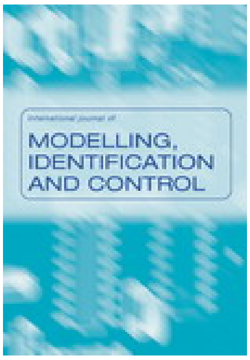

International Journal of Modelling, Identification and Control

ISSN online: 1746-6180 - ISSN print: 1746-6172
https://www.inderscience.com/ijmic

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DOI: 10.1504/IJMIC.2023.10060804

Article History:

Received:	31 January 2023
Last revised:	12 April 2023
Accepted:	16 May 2023
Published online:	30 September 2024

A network control system for solving a speed coordination problem in a networked multi-motor drive

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Abstract: A control system connected to sensor and actuator via communication network plays pivotal role in a today's emerging world. The problem of obtaining a consensus in a group of networks connected agents is one of the major areas of research in the network control systems. In industry, a multi-motor system is very much in demand due to common load driven capacity, and cost saving. Coordinated speed plays vital role to control the in-flight movement of multi-rotor UAV/drones, producing hovering, tilting or other necessary flight control movements. Thus, this study uses a leaderless multi-agent consensus model to achieve coordinated control of network connected motor drives such that all the drives reach identical speed. Moreover, this study also incorporates event-based control, so that the continuous time controller update can be avoided, thus offering energy saving. To ensure stable system design, the Lyapunov stability criteria are used, while the obtained design is simulated in MATLAB. The simulated results endorse the design concept, such that the system attains a consensus on motor speed along with energy saving.

Keywords: network control system; NCS; leaderless multi-agent system; event-based consensus; networked multi-motor system.

Reference to this paper should be made as follows: Jiexian, H., Masroor, S. and Ali, Z.A. (2024) 'A network control system for solving a speed coordination problem in a networked multi-motor drive', *Int. J. Modelling, Identification and Control*, Vol. 45, No. 1, pp.31–39.

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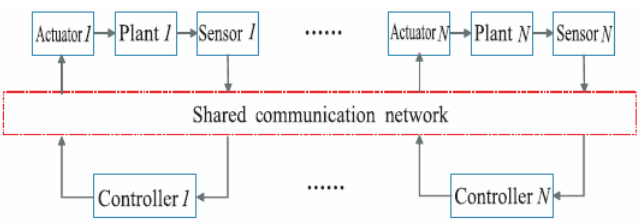
1 Introduction

Over the last decade, control loop with a network, a.k.a. a network system, opened a new era in control theoretical concepts that can handle a wide range of control issues, such as those in Zhong and Cao (2016), Chen and Yue (2012) and Faschang et al. (2013), offering a flexible system structure, being a major advantage over a traditional control technique. That is, even if a node fails, the networked system remains stable.

Traditionally, a wired point-to-point communication architecture, with a control unit for every sensor and actuator, was in practice. Thus, expanding the system is more difficult, due to the nature of point-to-point communication architecture. This disadvantage of point-to-point communication led to common bus communication architecture, even though the common bus network has its own issues such as delay in the communication between sensors and actuators, or sensory signals or actuating signals from the controller may be lost during communication. Figure 1 shows the concept of network control system (NCS) (Zhang et al., 2015).

Figure 1 Control system connected via a network (see online version for colours)

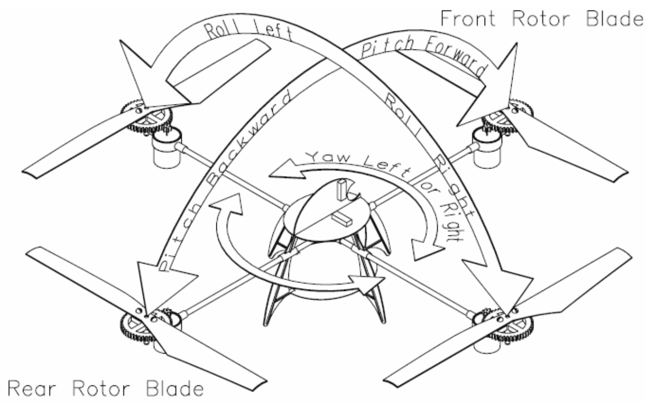


Source: Zhang et al. (2015)

