A new analysis method for interval time-varying delay systems with probabilistic actuator-fault-occurrence

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Abstract: The paper addresses the problem of a class of reliable control for interval time-varying delay systems with frequent actuator fault. A new type reliable control system model is proposed by introducing a stochastic parameter. Based on the new systems model, sufficient conditions for the exponential mean square stability of the system are derived by using the Lyapunov functional method and the linear matrix inequality (LMI) technique. The derived criteria, which are expressed in terms of a set of LMIs, are fault-occurrence rate and delay-dependent, that is, the solvability of the criteria depends on not only the variation range of the delay but also the probability distribution of fault-occurrence. The illustrative example and the respective simulation results demonstrate the feasibility and effectiveness of the proposed design synthesis.

Key Words: Reliable control, fault frequency , Interval time-varying delay

1 Introduction

Time-delay phenomenon is often encountered in various practical systems, such as chemical engineering systems, distributed networks, inferred grinding model, manual control, microwave oscillator, neural network, population dynamic model, ship stabilization, and systems with lossless transmission lines. The existence of the time delay may cause instability or bad performances in dynamic systems. Hence the stability and stabilization problems for time-delay systems have received some attenuation [1, 2, 3, 4].

Actuators play a very important role in control system, which are responsible for transforming the controller output to the plant, how to preserve the closed-loop control system performance under actuator fault condition will be more meaningful. However, all the aforementioned results are under a full reliability assumption that all actuators are operational. In practical situations, since actuator failure often occur in real world due to various factors. The main task of this study is to design a controller such that the closed-loop system can maintain stability and performance, not only when all control components are operational, but also in case of existing some abnormal actuators including fully outages. This motivates the development of the so-called reliable control theory.

Over the past few decades, reliable control problems have been extensively studied [5, 6, 7, 8, 9, 10, 11, 12] and the references therein. Most of the existing literatures on reliable control view the fault as a permanent case once the fault occurrence. However, In many cases, normal case alternates with the fault case according to a certain probability , such as unreliable links in networked control systems, spasmodic external disturbance acting on actuators. The common feature of those situations is that the fault can be recovery. By employing statistical method, one can know the probability of a certain fault beforehand, the less conservative controller could be obtained by employing the information of fault-occurrence distribution than the controller without any faulty information when encountering the intermittent fault. Unfortunately, the existing design methods of reliable control do not work. Therefore, new techniques need to be developed. This motivates us to investigate the problem.

In this paper, A more general systems model is adopted to analyze the reliable control systems with spasmodic fault. we are interesting in designing a reliable controller such that the dynamic system is exponentially mean-square stable despite frequent actuator failures. By using the linear matrix inequality (LMI) method, sufficient conditions are derived to ensure the existence of the controller which is characterized by the solution to a set of LMIs, Illustrative examples are exploited to demonstrate the applicability of the proposed design approach.

Notation: $\mathbb{R}^n$ denotes the n-dimensional Euclidean space, $\mathbb{R}^{n\times m}$ is the set of real $n \times m$ matrices, I is the identity matrix of appropriate dimensions, $\|\cdot\|$ stands for the Euclidean vector norm or spectral norm as appropriate. The notation $X > 0$ (respectively, $X < 0$), for $X \in \mathbb{R}^{n\times n}$ means that the matrix X is a real symmetric positive definite (respectively, negative definite). When x is a stochastic variable , $\mathscr{E}\{x\}$ stands for the expectation of x. The asterisk $*$ in a matrix is used to denote term that is induced by symmetry, Matrices, if they are not explicitly stated , are assumed to have compatible dimensions.

2 Problem formulation

Consider the following interval time-varying delay system:

$$\dot{x}(t) = Ax(t) + A_d x(t-\tau(t)) + Bu(t) \tag{1}$$

$$x(t) = \phi(t) \quad t \in [-\tau_2, 0] \tag{2}$$

where $x(t) \in R^n$ is the state, $u(t) \in R^l$ is the control input, $\phi(t)$ is a continuous vector-valued initial function, $\tau(t)$ denotes the state delay and satisfies $\tau_1 \le \tau(t) \le \tau_2$, A, A_d and B are known constant matrices.

