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Fault Detection and Isolation of Multi-Agent Systems via Complex Laplacian

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ABSTRACT: This paper studies the problem of fault detection and isolation (FDI) for multi-agent systems (MAS) via complex Laplacian subject to actuator faults. Using simple and linear interaction rules related to complex Laplacian, a planar formation of agents in the plane is achieved. The communication network is a directed, and yet connected graph with a fixed topology. The loss of symmetry in the digraph Laplacian matrix is also considered. Both the partial actuator effectiveness and the actuator bias faults are taken into account. For this purpose, a virtual agent whose dynamics structure is identical to that of the leader agent is introduced to determine the center of the planar formation. The FDI scheme requires no additional fault isolation model which is an essential part in the traditional FDI scheme. Finally, numerical example results are presented to show the effectiveness of the proposed scheme.

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1- Introduction

A dynamic MAS is composed of interacting intelligent agents that together perform a complex task that cannot be achieved by individual members of the group. MAS is distributed, meaning that each agent is often capable of local communications and sensing and acts autonomously based on relative information exchanges with the neighboring agents. Nowadays, MAS has received attention from various scientist communities due to its important applications in various fields, such as spacecraft formation flying, sensor networks, mobile robot and so forth (see [1] and references therein). Since the overall distributed MAS is required to operate safely and reliably all the time, even the presence of faults, the development appropriate distributed FDI schemes are generally a challenging task for MAS, due to the interaction topology between agents and the cooperative control laws. In the last two decades, FDI schemes have been extensively studied and quite a large number of research works have been reported. Most of these methods are based on centralized architecture.

Due to the limitations on computational power and communication bandwidth, it is very difficult to address the problem of FDI for MAS with the centralized architecture. As a result, recently, some relative studies have been done on the distributed FDI schemes. In [2], the problem of distributed FDI in a class of second-order MAS was developed. The authors in [3], developed an FDI schema that allows each robot to detect and isolate faults on the board of the other robots. [4] studied the distributed FDI problem for a class of second-order discrete-time MAS by using an optimal robust approach. A robust distributed FDI problem for a network of nonhomogeneous MAS is considered in [5]. [6] presented an architecture that takes advantage of the analytical and sensor redundancy present in groups of cooperative mobile robots in order to increase the reliability of the whole system.

In [7], two communication-based distributed schemes were proposed to detect communication faults for MAS. In [8], statistical analysis was used to deal with fault diagnosis for a swarm system. In [9-11], fault diagnosis was achieved by observers designed based on the geometric approach. In [12], a geometric approach to the problem of FDI of discrete-time Markovian jump linear systems is presented.[13] proposed FDI algorithm based on a hybrid architecture that is composed of a bank of continuous-time residual generators and a discrete-event system fault diagnosis. [14] performed a formal analysis and provided an insight into the effects of actuator faults on the performance of a team of unmanned vehicles. [15] considered the problem of Distributed FDI in large networked systems with imprecise models. [16], [17] developed a dynamic neural network-based FDI scheme for multiple satellite formation flying missions. [18] presented a robust fault detection and diagnosis strategy in a class of nonlinear MAS. A nonlinear observer which synthesizes second-order sliding mode techniques and wavelet networks is proposed for online monitoring.

[19] presented a novel cooperative fault-tolerant fuzzy control scheme for MAS with actuator faults. [20] addressed the cooperative fault-tolerant control (FTC) problem for a MAS subject to external disturbances, parameter uncertainties, and actuator faults. [21] investigated a robust FTC problem for a MAS with double integrator dynamics in the presence of actuator faults. A constructive design method of robust FTC was presented. [22] considered the problem of FTC for linear and Lipschitz nonlinear MAS subject to the leader's bounded unknown input and actuator faults.

