varepsilon^2(\zeta),\\
\frac{\mathrm{d}\zeta}{\mathrm{d}t} &= -\xi\varepsilon\frac{\mathrm{d}\varepsilon}{\mathrm{d}\Phi}.
\end{aligned} \tag{16}$$

Thus, as per the cost function derivative, the F-RST polynomials are given as

$$\begin{aligned}
\frac{\mathrm{d}r_1}{\mathrm{d}t} &= -\xi\frac{\delta\varepsilon}{\delta r_1}\frac{\mathrm{d}r_1}{\mathrm{d}t} = \xi\frac{Az^{-1}}{A_r}\mathcal{Y}_a,\\
\frac{\mathrm{d}r_2}{\mathrm{d}t} &= -\xi\frac{\delta\varepsilon}{\delta r_2}\frac{\mathrm{d}r_2}{\mathrm{d}t} = \xi\frac{Az^{-2}}{A_r}\mathcal{Y}_a,\\
\frac{\mathrm{d}r_3}{\mathrm{d}t} &= -\xi\frac{\delta\varepsilon}{\delta r_3}\frac{\mathrm{d}r_3}{\mathrm{d}t} = \xi\frac{Az^{-3}}{A_r}\mathcal{Y}_a,\\
\frac{\mathrm{d}s_0}{\mathrm{d}t} &= -\xi\frac{\delta\varepsilon}{\delta s_0}\frac{\mathrm{d}s_0}{\mathrm{d}t} = \xi\frac{B}{A_r}\mathcal{Y}_a,\\
\frac{\mathrm{d}s_1}{\mathrm{d}t} &= -\xi\frac{\delta\varepsilon}{\delta s_1}\frac{\mathrm{d}s_1}{\mathrm{d}t} = \xi\frac{Bz^{-1}}{A_r}\mathcal{Y}_a,\\
\frac{\mathrm{d}s_2}{\mathrm{d}t} &= -\xi\frac{\delta\varepsilon}{\delta s_2}\frac{\mathrm{d}s_2}{\mathrm{d}t} = \xi\frac{Bz^{-2}}{A_r}\mathcal{Y}_a,\\
\frac{\mathrm{d}s_3}{\mathrm{d}t} &= -\xi\frac{\delta\varepsilon}{\delta s_3}\frac{\mathrm{d}s_3}{\mathrm{d}t} = \xi\frac{Bz^{-3}}{A_r}\mathcal{Y}_a,\\
\frac{\mathrm{d}t_0}{\mathrm{d}t} &= -\xi\frac{\delta\varepsilon}{\delta t_0}\frac{\mathrm{d}t_0}{\mathrm{d}t} = -\xi\frac{A_0}{T}\mathcal{Y}_a,\\
\frac{\mathrm{d}t_1}{\mathrm{d}t} &= -\xi\frac{\delta\varepsilon}{\delta t_1}\frac{\mathrm{d}t_1}{\mathrm{d}t} = -\xi\frac{A_0 z^{-1}}{T}\mathcal{Y}_a,\\
\frac{\mathrm{d}t_2}{\mathrm{d}t} &= -\xi\frac{\delta\varepsilon}{\delta t_2}\frac{\mathrm{d}t_2}{\mathrm{d}t} = -\xi\frac{A_0 z^{-2}}{T}\mathcal{Y}_a,\\
\frac{\mathrm{d}t_3}{\mathrm{d}t} &= -\xi\frac{\delta\varepsilon}{\delta t_3}\frac{\mathrm{d}t_3}{\mathrm{d}t} = -\xi\frac{A_0 z^{-3}}{T}\mathcal{Y}_a.
\end{aligned} \tag{17}$$

The proposed system controller is modified as

Table 3: If-then rule of fuzzy controller for "KS."

$(\overrightarrow{d\varepsilon/dt})$	BN	SN	ZR	SP	BP
Error ↓					
BN	SP	SP	ZR	ZR	ZR
SN	BP	SP	SP	SP	BP
ZR	BP	SP	SP	SP	BP
SP	BP	SP	SP	SP	SP
BP	BP	BP	BP	SP	SP

Table 4: If-then rule of fuzzy controller for "KT."