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We design two kinds of static state feedback controllers for the system (1): one is for the system without actuator failures, the other is for the system with faulty actuators similar to [7, 13, 14].

$$u(t) = Kx(t) \quad (3)$$
$$u_F(t) = \Xi Kx(t) \quad (4)$$

where $u(t)$ and $u_F(t)$ denote that the controller for system (1) without and with failure, respectively. the scaling factor Ξ is the actuator fault matrix with

$$\Xi = \mathrm{diag}\{\xi_1, \cdots, \xi_m\}, \quad 0 \leq \underline{\xi_i} \leq \xi_i \leq \bar{\xi_i}, \; i = 1, 2, \cdots, m \quad (5)$$

$\underline{\xi_i}$ and $\bar{\xi_i}$ $(i = 1, 2, \cdots, m)$ are some given constants. $\xi_i = 0$ means that ith actuator completely failure, $\xi_i = 1$ means that ith actuator is normal, and K is a feedback matrix to be determined.

Assumption 1. *$\delta(t)$ is a Bernouli distributed sequence with*

$$Prob\{\delta(t) = 1\} = \mathscr{E}\{\delta(t)\} = \delta_0 \quad (6)$$
$$Prob\{\delta(t) = 0\} = 1 - \mathscr{E}\{\delta(t)\} = 1 - \delta_0 \quad (7)$$

where $0 \leq \delta_0 \leq 1$ is a constant, and $\mathscr{E}\{\delta(t)\}$ is the expectation of $\delta(t)$.

Then, the system (1) can be rewritten as

$$\begin{aligned} \dot{x}(t) &= Ax(t) + A_d x(t - \tau(t)) + \delta(t)Bu(t) \quad (8) \\ &\quad +(1 - \delta(t))Bu_F(t) \\ x(t) &= \phi(t) \quad t \in [-\tau_2, 0] \quad (9) \end{aligned}$$

Remark 1. *From Assumption 1, it can be shown that δ_0 and $1 - \delta_0$ denote that probabilities of the system without and with faulty actuator, respectively. Especially, if let $\delta(t) = 0$, then the system (8) can be converted to the case of the most of the existing literatures on reliable control. Therefore, this model is more general to study on the problem of reliable control systems.*

Remark 2. *The system (8) denote that the normal case alternates with the fault case according to a certain probabilistic distribution. This situation is frequently encountered in practical control systems due to various factors, for example, electromagnetic disturbance caused by lighting acts on the actuators such that the actuators work in abnormal situation and it will be recovery when the disturbance disappears.*

Remark 3. *It will be with less conservative to design reliable controller by employing the information on the probability of a certain fault-occurrence when encountering the intermittent fault.*

For convenience, we define $A_1 = A + B\Xi K + \delta_0 B(I - \Xi)K$, $A_2 = B(I - \Xi)K$, then the close-loop systems can be further expressed as

$$\dot{x}(t) = A_1 x(t) + (\delta(t) - \delta_0)A_2 x(t) + A_d x(t - \tau(t)) \quad (10)$$

The objective of this study is to develop a reliable controller for the closed-loop system with intermittent fault described by (10). For this purpose, the following lemma derived from Jessen's inequality and definitions are introduced.

Lemma 1. *[2] For any constant matrix $T \in \mathbb{R}^{n \times n}$, $T > 0$, scalars $\tau_1 \leq \tau(t) \leq \tau_2$, and vector function $\dot{x} : [-\tau_1, 0] \rightarrow \mathbb{R}^n$ such that the following integration is well defined, it holds that*

$$-(\tau_2 - \tau_1) \int_{t-\tau_2}^{t-\tau_1} \dot{x}(t) T \dot{x}(t) \leq \begin{bmatrix} x(t-\tau_1) \\ x(t-\tau(t)) \\ x(t-\tau_2) \end{bmatrix}^T \begin{bmatrix} -R & R & 0 \\ * & -2R & R \\ * & * & -R \end{bmatrix} \begin{bmatrix} x(t-\tau_1) \\ x(t-\tau(t)) \\ x(t-\tau_2) \end{bmatrix} \quad (11)$$

Remark 4. *It will be shown that Lemma 1 plays a key role in the derivation of a criterion in this paper, which will lead to less conservation demonstrated in [15].*

Definition 1. *The system (10) is said to be exponentially stable in the mean-square sense (ESMSS), if there exist constants $\alpha > 0, \lambda > 0$, such that $t > 0$*

$$\mathscr{E}\{\|x(t)\|^2\} \leq \alpha e^{-\lambda t} \sup_{-\tau_2 < s < 0} \{\|\phi(s)\|^2\} \quad (12)$$

Definition 2. *For a given function $V : C^b_{F_0}([-\tau_2, 0], R^n) \times S$, its infinitesimal operator $\mathcal{L}$[16] is defined as*

$$\mathcal{L}V(x_t) = \lim_{\Delta \to 0^+} \frac{1}{\Delta}[\mathscr{E}(V(x_{t+\Delta}|x_t) - V(x_t))] \quad (13)$$

3 Main result

In this section, we aim to develop an innovative approach to guarantee the system (10) is exponentially mean-square stable. The controller K could be solved from the following results.

