Consensus of the Second-order Multi-agent Systems under Asynchronous Switching with a Controller Fault

Dianhao Zheng*, Hongbin Zhang, J. Andrew Zhang and Yang Li

Abstract: Asynchronous switching differing from asynchronous consensus may hinder the system to reach a consensus. This receives very limited attention, especially when the multi-agent systems have a controller fault. In order to analyze the consensus in this situation, this paper studies the consensus of the second-order multi-agent systems under asynchronous switching with a controller fault. We convert the consensus problems under asynchronous switching into stability problems and obtain important results for consensus with the aid of linear matrix inequalities. An example is given to illustrate the effect of asynchronous switching on the consensus, and to validate the analytical results in this paper.

Keywords: Consensus, Multi-agent systems, Asynchronous switching, Controller faults

1. INTRODUCTION

Multi-agent systems, as a class of complicated dynamic systems, are composed of multiple interactive intelligences. Such systems appear in many applications, such as robot communication networks [1, 2], and unmanned vehicles [3]. Therefore multi-agent systems have drawn considerable attention in recent years [4–8]. In multi-agent systems, all agents coordinate to solve a global common problem, such as consensus [4], containment control [9, 10], and vehicle formations.

Consensus, as the most basic problem of the coordination in multi-agent systems, is to design or analyze a distributed control law to make all agents reach a common value [11]. Whenever the nodes of a network are all in agreement, this common value is called the group decision value. Reaching the group decision value needs to apply inputs that only depend on the states of every node and its own neighbours in a distributed way [4].

The consensus problem has been extensively studied. Some basic concepts on consensus and topologies were introduced in [4,12]. In [13], results for second-order consensus under fixed topologies are presented. Second-order consensus under switched topologies was studied in [14]. The paper [11] studied the consensus problem for a class of uncertain multi-agent systems under directed switching networks with uncertainty. The papers [15,16] studied the consensus problem for a class of general second-order multi-agent systems and presented some results about the necessary and sufficient condition for the consensus. Fixed-time consensus tracking control for second-order multi-agent systems with bounded input uncertainties was introduced in [17]. A distributed protocol was proposed in [18] based on the information of second-order neighbours for the robust consensus problem of fractional-order linear multi-agent systems with positive real uncertainty under a fixed undirected topology.

So far, almost all the research efforts on the consensus of multi-agent under switched topologies are devoted to networks without feedback control or with only synchronous switching despite the great importance of the consensus under asynchronous switching control in both theoretical and practical aspects [19]. According to the definition in [20–22], the consensus is called asynchronous consensus if the individuals in systems respond to the new information from their neighbours at different update times. This is different to the consensus under asynchronous switching, which means that the switching between the candidate controllers and topologies are asynchronous [19]. For switched systems, the asynchronous switching often means that the switching of the controllers

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to be designed has a lag to the switching of the system models [23] and the switching between the candidate controllers and system modes is asynchronous [24]. Therefore, although asynchronous consensus and consensus under asynchronous switching sound similar in their names, their definitions are different and asynchronous switching may hinder the way to a consensus.

Asynchronous switching has been studied for switched systems in the past few years and the research results on switched systems have advanced the study on switched topologies [23–25]. Due to link failures or reconnection, the topologies of multi-agent systems often change. When the changing is modelled in a switched way, the multi-agent systems under switching topologies can be described and analyzed by switched systems theorems [24]. However, the consensus problem for asynchronous switching is yet to be solved. Since asynchronous switching widely exists in switched topologies, the consensus of multi-agent systems under asynchronous switching needs to be investigated urgently, especially for the systems with a controller fault.

The main purpose of this paper is to study the consensus of the second-order multi-agent systems under asynchronous switching with a controller fault. We will tackle the problem via converting the consensus problems under asynchronous switching into stability problems. The rest of the paper is organized as follows. In Section 2, some basic concepts and algebraic graph theories are given. Main results about asynchronous switching are presented in Section 3. The simulation results are presented in Section 4. Finally, conclusions are provided in Section 5.

Notations: The superscript “T" stands for matrix transposition. The mathematical symbols I_{n-1} and 0_{n-1} mean an identity matrix and a zero matrix with $(n-1)\times(n-1)$ dimension, respectively. The sign $diag\{\cdots\}$ represents a block-diagonal matrix with proper dimension. If P is a given matrix, $P > (or \ \ <)\ 0$ signifies a symmetric and positive (or negative) definite matrix P. For a function γ, it is said to be of a class K_∞ function if the function $\gamma : [0,\infty) \to [0,\infty)$, $\gamma(0) = 0$, is strictly increasing, continuous, and unbounded. Scalar multiplication of matrices is defined as a regular number(called a "scalar") multiplying every element in the matrix [26].

2. PRELIMINARIES

In this section, some basic concepts and algebraic graph theories are introduced.