$(\overrightarrow{d\varepsilon/dt})$	BN	SN	ZR	SP	BP
Error ↓					
BN	ZR	SP	MP	MP	SP
SN	SP	SP	SP	MP	MP
ZR	SP	MP	MP	MP	MP
SP	SP	SP	MP	SP	SP
BP	ZR	SP	MP	LP	S

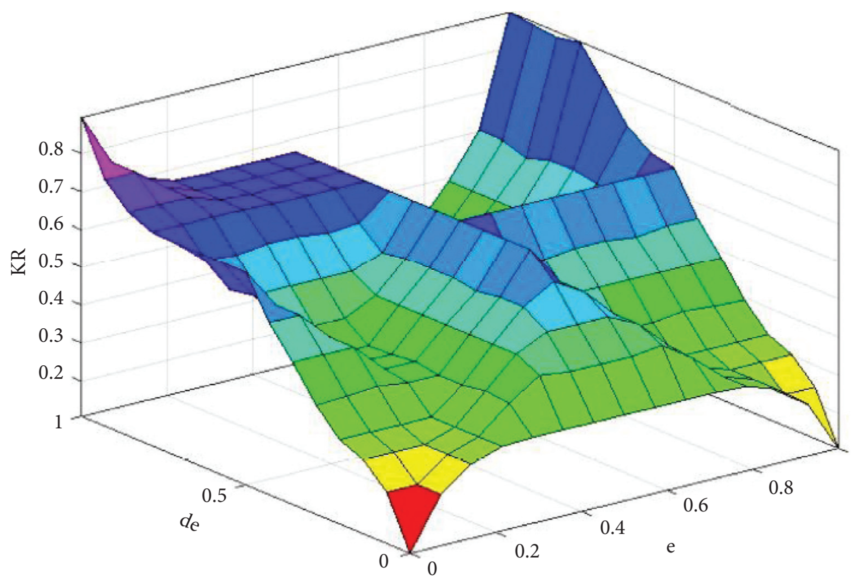


Figure 5: Fuzzy logic membership function of the regulation output gain (KR) with respect to the input error and derivative of error membership functions.

$$\mathcal{U}_F(t) = \left(\frac{F\left(t_0 + t_1 z^{-1} + t_2 z^{-2} + t_3 z^{-3}\right) A_0}{F\left(1 + r_1 z^{-1} + r_2 z^{-2} + r_3 z^{-3}\right)}\right)\mathcal{U}_c - \left(\frac{F\left(s_0 + s_1 z^{-1} + s_2 z^{-2} + s_3 z^{-3}\right)}{F\left(1 + r_1 z^{-1} + r_2 z^{-2} + r_3 z^{-3}\right)}\right)\mathcal{Y}_a(t). \tag{18}$$

For the fuzzy controller, the rules are given in Tables 2–4, having the following linguistics:

(i) Below negative (BN)

(ii) Small negative (SN)

(iii) Zero (ZR)

(iv) Small positive (SP)

(v) Big positive (BP)

The range of fuzzy controller output is 0 to 1, with FR = 0.9 and FS = FT = 0.85, while the error and derivative of error are also in the range of 0 to 1, respectively.

Finally, Figures 5–7 show the 3D view of the 3 variables collectively, namely, the membership function of input error and its derivative with respect to the regulation output gain KR, pole placement output gain KS, and tracking output gain KT, respectively.