[23] studied the FTC of MAS by considering the shortest connection topology. [24] proposed an FTC for a class of nonlinear MAS such that the states of all agents reach a common target point in spite of the agent process faults. A

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cooperative actuator fault accommodation strategy for a team of linear time-invariant MAS with a switching topology and directed communication network graph is studied in [25]. [26] presented an adaptive FTC scheme for leader-follower consensus control of MAS with actuator faults. In [27], the problem of FTC of linear MAS is investigated using two control protocols, namely the fixed-gain control protocol and the adaptive-gain-control protocol. In [28], fault detection for a class of high-order MAS with distributed was presented. [29] considered the problem of FDI in large networked systems with imprecise models.

Up to now, all of these studies have only dealt with FDI of MAS via real Laplacian[2-29]. In many applications involving MAS, groups of agents are required to reach a planar formation subject to four degrees of freedom translation, rotation, and scaling. A planar formation can be achieved via a distributed control law using complex-weighted relative sate information related to the complex-valued Laplacian. Based on [30], compared with the existing approaches such as integrant distances and nonlinear gradient control laws, the complex Laplacian-based approach leads to linear control laws which can guarantee global convergence while nonlinear steepest descent control laws [31-35] cannot. Furthermore, the complex Laplacian-based approach requires much less relative position measurements and does not require a common coordinate as those displacement-based formation control strategies in [36-39]. Some works have been reported for distributed control via complex Laplacian (see [40] and references therein).

However, it is more practical but more challenging when one or more agents of MAS via complex Laplacian is faulty. Knowing the fact that all of the studies in this literature have only dealt with FDI of MAS via real Laplacian, and they cannot be directly applied to MAS via complex Laplacian due to complex coefficients. Although many protocols for the FDI problem for MAS have been developed over the last several years, the development of the FDI problem of MAS via complex Laplacian has not been considered so far. In this paper, a distributed FDI scheme has been proposed based on a geometric approach which requires only local measurements. The outline of the paper is as follows. Basic descriptions will be presented in section 2.We introduce our FDI schemes in section 3. To demonstrate the validity of the theoretical results, an illustration example is given in section 4. Finally, section 5 draws the conclusion.

2- Background and Preliminaries

In this section, some notations and the basic graph theory are first introduced. Then, the distributed formation control of MAS via complex Laplacian is discussed.

2- 1- Notation

The notation used in the paper is quite standard. $\mathbb{R}$ denotes the set of real numbers. I_n represents the identity matrix of order n and $1_n \in R^n$ denotes a vector with each entry that is 1.

2- 2- Graph Theory

In recent years, graph theory has a wide application for modeling of MAS. Every agent is represented by a node and interactions due to sensing and communication that are represented as the edges of the graph. Let G=(V,E) be a digraph of order n with the set of nodes V={1,2,…,n} and edges $E \subseteq V\times V$. An edge (j,i) indicates that a node i can measure the relative position of node *j*. The set of neighbors of node *i* is defined by $N_i=\{j\in V: (j,i)\in E\}$. Throughout the paper, we assume $a_{ii}= 0$ for all *i* (or the digraph has no self-loops, meaning $(i,i)\notin E$) . For a digraph G, we associate each edge (j,i) with a complex number $w_{ij}\neq 0$, called complex weight and define a corresponding complex Laplacian L is as follows:

$$\mathcal{L}=\left[l_{ij}\right]=\begin{cases} -w_{ij} & if\ i\neq j\ and\ j\in\mathcal{N}_i \\ 0 & if\ i\neq j\ and\ j\notin\mathcal{N}_i \\ \sum_{j\in\mathcal{N}_i} w_{ij} & if\ i=j \end{cases} \tag{1}$$

2- 3- Problem Setup

We consider a group of n agents consisting of two leaders and followers in the plane. The position of n integrator agents are denoted by complex numbers $z_1,\ldots,z_n\in C$ with dynamics $\dot{z}_i(t)=u_i(t)$. Each agent *i* takes a local information based linear control strategy:

$$u_i\left(t\right)=\sum_{j\in N_i} w_{ij}\left(z_j-z_i\right)+v_0\left(t\right)\ ,\ i=1,\ldots,n \tag{2}$$

where $w_{ij}=r_{ij}e^{i\theta_{ij}}$ with $r_{ij}>0$ and $\theta_{ij}\in[-\pi,\pi)$, is a complex weight to be designed attributed on edge (j,i).

