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FAULT TOLERANT CONTROL BASED ON DYNAMIC SLIDING MODE FOR SPACE MANIPULATOR

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Abstract. *Aiming at a dual joints space manipulator with actuator fault case and external disturbance, a fault tolerant control scheme based on adaptive dynamic sliding mode control method is proposed in this paper. Firstly, the dual joint dynamic equation and faulty modeling are introduced. Secondly, the dynamic system for fault-free controller is based on sliding mode control method to design nominal controller. Then through online adaptive method, both parameters of fault and external disturbance are to be estimated and corresponding controller parameters are updated. Finally, system's fault-tolerant performance and reliability can be verified by experiment simulation results.*
Keywords: Space manipulator, Fault tolerant control, Sliding mode control, Actuator fault

1. **Introduction.** Space manipulator has become the trend of space development to assist mankind to complete the task of space exploration; advanced space manipulator application can improve the large space station construction, use, maintenance and other aspects of the efficiency and safety, can replace astronauts for space monitoring, space assembly, solar cell windsurfing maintenance, faulty satellite repair, auxiliary interactive docking and other space missions, greatly reducing the risk of astronauts out of the cabin activities. In recent years, with the development of space technology, space manipulator arm has gradually become an important tool on the spacecraft. At present, Canada, Russia, Germany and other countries have mastered the space manipulator technology, the typical space manipulator has the Canadian robot arm SRMS (Shuttle Remote Manipulator System) and SSRMS (Space Station Remote Manipulator System), European arm ERA (European Robotic Arm), etc., and China is also carrying out the relevant technical research work. In the current industrial applications, multi-joint robots occupy a large market. However, the multi-joint manipulator is a very complex multi-input and multi-output nonlinear system with time-varying, coupling and nonlinear dynamic characteristics. The specific characteristics of the kinetic equation model are as follows: 1) a high degree of non-linearity, because each item of the equation contains the number of items, and the number of items is increased by the number of joints; 2) high degree of coupling refers to the serious coupling between the joints. In addition, due to the mechanical arm in the work of the load at any time changes, as well as the joint friction coefficient is constantly changing, while external interference and other uncertain factors will lead to the control of the robot there are different problems, seriously it even leads the robot arm to fault. Therefore, the design of the control system will be more complex

[1-3]. Since huge economic costs and high maintenance and other factors for integrated space operations, fault-tolerant control technology will have a very high practical and economic value [4]. Fault-tolerant control has the characteristics of ensuring the stability of system in the event of system fault, which has a high practical value in the field of space manipulator system. Generally, there are three typical component fault modes for space, position fault, torque fault, hard fault [5]. Position fault, also called a joint locked fault refers to the case when one joint is locked in place and cannot move. Torque fault, also known as free swing fault, refers to a hardware or software fault in a robotic manipulator that causes the loss of torque (or force) on an actuator. Hard fault refers to the case when a strut is totally lost.

However, there are few studies on the combination of fault-tolerant control technology and space manipulator system. Most of the theoretical research is applied to the fixed-carrier ground arm system. A robust adaptive control method is designed compensation for system faults [3]. For the robot joint stuck problem, the design of an optimal path is given to avoid the fault of the system [4]. [6] proposed a more effective solution to the problem of mechanical vibration in engineering, which can be used to solve the vibration problem of flexible robot. In [7], an off-line fault-tolerant control method based on pseudo-inverse reconstruction is proposed for joint fault of redundant serial manipulator. In [8], a fault-tolerant control scheme is proposed for the case of a single joint fault of a class of non-redundant space manipulators, taking account of the kinematics, workspace and trajectory planning. In [5], three kinds of common pillar faults of the manipulator are considered, including the joint jamming, the unactivated actuator and the joint fault completely, and the corresponding fault tolerance scheme is given to deal with the above different fault problems. When any joint of a redundant manipulator fails or stuck somewhere, the design of the fault-tolerant control scheme ensures that the given task is complete by limiting the range of motion of the robot [9]. In [10], an effective fault-tolerant control scheme is given for a class of joint fault. This paper focused on adaptive dynamic sliding-mode control for dual-joint space manipulator under actuator fault. The main contributions include: 1) proposing an adaptive sliding mode fault tolerant control scheme aiming at actuator fault; 2) estimating the information for fault and external disturbances online based on adaptive mechanism; 3) in order to avoid the actuator chattering, dynamic sliding mode control is adopted and chattering phenomenon of the system is successfully reduced.