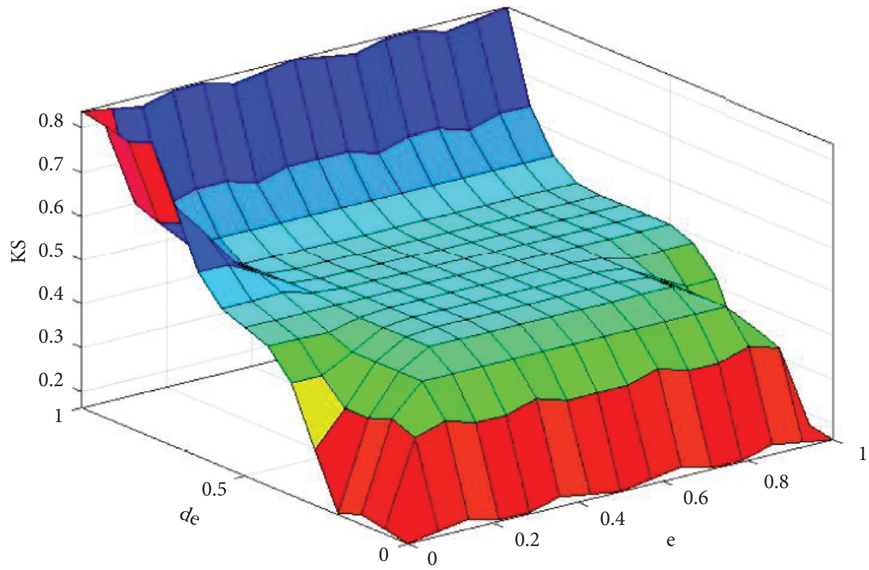


Figure 6: Fuzzy logic membership function of the pole placement output gain (KS) with respect to the input error and derivative of error membership functions.

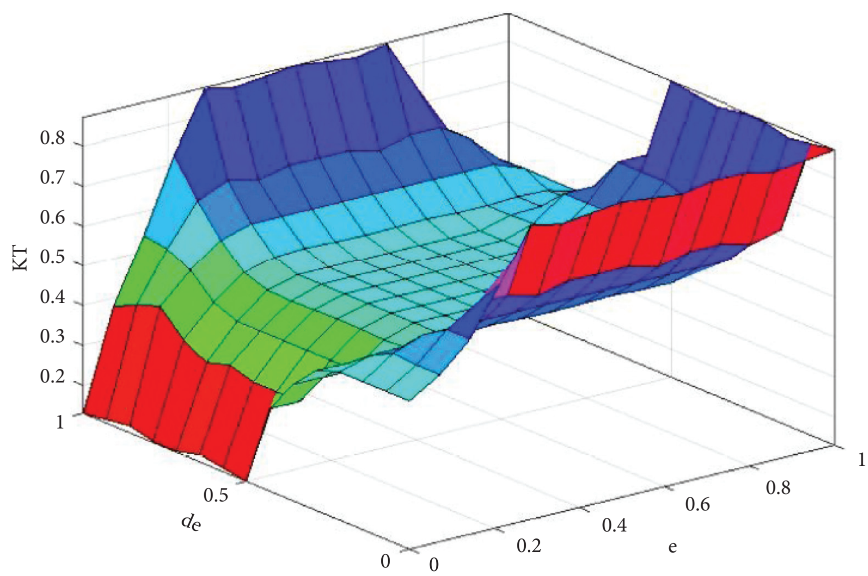


Figure 7: Fuzzy logic membership function of the tracking output gain (KT) with respect to the input error and derivative of error membership functions.

5. Results

In this part, the simulated results of the proposed study are presented by considering the agent's connectivity within the network as depicted in Figure 8. It is shown that the proposed system consists of a single leader and three following agents, connected via a network in fixed undirected topology.

Now, to analyze this network structure, this study uses the graph theory concepts, established in the earlier section, which yields

$$\mathscr{L}(G) = \begin{bmatrix} 1 & -1 & 0 \\ -1 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad d = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{19}$$

Observing the matrices $\mathscr{L}(G)$ and d, it is proved that Lemmas 1 and 2 are endorsed, such that $\mathscr{L}(G)$ has

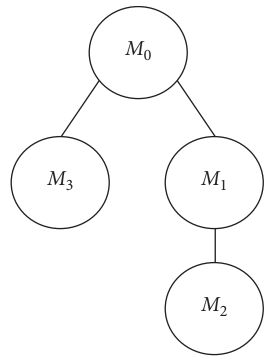


Figure 8: Connection topology.