Moreover, in recent times, control science saw a surge in a bio-inspired control techniques to address numerous real-world problems. A multi-agent system (MAS) consensus problem, one of the most attractive bio-inspired control techniques, received major attraction. Plentiful researchers address several problems via MAS consensus technique (Zhang et al., 2023; Ni and Cheng, 2010; Kim et al., 2014; Liu et al., 2006; Masroor and Peng, 2022a; Shafiq and Khan, 2021; Ghosh et al., 2021), with different scenarios such as leaderless or leader following, first or second order, event triggered, fixed, switched, directed, and undirected topologies. Olfati-Saber et al. (2007), laid the foundation for the consensus protocol design. Furthermore, the multifunctional character of MAS attracts researchers from various fields of study, such as computer science, biology, information science, and so on (Ren and Beard, 2008). Moreover, the adaptability of the MAS design method makes it an appealing field for addressing a wide range of real-world challenges. Masroor et al. (2019) addressed the problem of coordinated speed via MAS consensus protocol for network connected motors, having undirected and fixed network architecture, while the system stability is validated via Lyapunov criteria.

Even though the addition of a network offers greater flexibility, another issue which is faced while dealing with this kind of a network model is the continuous consumption of energy that can be addressed by designing an event-based control strategy. In such approach, an event condition is proposed, thereby establishing a threshold, thus whenever that threshold is achieved, an event is triggered, allowing control action to be transmitted and thereby resetting the system fault. Moreover, an event can be centralised or distributed. Therefore, as discussed in Dimarogonas and Johansson (2009), the consensus control issue may alternatively be presented as a centralised or distributed event triggered MAS.

Figure 2 Motion control of multi-rotor drone via BLDC motors



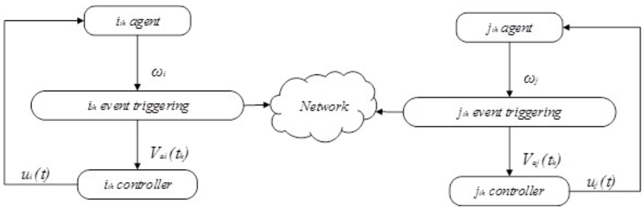
Source: Sanchez et al. (2011)

It is already known that the multi-motor system is widely used in the industrial sector, in numerous forms, depending up on their nature of work. The stability of these kind of systems depends upon the coordinated speed to ensure smooth operation. Conversely, if the systems are made intelligent enough, and are made to exchange speed information with each other, then it is possible to isolate the faulty motor and retain the stability, i.e., identical speed, and it continues to perform in a coordinated manner. There are plenty of researchers who address the multi-motor coordinated speed problem under different conditions, as presented in Nunez et al. (2004) and Masroor and Peng (2018). In Ren et al. (2009), coordinated speed problem in a network coupled IM is addressed via rotor tracking, such that the network also induces delays in the communication. Similarly, in Zhao et al. (2013), a controller gain is developed using a Lyapunov candidate to solve the NIM speed problem, whereas correction in system gain is done using FLC. Moreover, in multi-rotor drones, rotor speed coordination may offer ease in operation and controlling the in-flight movement. Yang et al. (2017) gives a concept of multi-rotor drones, their controlling, and also describes their capabilities to handle different real-world problems. Similarly, in Sanchez et al. (2011), a hovering of multi-rotor drone is improved via BLDC motors, such that the rotors are powered by BLDC motors, thereby producing required torque and angular speed.

Therefore, inspired by the preceding works and considerate of their limitations, this study proposes a network-controlled MAS consensus-based model to address the above said coordination problem along with the energy saving scheme. The motive of this study came from a recent surge in a multi-rotor drone utilisation. The proposed study gives a concept of how a NCS and MAS algorithm can be implemented to control the speed of motors used to drive the rotors of a multi-rotor UAV.

The study presents a novel network connected multiple DC motor speed coordination design with an energy saving mechanism having an event-triggered leaderless MAS consensus algorithm. The proposed concept is given in Figure 3. It is seen that each motor drive is connected to a common network sharing its speed information with the other drives, thus achieving a global consensus, i.e., identical speed. Moreover, it is also evident from Figure 3 that the controller update is event driven, such that whenever the threshold condition is violated an event is triggered, which regulates the input to the i^{th} controller, thereby regulating the input to the i^{th} agent, thus producing a coordinated output.

Figure 3 Event-based network model for a multi-motor system



Thus, the key contribution of this study includes.

- Designing of a network model to address the speed coordination problem in network connected motor drives.
- Designing of a leaderless event triggered speed coordination algorithm, and a threshold condition for event-based control to achieve desired objectives.