Then, the overall close-loop dynamics of the digraph of agents following the distributed control law (2) can be written as

$$\dot{\boldsymbol{z}}\left(t\right)=-L\boldsymbol{z}\left(t\right)+\boldsymbol{b}v_0\left(t\right) \tag{3}$$

where $\mathbf{b}=[1,1,\ldots,1]^T$ is an n-dimensional vector of ones so that the velocity is available to all the agents, as a control input for the leaders and as a parameter for the followers.

Without the loss of generality, we suppose that nodes {1,2} are leaders and other nodes are followers. In a leader-follower network, leader agents never access the relative position information of others, which means, these nodes do not have any incoming edge from others. The Laplacian of digraph G takes the following general form.

$$\mathcal{L}=\begin{bmatrix} 0_{2\times 2} & 0_{2\times(n-2)} \\ L_1 & L_2 \end{bmatrix} \tag{4}$$

Finally, based on [40], we recall a result about leader-follower formation via complex Laplacian Laplacian.

Lemma 1:[40] Assume that $\xi\in C^n$ satisfies $\xi_i\neq\xi_j$ for $i\neq j$. Then, every equilibrium state of (3) forms a planar formation $F_\xi=c_1 1_n+c_2\xi$ with

$$\begin{bmatrix} c_1 \\ c_2 \end{bmatrix}=\begin{bmatrix} 1 & \zeta_1 \\ 1 & \zeta_2 \end{bmatrix}^{-1}\begin{bmatrix} z_1(0) \\ z_2(0) \end{bmatrix} \tag{5}$$

If and only if $L\xi=0$ and $\det(L_2)\neq 0$,where ξ is called a formation basis for n agents in the plane. However, unlike real Laplacian, a complex Laplacian might have eigenvalues in the left complex plane, a situation that would lead to the instability of overall system. [40] proposed a design approach that updates the Laplacian and re-assign the eigenvalues by pre-multiplying a diagonal matrix called a stabilization matrix. This approach is given briefly in following lemma.

Lemma 2:[40] Every equilibrium state of the system (3) forms a planar formation F_ξ if and only if every equilibrium states the following system.

$$\dot{z}(t) = -DLz(t) + \boldsymbol{b}v_0(t) \tag{6}$$

where $D=diag\{d_1,...,d_n\} \epsilon C^{n,n}$ represents the stabilization matrix.

3- Actuator FDI Algorithm

In practical applications, the actuator may become faulty. Actuator fault considered in this paper includes the loss of effective actuator fault and bias fault. To formulate the FDI problem, the following actuator fault model is adopted as:

$$u_{oi} = \begin{cases} u_i & \text{No fault} \\ \rho_i(.)u_i & \forall t \geq t_{if}, 0 \leq \rho_i(.) \leq 1 \text{ (loss of effective)} \\ b_i(.) & \forall t \geq t_{if}, b_i(.) \neq 0 \text{ (bias fault)} \\ \rho_i(.)u_i + b_i(.) & \forall t \geq t_{if} \text{ (loss of effective with bias fault)} \end{cases}$$

where t_{if} denotes the time of fault occurrence in the actuator, $0 \leq \rho_i(.) \leq 1$ indicates the loss of effective actuator fault of the ith agent and $b_i(.)$ is the actuator bias fault. Both $\rho_i(.)$ and $b_i(.)$ are assumed to be unknown and undetectable. The above cases can be integrated into a single representation as:

$$u_{oi} = \rho_i(.)u_i + b_i(.) \quad , \forall t \geq t_{if}$$

A complete FDI algorithm generally consists of two components:

- residual generation
- residual evaluation.

Typically, the residual signal is defined as a comparison between the measured output of the system and its estimate obtained with the mathematical model. As a result, it is expected to be close to zero under normal operating conditions and large when a fault is acting on the system. Then, the fault detection can be performed using the following mechanism:

$$\begin{cases} r \leq tr & \textit{normal mode} \\ r > tr & \textit{faulty mode} \end{cases} \tag{7}$$

where r, tr are residual and the threshold, respectively.

