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# Reliable Consensus Problem for Multi-Agent Systems with Sampled-Data

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***Abstract*—**In this paper, reliable consensus of multi-agent systems with sampled-data is investigated. By using a suitable Lyapunov-Krasovskii functional and some techniques such as Wirtinger Inequality, Schur Complement and Kronecker Product, the results of such system are obtained by solving a set of Linear Matrix Inequalities (LMIs). One numerical example is included to show the effectiveness of the proposed criteria.

***Keywords*—**Multi-agent, Linear Matrix Inequalities (LMIs), Kronecker Product, Sampled-Data, Lyapunov method.

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## I. Introduction

IN recent years, many problem of multi-agent systems has received considerable attentions due to their extensive applications in cooperative control of mobile autonomous robots, the design of distributed sensor networks, spacecraft formation flying and so on. A main problem in its systems is the consensus problem that it is the agreement of a group of agents on their states of leader by interaction [1]-[5]. Nevertheless, this problem recently has been applied in various fields such as vehicle systems [6], [7], groups of mobile autonomous agent [8], networked control systems [9], other applications. However, it is considered to use the problems of multi-agent systems due to the limited speed of information processing in the implementation of this system. Specially, it is well known that time-delay often causes unwanted signal like oscillations and noises of the system [4]. Thus, it is essential to study them. So motivated by this mentioned above, in this paper, new consensus problem for multi-agent systems with both sampled -data and reliable will be studied.

At first, in industrial process control, the digital control, digital filtering, and signal processing are widely used, which makes the closed-loop systems hybrid so-called sampled-data system; its states suffer successive impulses at fixed times. The sampled-data system is a hybrid one involving continuous time and discrete time signals [10].

Next, networked control systems use data networks to close both information and control loops. Networked control systems integrate information, communications and control with control loops being closed through the network [11]. They are becoming increasingly important in industrial process control because of their cost-effectiveness, reduced weight and power requirement, simple installation and maintenance and high reliability. The problem of designing reliable control systems has been attracted since practical systems often have actuator failures [11], [12]. It has been known that the class of reliable control systems is to stabilize the systems against actuator failures or to design fault-tolerant control systems. So the actuator failure model which consists of a scaling factor with upper and lower bounds to the signal to be measured or to the control action is introduced [13].

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In this paper, reliable consensus of multi-agent systems with sampled-data was supposed. Also, in order to better results, this paper was used to Wirtinger-based integral inequality.

Notation: $\Re^n$ is the $n$-dimensional Euclidean space, and $\Re^{m\times n}$ denotes the set of all $m\times n$ real matrices. For symmetric matrices $X$ and $Y$, $X>Y$ means that the matrix $X-Y$ is positive definite. $X^T$ denotes the transpose for $X$. If the context allows it, the dimensions of these matrices are often omitted. $I_n$, $0_n$ respectively denote $n\times n$ identity matrix and zero matrix. $X^\perp$ denotes a basis for the null-space of $X$. For a given matrix $X\in\Re^{n\times n}$, we define $X^\perp\in\Re^{n\times(n-r)}$ as the right orthogonal complement of $X$ by $XX^\perp=0$. $dia\{\cdots\}$ denotes the block diagonal matrix. $*$ represents the elements the main diagonal of a symmetric matrix. $\otimes$ denotes the notation of Kronecker product.

## II. Problem Statements

Consider the multi-agent systems with the following dynamic of agent $i$

$$\dot{x}_i(t)=Ax_i(t)+Bu_i(t),\ i=1,...,N, \tag{1}$$

where $N$ is the number of agents, $x_i(t)\in\mathbf{R}^n$ is the state of agent $i$, $u_i(t)\in\mathbf{R}^m$ is the consensus protocol, and $A\in\mathbf{R}^{n\times n}$ and $B\in\mathbf{R}^{n\times m}$ are known constant matrices.

An algorithm of consensus protocol can be described as

$$u_i(t)=-\sum_{j\in N_i} g_{ij}(x_i(t)-x_j(t))),\ i=1,...,N, \tag{2}$$

where $g_{ij}$ are the interconnection weights defining

$$\begin{cases} g_{ij}>0, \text{ if agent } i \text{ is connected to agent } j, \\ g_{ij}=0, \text{ otherwise.} \end{cases}$$

The multi-agent system is said to achieve consensus if the following definition.