Remark 1: The proposed study is unique in the sense that it gives a model of connecting the motors in a common network and designing of a network-based speed controller which ensures identical speed output. The identical speed is obtained by regulating the input to the motors via controller output designed by using leaderless MAS consensus rule. Moreover, this study also highlights the deficiency of existing control system architecture which continuously monitors the output and thereby updates the controller, thus causing increase in the energy consumption. Therefore, this study includes event-based controller update mechanism which ensures energy saving by updating the controller whenever an event is triggered. In other words, sequence of event triggering is basically controlling updates, while between control updates, the input to the motor remains constant, and equals the last update, i.e., control law is piecewise constant.

The manuscript is organised into five sections, such that Section 1 give a brief understanding about the background of the proposed work, followed by preliminaries in Section 2. Furthermore, agent and the network controller design is presented in Section 3, whereas Section 4 presents results of the proposed work, and finally the study proposed in this paper is concluded in Section 5.

2 Preliminaries

In leaderless MAS design, the agent and its neighbour in a network can share the data, the network plays a significant part in any of the MAS modalities. To work in a coordination, every agent must be network connected, thus gaining access to the neighbouring agent data, i.e., speed trajectories. An algebraic graph theory is a key prerequisite for modelling the network connection between the agents. The main variables in the graph G are the nodes θ and edges ρ, so that nodes are connected by edges, producing a graph $G = (\theta, \rho)$, such that $\theta = \{\theta_i\}$, $i \in N(1, n)$ and $\rho \subseteq \theta \times \theta$. In MAS, the node denotes an agent, and the edges signifies the interconnectivity of agents, such that $(\theta_i, \theta_j) \in \rho$, $i, j \in N(1, n)$ holds, if agent i and j are neighbours. Similarly, certain significant matrices linked to graphs play a vital part in understanding the MAS, such as adjacency $\mathcal{A}$, degree D, and the Laplacian L. A neighbouring agent is given as $N_i = \{j\text{: as } (\theta_i, \theta_j) \in \rho, j \neq i\}$ whereas the complete set of neighbours is defined as $D(G) = diag(d_1, d_2, \ldots, d_n)$ such that $D = 1$ if $i = j$ or 0 otherwise. The adjacency of agents is given as $\mathcal{A}(G) = (a_{ij}) \in \mathbb{R}^{N \times N} = 1$ if $(i, j) \in \rho$ or 0 otherwise. Furthermore, because we employed the undirected version of the network in this study, thus $a_{ij} = a_{ji}$ and $a_{ii} = 0$. Finally, the graph's Laplacian is derived as $L = D - \mathcal{A}$, with a row sum of 0 and a left eigenvector of 1, i.e., $L(G)1^T = 0$. Moreover, in an undirected connected network architecture, the property $L(G) \geq 0$ holds, yielding $\lambda_1 = 0$ and $\lambda_1 \leq \lambda_2 \leq \ldots \leq \lambda_N$. Aside from these graph matrices, the following lemmas are also important in the MAS analysis to validate the claimed system connectedness.

Lemma 1 (Masroor and Peng, 2022b): In an undirected connected network architecture, the property $L(G) = \min\limits_{x \neq 0.1^T x = 0} \dfrac{x^T L x}{x^T x}$ holds, satisfying $\lambda_2(G) > 0$.

Remark 2: The proposed work is carried out by assuming an undirected connected graph, as given in Figure 5, therefore the graph Laplacian must hold $L(G) \geq 0$, thus sum of squares property given as

$$x^T Lx = \frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N} a_{ij}\left(x_i - x_j\right)^2$$

Problem definition: In a proposed network multi-motor system, a consensus is said to be achieved, once all the network connected motor drives, defined in equations (3)–(4), reaches identical speed from any initial speed, i.e., $\omega_i(0)$, via i^{th} control input $u_i(t)$ validating $\lim_{t\to\infty}\left\|\omega_i(t)-\omega_j(t)\right\| = 0$ for $i, j \in R(1, n)$.

Assumption 1: This study assumes stable and controllable system matrices (A, B).

Remark 3: If the graph is connected, as given in Lemma 1, and also the Assumption 1 holds, only than it is possible to have a solution of the Riccati inequality, such that a matrix $P > 0$ and a feedback matrix K is obtained.