Theorem 1. *For a given matrix K and scalars τ_1, τ_2, δ_0, the system (10) is EMSS if there exist positive definite matrices $P, Q_i (i = 1, 2), R_j (j = 1, 2, 3)$ of appropriate dimensions, such that LMI (14) holds.*

$$\Omega = \begin{bmatrix} \Gamma_{11} + \hat{\Gamma}_{11} & R_1 & PA_d + A_1^T \mathcal{R} A_d + R_2 & 0 \\ * & -R_1 - R_3 - Q_1 & R_3 & 0 \\ * & * & -2R_2 - 2R_3 + A_d^T RA_d & R_2 + R_3 \\ * & * & * & -R_2 - R_3 - Q_2 \end{bmatrix} < 0 \quad (14)$$

where

$$\begin{aligned} \Gamma_{11} &= PA_1 + A_1^T P + Q_1 + Q_2 - R_1 - R_2 \\ \hat{\Gamma}_{11} &= A_1^T \mathcal{R} A_1 + \delta_0(1 - \delta_0) A_2^T \mathcal{R} A_2 \\ \mathcal{R} &= \tau_1^2 R_1 + \tau_2^2 R_2 + (\tau_2 - \tau_1)^2 R_3 \end{aligned}$$

Proof. Construct a Lyapunov-Krasovskii functional candidate as

$$\begin{aligned}
V(x_t) &= \sum_{i=1}^{3} V_i(x_t) \\
V_1(x_t) &= x^T(t)Px(t) \\
V_2(x_t) &= \int_{t-\tau_1}^{t} x^T(s)Q_1x(s)ds + \int_{t-\tau_2}^{t} x^T(s)Q_2x(s)ds \\
V_3(x_t) &= \tau_1 \int_{-\tau_1}^{0}\int_{t+s}^{t} \dot{x}^T(v)R_1\dot{x}(v)dvds \\
&+ \tau_2 \int_{-\tau_2}^{0}\int_{t+s}^{t} \dot{x}^T(v)R_2\dot{x}(v)dvds \\
&+ (\tau_2-\tau_1) \int_{-\tau_2}^{-\tau_1}\int_{t+s}^{t} \dot{x}^T(v)R_3\dot{x}(v)dvds
\end{aligned}$$

From Assumption 1, it can be shown that

$$\begin{cases} \mathscr{E}\{\delta(t)-\delta_0\}=0 \\ \mathscr{E}\{(\delta(t)-\delta_0)^2\}=\delta_0(1-\delta_0) \end{cases} \tag{15}$$

Using Lemma 1, (15) and the infinitesimal operator (13) for system (10), we have

$$\begin{aligned}
\mathcal{L}V_1(x_t) &= 2x^T(t)P[A_1x(t)+A_dx(t-\tau(t))] \\
\mathcal{L}V_2(x_t) &= x^T(t)(Q_1+Q_2)x(t) \\
&- \sum_{i=1}^{2} x^T(t-\tau_i)Q_ix(t-\tau_i) \\
\mathcal{L}V_3(x_t) &= \dot{x}^T(t)\mathcal{R}\dot{x}(t) - \tau_1\int_{t-\tau_1}^{t}\dot{x}^T(s)R_1\dot{x}(s)ds \\
&- \tau_2\int_{t-\tau_2}^{t}\dot{x}^T(s)R_2\dot{x}(s)ds \\
&- (\tau_2-\tau_1)\int_{t-\tau_2}^{t-\tau_1}\dot{x}^T(s)R_3\dot{x}(s)ds \\
&\le x^T(t)\left(A_1^T\mathcal{R}A_1+\delta_0(1-\delta_0)A_2^T\mathcal{R}A_2\right)x(t) \\
&+ x^T(t-\tau(t))A_d^T\mathcal{R}A_dx(t-\tau(t)) \\
&+ 2x^T(t)A_1^T\mathcal{R}A_dx(t-\tau(t))
\end{aligned}$$

