Hindawi
Mathematical Problems in Engineering
Volume 2018, Article ID 4631371, 6 pages
https://doi.org/10.1155/2018/4631371

Research Article

Optimal Fault-Tolerant Control against Descriptor Time-Varying Systems with Nonlinear Input

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Received 9 November 2017; Accepted 2 April 2018; Published 28 June 2018

Academic Editor: Emilio Turco

The problem of optimal fault-tolerant control for a class of descriptor time-varying systems with nonlinear input is considered. Based on the Lyapunov stability theorem, the sufficient conditions of the stability are obtained when the system is normal and ineffective. Furthermore, the fault-tolerant control of the systems is carried out in two cases, and the state feedback fault-tolerant controller is obtained to satisfy the quadratic performance index and reach the minimum value in order to achieve the optimal fault-tolerant control. Finally, the validity of the proposed approach is illuminated by a numerical example.

1. Introduction

Descriptor systems were first studied in the 1970s and are now widely used in control systems, electrical circuits, mechanical systems, economics, and other areas. Because descriptor systems can better describe the actual system, there has been an extensive research in this area, resulting in insubstantial outcomes during the past 40 years. The theory underlying descriptor systems has become a critical area of research in modern control theory. But in the actual control systems, there are usually a series of unforeseen and unavoidable problems, such as the actuator failure and sensor failure in the systems. Therefore, focusing on these problems, the systems should have certain fault-tolerant performance to continue to maintain the original operation ability while the actuators or sensors of the systems are under fault. In addition, in the actual control system, according to the input of the system there will be some nonlinear input and the controller design is more complex; it is necessary to solve the problem of the fault-tolerant control against descriptor time-varying systems with nonlinear input.

In recent years, fault-tolerant control has attracted many scholars' attention; Zhou and Ding [1] summarized the main results of the recent research on classical fault-tolerant control and robust fault-tolerant control. Chen and Patton [2] and Duan et al. [3] proposed a new parametric approach for robust fault detection in descriptor linear multivariable systems with unknown disturbances. Chen and Zhang [4] studied the design of integrity controller for linear time-invariant discrete descriptor system and some conditions for integrity of the system are obtained by Lyapunov method. Zhu et al. [5] studied the problems of robust fault-tolerant guaranteed cost control for T-S fuzzy descriptor system with uncertain parameters and actuator failure. Gao et al. [6] proposed a novel state and sensor fault observer for systems with both state and input time delays to estimate system states and sensor faults simultaneously. Hashimoto and Amemiya [7] investigated the controllability and observability of linear time-invariant uncertain systems. Yang et al. [8] and Zheng and Cui [9] investigated the problems of robust passive fault-tolerant control for uncertain singular systems with time delay. Jin et al. [10] were concerned with the robust fault-tolerant $H\infty$ control problem of linear time-invariant systems with an adaptive mechanism for the general actuator fault and perturbation compensations. Wang and Lei [11] discussed the fault-tolerant control problem for uncertain singular systems when actuator is normal and ineffective. Feng et al. [12] considered a class of the time-varying periodically singular system and put forward the concept of robust stability and robust stabilization for the time-varying periodically singular system by using analysis method of inequalities of linear matrix and Lyapunov inequalities. Qiu et al. [13] studied fault-tolerant control problem for uncertain nonlinear singular systems, a new fault-tolerant control criteria is proposed in terms of Lyapunov-Krasovskii functional approach, and the sufficient condition for the existence of fault-tolerant controller is derived by the form of the linear matrix inequality (LMI) approach. Liang and Wei-Guo [14] studied a class of singular systems with uncertain perturbation and presented the design method of fault-tolerant control to ensure the system is finite time stable when the actuator fails. Yao et al. [15] proposed a new optimal fault-tolerant control algorithm for linear time-varying singular systems and in order to develop an effective scheme to make time-varying systems work normally when faults occur, Riccati matrix equation is used to get the optimal fault-tolerant law for the faulty system. Li et al. [16] deal with the problems of fault diagnosis and fault-tolerant control for systems with delayed measurements and states. Song et al. [17] presented the design method for reliable tracking controller against actuator faults for a class of linear systems which are subject to both time-varying norm-bounded parameter uncertainty and exogenous disturbance. Vrabie et al. [18] proposed a new scheme based on adaptive critics for finding online the state feedback, infinite horizon, optimal control solution of linear continuous-time systems using only partial knowledge regarding the system dynamics. Ji and Qiu [19] focused on the state and static output feedback stabilization for fractional-order singular uncertain linear systems with the fractional commensurate order, and suitable feedback controllers that guarantee the stability of resulting closed-loop control systems were designed.