3 Agent and controller design

A stable system designing require precise dynamic modelling of the system, and its subsystem, to ensure proper input output variable selection, and subsystem values. This section presents the proposed model of i^{th} agent, along with the controller design, and stability analysis. The dynamic state space model of a DC motor is given as

$$\begin{bmatrix} i_a \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} -\frac{r_a}{\ell_a} & -\frac{k_e}{\ell_a} \\ \frac{k_e}{j} & 0 \end{bmatrix}\begin{bmatrix} i_a \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{1}{\ell_a} \\ 00 \end{bmatrix} v_a \tag{1}$$

where $i_a, \ell_a, r_a, v_a, \omega, j$ and k_e are the armature current, inductance, resistance, voltage, speed, inertia, and back e.m.f. constant respectively. The switched DC chopper in state space is given as

$$\begin{bmatrix} i_\ell \\ \dot{v}_c \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{\ell} \\ \frac{1}{c} & -\frac{1}{r_a c} \end{bmatrix}\begin{bmatrix} i_\ell \\ v_c \end{bmatrix} + \begin{bmatrix} \frac{1}{\ell} \\ 0 \end{bmatrix} v \tag{2}$$

where v_c, v, i_ℓ, ℓ, and c are the capacitor voltages, input voltages, inductor current, inductance, and capacitance of the buck chopper. Thus, a complete motor drive in state space is given as

$$\dot{x}_i = Ax_i + Bu_i \tag{3}$$

$$y = Cx_i \tag{4}$$

$$\begin{bmatrix} i_\ell \\ \dot{v}_c \\ i_a \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{\ell} & 0 & 0 \\ \frac{1}{c} & -\frac{1}{r_a c} & 0 & 0 \\ 0 & \frac{1}{\ell_a} & -\frac{r_a}{\ell_a} & \frac{k_e}{\ell_a} \\ 0 & 0 & \frac{k_e}{j} & 0 \end{bmatrix}\begin{bmatrix} i_\ell \\ v_c \\ i_a \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{v\mathcal{S}}{\ell} \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{5}$$

$$\omega = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} i_\ell \\ v_c \\ i_a \\ \omega \end{bmatrix} \tag{6}$$

where $\mathcal{S}$ reflects the position of the switch, i.e., 0 or 1, in Figure 4. This leads to array of switching position, given as $\varsigma = [0, \infty)$ having $(1, \ldots, n)$ sequences. If $\varsigma = 1$, $\mathcal{S} = 0$ then

$$A_1 = \begin{bmatrix} 0 & -\frac{1}{\ell} & 0 & 0 \\ \frac{1}{c} & -\frac{1}{r_a c} & 0 & 0 \\ 0 & \frac{1}{\ell_a} & -\frac{r_a}{\ell_a} & \frac{k_e}{\ell_a} \\ 0 & 0 & \frac{k_e}{j} & 0 \end{bmatrix} \text{ and } B_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{7}$$

For the second sequence, if $\varsigma = 2$, $\mathcal{S} = 1$, then

$$A_2 = \begin{bmatrix} 0 & -\frac{1}{\ell} & 0 & 0 \\ \frac{1}{c} & -\frac{1}{r_a c} & 0 & 0 \\ 0 & \frac{1}{\ell_a} & -\frac{r_a}{\ell_a} & \frac{k_e}{\ell_a} \\ 0 & 0 & \frac{k_e}{j} & 0 \end{bmatrix} \text{ and } B_2 = \begin{bmatrix} \frac{v}{\ell} \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{8}$$

This gives a perception of complete i^{th} agent model as

$$A_T = \begin{bmatrix} 0 & -\frac{1}{\ell} & 0 & 0 \\ \frac{1}{c} & -\frac{1}{r_a c} & 0 & 0 \\ 0 & \frac{1}{\ell_a} & -\frac{r_a}{\ell_a} & \frac{k_e}{\ell_a} \\ 0 & 0 & \frac{k_e}{j} & 0 \end{bmatrix} \text{ and } B_T = \begin{bmatrix} \frac{v\Xi}{\ell} \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{9}$$

With $\Xi \in \{0, 1\}$. The motor drive and its design parameters are given in Figure 4 and Table 1 respectively.