In this paper, a distributed FDI scheme has been proposed based on a geometric approach which requires only local measurements. Consider a MAS consisting of N agents and a virtual agent. The virtual agent, labeled as *i*=0, whose dynamics structure is identical to that of the leader agent is introduced to determine the center of planar formation. The daynamic equation of the virtual agent is defined as:

$$\begin{aligned} &\dot{z}_0(t) = v_0(t) \\ &z_{0(initial)} = \frac{\sum_{i=0}^{N} z_{i(initial)}}{N} \\ &z_{0(final)} = \frac{\sum_{i=0}^{N} \xi_i}{N} \end{aligned} \tag{8}$$

where $z_{0(initial)}$,$z_{0(final)}$ are the initial and final states of the virtual agent, respectively.

Finally, the residual signal can be given as:

$$r_i = |z_i - z_0| \qquad i=1,\dots,n \tag{9}$$

where z_i is the agent position and z_0 is the virtual agent position.

After constructing the residual signals, the last step for a successful FDI algorithm is the residual evaluation stage; this should reveal that when and where the faults occur. Note that for the distributed approach, only local state information is available.

Theorem 1: Consider the signal (8) as residual. Choose an adaptive threshold as:

$$ti = (1/(n-1)) \sum_{l \in N_i} r_l - r_i \tag{10}$$

when an actuator fault occurs in the system, the ith agent is called faulty provided that the residual signal r_i exceeds the threshold t_i.

Proof:

Let $e(t)=z(t)-z_0(t)$ .Taking the time derivative of e along Eqs. (6), (8) yields

$$\dot{e} = \dot{z} - \dot{z}_0 = -DLz(t) + \\ bv_0(t) - bv_0(t) = -DLz(t)$$

We can rewrite the above equation as:

$$\begin{aligned} \dot{e} &= -DLz(t) + DLz_0(t) - DLz_0(t) \\ &= -DL(z(t) - z_0(t)) - DLz_0(t) \\ &= -DLe(t) - DLz_0(t) \end{aligned}$$

in fault-free mode, since matrix *-DL* is sable, we can conclude that the residual signals $r_i = |z(t)-z_0(t)| = |e_i|$ converges to a constant value and every equilibrium state of (6) forms a planar formation. When a fault occurs in agent i , r_i gets larger and exceeds the threshold t_i. This leads us to the conclusion that threshold t_i isolates the faulty agent from the healthy agents.

Remark: In contrast to the method in [42], the proposed FDI scheme does not require the additional isolation model. The faulty agents can be identified by applying Theorem 1.

4- Numerical Simulation

In this subsection, a simulation example of MAS with five-node in the presence of actuator fault is provided to verify the effectiveness of the proposed FDI method. The direct communication graph for the MAS is given in Fig. 1. Suppose that nodes {1,2} are leaders and other nodes are followers. The formation basis $\xi=[-2,2,2-2i,-2-2i,-3i]^T$ shown in Fig.2. According to the given digraph of Fig.1 and the defined formation basis (Fig. 2), the following related Laplacian matrix can be determined in order to achieve a planar formation

$$L = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 8+5i & 0 & 9.6-11.8i & 0 & -17.6+6.8i \\ 3-4i & 0 & 0 & -1+8i & -2-4i \\ 0 & 8-5i & 8-3i & 16.8+16.4i & -32.8-8.4i \end{bmatrix}$$

The only problem is that the Laplacian matrix is not Hurwitz due to its eigenvalues:

$eig(L)=\{0,0,6-8.5i,-1.5+3.9i,-28.7-7.6i\}$

In order to reach the desired planar formation, these eigenvalues must have positive real parts. In this case, however, the Laplacian matrix has two eigenvalues with the negative real part, and then L needs to be stabilized by a complex diagonal matrix. The diagonal matrix is:

$$D = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & -0.415-0.051i & 0 & 0 \\ 0 & 0 & 0 & 10i & 0 \\ 0 & 0 & 0 & 0 & 0.1i \end{bmatrix}$$