**Definition 1.** [17], [18] Given an undirected communication graph $G$, the multi-agent systems (1) are said to be consensusable under the protocol (2) if for any finite $x_i(0), i=1,...,N$, the control protocol can asymptotically drive all agents close to each other, i.e.,

$$\lim_{t\to\infty} \| x_i(t) - x_j(t) \| = 0,\ i = 1,...,N.$$

In this paper, it is concerned that actuator has behavior of faulty. The control input of actuator fault can be described as

$$u^F(t) = Ru(t) \tag{5}$$

where $R$ is the actuator fault matrix with

$$R = diag\{r_1, r_2, \cdots, r_m\},\ 0 \le \underline{r}_i \le r_i \le \overline{r}_i,\ \overline{r}_i \ge 1,\ (i = 1,2,\cdots,m) \tag{6}$$

where $\underline{r}_i$ and $\overline{r}_i$ $(i=1,2,\cdots,m)$ are given constants. When $r_i = 1$, it means the complete failure of i-th actuator. If $r_i = 1$, then i-th actuator is normal.

Let us define

$$R_0 = diag\{r_{10}, r_{20}, \cdots, r_{m0}\},\ r_{i0} = \frac{\overline{r}_i + \underline{r}_i}{2} \tag{7}$$

$$R_1 = diag\{r_{11}, r_{21}, \cdots, r_{m1}\},\ r_{i1} = \frac{\overline{r}_i - \underline{r}_i}{2} \tag{8}$$

Then, the actuator fault matrix $R$ can be rewritten as

$$R = R_0 + R_1 \Delta J \tag{9}$$

where $\Delta J = diag\{j_1, j_2, \cdots, j_m\},\ -1 \le j_i \le 1$.

The updating instant time of the Zero-Order Hold is denoted by $t_k$. We assume that the sampling intervals are bounded $t_{k+1} - t_k \le h_s$. The state-feedback controller has a form $u(t) = x(t_k)$. Defining $h(t) = t - t_k$, we have $u(t) = x(t - h(t))$, $t_k \le t \le t_{k+1}$, $k = 0,1,2,\cdots$.

We obtain reliable following the consensus of multi-agent systems with sampled-data. With the concept introduced at (3)-(9), let us consider reliable consensus of multi-agent systems with sampled-data and actuator failures given by

$$\dot{x}_i(t) = Ax_i(t) + \sum_{j\in N_i} g_{ij} Bx_j(t - h(t)), \qquad i = 1,...,N,\quad t_k \le t \le t_{k+1},\quad k = 0,1,2,\cdots \tag{10}$$

Then, the system (10) can be rewritten as

$$\dot{x}(t) = (I_N \otimes A)x(t) + (G \otimes B(R_0 + R_1 \Delta J))x(t - h(t)) \tag{11}$$

where $x(t) = [x_1(t) \quad x_2(t) \quad \cdots \quad x_N(t)]^T \in \Re^n$, $G^k = [a_{ij}^k]_{N\times N}$.

Before deriving main results, the following lemmas are introduced.

**Lemma 1. (Reciprocally convex combination) [14]:** For a scalar $\alpha$ in the interval (0,1), a given matrix $R \in \Re^{n\times n} > 0$, two matrices $W_1 \in \Re^{n\times m}$ and $W_2 \in \Re^{n\times m}$, for all vector $\zeta \in \Re^m$, let us define the function $\theta(\alpha, \mathrm{R})$ given by:

$$\theta(\alpha, \mathrm{R}) = \frac{1}{\alpha}\zeta^T W_1^T R W_1 \zeta + \frac{1}{1-\alpha}\zeta^T W_2^T R W_2 \zeta$$

Then, if there exists a matrix $X \in \Re^{n\times m}$, then the following inequality holds

$$\min_{\alpha\in(0,1)} \theta(\alpha, \mathrm{R}) \ge \begin{bmatrix} W_1\zeta \\ W_2\zeta \end{bmatrix}^T \begin{bmatrix} R & X \\ * & R \end{bmatrix} \begin{bmatrix} W_1\zeta \\ W_2\zeta \end{bmatrix}$$

**Lemma 2. (Wirtinger inequality):** For a given matrix $R > 0$, the following inequality holds for all continuously differentiable function $w$ in $[a,b] \to \Re^n$.

$$\begin{aligned} &\int_a^b w^T(u) R w(u) du \\ &\ge \frac{1}{b-a}(w(b) - w(a))^T R (w(b) - w(a)) + \frac{3}{b-a}\Omega^T R \Omega \\ &\quad where\ \ \Omega = w(b) + w(a) - \frac{2}{b-a}\int_a^b w(u) du \end{aligned}$$

**Lemma 3. (Kronecker product) [15]:** Let $\otimes$ denote the notation of Kronecker product. Then, the following properties of the Kronecker product are easily established:

$(i)(\alpha A) \otimes B = A \otimes (\alpha B),$

$(ii)(A + B) \otimes C = A \otimes C + B \otimes C,$

$(iii)(A \otimes B)(C \otimes D) = (AC) \otimes (BD),$

$(iv)(A \otimes B)^T = A^T \otimes B^T.$

**Lemma 4. [16]:** Let $E$, $H$ and $F(t)$ be real matrices of appropriate dimensions, and let $F(t)$ satisfy $F^T(t)F(t) \le I$. Then, for any scalar $\varepsilon > 0$, the following matrix inequality holds:

$$EF(t)H + H^{\mathrm{T}} + F^{\mathrm{T}}(t)E^{\mathrm{T}} \le \varepsilon H^{\mathrm{T}} H + \varepsilon^{-1} EE^{\mathrm{T}}$$

## III. Main Result

In this section, we propose new stability and stabilization criteria for system (9). The notations of several matrices are defined as:

$$\zeta^T(t) = \left[ x^T(t) \quad x^T(t - h(t)) \quad x^T(t - h_M) \quad \frac{1}{h(t)}\int_{t-h(t)}^t x(s)ds \quad \frac{1}{h_M - h(t)}\int_{t-h_M}^{t-h(t)} x(s)ds \right],$$

$$e_i = \left[ 0_{(i-1)n} \quad I_n \quad 0_{(5-i)n} \right]^T,\ (i = 1,2,\cdots,5),$$

$$\Phi = \Phi_1 + \Phi_2 + \Phi_3 + \Phi_4,\ \ \Phi_1 = e_1(I_N \otimes P)\psi^T + \psi(I_N \otimes P)e_1^T,$$

$$\Phi_2 = e_1(I_N \otimes Q_1)e_1^T - (1 - h_d)e_2(I_N \otimes Q_1)e_2^T,$$

$$\Phi_3 = e_1(I_N \otimes Q_2)e_1^T - e_3(I_N \otimes Q_2)e_3^T,$$

$$\Phi_4 = -\begin{bmatrix} e_1^T - e_2^T \\ e_1^T + e_2^T - 2e_5^T \\ e_2^T - e_3^T \\ e_2^T + e_3^T - 2e_6^T \end{bmatrix}^T \begin{bmatrix} I_N \otimes R_1 & I_N \otimes M \\ * & I_N \otimes R_1 \end{bmatrix} \begin{bmatrix} e_1^T - e_2^T \\ e_1^T + e_2^T - 2e_5^T \\ e_2^T - e_3^T \\ e_2^T + e_3^T - 2e_6^T \end{bmatrix},$$

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$$R_1=\begin{bmatrix} I_N\otimes R & 0 \\ * & I_N\otimes 3R \end{bmatrix},\ \psi=\psi_1+\psi_2\ ,$$

$$\psi_1=\left(I_N\otimes A\right)e_1^{\mathrm{T}}+\left(G\otimes BR_0\right)e_2^{T}\ ,\ \psi_2=\left(G\otimes BR_1\Delta J\right)e_2^{T}\ ,$$

$$H_1=G\otimes BR_1,\ H_1=G\otimes BR_1,\ \Psi=\varepsilon_2\left(GG^T\otimes BR_1\left(BR_1\right)^T\right),$$

$$\Xi=\Phi+\varepsilon_1 e_1\left(G\otimes PBR_1\right)^T\left(G\otimes PBR_1\right)e_1^T,$$

$$\prod=\begin{bmatrix} \Xi & h_M\psi_1^{\ T} & e_2^{\ T} & e_2^{\ T} \\ h_M\psi_1 & -\left(I_N\otimes\alpha X\right)+\Psi & 0 & 0 \\ e_2 & 0 & -\varepsilon_1 I & 0 \\ e_2 & 0 & 0 & -\varepsilon_2 I \end{bmatrix}$$

Now we have Theorem 1.

**Theorem 1.** For given scalars $h_M$, $\overline{r}_i$, $\underline{r}_i$, $\alpha$, and the matrices $A$, $B$, $G$, the agent in the system (11) converge to the state of leader, if there exist positive definite matrices $P\in\Re^{n\times n}$, $Q_1\in\Re^{n\times n}$, $Q_2\in\Re^{n\times n}$, $X\in\Re^{n\times n}$ and positive scalar $\varepsilon_1$, $\varepsilon_2$, any matrix $M\in\Re^{2n\times 2n}$. Then system is asymptotically stable for ~~~when satisfying the following LMIs:

$$\prod<0 \tag{12}$$

$$\begin{bmatrix} I_N\otimes R_1 & I_N\otimes M \\ * & I_N\otimes R_1 \end{bmatrix}\geq 0 \tag{13}$$