Figure 4 Motor drive

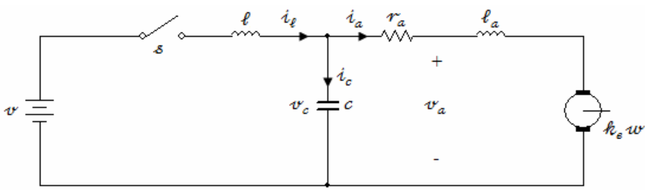


Table 1 Motor drive design specification

Variable	*Value (unit)*
ℓ_a	1.5 (mH)
r_a	0.6 (Ω)
c	470 (µF)
ℓ	1.3 (mH)
v	50 (V)
j	5.5 × 10^{-5} (kg·m^2)
k_e	0.05 (V/rad/s)
w	120 (rad/s)

Now, to design an appropriate controller, let's recall the standard form of leaderless multi-agent consensus controller.

$$u_i = K\sum_{j\in N_i} a_{ij}\left(x_i - x_j\right) \tag{10}$$

Since, the proposed study require to have speed coordination and to obtain identical speed, the consensus algorithm of equation (10) is modified as

$$u_i = K\sum_{j\in N_i} a_{ij}\left(\omega_i - \omega_j\right) \tag{11}$$

Thus, for the i^{th} agent, the system describe in equation (3) can be written as

$$\dot{x}_i = Ax_i - B\left(K\sum_{j\in N_i} a_{ij}\left(\omega_i(t) - \omega_j(t)\right)\right) \tag{12}$$

And the complete system can be written as

$$\dot{x} = (I_N \otimes A)x(t) - \left[(I_N \otimes B)(I_N \otimes K)(I_M \otimes L)\right]x(t) \tag{13}$$

$$\dot{x} = [I_N \otimes A - BK \otimes L]x(t) \tag{14}$$

For centralised triggering, the error is defined as

$$\begin{aligned} &e(t) = \omega(t_k) - \omega(t); \\ &\text{such that } t \in [t_k, t_{k+1}); k = 0, 1, 2, \ldots \end{aligned} \tag{15}$$

$$\dot{e}_i(t) = Ae_i + u_i \tag{16}$$

$$e_i(t) = Ae_i(t) - B\left(K\sum_{j\in N_i} a_{ij}\left(e_i(t) - e_j(t)\right)\right) \tag{17}$$

$$\begin{aligned} \dot{e}(t) &= (I_N \otimes A)e(t) \\ &\quad -\left[(I_N \otimes B)(I_N \otimes K)(I_M \otimes L)\right]e(t) \end{aligned} \tag{18}$$

$$\dot{e}(t) = [I_N \otimes A - BK \otimes L]e(t) \tag{19}$$

From equation (15), it is deduced that, at time t_k the i^{th} agent will be triggered having k^{th} sequencing. Now, for the linear quadratic regulator (LQR) control, the cost function l is given as

$$J = \int_0^\infty \left(e^T (I_N \otimes Q)e + u^T R u\right)dt \tag{20}$$

where Q and R are symmetric matrices, holding the property $Q > 0$ and $R > 0$. Moreover, if the Assumption 1 holds, then l will decrease given that there exists a symmetric matrix P, holding property $P > 0$, and a matrix K to a given algebraic Riccati inequality

$$A^T P + PA - 2\alpha R^{-1}B^T PBP + \alpha Q = 0 \tag{21}$$

Such that $K = R^{-1}B^T P$. And $0 < \alpha \le 2\varsigma_2$ while the centralised triggering condition is given as

$$t_{k+1} = \left\|(L \otimes I_N)e(t)\right\| \le \delta\left\|(L \otimes I_N)\omega(t)\right\| \tag{22}$$

where $\delta = \sqrt{2\alpha\left(1 - \frac{\alpha(B^T PBP)^2}{2}\right)}$. To ensure stability, a Lyapunov function is considered as

$$V = e^T (I_N \otimes P)e \tag{23}$$

$$\dot{V} = \dot{e}^T (I_N \otimes P)e + e^T (I_N \otimes P)\dot{e} \tag{24}$$

$$\begin{aligned} &= (I_N \otimes A^T - B^T K^T \otimes L)e^T (I_N \otimes P)e \\ &+ e^T (I_N \otimes P)(I_N \otimes A - BK \otimes L)e \end{aligned} \tag{25}$$

$$\begin{aligned} &= e^T (I_N \otimes A^T - B^T K^T \otimes L)(I_N \otimes P)e \\ &+ e^T (I_N \otimes P)(I_N \otimes A - BK \otimes L)e \end{aligned} \tag{26}$$

$$\begin{aligned} &= e^T\left[(I_N \otimes A^T - B^T K^T \otimes L)(I_N \otimes P)\right. \\ &\left. + (I_N \otimes A - BK \otimes L)(I_N \otimes P)\right]e \end{aligned} \tag{27}$$

$$= e^T\left[(I_N \otimes A^T P + AP) - L \otimes (B^T K^T P + BKP)\right]e \tag{28}$$

$$\begin{aligned} &= e^T\left[(I_N \otimes A^T P + AP)\right. \\ &\left. - L \otimes \left(B^T (R^{-1})^T (B^T)^T P^T P + BR^{-1}BTPP\right)\right]e \end{aligned} \tag{29}$$

$$= e^T\left[(I_N \otimes A^T P + AP) - L \otimes (2R^{-1}B^T PBP)\right]e \tag{30}$$