The network of multi-agent systems is often modelled by graph theories. For the multi-agent systems with n agents and the node indexes set $\mathcal{I} = \{1,2,\ldots,n\}$, the digraph can be denoted by $\mathcal{G} = (\mathcal{V},\mathcal{E},\mathcal{A})$, where $\mathcal{V} = \{v_1, v_2,\ldots,v_n\}$, $\mathcal{E} \subseteq \mathcal{V}\times\mathcal{V}$, $\mathcal{A} = [a_{ij}]$ are the set of nodes, the set of edges and the adjacency matrix. The edge between nodes i and j can be described as $e_{ij} = (v_i, v_j)$. This method can represent any edge of the graph $\mathcal{G}$. We assume $i \neq j$ for any edge. The set of neighbours of node v_i is denoted by $\mathcal{N}_i = \{v_j \in \mathcal{V} : (v_i, v_j) \in \mathcal{E}, j \neq i\}$. The Laplacian matrix L is defined as: $l_{ij} = \sum_{k=1,k\neq i}^{n} a_{ik}$ for $i = j$, and $l_{ij} = -a_{ij}$, for $i \neq j$, $i, j \in \mathcal{I}$. A Laplacian-like matrix H is defined as $H = [h_{ij}]$, where $h_{ij} = l_{ij} - l_{nj}$. The function $\sigma(t) : [0,+\infty) \to \mathcal{M} = \{1,2,\cdots,m\}$ stands for the switching signal of the switching topologies, where m is the total amount of topologies. The function $\sigma'(t)$ denotes the asynchronous switching of $\sigma(t)$.

For the switched topologies, t_1, t_2, t_3, $\cdots$, t_l, t_{l+1}, $\cdots$ stand for the switching times of the topologies of the multi-agent systems. Let $\Delta_{\sigma(t_l)}(t_l,t_{l+1})$ (or $\nabla_{\sigma(t_l)}(t_l,t_{l+1})$) represent the asynchronous (or synchronous) time between the time slots $[t_l,t_{l+1})$. The symbol $T_p(0,t)$ denotes the running time of the p^{th} topology between the time slots $[0,t)$.

For a group of n agents systems, every agent is modelled by the second-order dynamics as

$$\begin{aligned} \dot{x}_i(t) &= v_i(t), \\ \dot{v}_i(t) &= u_i(t), \end{aligned} \tag{1}$$

where $x_i(t)$ is the state of the i^{th} agent, u_i is the control input.

For asynchronous switching, there exists a time lag Δ between the topologies switching signal $\sigma(t)$ and the feedback controller coefficients switching $\sigma'(t)$. When the lag is small enough, the models tend to be synchronous. Using one of the many algorithms for synchronous switching [27,28] as an example, the corresponding consensus algorithm with asynchronous switching can be represented as

$$\begin{aligned} &u_i(t) \\ =&f\beta_{0_{\sigma(t-\Delta)}} \sum_{j\in\mathcal{N}_i(t)} a_{ij_{\sigma(t)}}(x_j(t)-x_i(t)) - f\beta_{1_{\sigma(t-\Delta)}} v_i(t), \end{aligned} \tag{2}$$

where $a_{ij_{\sigma(t)}}, i, j \in \mathcal{I}$ are the elements in the adjacency matrix $\mathcal{A}(\mathcal{G})$. The topology $\mathcal{G}$ and $\sigma(t)$ change at the switching times $t_1,t_2,t_3,\cdots,t_l,t_{l+1},\cdots$. The positive parameters β_0, β_1 are the coefficients, and f is defined as

$$f \triangleq \frac{measured \quad value}{actual \quad value}.$$

The fault considered in this model is uncertain and

$$\begin{cases} 0 < f_d \leq f \leq f_u, \\ f_d \leq 1 \leq f_u, \end{cases} \tag{3}$$

where f_d and f_u are known constants. In this paper, we only assume the range of the deviation is known.

Remark 1: When the positive constants $f_d \neq 1$ or $f_u \neq 1$ are known, it is implied that consensus feedback has an uncertain parameter f. It may originate from inaccurate coefficient β or other factors and results in a controller fault.

Remark 2: Because of Δ in the system (2), the switching time of topologies and controllers is different and the system (2) is under asynchronous switching. Since all agents update their states at the same time t, it is also a synchronous system. Therefore, the system (2) is a synchronous system with asynchronous switching. For asynchronous consensus, every agent has its own update time t_i, which is different from agent to agent. For the system (2), the controller could be at fault and the parameters could be uncertain and mismatched. How to reach a consensus in this situation is challenging.

For all initial conditions, the multi-agent systems (1) are said to reach a consensus if

$$\lim_{t\to+\infty}[x_i - x_j] = 0, \lim_{t\to+\infty}[v_i - v_j] = 0, \forall i, j \in \mathcal{M}, i \neq j.$$

For a switching $\sigma(t)$ at any time $t_k > t_l \geq 0$, the switching number in the p^{th} subsystem is denoted by $N_{\sigma p}(t_l,t_k)$, and the total running time of p^{th} subsystem is denoted by $T_p(t_l,t_k)$ over the interval $[t_l,t_k)$. In [29], it is shown that the system has a mode-dependent average dwell time (MDADT) τ_{ap} if there exist positive numbers $N_{0p}(t_l,t_k)$ and τ_{ap} such that

$$N_{\sigma p}(t_l,t_k) \leq N_{0p}(t_l,t_k) + \frac{T_p(t_l,t_k)}{\tau_{ap}} \tag{4}$$

Based on the concept on MDADT, we can get the following Lemma 1.