**Proof:** Let us consider the following Lyapunov-krasovskii functional candidate as

$$V\left(x(t)\right)=V_1\left(x(t)\right)+V_2\left(x(t)\right)+V_3\left(x(t)\right)+V_4\left(x(t)\right) \tag{14}$$

where

$$V_1\left(x(t)\right)=x^T(t)\left(I_N\otimes P\right)x(t)$$
$$V_2(x(t))=\int_{t-h(t)}^{t}x^T(s)\left(I_N\otimes Q_1\right)x(s)ds$$
$$V_3(x(t))=\int_{t-h_M}^{t}x^T(s)\left(I_N\otimes Q_2\right)x(s)ds$$
$$V_4(x(t))=h_M\int_{t-h_M}^{t}\int_{s}^{t}\dot{x}^T(u)\left(I_N\otimes R\right)\dot{x}(u)duds$$

By using Lemma 3 and 4 the time derivative of $V_1$ is calculated as

$$\begin{aligned}\dot{V}_1(x(t))&=\zeta^T(t)(e_1\left(I_N\otimes P\right)\psi^T+\psi\left(I_N\otimes P\right)e_1^T)\zeta(t)\\&=\zeta^T(t)(\Phi_1+e_1\left(I_N\otimes P\right)\psi_2^{\ T}+\psi_2\left(I_N\otimes P\right)e_1^T)\zeta(t)\end{aligned} \tag{15}$$

By using Lemma 4, the upper-bound of time derivative of $V_2$ is calculated as

$$\begin{aligned}\dot{V}_2(x(t))&=\frac{d}{dt}\int_{t-h(t)}^{t}x^T(s)\left(I_N\otimes Q_1\right)x(s)ds\\&\leq\zeta^T(t)\left(e_1\left(I_N\otimes Q_1\right)e_1^T-\left(1-h_d\right)e_2\left(I_N\otimes Q_1\right)e_2^{\ T}\right)\zeta(t)\\&=\zeta^T(t)\Phi_2\zeta(t)\end{aligned} \tag{16}$$

By using Lemma 4, the upper-bound of time derivative of $V_3$ is calculated as

$$\begin{aligned}\dot{V}_3(x(t))&=\zeta^T(t)\left(e_1\left(I_N\otimes Q_1\right)e_1^{\ T}-e_3\left(I_N\otimes Q_2\right)e_3^{\ T}\right)\zeta(t)\\&=\zeta^T(t)\Phi_3\zeta(t)\end{aligned} \tag{17}$$

By using Lemma 4, the time derivative of $V_4$ is calculated as

$$\dot{V}_4(x(t))=h_M^2\,\dot{x}^T(t)\left(I_N\otimes R\right)\dot{x}(t)-h_M\int_{t-h_M}^{t}\dot{x}^T(u)\left(I_N\otimes R\right)\dot{x}(u)du$$

Finally, by using Lemma 1 and 2, the upper-bound of time derivative of $V_4$ is calculated as

$$\dot{V}_4\left(x(t)\right)\leq\zeta^T(t)\left(h_M^2\psi^T\left(I_N\otimes R\right)\psi+\Phi_4\right)\zeta(t) \tag{18}$$

By combining (15)-(18), an upper bound of $\dot{V}$ is obtained as:

$$\begin{aligned}\dot{V}&\leq\zeta^T(t)(\Phi+e_1\left(I_N\otimes P\right)\psi_2^{\ T}+\psi_2\left(I_N\otimes P\right)e_1\\&+h_M^2\psi^T\left(I_N\otimes R\right)\psi)\zeta(t)\end{aligned} \tag{19}$$

Using Lemma 4 and Schur complement, stabilization criterion for the system (19) is equivalent to

$$\begin{bmatrix} \Xi & h_M\psi_1^{\ T} & e_2^{\ T} & e_2^{\ T} \\ h_M\psi_1 & -\left(I_N\otimes R\right)^{-1}+\Psi & 0 & 0 \\ e_2 & 0 & -\varepsilon_1 I & 0 \\ e_2 & 0 & 0 & -\varepsilon_2 I \end{bmatrix}<0 \tag{20}$$

It should be note that the stabilization condition (20) have the non-linear term $R^{-1}$. So a simple method to solve it is to set $R^{-1}=\alpha X$, where $\alpha>0$ is a tuning parameter. If the LMIs (12) and (13) hold, then stability condition (11) is satisfied. This completes our proof.

## IV. Numerical Example

In this section, one numerical example will be shown to illustrate the effectiveness of the proposed Theorem 1.