This paper is arranged as follows. First, the kinematics of a general dual manipulator and its faulty model are derived in Section 2. Then, in Section 3, actuator faults are analyzed, and fault-tolerant strategies based on dynamic sliding mode are proposed. In Section 4, simulation results and analyses are given. This paper ends with conclusions in Section 5.

2. Dynamic Model of Space Manipulator.

In this paper, the kinetic equation of the double joint manipulator (see Figure 1) is considered as follows:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + F(\dot{q}) = u + u_d \tag{1}$$

where $q = [q_1, q_2]^T$ denotes the vector of joint positions, and q, $\dot{q}$, $\ddot{q}$ are respectively joint position, velocity and acceleration vector. $M(q) \in R^{2\times 2}$ the inertia matrix; $C(q,\dot{q}) \in R^{2\times 2}$ the coriolis and centripetal force; $G(q) \in R^2$ the gravity term; $F(\dot{q}) \in R^{2\times 1}$ denotes the static and dynamic friction matrix; $u_d = [u_{d1}, u_{d2}]^T$ is disturbance vector; $u = [u_1, u_2]^T$ is control torque.

In this paper, we consider actuator fault issue of space manipulator, and further analyze the actuator fault situations and give the design of fault-tolerant control. First of all, give the following actuator fault dynamics equation:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + F(\dot{q}) = u_f + u_d \tag{2}$$

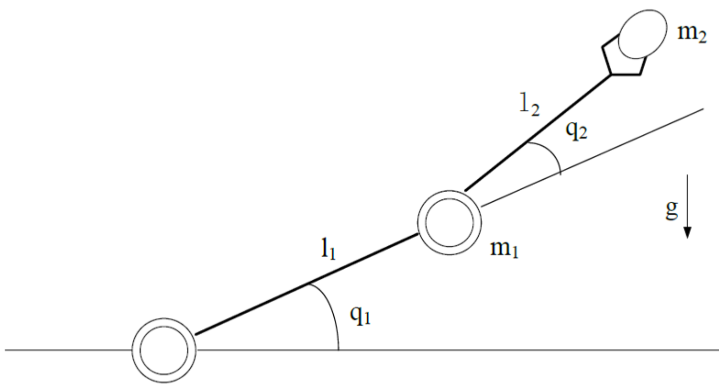

FIGURE 1. Double joint manipulator

The above system (2) is subject to motor fault, that is, torque fault. $u_f = Ku$, $K = diag\{k_i\}$, $i = 1, 2$ and $0 \le k_i \le 1$ denotes faulty factor, as $k_i = 0$ presents actuator total loss efficacy; as $k_i = 1$, actuator is healthy. As $0 < k_i < 1$ represents partial loss efficacy.

In order to deal with the information of uncertainties and fault, let $x_1 = q$, $x_2 = \dot{q}$, system (2) can be rewritten as the following form

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x) + g(x)(u_f + u_d) \\ y = x_1 \end{cases} \tag{3}$$

where $f(x) = -M^{-1}(q)\left[C(q, \dot{q})\dot{q} + G(q) + F(\dot{q})\right]$, $g(x) = M^{-1}(q)$.

3. **Dynamic Sliding Mode Fault Tolerant Control.** Control objectives in this paper are as follows: the designed fault tolerant control enables the system to be stable under the actuator fault conditions; also for any given initial state, the desired signals can be tracked accurately and timely.

3.1. **Nominal control design.** Let joint position tracking expectation $q_d = [q_{d1}, q_{d2}]^T$, and $e = q - q_d$ is the track error of system. We chose the sliding surface as follows:

$$s = L\dot{e} + Pu \tag{4}$$

where $L = diag\{l_i\}$, $l_i < 0$; $P = diag\{p_i\}$, $p_i > 0$ $(i = 1, 2)$.

Then the derivative of (4) can be obtained

$$\dot{s} = L\ddot{e} + P\dot{u} \tag{5}$$

In order to ensure that the system reaches the sliding mode surface within finite time, so the asymptotical reaching law is adopted:

$$\dot{s} = -\rho_1 s - \rho_2 \text{sgn}(s) \tag{6}$$

Here $\rho_1 > 0$, $\rho_2 > 0$ are sliding mode gains which will be designed later.

P is a nonsingular matrix, and based on (5) and (6), the nominal control law is designed as follows:

$$\dot{u} = P^{-1}\{-\rho_1 s - \rho_2 \text{sgn}(s) - L[f(x) + g(x)(Ku + u_d)] + L\ddot{q}_d\} \tag{7}$$

Remark 3.1. *Since faulty factor and disturbance are unknown in Equation (7), in the following we will obtain their estimation values $\hat{K}$, $\hat{u}_d$ based on adaptive method online, and further step update parameters of control law.*

3.2. **Fault tolerant control design.** From the above analysis, we can obtain the following results.