Lemma 1: Consider a system $\dot{z}_t = A_{\sigma(t-\Delta)}z_t$, $\sigma(t-\Delta) \in \mathcal{M}$ with give constants $\lambda_p > 0$, $\mu_p > 1$, $\alpha_p > 0$, $p \in \mathcal{M}$. For $\forall p \in \mathcal{M}$, $\forall t \in [t_l,t_{l+1})$, and $\forall(\sigma(t_l) = p, \sigma(t_l^-) = q) \in \mathcal{M}\times\mathcal{M}, p \neq q$, if there exist symmetric matrices $P_p > 0$, such that

$$A_q^T P_p + P_p A_q \leq \alpha_p P_p, \forall t \in [t_l, t_l + \Delta_l), \tag{5}$$

$$A_p^T P_p + P_p A_p \leq -\lambda_p P_p, \forall t \in [t_l + \Delta_l, t_{l+1}) \tag{6}$$

$$\text{and } P_p(z(t_l)) \leq \mu_p P_q(z(t_l^-)), \tag{7}$$

then the system is globally uniformly asymptotically stable with MDADT

$$\tau_{ap} > \tau_{ap}^* \triangleq \frac{\Delta_{p\_\max}(\lambda_P + \alpha_p) + \ln\mu_p}{\lambda_p}, \tag{8}$$

where $\Delta_{p\_\max} \triangleq max_{l,\sigma(t_l)=p}\Delta_{\sigma(t_l)}\,[t_l,t_{l+1})$, for $\forall l \in \mathbb{N}$.

Proof: For any $t > 0$, $\forall t \in (t_l,t_{l+1})$.
From (8), one has

$$\frac{\ln\mu_p + (\lambda_p+\alpha_p)\Delta_{p\_\max}}{\tau_{ap}} - \lambda_p < 0, \tag{9}$$

and

$$\max_{p\in\mathcal{M}}\{\frac{\ln\mu_p + (\lambda_p+\alpha_p)\Delta_{p\_\max}}{\tau_{ap}} - \lambda_p\} < 0. \tag{10}$$

A multiple Lyapunov function is constructed as

$$V_p(z(t)) = z(t)^T P_p z(t). \tag{11}$$

According to (5), (6) and (7), it holds that

$$\begin{aligned}
&V_{\sigma(t)}(x(t))\\
&\leq \exp\left\{\alpha_{\sigma(t_l)}\Delta_{\sigma(t_l)}(t_l,t) - \lambda_{\sigma(t_l)}\triangledown_{\sigma(t_l)}(t_l,t)\right\}V_{\sigma(t_l)}(x(t_l))\\
&\leq \exp\left\{\alpha_{\sigma(t_l)}\Delta_{\sigma(t_l)}(t_l,t) - \lambda_{\sigma(t_l)}\triangledown_{\sigma(t_l)}(t_l,t)\right\}\\
&\quad\times \mu_{\sigma(t_l)}V_{\sigma(t_l)}(x(t_l{}^-))\\
&\ldots\ldots\\
&\leq \left\{\prod_{p=1}^{l}\mu_{\sigma(t_p)}\right\}\\
&\quad\times \exp\left\{\alpha_{\sigma(t_l)}\Delta_{\sigma(t_l)}(t_l,t) + \cdots + \alpha_{\sigma(t_0)}\Delta_{\sigma(t_0)}(t_{l-1},t_l)\right\}\\
&\quad\times \exp\left\{-\lambda_{\sigma(t_l)}\triangledown_{\sigma(t_l)}(t_l,t) - \cdots - \lambda_{\sigma(t_0)}\triangledown_{\sigma(t_0)}(t_0,t_1)\right\}\\
&\quad\times V_{\sigma(t_0)}(x(t_0)).
\end{aligned} \tag{12}$$

Because of the total switching numbers $N(0,t) = \sum_{p=1}^{m} N_{\sigma p}(0,t)$ and $t_0 = 0$, one can get

$$\begin{aligned}
&V_{\sigma(t)}(x(t))\\
&\leq \left\{\prod_{p=1}^{m}\mu_p^{N_{\sigma p}(0,t)}\right\}\exp\left\{\sum_{p=1}^{m}\alpha_p\Delta_p(0,t) - \lambda_p\triangledown_p(0,t)\right\}\\
&\quad\times V_{\sigma(0)}(x(0)).
\end{aligned} \tag{13}$$

According to (4), one has

$$\begin{aligned}
&\prod_{p=1}^{m}\mu_p^{N_{\sigma p}(0,t)} = \prod_{p=1}^{m}\mu_p^{N_{0p}+\frac{T_p(0,t)}{\tau_{ap}}}\\
&= \exp\left\{\sum_{p=1}^{m}\left\{N_{0p}\ln\mu_p + \frac{T_p(0,t)}{\tau_{ap}}\ln\mu_p\right\}\right\}
\end{aligned} \tag{14}$$

and

$$\begin{aligned}
&V_{\sigma(t)}(x(t))\\
&\leq \exp\left\{\sum_{p=1}^{m}\left\{N_{0p}\ln\mu_p + \frac{T_p(0,t)}{\tau_{ap}}\ln\mu_p\right\}\right\}\\
&\quad\times \exp\left\{\sum_{p=1}^{m}\{\alpha_p\Delta_p(0,t) - \lambda_p T_p(0,t) + \lambda_p\Delta_p(0,t)\}\right\}\\
&\quad\times V_{\sigma(0)}(x(0))\\
&\leq \exp\left\{\sum_{p=1}^{m}N_{0p}\ln\mu_p + (\frac{\ln\mu_p}{\tau_{ap}} - \lambda_p)T_p(0,t)\right\}\\
&\quad\times \exp\left\{\sum_{p=1}^{m}(\lambda_p+\alpha_p)\Delta_p(0,t)\right\}V_{\sigma(0)}(x(0)).
\end{aligned} \tag{15}$$