For i^{th} agent, above equation can be written as

$$\dot{V}_i \le \sum_{i=1}^{N} e_i^T\left[A^T P + AP - \lambda_i\left(2R^{-1}B^T PBP\right)\right]e_i \tag{31}$$

And, comparing with cost function l of equation (20), we obtain

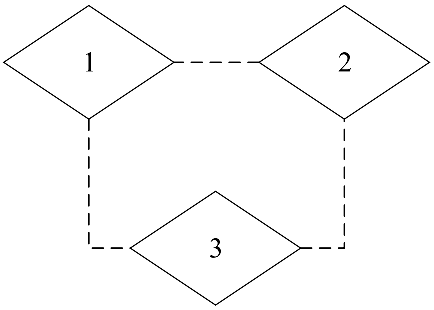
$$\dot{V}_i \le -\alpha_i \sum_{i=1}^{N} e_i^T e_i \tag{32}$$

Remark 4: From equation (32), it is concluded that the system is stable, i.e., $\dot{V} < 0$ for all $e \neq 0$, therefore it is deduced that all the network agents are coordinating with each other to solve the speed coordination problem.

4 Results

This section endorses the theory established above by simulating the network of agents connected in a fixed undirected network architecture, as given in Figure 5. Moreover, it is already understood that each agent in the Figure 5 is representing a motor drive, and they are connected in a manner to coordinate with each other to reach the identical speed.

Figure 5 Fixed and undirected communication topology among the agents



The undirected fixed network of Figure 5 gives.

$$D = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 2 \end{bmatrix}$$

$$A = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$$

$$L = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$$

Thus, endorsing the Lemmas 1 and 2 such that $\lambda_1 = 0$, and $\lambda_2 = 3$. Now, upon using the specification of i^{th} agent, given in Table 1, one can obtain.

$$A = \begin{bmatrix} 0 & -0.0077 & 0 & 0 \\ 2.1277 & 0 & 0 & 0 \\ 0 & 0.0067 & -0.0040 & 0.003 \\ 0 & 0 & 0.0091 & 0 \end{bmatrix}$$

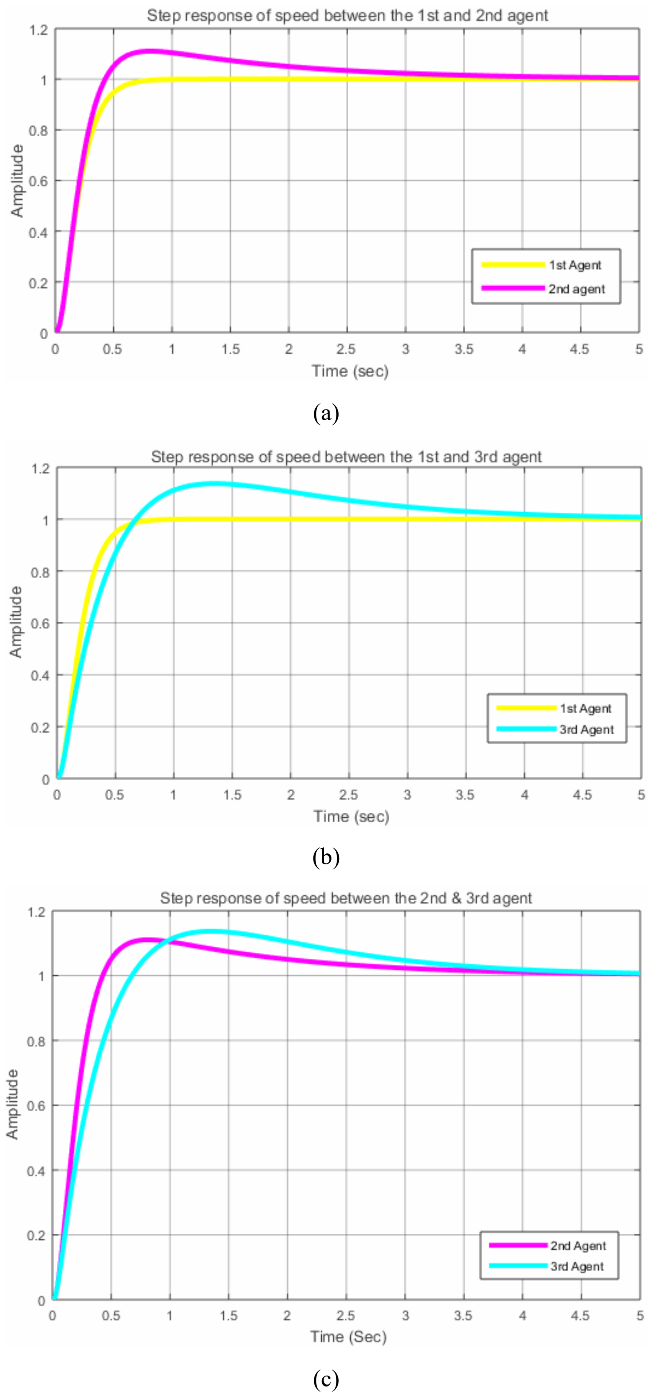
$$B = \begin{bmatrix} 3.8462 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