In the past literatures, we have had a lot of work on stability analysis and fault-control problems for descriptor systems, but the related results on descriptor time-varying systems with nonlinear input remain undiscovered. Considering the importance of the systems in real world, in this paper, we investigate the optimal fault-tolerant control against time-varying descriptor systems with nonlinear input; the sufficient conditions are obtained by Lyapunov stability theorem when the system is normal and ineffective. Further, based on the stability condition, the optimal fault-tolerant controller for the system is obtained through the boundary conditions, which met the given quadratic performance index. Finally, an example is given to solve the problem by MATLAB.

2. Problem Statements

Consider the following descriptor time-varying system with nonlinear input:

$$\begin{aligned} E(t)\dot{x}(t) &= A(t)x(t) + B(t)\left(u_1(t) + u_2(t, x(t))\right) \\ &\quad + f(t), \\ y(t) &= C(t)x(t), \end{aligned} \tag{1}$$

where $x(t) \in R^n$ is the state vector, $f(t)$ is the boundary failure of system (1) and $\|f(t)\| \leq F(t)x(t)$, $F(t) \geq 0$. $E(t)$, $A(t)$, $B(t)$, and $C(t)$ are the time-varying analytic function matrices with the appropriate dimensions, and $\operatorname{rank}(E(t)) = q \leq n$. $u_1(t) \in R^m$ control input, $u_2(t, x(t))$, is the nonlinear input of system (1) and it satisfies Lipschitz condition that there is a scalar $\alpha > 0$ such that

$$\left\|u_2(t, x_1(t)) - u_2(t, x_2(t))\right\| \leq \alpha \left\|U(x_1(t) - x_2(t))\right\|, \tag{2}$$

where U is the continuous constant matrix with the appropriate dimension, and according to formula (2), the following inequality is obtained:

$$\left\|u_2(t, x(t))\right\| \leq \alpha \left\|Ux(t)\right\|. \tag{3}$$

And it can be obtained from the above formula that

$$u_2(t, x(t)) \leq Ux(t). \tag{4}$$

For convenience, let

$$u_1(t) + Ux(t) = u(t). \tag{5}$$

The fault-tolerant control law for system (1) is that system (1) can remain asymptotically stable when the fault occurs; we select the following quadratic performance indicators of infinite time:

$$J = \int_0^\infty \left(x^T(t)Qx(t) + u^T(t)Ru(t)\right)dt, \tag{6}$$

where $Q \in R^{n\times n}$ is a semipositive matrix and $R = R^T \in R^{n\times n}$ is a positive matrix.

Definition 1. The descriptor time-varying system (1) is said to be regular, if there is a constant s, for any t in the time domain; then $\det(sE(t) - A(t)) \neq 0$.

Definition 2. The descriptor time-varying system (1) is said to be impulse-free, if there is a constant s, for any t in the time domain; then $\operatorname{rank}(sE(t) - A(t)) = \operatorname{rank}(E(t))$.

Definition 3. The descriptor time-varying system (1) is said to be admissible, if it is uniformly regular, impulse-free, and stable.

3. Main Results

3.1. Stability Analysis. In order to solve the optimal control problem of system (1), the stability of the system should be analyzed, and the stability conditions of system (1) are given as follows.