From the definition of $\Delta_{p\_\max}$ one can get

$$\Delta_p(0,t) \leq N_{\sigma p}(0,t)\Delta_{p\_\max} \leq N_{0p} + \frac{T_p(0,t)}{\tau_{ap}}. \tag{16}$$

Then, based on (4), one can get

$$\begin{aligned} &V_{\sigma(t)}(x(t)) \\ &\leq \exp\left\{\sum_{p=1}^{m}\{N_{0p}\ln\mu_p+(\lambda_p+\alpha_p)N_{0p}\Delta_{p\_\max})\}\right\} \\ &\times\exp\left\{\sum_{p=1}^{m}\{(\frac{\ln\mu_p+(\lambda_p+\alpha_p)\tau_{ap}}{\tau_{ap}}-\lambda_p)\}T_p(0,t)\right\} \\ &\times V_{\sigma(0)}(x(0)). \end{aligned} \tag{17}$$

From (9), we can conclude that $V_{\sigma(t)}(x(t))$ convergences to zero, as $t\to+\infty$, if the dwell time satisfies $\tau_{ap}>(\lambda_p+\alpha_p)\Delta_{p\_\max}+\ln\mu_p)/\lambda_p$.

Therefore, we can see that the asymptotic stability is reduced. This completes the proof. □

In order to solve the problems with an uncertain parameter, the following Lemma 2 is introduced.

Lemma 2: [30] Given matrices Q, R, E and H with proper dimensions, and $Q=Q^T$, $R=R^T>0$, the inequality

$$Q+HFE+E^TF^TH^T<0$$

holds for all F satisfying $F^TF\leq R$, if and only if there exists some $\varepsilon>0$, such that

$$Q+\varepsilon HH^T+\varepsilon^{-1}E^TRE<0.$$

3. MAIN RESULTS

In this section, we mainly complete the following three objectives:

Firstly, we design a transformation from consensus under asynchronous switching to stability. For asynchronous switching, the states of agents may go to divergences when some necessary and sufficient conditions cannot be met [15] in the asynchronous switching time slots. We analyze the relationship between consensus under asynchronous switching and the asynchronous stability of switched systems and then present the conversion between them. Based on the conversion and the relationship between energy functions and stability, the divergences will cause the increase of the energy functions. That is, asynchronous switching may result in the divergences of states, which are marked by the increasing of the energy function.

Secondly, we analyze the consensus with a controller fault. We rewrite the formation of f and analyze the conditions for reaching a consensus when the multi-agent systems are switching with a controller fault based on the method of the mode-dependent average dwell time. Using this method, we can decrease the overall energy function by adjusting the dwell time of topologies, and hence force the system to reach a consensus.

Thirdly, we extend the results on asynchronous switching to the synchronous switching.

3.1. Transformation from Consensus to Asynchronous Switching

By the following Theorem 1, the problem of the consensus under asynchronous switching is converted into that of the asynchronous stability of switched systems.

Theorem 1: For the multi-agent systems with directed network $\mathcal{G}(t)$, if the system

$$\dot{z}(t)=FK_{\sigma(t-\Delta)}B_{a\sigma(t)}z(t),z(t_0)=z(0), \tag{18}$$

is globally uniformly asymptotically stable, then the multi-agent systems with the dynamic system (1) will reach a consensus with the consensus algorithm (2), where

$$F=\begin{bmatrix} I_{n-1} & 0_{n-1} \\ 0_{n-1} & f_{diag}\end{bmatrix}, \tag{19}$$

$$K_{\sigma(t-\Delta)}=\begin{bmatrix} 0_{n-1} & I_{n-1} \\ -\beta_0 I_{n-1} & -\beta_1 I_{n-1}\end{bmatrix}_{\sigma(t-\Delta)}, \tag{20}$$

$$B_{a\sigma(t)}=\begin{bmatrix} H & 0_{n-1} \\ 0_{n-1} & I_{n-1}\end{bmatrix}_{\sigma(t)}, \tag{21}$$

$$f_{diag}=diag\{\underbrace{f,\cdots,f}_{n-1}\}. \tag{22}$$

Proof: Firstly, we define $z(t)\triangleq[x_1-x_n,\ldots,x_{n-1}-x_n,v_1-v_n,\ldots,v_{n-1}-v_n]^T(t)$.

According to the definition of the consensus, if $\lim_{t\to+\infty}z(t)=0$, the multi-agent systems will reach a consensus.

From (2), one can get

$$\begin{aligned} &u_i-u_n \\ =&f\beta_{0_{\sigma(t-\Delta)}}\sum_{j\in\mathcal{N}_i(t)}a_{ij_{\sigma(t)}}(x_j(t)-x_i(t))-f\beta_{1_{\sigma(t-\Delta)}}v_i(t) \\ &-f\beta_{0_{\sigma(t-\Delta)}}\sum_{k\in\mathcal{N}_n(t)}a_{nk_{\sigma(t)}}(x_k(t)-x_n(t))+f\beta_{1_{\sigma(t-\Delta)}}v_n(t) \\ =&-f\beta_{0_{\sigma(t-\Delta)}}L_i(t)x(t)-\beta_{1_{\sigma(t-\Delta)}}fv_i(t) \\ &+f\beta_{0_{\sigma(t-\Delta)}}L_n(t)x(t)+\beta_{1_{\sigma(t-\Delta)}}fv_n(t) \\ =&-f\beta_{0_{\sigma(t-\Delta)}}(L_i(t)-L_n(t))x(t)-f\beta_{1_{\sigma(t-\Delta)}}(v_i(t)-v_n(t)) \\ =&-f\beta_{0_{\sigma(t-\Delta)}}H_i(t)[x_1-x_n,\ldots,x_{n-1}-x_n]^T \\ &-f\beta_{1_{\sigma(t-\Delta)}}(v_i(t)-v_n(t)) \end{aligned} \tag{23}$$