$$\begin{aligned}
&+ \begin{bmatrix} x(t) \\ x(t-\tau_1) \end{bmatrix}^T \begin{bmatrix} -R_1 & R_1 \\ R_1 & -R_1 \end{bmatrix} \begin{bmatrix} x(t) \\ x(t-\tau_1) \end{bmatrix} \\
&+ \begin{bmatrix} x(t) \\ x(t-\tau(t)) \\ x(t-\tau_2) \end{bmatrix}^T \begin{bmatrix} -R_2 & R_2 & 0 \\ * & -2R_2 & R_2 \\ * & * & -R_2 \end{bmatrix} \begin{bmatrix} x(t) \\ x(t-\tau(t)) \\ x(t-\tau_2) \end{bmatrix} \\
&+ \begin{bmatrix} x(t-\tau_1) \\ x(t-\tau(t)) \\ x(t-\tau_2) \end{bmatrix}^T \begin{bmatrix} -R_3 & R_3 & 0 \\ * & -2R_3 & R_3 \\ * & * & -R_3 \end{bmatrix} \begin{bmatrix} x(t-\tau_1) \\ x(t-\tau(t)) \\ x(t-\tau_2) \end{bmatrix}
\end{aligned}$$

Hence,

$$\mathcal{L}V(x_t) \le \zeta^T(t)\Omega\zeta(t) \tag{16}$$

where $\zeta(t)=[x^T(t)\ x^T(t-\tau_1)\ x^T(t-\tau(t))\ x^T(t-\tau_2)]^T$, $\mathcal{R}$ and Ω are defined in Theorem 1.
From (14) and (16), the following inequality can be concluded

$$\mathscr{E}\{\mathcal{L}V(x(t))\} < -\lambda_{min}(\Omega)\mathscr{E}\{\zeta^T(t)\zeta(t)\} \tag{17}$$

where $\lambda_{min}$is the minmum eigenvalue of Ω.
Define a new function as

$$W(x_t)=e^{\epsilon t}V(x_t) \tag{18}$$

Its infinitesimal operator $\mathcal{L}$ is given by

$$\mathcal{W}(x_t)=\epsilon e^{\epsilon t}V(x_t)+e^{\epsilon t}\mathcal{L}V(x_t) \tag{19}$$

By the generalized $It\hat{o}$ formula[16] , we can obtain from (19) that

$$\begin{aligned}
&\mathscr{E}\{W(x_t)\}-\mathscr{E}\{W(x_0)\} = \int_0^t \epsilon e^{\epsilon s}\mathscr{E}\{V(x_s)\}ds \\
&+ \int_0^t e^{\epsilon s}\mathscr{E}\{\mathcal{L}V(x_s)\}ds
\end{aligned} \tag{20}$$

Then, using the similar method of [17], we can see that there exists a positive number α such that for $t>0$

$$\mathscr{E}\{V(x_t)\} \le \alpha \sup_{-\tau_2\le s\le 0}\left\{\|\phi(s)\|^2\right\}e^{-\epsilon t} \tag{21}$$

since $V(x_t)\ge\{\lambda_{min}(P)\}x^T(t)x(t)$, it can be shown from (21) that for $t\ge 0$

$$\mathscr{E}\{x^T(t)x(t)\} \le \bar{\alpha}e^{-\epsilon t}\sup_{-\tau_2\le s\le 0}\left\{\|\phi(s)\|^2\right\} \tag{22}$$

where $\bar{\alpha}=\alpha/(\lambda_{min}P)$. Recalling Definition 1, the proof can be completed

□

In the following, we are seeking to design the reliable controller gain K based on Theorem 1.