Theorem 4. *The descriptor time-varying system (1) with nonlinear input is said to be asymptotically stable, when system (1) is in fault, if there is a positive definite matrix $P(t) \in R^{q\times q}$ such that*

$$\begin{aligned} &\Xi + U^T(t)B^T(t)P(t) + P(t)B(t)U(t) \\ &\quad + F^T(t)P(t)E(t) + E^T(t)P(t)F(t) \leq 0, \end{aligned} \tag{7}$$

where

$$\begin{aligned} \Xi &= A^T(t)P(t)E(t) + k_1^T(t)B^T(t)P(t)E(t) \\ &\quad + \dot{E}^T(t)P(t)E(t) + E^T(t)\dot{P}(t)E(t) \\ &\quad + E^T(t)P(t)A(t) + E^T(t)P(t)B(t)k_1(t). \end{aligned} \tag{8}$$

Proof. Consider the control input $u_1(t)$ and design the following state feedback:

$$u_1(t) = k_1(t)\, x(t). \tag{9}$$

Then system (1) is written as follows:

$$\begin{aligned} E(t)\,\dot{x}(t) &= \left(A(t) + B(t)\,k_1(t)\right) x(t) + B(t)\,u_2(t) \\ &\quad + f(t), \\ y(t) &= C(t)\,x(t). \end{aligned} \tag{10}$$

Therefore, solving the stability condition of system (1) is equivalent to the stability condition of system (10); focusing on system (10), we choose the following Lyapunov function:

$$V(x(t)) = x(t)\,E^T(t)\,P(t)\,E(t)\,x(t). \tag{11}$$

It is not difficult to know $V(x(t)) \geq 0$; differentiating (11) with respect to t on both sides yields the following formula:

$$\begin{aligned} \dot{V}(x(t)) &= \dot{x}^T(t)\,E^T(t)\,P(t)\,E(t)\,x(t) + x^T(t)\,\dot{E}^T(t) \\ &\quad \cdot P(t)\,E(t)\,x(t) + x^T(t)\,E^T(t)\,\dot{P}(t)\,E(t)\,x(t) \\ &\quad + x(t)\,E^T(t)\,P(t)\,E(t)\,\dot{x}(t) \\ &= \left(\left(A(t) + B(t)\,k_1(t)\right) x(t) + B(t)\,u_2(t) + f(t)\right)^T \\ &\quad \cdot P(t)\,E(t)\,x(t) + x^T(t)\,\dot{E}^T(t)\,P(t)\,E(t)\,x(t) \\ &\quad + x^T(t)\,E^T(t)\,\dot{P}(t)\,E(t)\,x(t) + x(t)\,E^T(t)\,P(t) \\ &\quad \cdot \left(\left(A(t) + B(t)\,k_1(t)\right) x(t) + B(t)\,u_2(t) + f(t)\right) \\ &= x^T(t)\,\Xi x(t) + u_2^T(t)\,B^T(t)\,P(t)\,E(t)\,x(t) \\ &\quad + x(t)\,E^T(t)\,P(t)\,B(t)\,u_2(t) + f^T(t)\,P(t)\,E(t)\,x(t) \\ &\quad + x(t)\,E^T(t)\,P(t)\,f(t), \end{aligned} \tag{12}$$

where

$$\begin{aligned} \Xi &= A^T(t)\,P(t)\,E(t) + k_1^T(t)\,B^T(t)\,P(t)\,E(t) \\ &\quad + \dot{E}^T(t)\,P(t)\,E(t) + E^T(t)\,\dot{P}(t)\,E(t) \\ &\quad + E^T(t)\,P(t)\,A(t) + E^T(t)\,P(t)\,B(t)\,k_1(t). \end{aligned} \tag{13}$$

Because of $\|f(t)\| \leq F(t)x(t)$ and $u_2(t, x(t)) \leq Ux(t)$, then (12) can be written as

$$\begin{aligned} \dot{V}(x(t)) &= x^T(t)\,\Xi x(t) + u_2^T(t)\,B^T(t)\,P(t)\,E(t)\,x(t) \\ &\quad + x(t)\,E^T(t)\,P(t)\,B(t)\,u_2(t) + f^T(t)\,P(t)\,E(t)\,x(t) \\ &\quad + x(t)\,E^T(t)\,P(t)\,f(t) \leq x^T(t)\,\big(\Xi \\ &\quad + U^T(t)\,B^T(t)\,P(t) + P(t)\,B(t)\,U(t) \\ &\quad + F^T(t)\,P(t)\,E(t) + E^T(t)\,P(t)\,F(t)\big)\,x(t). \end{aligned} \tag{14}$$