and

$$\begin{aligned} &[\dot{v}_1-\dot{v}_n,\ldots,\dot{v}_{n-1}-\dot{v}_n]^T(t) \\ =&[u_1-u_n,\ldots,u_{n-1}-u_n]^T \\ =&-f\beta_{0_{\sigma(t-\Delta)}}H(t)[x_1-x_n,\ldots,x_{n-1}-x_n]^T(t) \\ &-f\beta_{1_{\sigma(t-\Delta)}}[v_1-v_n,\ldots,v_{n-1}-v_n]^T(t) \\ =&[-f\beta_{0_{\sigma(t-\Delta)}}H(t),-f\beta_{1_{\sigma(t-\Delta)}}I]z(t). \end{aligned} \tag{24}$$

where L_i (or H_i) is the i^{th} row vector of the Laplacian (or H) matrix.

From (1), one can get

$$\begin{aligned}&[\dot{x}_1-\dot{x}_n,\dots,\dot{x}_{n-1}-\dot{x}_n]^T\\=&[v_1-v_n,\dots,v_{n-1}-v_n]^T\\=&[0_{n-1},I_{n-1}]z.\end{aligned}\tag{25}$$

Now, combining (24) and (25), we can get

$$\dot{z}(t)=\begin{bmatrix}0_{n-1} & I_{n-1}\\ -f\beta_{0_{\sigma(t-\Delta)}}H(t) & -f\beta_{1_{\sigma(t-\Delta)}}I_{n-1}\end{bmatrix}z(t),z(t_0)=z(0).\tag{26}$$

We further have

$$\begin{aligned}&\begin{bmatrix}0_{n-1} & I_{n-1}\\ -f\beta_{0_{\sigma(t-\Delta)}}H(t) & -f\beta_{1_{\sigma(t-\Delta)}}I_{n-1}\end{bmatrix}\\=&\begin{bmatrix}I_{n-1} & 0_{n-1}\\ 0_{n-1} & f\,I_{n-1}\end{bmatrix}\begin{bmatrix}0_{n-1} & I_{n-1}\\ -\beta_0 I_{n-1} & -\beta_1 I_{n-1}\end{bmatrix}_{\sigma(t-\Delta)}\\&\times\begin{bmatrix}H & 0_{n-1}\\ 0_{n-1} & I_{n-1}\end{bmatrix}_{\sigma(t)}\\\triangleq& FK_{\sigma(t-\Delta)}B_{a\sigma(t)},\end{aligned}\tag{27}$$

where f is a scalar, and f_{diag} denotes the diagonal matrix with diagonal elements. The equation (18) can now be proved.

According to the definition of $z(t)$, the consensus problem can be solved if the system (18) is globally uniformly asymptotically stable. This completes the proof of this theorem. □

Remark 3: For the case without a controller fault or an uncertain parameter, it can be denoted by $f=1$. From the proof of Theorem 1, we can see that Theorem 1 is also applicable to the situations without a controller fault.

3.2. Consensus with a controller fault

For the multi-agent systems with a controller fault represented by the uncertain parameter, we only know the range of f. In order to solve the asynchronous switching with an uncertain parameter f, we rewrite the formation of f.

We define $F_u \triangleq diag(1,\cdots,1,f_u,\cdots f_u)$, $F_d \triangleq diag(1,\cdots,1,f_d,\cdots f_d)$, $F_0 \triangleq \frac{1}{2}(F_u+F_d)$, $F_1 \triangleq \frac{1}{2}(F_u-F_d)$, then

$$F=F_0+EF_1,\tag{28}$$

where $E=diag\,(1\cdots 1,e,\cdots,e)$, and $-1\leqslant e\leqslant 1$.

Systems (18) can be replaced with

$$\begin{aligned}\dot{z}(t)&=FK_{\sigma(t-\Delta)}B_{a\sigma(t)}z(t)\\&=(F_0+EF_1)K_{\sigma(t-\Delta)}B_{a\sigma(t)}z(t)\\&=F_0K_{\sigma(t-\Delta)}B_{a\sigma(t)}z(t)+EF_1K_{\sigma(t-\Delta)}B_{a\sigma(t)}z(t)\\&=\bar{A}_{\sigma(t-\Delta)}z(t),\end{aligned}\tag{29}$$

where $\bar{A}_{\sigma(t-\Delta)}=F_0K_{\sigma(t-\Delta)}B_{a\sigma(t)}z(t)+EF_1K_{\sigma(t-\Delta)}B_{a\sigma(t)}z(t)$.