Therefore, the eigenvalues of *-DL* lie in the left complex plane and the overall closed-loop system $\dot{z}=-DLz$ is asymptotically stable with respect to the equilibrium subspace ker(L).
Based on the above discusstion, the complex weight can be defined as:

$$w_{31}=-0.078-0.62i;w_{32}=0;w_{33}=1;$$
$$w_{34}=0;w_{35}=1.08+0.62i;\ w_{41}=40+30i;$$
$$w_{42}=0;w_{43}=0;w_{44}=80+10i;w_{45}=40-20i;$$
$$w_{51}=0;w_{52}=-0.5-0.8i;w_{53}=-0.3-0.8;$$
$$w_{54}=1.64-1.68i;w_{55}=0.84-3.28i$$

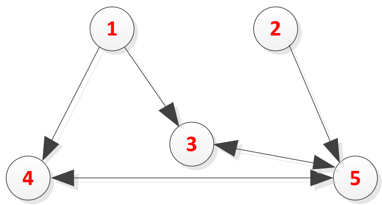


Fig. 1. Communication Graph

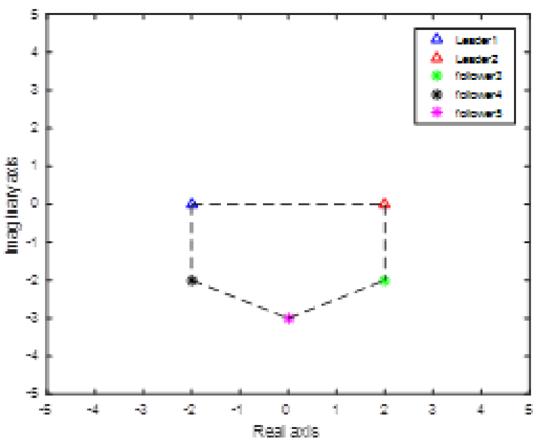
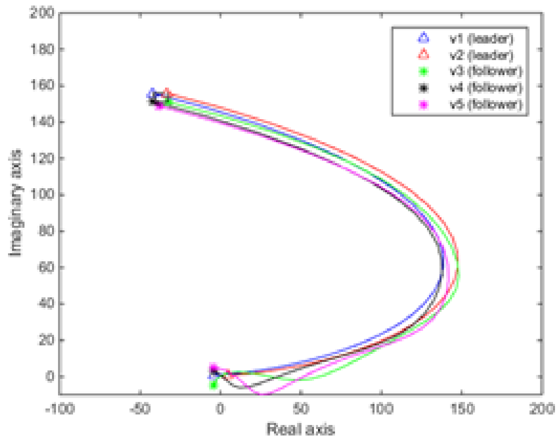
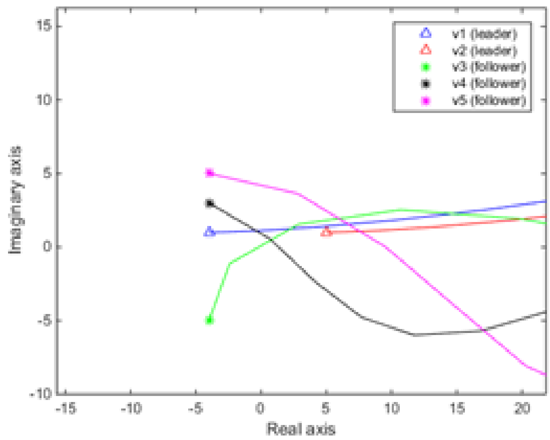