Theorem 2. *For given scalars δ_0,τ_1,τ_2, the closed-loop system (10) is EMSS, if there exist matrices $X>0,\tilde{Q}_i>0(i=1,2),R_j>0(j=1,2,3)$ and matrix Y of appropriate dimensions satisfying (23). Furthermore, the reliable controller gain $K=YX^{-1}$.*

$$\Theta = \begin{bmatrix}
\tilde{\Gamma}_{11} & \tilde{R}_1 & A_dX+\tilde{R}_2 & 0 & \Gamma_{15} & \Theta_{61} \\
* & -\tilde{R}_1-\tilde{R}_3-\tilde{Q}_1 & \tilde{R}_3 & 0 & 0 & 0 \\
* & * & -2\tilde{R}_2-2\tilde{R}_3 & \tilde{R}_2+\tilde{R}_3 & XA_d^T & 0 \\
* & * & * & -\tilde{R}_2-\tilde{R}_3-\tilde{Q}_2 & 0 & 0 \\
* & * & * & * & -2\varepsilon X+\varepsilon^2\tilde{\mathcal{R}} & 0 \\
* & * & * & * & * & -2\varepsilon X+\varepsilon^2\tilde{\mathcal{R}}
\end{bmatrix} < 0 \tag{23}$$

where

$$\begin{aligned}
\tilde{\Gamma}_{11} &= AX+XA^T+B\Xi Y+Y^T\Xi B^T+\delta_0B(I-\Xi)Y \\
&+ \delta_0Y^T(I-\Xi)B^T+\tilde{Q}_1+\tilde{Q}_2-\tilde{R}_1-\tilde{R}_2 \\
\tilde{\Gamma}_{15} &= XA^T+Y^T\Xi^TB^T+\delta_0Y^T(I-\Xi)B^T \\
\tilde{\mathcal{R}} &= \tau_1^2\tilde{R}_1+\tau_2^2\tilde{R}_2+(\tau_2-\tau_1)^2\tilde{R}_3 \\
\Theta_{61} &= \sqrt{\delta_0(1-\delta_0)}Y^T(I-\Xi)B^T
\end{aligned}$$

Proof. By Schur complement, the matrix inequality (14) holds if and only if

$$\begin{bmatrix} \Gamma_{11} & R_1 & PA_d + R_2 & 0 & A_1^T P & \sqrt{\delta_0(1-\delta_0)}A_2^T P \\ * & -R_1 - R_3 - Q_1 & R_3 & 0 & 0 & 0 \\ * & * & -2R_2 - 2R_3 & R_2 + R_3 & A_d^T P & 0 \\ * & * & * & -R_2 - R_3 - Q_2 & 0 & 0 \\ * & * & * & * & -PR^{-1}P & 0 \\ * & * & * & * & * & -PR^{-1}P \end{bmatrix} < 0 \tag{24}$$

Due to

$$(\mathcal{R} - \varepsilon^{-1}P)R^{-1}(\mathcal{R} - \varepsilon^{-1}P) \geq 0 \tag{25}$$

which gives

$$-P\mathcal{R}^{-1}P \leq -2\varepsilon P + \varepsilon^2 \mathcal{R} \tag{26}$$

we have that (24) holds if

$$\begin{bmatrix} \Gamma_{11} & R_1 & PA_d + R_2 & A_1^T P & \sqrt{\delta_0(1-\delta_0)}A_2^T P & \\ * & -R_1 - R_3 - Q_1 & R_3 & 0 & 0 & 0 \\ * & * & -2R_2 - 2R_3 & R_2 + R_3 & A_d^T P & 0 \\ * & * & * & -R_2 - R_3 - Q_2 & 0 & 0 \\ * & * & * & * & -2\varepsilon P + \varepsilon^2 R & 0 \\ * & * & * & * & * & -2\varepsilon P + \varepsilon^2 R \end{bmatrix} < 0 \tag{27}$$

Defining $X = P^{-1}$, and applying the congruence transformation $diag\{X, X, X, X, X, X\}$ to (**??**) and setting $\tilde{Q}_i = XQ_iX (i = 1, 2)$, $\tilde{R}_j = XR_jX (j = 1, 2, 3)$ and $Y = KX$. The result can be concluded from Theorem 1. This completes the proof. □

Remark 5. *From Theorem 2, it can be seen that the solvability of LMI (23) depends not only on the state time delay, but also on the distribution of the actuator fault-occurrence.*

4 An illustrative example

In this section, a well-studied example is used to illustrate the the effectiveness of the approaches proposed in this paper.

Consider the following interval time-varying delay system (1) with the parameters[18]:

$$A = \begin{bmatrix} -1 & 1 & 0 & 0 \\ -1 & 0 & -0.5 & 0 \\ 0 & 0 & 1 & 1 \\ 0.5 & 0 & 0.5 & -0.1 \end{bmatrix}$$

$$A_d = \begin{bmatrix} -0.3 & 0.2 & 0.3 & 0.1 \\ 0 & 0.2 & 0.3 & 0.3 \\ 0.1 & -0.2 & 0.2 & 0.2 \\ 0.2 & 0.1 & 0.2 & 0.3 \end{bmatrix}$$

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

$0.01 < \tau(t) < 2$, and the initial conditions $x(t) = [-2.2\ 2.2\ 2.1\ \ -2.1]^T, t \in [-2\ 0]$.