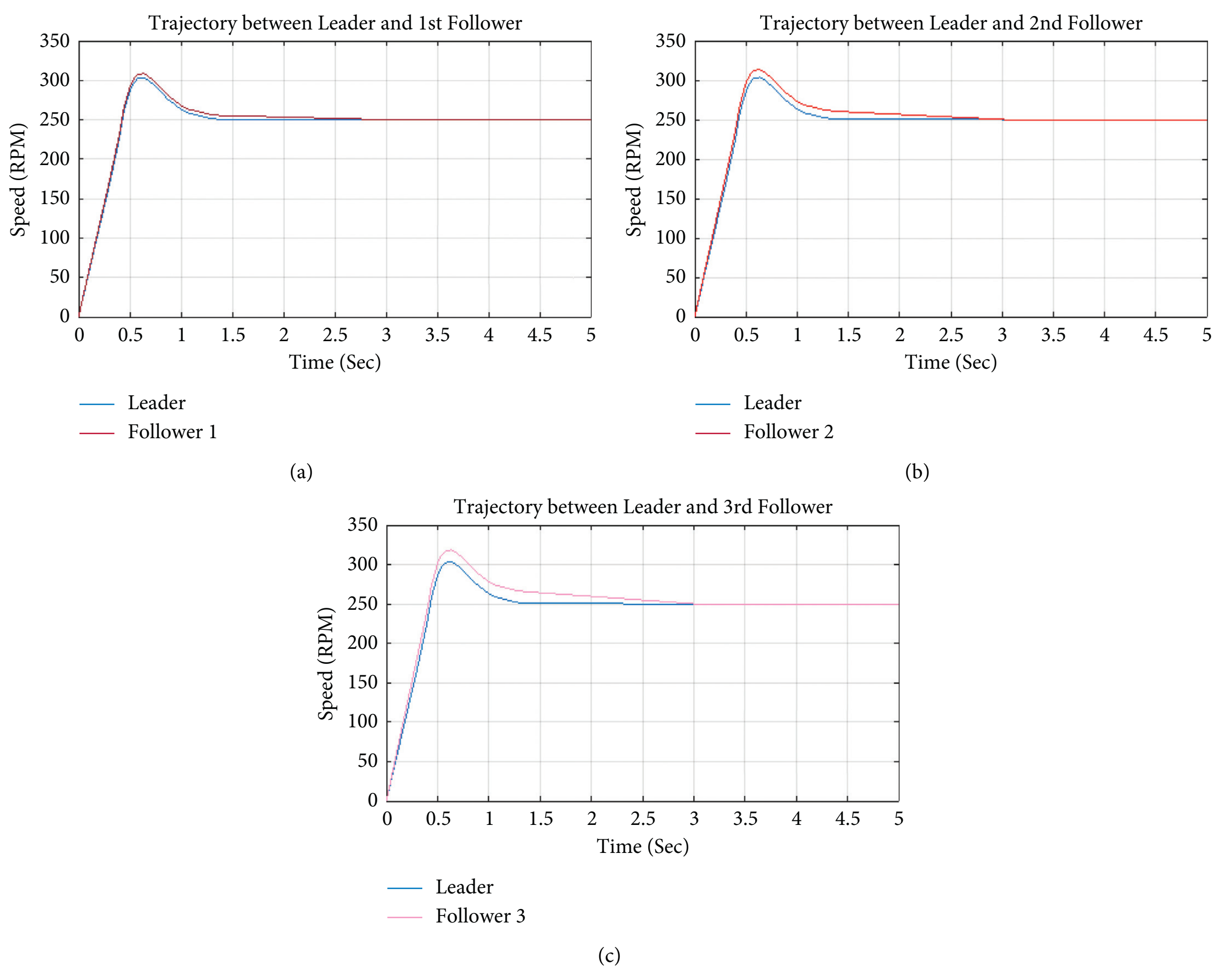


Figure 9: (a) Leader and 1st follower trajectory. (b). Leader and 2nd follower trajectory. (c). Leader and 3rd follower trajectory.

eigenvalues 0 and 2, respectively. Moreover, Lemma 3 is also endorsed by obtaining the $\mathscr{H}(G)$, which is found to be symmetric positive definite, as given by equation (20). Moreover, for simulation, the F-RST controller parameters are found to be FR = 0.9 and FS = FT = 0.85.

$$\mathscr{H}(G) = \begin{bmatrix} 2 & -1 & 0 \\ -1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{20}$$

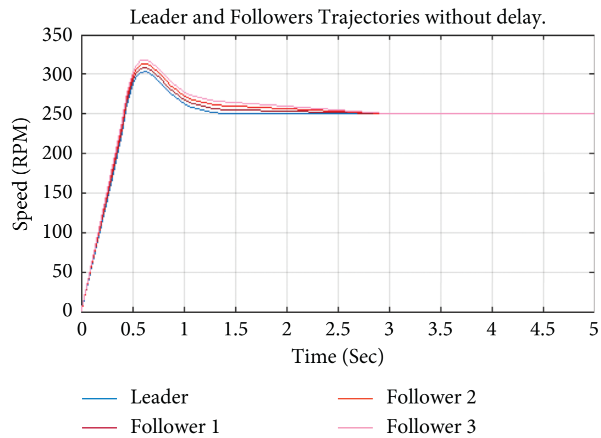


Figure 10: Complete leader and followers trajectories.