Fig. 2. Basic Formation

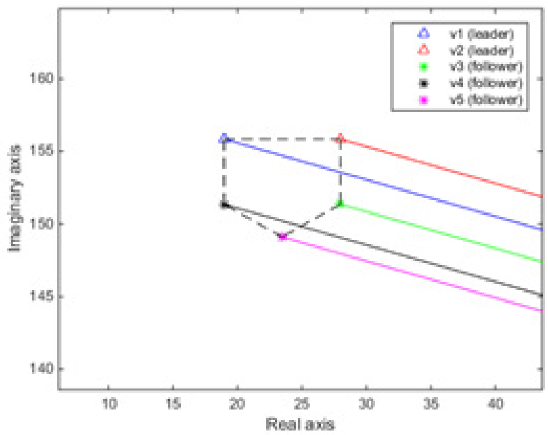
The following two possible modes are considered:
(1) Normal mode: The actuator is normal, $\rho_i(.)=1$ and $b_i(.)=0$
(2) Faulty mode: An actuator is faulty. $0\le\rho_i(.),b_i(.)\le1$
(1) Normal mode: With all actuators function healthily, the follower agents take the interaction law (2). Hence, by lemma 1, the equilibrium state of the system exactly corresponds to the planar formation. Therefore, the five agents asymptotically reach a planar formation F_ξ with the complex-valued Laplacian DL. With a synchronized velocity $v_0(t)=2t\cos(0.2t)+it\sin(0.2t)$, the trajectories of five agents are shown in Fig. 3. Fig. 4. plots the evolution of the components of Lz. As we can see, all the components converge to zero which also means that the trajectories of the five agents approach the null space of L (or equivalently to say, reach the desired formation). The Residual signals of all agents in normal mode are plotted in Fig.5. It is obvious that no fault occurred in an agent.
2) faulty mode: In this case, we considered two different scenarios. In the first scenario, one of the agents has an actuator fault while in the second two of the agents possess



(a) Agents Converge to Basic Formation



(b) Initial Position of Agents



(c) Final Position of Agents
Fig. 3. Agents Reaching a Moving Formation (Normal Mode).

faulty actuators. In the first case, we assume that an actuator fault occurs in the agent {4} as:

$$u_{o4}=\begin{cases}u_4 & 0s\le t<8s(normal\ mode)\\ a_4(.)u_4+b_4(.) & t\ge 8s(faulty\ mode)\end{cases}$$

where $0\le\rho_i(.),b_i(.)\le1$.

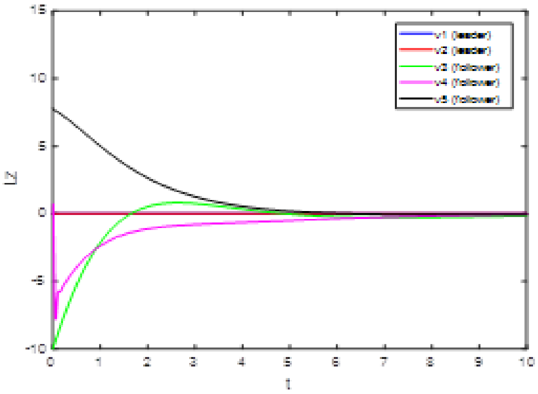


Fig. 4. Evolution of Formation Errors (Normal Mode).

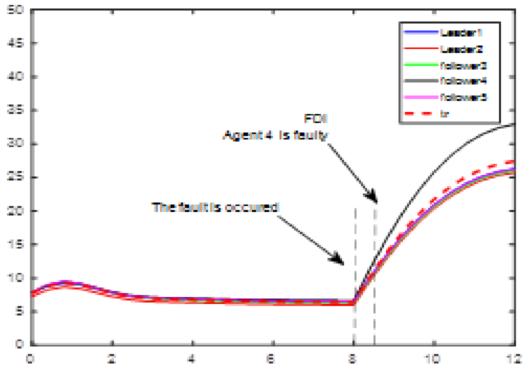


Fig. 6. Virtual Agent (Red Line).