From (29) and the inequality in Lemma 2, we now have the following theorem:

Theorem 2: For the given constants $\lambda_p>0$, $\mu_p>1$, and the multi-agent systems with switched topologies $\mathcal{G}_p$, $p\in\mathcal{M}$, $\forall(\sigma(t_i)=p,\sigma(t_i^-)=q)\in\mathcal{M}\times\mathcal{M}, p\neq q$, if there exist symmetric matrices $P_p>0$, positive constants ε_p, and ε_{pq}, $\forall p\in\mathcal{M}$, such that

$$\begin{bmatrix}D_p & \varepsilon_pF_1 & P_p(K_pB_{ap})^T\\ \varepsilon_pF_1{}^T & -\varepsilon_pI_{n-1} & 0_{n-1}\\ K_pB_{ap}P_p & 0_{n-1} & -\varepsilon_pI_{n-1}\end{bmatrix}<0,\tag{30}$$

where $D_p=(F_0K_pB_{ap})P_p+P_p(F_0K_pB_{ap})^T+\lambda_pP_p$, and

$$P_p^{-1}\leq\mu_pP_q^{-1},\tag{31}$$

$$\begin{bmatrix}\bar{D}_p & \varepsilon_{pq}F_1 & P_p(K_qB_{ap})^T\\ \varepsilon_{pq}F_1{}^T & -\varepsilon_{pq}I_{n-1} & 0_{n-1}\\ K_qB_{ap}P_p & 0_{n-1} & -\varepsilon_{pq}I_{n-1}\end{bmatrix}<0,\tag{32}$$

where $\bar{D}_p=(F_0K_qB_{ap})P_p+P_p(F_0K_qB_{ap})^T-\alpha_pP_p$, then the multi-agent systems (1) under consensus algorithm (2) with the fault tolerance (3) will reach a consensus with MDADT

$$\tau_{ap}>\tau_{ap}^*=\frac{\Delta_{p\_\max}(\lambda_P+\alpha_p)+\ln\mu_p}{\lambda_p}.$$

Proof: Based on the Schur complement lemma, one can see that the system (30) is equivalent to

$$D_p-S_p^T\begin{bmatrix}-\varepsilon_pI_{n-1} & 0_{n-1}\\ 0_{n-1} & -\varepsilon_pI_{n-1}\end{bmatrix}^{-1}S_p<0,\tag{33}$$

where $S_p=\begin{bmatrix}\varepsilon_pF_1{}^T\\(K_pB_{ap})P_p\end{bmatrix}$. This can be further written as

$$\begin{aligned}&D_p-S_p^T\begin{bmatrix}-\varepsilon_pI_{n-1} & 0_{n-1}\\ 0_{n-1} & -\varepsilon_pI_{n-1}\end{bmatrix}^{-1}S_p\\&=D_p+S_p^T\begin{bmatrix}\varepsilon_p{}^{-1}I_{n-1} & 0_{n-1}\\ 0_{n-1} & \varepsilon_p{}^{-1}I_{n-1}\end{bmatrix}S_p\\&=D_p+\begin{bmatrix}F_1 & \varepsilon_p{}^{-1}P_p(K_pB_{ap})^T\end{bmatrix}S_p\\&=D_p+\varepsilon_pF_1F_1{}^T+\varepsilon_p{}^{-1}P_p(K_pB_{ap})^T(K_pB_{ap})P_p\\&<0.\end{aligned}\tag{34}$$

According to Lemma 2, one can get

$$D_p+F_1E(K_pB_{ap})P_p+P_p(K_pB_{ap})^TE^TF_1{}^T<0.\tag{35}$$

This can also be further represented as

$$\begin{aligned}&D_p+F_1E(K_pB_{ap})P_p+P_p(K_pB_{ap})^TE^TF_1{}^T\\=&(F_0K_pB_{ap}+F_1EK_pB_{ap})P_p\\&+P_p(F_0K_pB_{ap}+F_1E(K_pB_{ap}))^T+\lambda_pP_p\\<&0.\end{aligned}\tag{36}$$

Using $diag\{P_p{}^{-1}\}$ to pre- and post-multiply both sides of systems (36), one has

$$\begin{aligned} &P_p{}^{-1}(F_0K_pB_{ap}+F_1EK_pB_{ap}) \\ &+(F_0K_pB_{ap}+F_1EK_pB_{ap})^T P_p{}^{-1}+\lambda_p P_p{}^{-1} \\ &<0. \end{aligned} \quad (37)$$

Denote $\bar{P}_p = P_p{}^{-1}$. We can also see that $\bar{P}_p > 0$ and systems (37) are equivalent to

$$\begin{aligned} &\bar{P}_p(F_0K_pB_{ap}+F_1EK_pB_{ap})+(F_0K_pB_{ap}+F_1EK_pB_{ap})\bar{P}_p \\ &+\lambda_p\bar{P}_p<0. \end{aligned} \quad (38)$$

Based on systems (29) and (38), one has

$$\bar{P}_p(FK_pB_{ap})+(FK_pB_{ap})^T\bar{P}_p < -\lambda_p\bar{P}_p. \quad (39)$$

Similarly, we can have

$$\bar{P}_p(FK_qB_{ap})+(FK_qB_{ap})^T\bar{P}_p < \alpha_p\bar{P}_p. \quad (40)$$

From (31), one has

$$\bar{P}_p \le \mu_p\bar{P}_q. \quad (41)$$

Combining the results in (39), (40) and (41) and Lemma 1, we can then establish the results in Theorem 2. The proof is completed. □

Remark 4: Theorem 2 is based on Lemma 1 and on the idea that the topologies changing replaces subsystem switching. Hence the results on MDADT and switched systems are also applicable to the multi-agent systems under switched topologies.