And thus, solving the Riccati inequality by considering $R = 1$ will gives.

$$P = \begin{bmatrix} 0.0001 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0.0022 & 0.0016 \\ 0 & 0 & 0.0016 & 0.0023 \end{bmatrix}$$

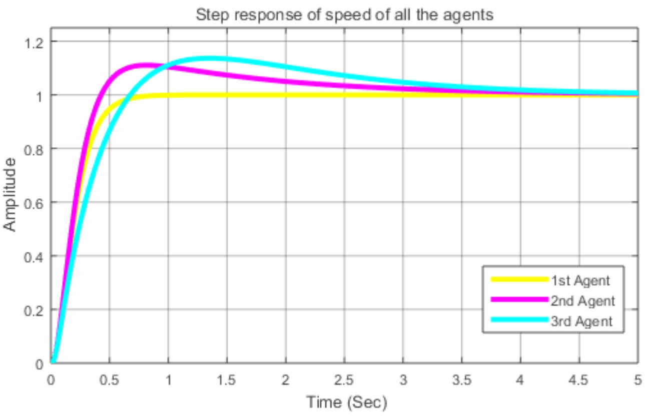
$$K = \begin{bmatrix} 3.4668 & 0.9959 & 1.4621 & 1.0520 \end{bmatrix}$$

Figure 6 Step response of speed coordination, (a) coordination response between the 1st and 2nd agents (b) coordination response between the 1st and 3rd agents (c) coordination response between the 2nd and 3rd agents (see online version for colours)



Finally, the simulated results given in Figures 6 and 7 endorse the design considerations, system modelling, and network topology by obtaining the identical speed in a proposed multi-motor system.

Figure 7 Complete response of the proposed network multi-motor system (see online version for colours)



For sake of comparison and to endorse better results obtained with the proposed methodology, the work in Chamorro et al. (2014) is used. The author has simulated induction motor speed control system via leader follower consensus approach. A Simulink model design was carried out to deal with variety of problem associated with MAS system such as node failure, delays, or presence of disturbances, as shown in Figure 8. In Figure 8(a), a leader follower consensus is seen to be reached with two leaders and three followers, whereas in Figure 8(b) the system reaches consensus with the addition of communication delay, and finally in Figure 8(c), a consensus is seen to be reached in the presence of a node failure. Thus, it is proved that MAS consensus approach can be used to address speed control problem of electric motors.

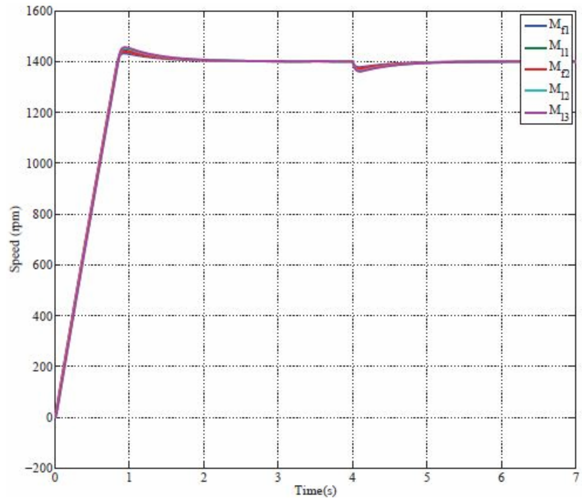
Thus, the proposed work attains better results and have novelty with the work in Chamorro et al. (2014), including.