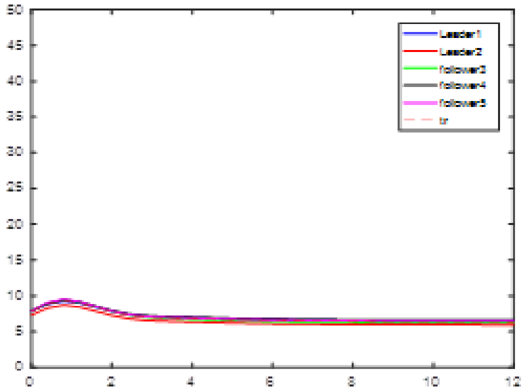
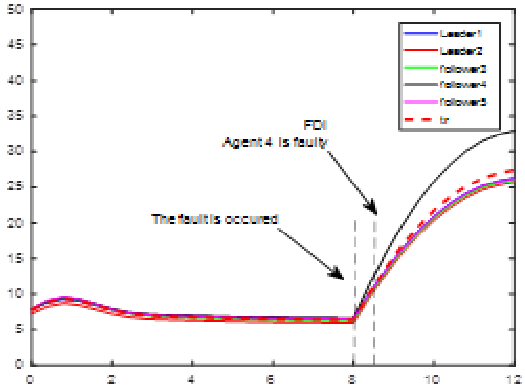


Fig. 5. Residual Signals (Normal Mode).



(a)

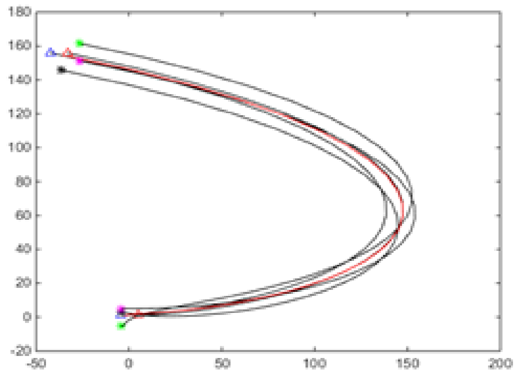
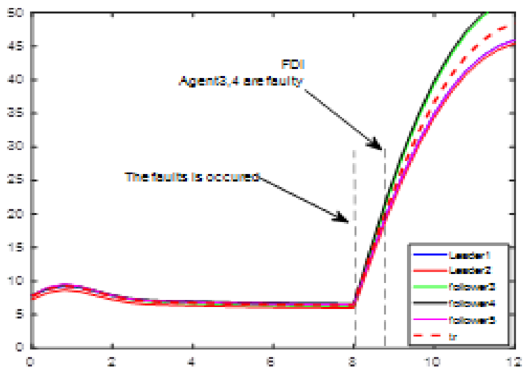


Fig. 6. Virtual Agent (Red Line).



(b)

Fig. 7. The Residual Signals and the Adaptive Threshold (Faulty Mode). (a). One of the Agents with an Actuator Fault (b). Two of the aAgents with an Actuator Fault

Moreover, the other agents are normal (i.e. $u_{oi}=u_i, i=1,2,3,5$). The virtual agent trajectory is shown in Fig. 6. From Fig. 7(a), we see that the residual of agent {4} exceeds the threshold *tr* (9). According to (7), we can easily conclude that agent 4 is faulty.

In the second case, we assume that actuator faults simultaneously occur in agent {3} and agent {4} as:

$$u_{o3} = \begin{cases} u_3 & 0s \le t < 8s(normal\ mode) \\ a_3(.)u_3 + b_3(.) & t \ge 8s(faulty\ mode) \end{cases}$$

and

$$u_{o4} = \begin{cases} u_4 & 0s \le t < 8s(normal\ mode) \\ a_4(.)u_4 + b_4(.) & t \ge 8s(faulty\ mode) \end{cases}$$

where $0 \le \rho_i(.), b_i(.) \le 1$.

From Fig. 7(b), we see that the residual of agents {3} and {4} exceeds the threshold tr (9). According to (7), we can easily conclude that agents {3} and {4} are faulty.

5- Conclusion

In this paper, we considered the problem of FDI for MAS via complex Laplacian subject to actuator faults. A distributed FDI has been proposed based on a geometric approach, which requires only local measurements. The numerical simulations showed the ability of the proposed method of distributed FDI for MAS. It is worthy to point out this work just considers the FDI problem for MAS under assumptions that there is only one agent which may have a fault and the communication network is a directed, connected graph with a fixed topology. Possible future research directions include the development of an approach which is capable of FDI in MAS the study of formation control problem of MAS with the communication faults or time-varying communication topology and exploration of the applicability of other faults detection that are more robust to the noise

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