Using a similar process, we can establish and prove Corollary 1 below when using a common P to replace P_p.

Corollary 1: For the multi-agent systems with switched topologies $\mathcal{G}_p$, $p\in\mathcal{M}, \forall(\sigma(t_i)=p,\sigma(t_i^-)=q)\in\mathcal{M}\times\mathcal{M}, p\neq q$, if there exist a symmetric matrix $P>0$, positive constants ε_p, $\forall p\in\mathcal{M}$, such that

$$\begin{bmatrix} D_p & \varepsilon_pF_1 & P(K_pB_{ap})^T \\ \varepsilon_pF_1{}^T & -\varepsilon_pI_{n-1} & 0_{n-1} \\ (K_pB_{ap})P & 0_{n-1} & -\varepsilon_pI_{n-1} \end{bmatrix} < 0, \quad (42)$$

where $D_p = (F_0K_pB_{ap})P+P(F_0K_pB_{ap})^T+\lambda_pP$,

$$\begin{bmatrix} \bar{D}_p & \varepsilon_{pq}F_1 & P(K_qB_{ap})^T \\ \varepsilon_{pq}F_1{}^T & -\varepsilon_{pq}I & 0_{n-1} \\ K_qB_{ap}P & 0_{n-1} & -\varepsilon_{pq}I_{n-1} \end{bmatrix} < 0, \quad (43)$$

where $\bar{D}_p = (F_0K_qB_{ap})P+P(F_0K_qB_{ap})^T-\alpha_pP$, then the multi-agent systems (1) under consensus algorithm (2) with the fault tolerance (3) will reach the consensus finally with MDADT

$$\tau_{ap} > \tau_{ap}^* = \frac{\Delta_{p\_\max}(\lambda_P+\alpha_p)}{\lambda_p}. \quad (44)$$

Remark 5: MDADT is used in the proof for reaching a consensus when the multi-agent systems are switching. In order to guarantee the condition of MDADT, the statistical information on the dwell time under each topology is required to confirm that the average dwell time is longer than the offset.

3.3. Extension to Synchronous Switching

One can see that if the time lag $\Delta(t)=0$, the asynchronous switching is replaced with synchronous switching in the algorithm (2).

In the synchronous switching situation, systems (2) change to

$$u_i(t) = f\beta_{0_{\sigma(t)}}\sum_{j\in\mathcal{N}_i(t)} a_{ij_{\sigma(t)}}(x_j(t)-x_i(t)) - f\beta_{1_{\sigma(t)}}v_i(t). \quad (45)$$

Likewise, the following corollaries can be obtained for the case of synchronous switching multi-agent systems.

Corollary 2: For the given constants $\lambda_p>0$, $\mu_p>1$, and the switched topologies $\mathcal{G}_p$ of the multi-agent systems, $p\in\mathcal{M}, \forall(\sigma(t_i)=p,\sigma(t_i^-)=q)\in\mathcal{M}\times\mathcal{M}, p\neq q$, if there exist symmetric matrices $P_p>0$, positive constants ε_p, $\forall p\in\mathcal{M}$, such that

$$\begin{bmatrix} D_p & \varepsilon_pF_1 & P_p(K_pB_{ap})^T \\ \varepsilon_pF_1{}^T & -\varepsilon_pI_{n-1} & 0_{n-1} \\ K_pB_{ap}P_p & 0_{n-1} & -\varepsilon_pI_{n-1} \end{bmatrix} < 0, \quad (46)$$

where $D_p = (F_0K_pB_{ap})P_p+P_p(F_0K_pB_{ap})^T+\lambda_pP_p$,

$$P_p^{-1} \le \mu_pP_q^{-1}, \quad (47)$$

then the multi-agent systems (1) under consensus algorithm (45) with the fault tolerance (3) reach the consensus when

$$\tau_{ap} > \tau_{ap}^* = \frac{\ln\mu_p}{\lambda_p}, \quad (48)$$

Corollary 3: For the switched topologies $\mathcal{G}_p$ of the multi-agent systems, $p\in\mathcal{M}$, if there exist a symmetric matrix $P>0$, positive constants ε_p, $\forall p\in\mathcal{M}$, such that

$$\begin{bmatrix} D_p & \varepsilon_pF_1 & P(K_pB_{ap})^T \\ \varepsilon_pF_1{}^T & -\varepsilon_pI_{n-1} & 0_{n-1} \\ (K_pB_{ap})P & 0_{n-1} & -\varepsilon_pI_{n-1} \end{bmatrix} < 0, \quad (49)$$

where $D_p = (F_0K_pB_{ap})P+P(F_0K_pB_{ap})^T+\lambda_pP$, then the multi-agent systems (1) under consensus algorithm (45) with the fault tolerance (3) will reach the consensus finally.

Remark 6: LMIs toolbox in MATLAB is often used to find proper matrices P and constants ε. Although the existence of proper matrices and constants is the sufficient condition, the results in this paper provide a guarantee on the consensus under asynchronous switching, especially when the systems are with an uncertain parameter.

Since there are many nonlinear cases and Takagi-Sugeno (T-S) fuzzy model has been popularly utilized in representing nonlinear systems [31–33], one of our future works is to investigate the coordination of the nonlinear multi-agent systems under asynchronous switching.