According to (7), the following formula can be obtained:

$$\begin{aligned} &\Xi + U^T(t)\,B^T(t)\,P(t) + P(t)\,B(t)\,U(t) \\ &\quad + F^T(t)\,P(t)\,E(t) + E^T(t)\,P(t)\,F(t) \leq 0. \end{aligned} \tag{15}$$

That is, $\dot{V}(x(t)) \leq 0$; according to the Lyapunov stability theorem, it is shown that system (10) is asymptotically stable. □

Based on Theorem 4, when there is no failure in system (1), the system is in the following form:

$$\begin{aligned} E(t)\,\dot{x}(t) &= A(t)\,x(t) + B(t)\left(u_1(t) + u_2(t, x(t))\right), \\ y(t) &= C(t)\,x(t). \end{aligned} \tag{16}$$

And because $f(t) = 0$ and according to $\|f(t)\| \leq F(t)x(t)$, we can let $F(t) = 0$, similar to Theorem 4; by Lyapunov method it is not difficult to obtain the following conclusions about the sufficient conditions of asymptotically stability for system (16).

Corollary 5. *The descriptor time-varying system (16) with nonlinear input is asymptotically stable, if there is a positive matrix $P(t) \in R^{q\times q}$ such that*

$$\Xi + U^T(t)\,B^T(t)\,P(t) + P(t)\,B(t)\,U(t) \leq 0, \tag{17}$$

where

$$\begin{aligned} \Xi &= A^T(t)\,P(t)\,E(t) + k_1^T(t)\,B^T(t)\,P(t)\,E(t) \\ &\quad + \dot{E}^T(t)\,P(t)\,E(t) + E^T(t)\,\dot{P}(t)\,E(t) \\ &\quad + E^T(t)\,P(t)\,A(t) + E^T(t)\,P(t)\,B(t)\,k_1(t). \end{aligned} \tag{18}$$

3.2. The Optimal Control without Fault. When there is no failure in system (1), the system form is (16); in this section, our aim is to determine an optimal control law for system (16).

Theorem 6. *For the descriptor time-varying system with nonlinear inputs described by (16), there exists a unique optimal control law with respect to the quadratic performance index (6), and*

$$u(t) = -R^{-1}B^T(t)\,\xi(t), \tag{19}$$

where

$$\xi(t) = P(t)\,E(t)\,x(t), \tag{20}$$

and $P(t) \in R^{q\times q}$ is a positive matrix, which is the solution of the following Riccati equation:

$$\begin{aligned} &A^T(t)\,P(t)\,E(t) + E^T(t)\,P(t)\,A(t) + \dot{E}^T(t)\,P(t)\,E(t) \\ &\quad + E^T(t)\,\dot{P}(t)\,E(t) + E^T(t)\,P(t)\,\dot{E}(t) + Q \\ &\quad - E^T(t)\,P(t)\,B(t)\,R^{-1}B^T(t)\,P(t)\,E(t) = 0. \end{aligned} \tag{21}$$

Proof. When there is no fault in the system function, according to the optimal control theory, solving the optimal control problem of the descriptor time-varying systems with nonlinear input described by (16) about quadratic performance index (6) is equivalent to solving the boundary value problem as follows:

$$\begin{aligned} &E(t)\dot{x}(t) = A(t)x(t) + B(t)(u_1(t) + u_2(t, x(t))), \\ &E^T(t)\xi(t) + E^T(t)\dot{\xi}(t) + Qx(t) + A^T(t)\xi(t) = 0. \end{aligned} \tag{22}$$