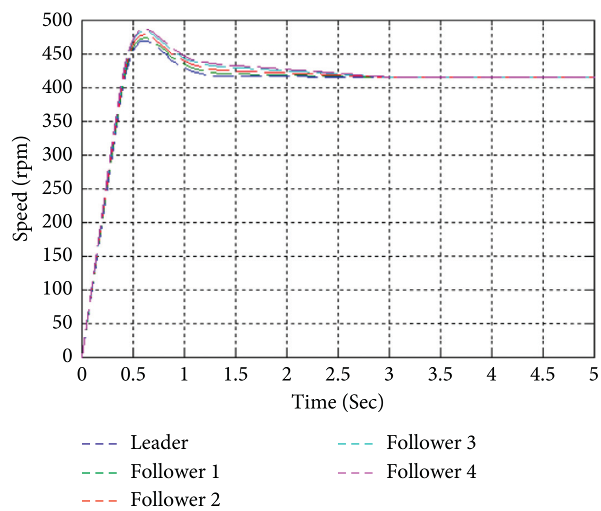


Figure 11: Multimotor speed trajectories without delay [36].

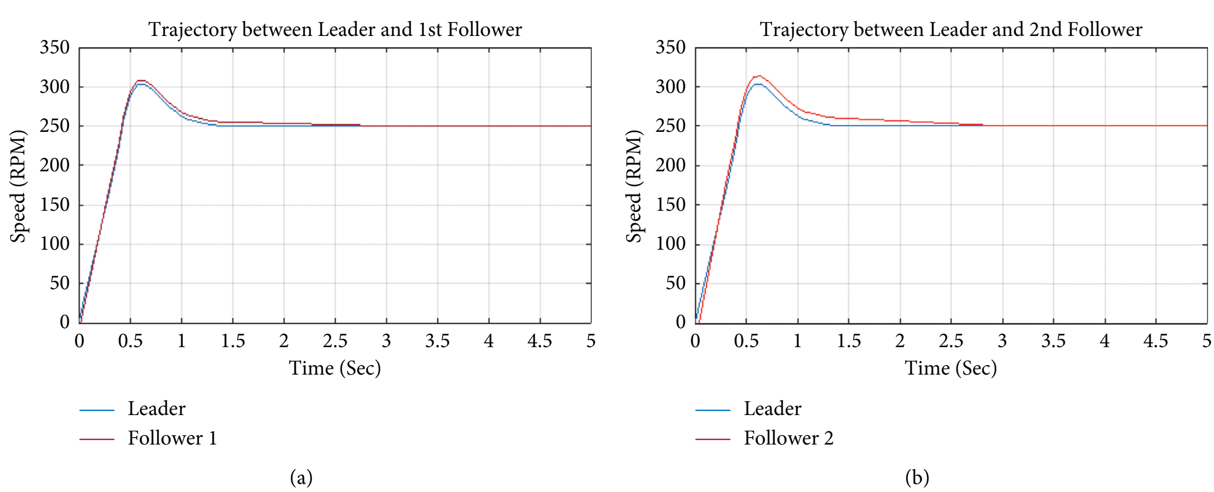
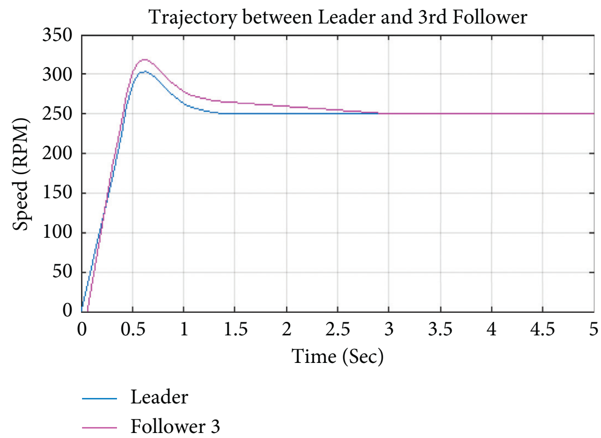


Figure 12: Continued.