Case 1: We assume the actuators are normal, that is, The probability of fault-occurrence $1 - \delta_0 = 0$. Selecting $\varepsilon = 4$, then according to Theorem 2, we obtain the standard controller

$$K = \begin{bmatrix} -0.6317 & 0.5048 & -0.5307 & -0.1679 \\ -0.1512 & -1.1212 & -2.6307 & -2.5028 \end{bmatrix}$$

Case 2: There exists frequently actuator-fault by some reasons such that the 2nd actuator has partial failure. Assuming the probability of fault-occurrence $1 - \delta_0 = 0.3$ is shown in Fig.(1) and $\bar{\Xi} = \begin{bmatrix} 1 & 0 \\ 0 & 0.1 \end{bmatrix}$ According to Theorem 2, we get the reliable controller

$$K = \begin{bmatrix} -0.7672 & 0.4624 & -1.2452 & -0.9192 \\ -0.1039 & -1.6438 & -3.6198 & -3.7027 \end{bmatrix} \tag{28}$$

Fig.(2) and Fig.(3) show the state response for normal situation using the standard controller and the reliable controller, respectively. It is clear that the two controllers both perform very satisfactorily when no failures occur. When the 2nd actuator is abnormal frequently, the state responses for the standard and the reliable controllers are shown in Fig.(4) and Fig.(5), respectively. It is observed that when actuator failure occurs, the closed-loop system with the standard controller is not even asymptotically stable, while the closed-loop system using the reliable controller still operates well and maintains an acceptable level of performance.

5 Conclusion

In this paper, A new reliable control systems model with frequent actuator-fault which obeys a certain probabilistic distribution is established. We concentrate on the reliable control design problem for a class of interval time-varying delay systems, and present a reliable control design methodology to achieve closed-loop stability, not only when the system is operating properly, but also when the actuators are encountered frequent failure. Different from the existing results in the literatures, our results explicitly dependent on not only the variation range of the delay but also the probability distribution of fault-occurrence. A numerical example is given to illustrate the design procedures.

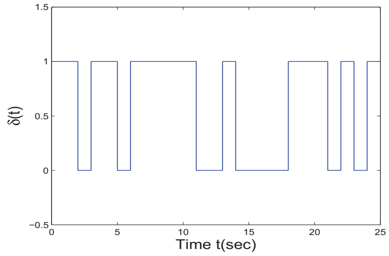

Fig. 1: Probabilistic distribution of fault-occurrence

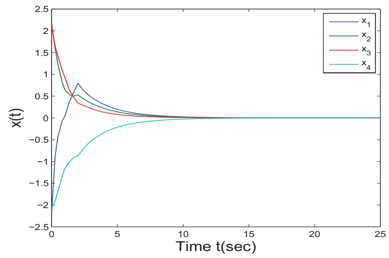

Fig. 2: Standard controller without failure

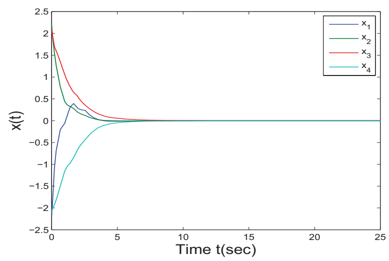

Fig. 3: Reliable controller without failure

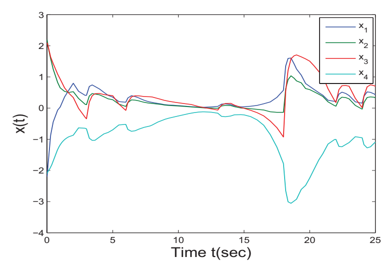

Fig. 4: Standard controller with failure

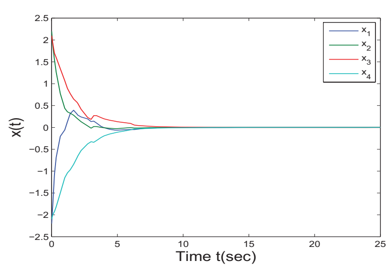

Fig. 5: Reliable controller with failure

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