According to formulas (4) and (9), the following is obtained:

$$\begin{aligned} u_1(t) + u_2(t, x(t)) &\leq u_1(t) + Ux(t) = u(t) \\ &= (k_1(t) + U)x(t). \end{aligned} \tag{23}$$

The following optimal control law can be obtained by analyzing the boundary value problem:

$$u(t) = k_1(t) + U = -R^{-1}B^T(t)\xi(t), \tag{24}$$

where

$$\xi(t) = P(t)E(t)x(t). \tag{25}$$

The derivative of $\xi(t)$ is

$$\begin{aligned} \dot{\xi}(t) = {} & \dot{P}(t)E(t)x(t) + P(t)\dot{E}(t)x(t) \\ & + P(t)E(t)\dot{x}(t). \end{aligned} \tag{26}$$

Substitute in (22) the following:

$$\begin{aligned} & A^T(t)P(t)E(t)x(t) + E^T(t)P(t)A(t)x(t) \\ & + \dot{E}^T(t)P(t)E(t)x(t) + E^T(t)\dot{P}(t)E(t)x(t) \\ & + E^T(t)P(t)\dot{E}(t)x(t) + Qx(t) \\ & - E^T(t)P(t)B(t)R^{-1}B^T(t)P(t)E(t)x(t) = 0. \end{aligned} \tag{27}$$

Then $P(t)$ is the solution of the following Riccati equation:

$$\begin{aligned} & A^T(t)P(t)E(t) + E^T(t)P(t)A(t) \\ & + \dot{E}^T(t)P(t)E(t) + E^T(t)\dot{P}(t)E(t) \\ & + E^T(t)P(t)\dot{E}(t) + Q \\ & - E^T(t)P(t)B(t)R^{-1}B^T(t)P(t)E(t) = 0. \end{aligned} \tag{28}$$

□

3.3. The Optimal Control with Fault

Theorem 7. *For the descriptor time-varying fault system with nonlinear inputs described by (1), there exists a unique optimal control law with respect to the quadratic performance index (6), and*

$$u^*(t) = -R^{-1}B^T(t)\xi^*(t), \tag{29}$$

where $\xi^*(t) = P(t)E(t)x(t) + P_1(t)f(t)$ and $P(t)$ and $P_1(t) \in R^{q\times q}$ are positive matrixes which are the solutions of the following Riccati equations:

$$\begin{aligned} & A^T(t)P(t)E(t) + E^T(t)P(t)A(t) + \dot{E}^T(t)P(t)E(t) \\ & \quad + E^T(t)\dot{P}(t)E(t) + E^T(t)P(t)\dot{E}(t) + Q - E^T(t) \\ & \quad \cdot P(t)B(t)R^{-1}B^T(t)P(t)E(t) = 0, \\ & \big(E^T(t)P(t) + \dot{E}^T(t)P_1(t) + E^T(t)\dot{P}_1(t) \\ & \quad + A^T(t)P_1(t) - E^T(t)P(t)B(t)R^{-1}B^T(t)P_1(t)\big) \\ & \quad \cdot f(t) + E^T(t)P_1(t)\dot{f}(t) = 0. \end{aligned} \tag{30}$$

Proof. Similar to the proof of Theorem 6, when the system has failures, according to the optimal control theory, solving the optimal control problem of the descriptor time-varying systems with nonlinear input described by (16) about quadratic performance index (6) is equivalent to solving the boundary value problem as follows:

$$\begin{aligned} & E(t)\dot{x}(t) \\ & \quad = A(t)x(t) + B(t)(u_1(t) + u_2(t, x(t))) + f(t), \\ & E^T(t)\xi^*(t) + E^T(t)\dot{\xi}^*(t) + Qx(t) + A^T(t)\xi^*(t) \\ & \quad = 0. \end{aligned} \tag{31}$$

Similarly, according to (4) and (9), let

$$\begin{aligned} u_1(t) + u_2(t, x(t)) &\leq u_1(t) + Ux(t) = u(t) \\ &= -R^{-1}B^T(t)\xi^*(t). \end{aligned} \tag{32}$$