(c)

Figure 12: (a) Leader and 1st follower trajectory with delay. (b). Leader and 2nd follower trajectory with delay. (c). Leader and 3rd follower trajectory with delay.

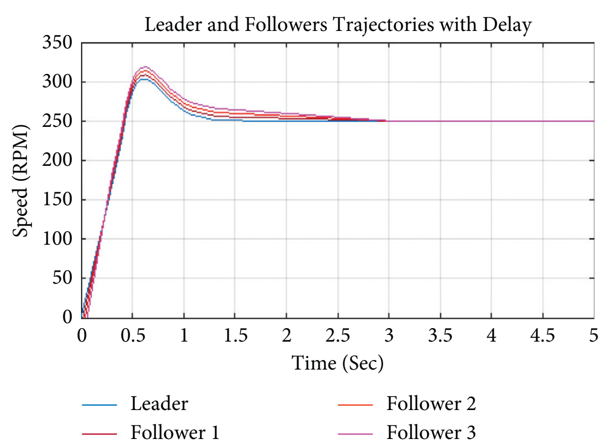


Figure 13: Complete leader and followers trajectories with delay.

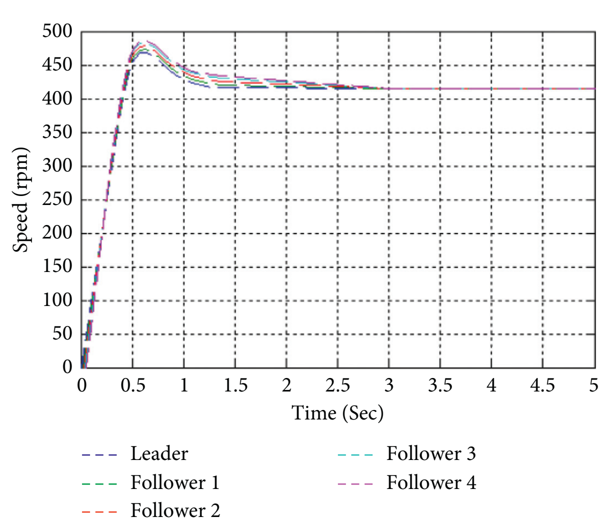


Figure 14: Multimotor speed trajectories with delay [36].

Now, based on data obtained, the proposed system is simulated, and the graphical results are given in Figures 9 to 14. In Figures 9 and 10, it is observed that the network is simulated without considering delays, and it is seen that each motor agent is following the speed of a leading motor, having a momentary distraction from the reference speed in the beginning, such that the controller came into effect, thus receives continuous feedback via the network, and keep conditioning the speed of followers until they reach consensus, i.e., synchronous speed.

For the second case, let us simulate the same system, but with the addition of network input delay. For this scenario, a delay $\tau = 0.02$ sec is introduced in the system. In Figures 12 and 13, it is seen that the following motors are initiated with delay, as expected. Once again, it is observable that the controller still performs exceptionally well, and the following agents keep tracking the leading motor speed and reach a consensus.

Remark 4. Now finally, upon comparing the obtained results with that in Figures 11 and 14, it is seen that the proposed fuzzy controllers responded more efficiently. They have a smaller overshoot peak and have almost identical consensus attainment time.

The problem of having an identical speed with multiple motors can be seen in the propellers of a small UAV's which uses a BLDC motor and attain identical speed for a smooth flight. Moreover, in textile mills, the synchronous speed between cloth wrapping and weaving spindle plays a vital role to avoid any damage. Furthermore, in the case of a lengthier conveyor belt driven by multiple motors, it is necessary to have an identical speed for smooth operation.

6. Conclusion

The motive behind addressing the network-based synchronous speed problem is two folds, first, multimotor systems have large industrial application domains, second, they lack the flexibility of design offered by the networked systems. Thus, in this study, a new multimotor system design is proposed, having wireless network architecture with fixed topology. The synchronous speed problem is modeled as a consensus problem and uses the leader following MAS consensus protocol in a supervisory role to ensure synchronous speed, while appropriate MRAC and F-RST-based local controllers are designed to keep the following motors speed at the reference speed, i.e., leading motor speed. The stability of the system is verified by developing an MIT-based cost function. Thus, the obtained results endorse the proposed networked system and corresponding methodology, as viewed in the graphical simulations.

Data Availability

The data used to support the findings of the study are available within the manuscript, or else can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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