- The proposed work is carried out with a leaderless consensus approach.
- The speed control of DC motor is carried out.
- Event triggered communication is adopted to ensure energy saving.
- The proposed work is carried out in state space instead of Simulink.
- The obtained results endorse the acquisition of better results.

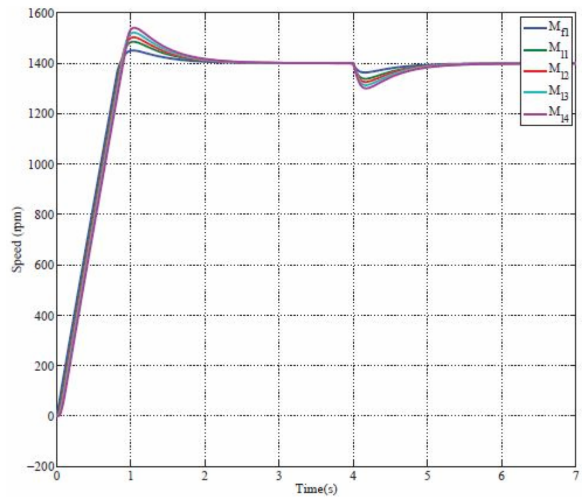
Finally, the event triggering time of the proposed methodology is given in Figure 9.

It is seen in Figure 9 that every time when the event condition is violated, the controller updates itself and the state information of i^{th} agent is communicated to the neighbours. Thus, Figure 9 clearly shows that considerable energy saving can be achieved with this method, as compared to continuous time controller.

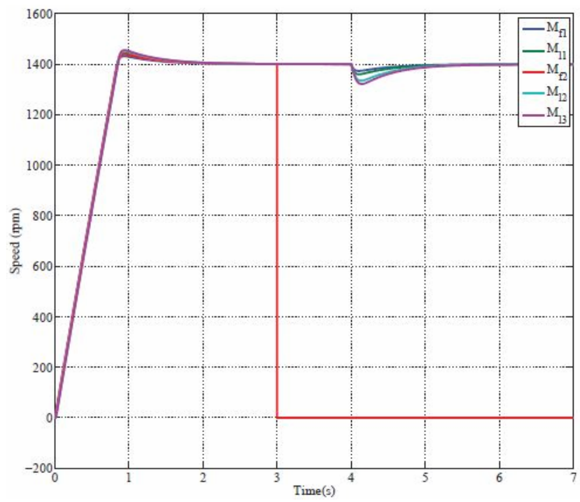
Figure 8 Leader follower speed consensus in the induction motors (see online version for colours)



(a)



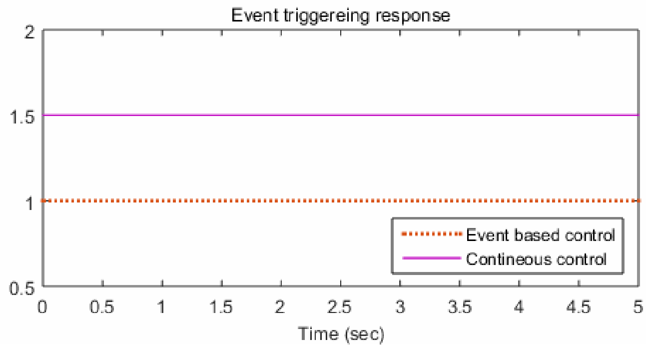
(b)



(c)

Source: Chamorro et al. (2014)

Figure 9 Event triggering time (see online version for colours)



5 Conclusions

The presented work utilises the concept of leaderless MAS consensus to attain coordinated speed control for a multi-motor system along with a centralised event triggered communication that ensure energy saving. The proposed multi-motor system design uses DC chopper drive, modelled as an i^{th} agent, and it is assumed that each motor in the network has the same dynamics, and thus forming a MAS architecture. The stability analysis of the proposed system is carried out via Lyapunov stability theorem, which validates the design, and the simulation results further authenticate the design concept. In future, the presented work can further be extended in multiple ways such as applying a random load to the motors, or to consider the switched communication topology, or exploring the effects of network induced delays on the system.

Acknowledgements

The author would like to acknowledge the facilities offered by Biomedical Engineering Department of Sir Syed University of Engineering and Technology, to carry out this study.

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