**Example 1.** Consider the multi-agent systems (11).

$$A=\begin{bmatrix} -1 & -2 \\ 2 & -1 \end{bmatrix},\ B=\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix},\ G=\begin{bmatrix} -1 & 1 \\ 1 & -1 \end{bmatrix}$$

which satisfied with $0\leq h(t)\leq h_M$. By applying Theorem 1, comparison with the same sampling interval $h_M$, when $\underline{r}_i=0.5$, $\overline{r}_i=1$ and $\underline{r}_i=1$, $\overline{r}_i=1$. In fact, when $\underline{r}_i=1$, $\overline{r}_i=1$, it is non- reliable systems. So we compared the reliable systems with the non-reliable systems by using Theorem 1. Their results are listed in Figs. 1-3.

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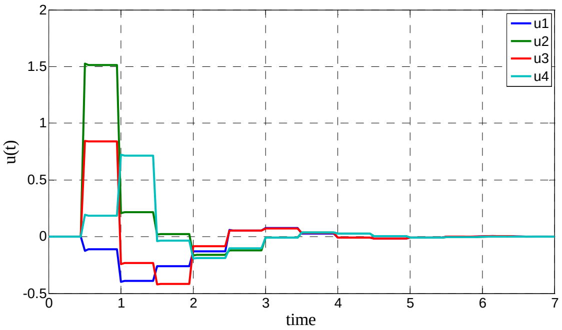
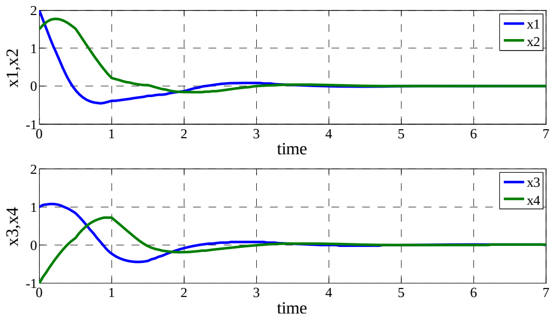
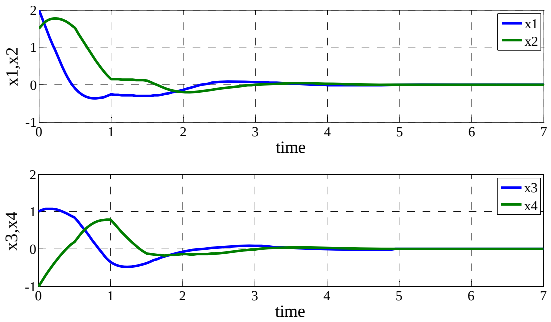



Fig. 1 The simulated result of $x(t-t(h))$ for Example 1

The switched interval $h_M$ is 0.5. Then, the result is shown in Fig. 1.




(a)




(b)

Fig. 2 The result of $x(t)$ for example 1 when (a) $\underline{r}_i = 0.5$, $\overline{r}_i = 1$ and (b) $\underline{r}_i = 1$, $\overline{r}_i = 1$

In order to confirm the this system result, we set that initial value of the state set up by $x(0) = [0 \quad 0]^T$. The system (11) is asymptotically stable with reliable sampled-data stability.

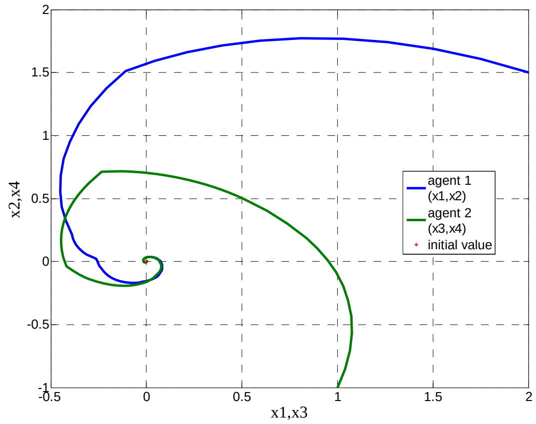



Fig. 3 $x_1(t)$, $x_2(t)$ state trajectories of the systems for example 1

The figure shows that $x_1(t)$, $x_2(t)$ state are set by initial states of

$$[x_1(0) \quad x_2(0)]^T = [2 \quad 1.5]^T, [x_3(0) \quad x_4(0)]^T = [1 \quad -1]^T.$$

## V. Conclusion

In this paper, reliable consensus of multi-agent systems with sampled-data is proposed. To do this, constructing a suitable lemmas such as Wirtinger inequality, Reciprocally approach and Kronecker product, etc. To show the effectiveness of the proposed theorem, one numerical example was included.

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