4. NUMERICAL EXAMPLE

In this section, numerical results are presented to demonstrate the potential and validity of our developed theoretical results. For this example, the second-order multi-agent systems are with 4 agents and the topologies are switched. Through this numerical example, the asynchronous switching's reaction to a consensus can also be seen clearly. In the same set-up, the corresponding validation can be done for the common P case and the synchronous switching cases. This is omitted due to space limitations.

Consider the adjacency matrices of the two considered topologies described by

$$\begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}, \text{ and } \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix}. \tag{50}$$

The two-level signal values (low and high) of switching signals $\sigma(t)$ stand for these two topologies. The purpose here is to show the influence of asynchronous switching and present the tendency of states and velocities of agents when the dwell times satisfy the corresponding conditions (8). In order to achieve this, the changing of energy function (Lyapunov function) is shown in Fig.1, and states and velocities are shown in Fig.2., when switching signals $\sigma(t)$ and $\sigma'(t)$ change.

Selection of the parameters for the system model and the controller is based on the physical meanings of parameters. The sign μ stands for the jumping strength when topologies change. The symbols λ and α denote the convergence rate and the divergence speed. Changing these parameters will affect constrained conditions which results in the changing of the average dwell time. The looser the constrained conditions are, the lager the average dwell time is.

The maximal delay of asynchronous switching of the first topology is 0, and the maximal delay of asynchronous switching of the second topology is 6 seconds. In this example, we just know the range $0.9 \le f \le 1.1$, i.e., $f_d = 0.9$ and $f_u = 1.1$. By providing proper constants $\lambda_1 = 0.020$, $\mu_1 = 1.88$, $\alpha_1 = 0$, $\lambda_2 = 0.183$, $\mu_2 = 2.47$, $\alpha_2 = 0.845$, the LMIs toolbox can find proper solutions and get the proper dwell time satisfying conditions (8). The simulation results are shown in Fig.1. and Fig.2.

At the running time slots [0,1.730), [8.04,9.77), [15.65,19.74) and [25.47,34.58), the network is synchronous, the energy function in Fig.1. drops down quickly except for at the topologies switching time spot, the states and velocities of agents in Fig.2. are reaching a consensus. At the running time slots [1.73,8.04), [9.77,15.65), [19.74,25.47) and [34.58, 40.37), the network is asynchronous, the energy function in Fig.1. increases quickly, the states and velocities of agents in Fig.2. tend to diverge. When the dwell times meet the conditions (8), the consensus is reached.

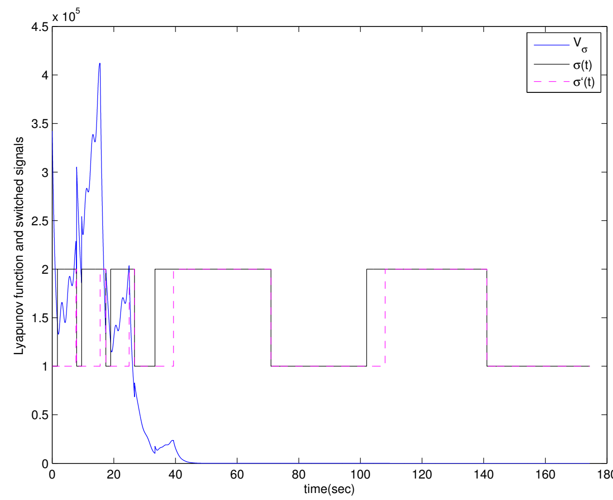

Fig. 1. The changing of the Lyapunov function and switched signals

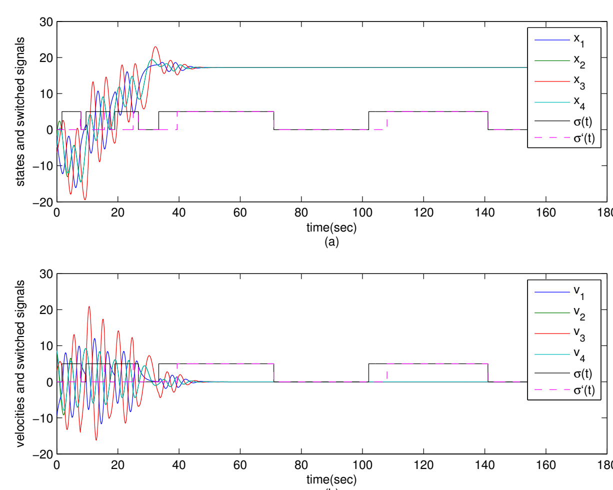

Fig. 2. The changing of the states, velocities and switched signals

5. CONCLUSIONS

The consensus of the second-order multi-agent systems under asynchronous switching with a controller fault is investigated. We analyzed the relationship between consensus and steadiness, and prove the consensus, and provided conditions for the consensus, and also extended the results to the synchronous switching multi-agent systems. Simulation results clearly demonstrate the asynchronous switching's reaction to a consensus. With both analytical and numerical results, we show that a consensus under asynchronous switching with a controller fault can also be reached under proper conditions despite the reaction of asynchronous switching. The methods developed in this paper can also be potentially applied to study other problems such as containment control and vehicle formations in the presence of asynchronous switching for the underlying systems.

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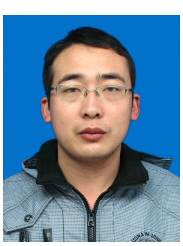

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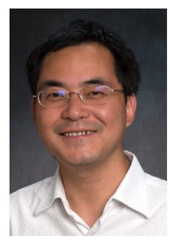

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