Based on the analysis,

$$\xi^*(t) = P(t)E(t)x(t) + P_1(t)f(t). \tag{33}$$

The derivative of $\xi(t)$ is

$$\begin{aligned} \xi^*(t) = {} & \dot{P}(t)E(t)x(t) + P(t)\dot{E}(t)x(t) \\ & + P(t)E(t)\dot{x}(t) + \dot{P}_1(t)f(t) + P_1(t)\dot{f}(t). \end{aligned} \tag{34}$$

Substitute in (31) the following:

$$\begin{aligned} & \big(\dot{E}^T(t)P(t)E(t) + E^T(t)\dot{P}(t)E(t) \\ & \quad + E^T(t)P(t)\dot{E}(t) + A^T(t)P(t)E(t) \\ & \quad - E^T(t)P(t)B(t)R^{-1}B^T(t)P(t)E(t)\big)x(t) \\ & \quad + \big(\dot{E}^T(t)P_1(t) + E^T(t)\dot{P}_1(t) \\ & \quad - E^T(t)P(t)B(t)R^{-1}B^T(t)P_1(t)\big)f(t) + E^T(t) \\ & \quad \cdot P_1(t)\dot{f}(t) = -\big(Q + A^T(t)P(t)E(t)\big)x(t) \\ & \quad - A^T(t)P_1(t)f(t). \end{aligned} \tag{35}$$

And then we have

$$\begin{aligned}&\dot{E}^T(t)P(t)E(t)+E^T(t)\dot{P}(t)E(t)+E^T(t)P(t)\dot{E}(t)\\&\quad+A^T(t)P(t)E(t)+Q+A^T(t)P(t)E(t)-E^T(t)\\&\quad\cdot P(t)B(t)R^{-1}B^T(t)P(t)E(t)=0,\\&\left(\dot{E}^T(t)P_1(t)+E^T(t)\dot{P}_1(t)\right.\\&\quad\left.-E^T(t)P(t)B(t)R^{-1}B^T(t)P_1(t)\right)f(t)+E^T(t)\\&\quad\cdot P_1(t)\dot{f}(t)=-A^T(t)P_1(t)f(t).\end{aligned} \tag{36}$$

Then $P(t)$ and $P_1(t)$ are positive definite matrices, which are solutions of the above two equations. □

4. Numerical Examples

Considering system (1), the parameters of each part are

$$E(t)=\begin{bmatrix}t&0\\0&0\end{bmatrix},\quad A(t)=\begin{bmatrix}-t&0\\0&t\end{bmatrix},\quad B(t)=\begin{bmatrix}-t&0\\1&t\end{bmatrix}. \tag{37}$$

Let the nonlinear input in system (1) be

$$u_2(t)=\sin(x(t)). \tag{38}$$

Then $\|u_2(t)\| = \|\sin(x(t))\| \le \|x(t)\|$; thus let $\det(U) \ge \det(I)$.

Select the following quadratic performance index:

$$J=\int_{t_0}^{t_1}\left(x^T(t)\begin{bmatrix}1&0\\0&0\end{bmatrix}x(t)+u^T(t)\begin{bmatrix}1&0\\0&1\end{bmatrix}u(t)\right)dt; \tag{39}$$

thus $Q=\left[\begin{smallmatrix}1&0\\0&0\end{smallmatrix}\right]$, $R=\left[\begin{smallmatrix}1&0\\0&1\end{smallmatrix}\right]$.

When there is no fault in the system, we choose $x_1(0) = 0.2$, and let $t_0 = 0$ and $t_1 = 20$; the control input of the system is obtained. According to Figure 1, the optimal control can be achieved when there is no fault in the system.

When there is failure in the system, we still choose the initial input $x_1(0) = 0.2$, and let $t_0 = 0$ and $t_1 = 20$, and the fault between t_0 and t_1 is $f(t) = [1\ \ 0.5]^T$; then the MATLAB simulation can be shown in Figure 2. It can be seen that the system is unstable at this time. The fault-tolerant controller is added to the fault system at $t = 2$ s. Figure 3 shows that the system gradually stabilizes after fault tolerance control. Through the above simulation, we can find out that the method used in this paper can keep the system stable when the system fails and realize fault tolerance control of the system.

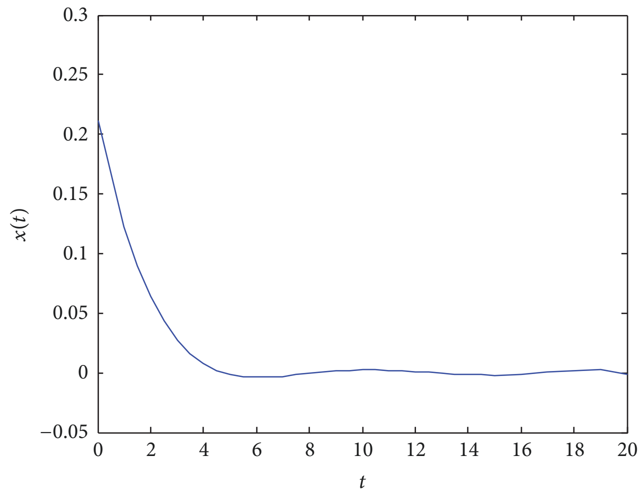

Figure 1: System state under optimal control when the system without fault.

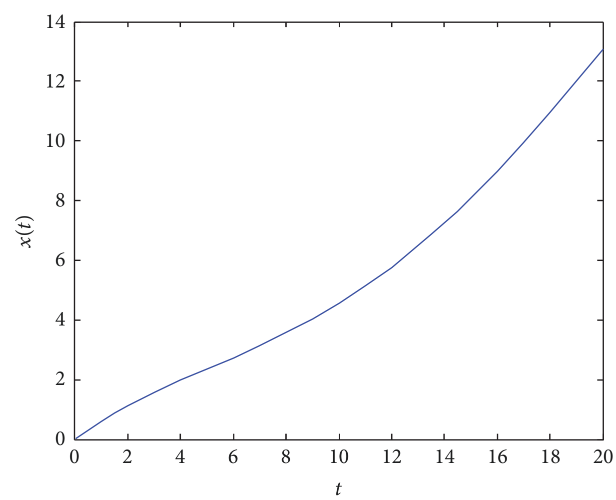

Figure 2: System state without fault-tolerant control.

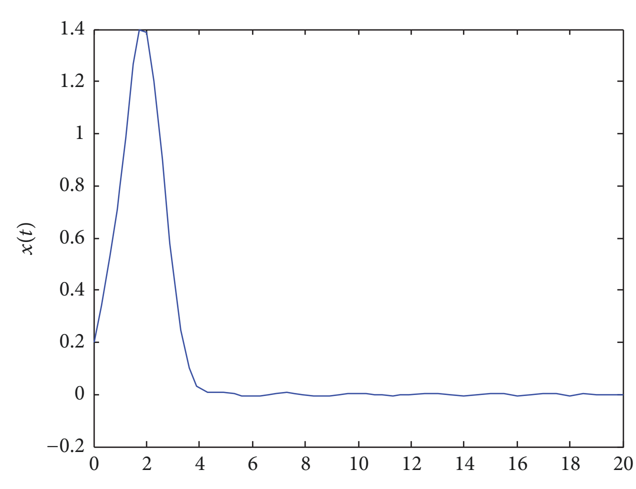

Figure 3: System state with fault-tolerant control.

5. Conclusions

This paper considers a class of descriptor time-varying systems with nonlinear input; sufficient conditions are obtained by Lyapunov stability theorem; on the basis of stability conditions, the optimal fault-tolerant controller of the system is obtained by using the optimal control theory, while fault occurs in the system; this method can realize fault tolerance control and reduce the impact of failure; then the example is carried on by MATLAB simulation. The method used in this paper is a general generalization of descriptor system to descriptor time-varying systems, and it has important theoretical significance for further study of some applications of descriptor time-varying systems.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by *National Natural Science Foundation of China* (61074005) and the *Talent Project of the High Education of Liaoning Province* (LR2012005).

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