Theorem 3.1. *For system (2) with disturbances and actuator fault, under the designed dynamic sliding mode surface (4), the sliding mode DTC law (8) and adaptive algorithm (9) and (10), system tracked error e can converge to zero, and the closed-loop system is globally asymptotically stable within a finite reaching time.*

$$\dot{u} = P^{-1}\left\{-\rho_1 s - \rho_2 \text{sgn}(s) - L\left[f(x) + g(x)\left(\hat{K}u + \hat{u}_d\right)\right] + L\ddot{q}_d\right\} \tag{8}$$

$$\dot{\hat{k}}_i = s_i^T l_i g_i \Gamma_i \text{sgn}(\lambda_i) \tag{9}$$

$$\dot{\hat{u}}_d = \eta s_i^T l_i g_i \text{sgn}(\lambda_i) \tag{10}$$

Proof: Take the Lyapnuov function as follows

$$V(x) = \frac{1}{2}s^T s + \frac{1}{2}\tilde{k}^T \Gamma \tilde{k} + \frac{1}{2\eta}\tilde{u}_d^T \tilde{u}_d \tag{11}$$

where $\hat{k}_i$ and $\hat{u}_d$ are respectively the estimations of k_i and u_d, $\tilde{k}_i = k_i - \hat{k}_i$, $\tilde{u}_d = u_d - \hat{u}_d$ are respectively estimated errors, and Γ, η are adaptive parameters. The derivative of V is given by

$$\dot{V}(x) = s^T \dot{s} + \tilde{k}^T \Gamma \dot{\tilde{k}} + \frac{1}{\eta}\tilde{u}_d^T \tilde{u}_d \tag{12}$$

Substituting (4) and (8) into (12), we obtain

$$\dot{V}(x) = s^T\left(L\ddot{e} + p\dot{u}\right) + \tilde{k}\Gamma^{-1}\dot{\tilde{k}} + \frac{1}{\eta}\tilde{u}_d^T \dot{\tilde{u}}_d = s^T\left(\ddot{q} - \ddot{q}_d + p\dot{u}\right) + \tilde{k}\Gamma^{-1}\dot{\tilde{k}} + \frac{1}{\eta}\tilde{u}_d^T \dot{\tilde{u}}_d$$

Further step simplification to yield,

$$\begin{aligned}
\dot{V}(x) &= s^T\left[L\left(\ddot{q} - \ddot{q}_d\right) - \rho_1 s - \rho_2 \text{sgn}(s) - L\ddot{e}\right] + \tilde{k}\Gamma^{-1}\dot{\tilde{k}} + \frac{1}{\eta}\tilde{u}_d^T \dot{\tilde{u}}_d \\
&= s^T\left[L\ddot{q} - L\ddot{q}_d - \rho_1 \text{sgn}(s) - L\left(f(x) + g(x)\left(\hat{u}_d + \hat{k}u\right) - \ddot{q}_d\right)\right] + \tilde{k}\Gamma^{-1} + \frac{1}{\eta}\tilde{u}_d^T \dot{\tilde{u}}_d \\
&= s^T\left[L\ddot{q} - \rho_1 s - \rho_2 \text{sgn}(s) - L\left(f(x) + g(x)\hat{u}_d + g(x)\tilde{k}u\right)\right] + \tilde{k}\Gamma^{-1}\dot{\tilde{k}} + \frac{1}{\eta}\tilde{u}_d^T \dot{\tilde{u}}_d \\
&= s^T\left[-\rho_1 s - \rho_2 \text{sgn}(s) + Lg(x)\left(u_d - \tilde{u}_d\right) + Lg(x)\tilde{k}u\right] + \tilde{k}\Gamma^{-1}\dot{\tilde{k}} + \frac{1}{\eta}\tilde{u}_d^T \dot{\tilde{u}}_d \\
&= -\rho_1 s^2 - \rho_2 \text{sgn}(s)s + s^T Lg(x)\left(\tilde{u}_d + \tilde{k}u\right) + \tilde{k}^T\Gamma^{-1}\left(\dot{k} - \dot{\hat{k}}\right) + \frac{\tilde{u}_d^T\left(\dot{u}_d - \dot{\hat{u}}_d\right)}{\eta} \\
&= -\rho_1 s^2 - \rho_2 \text{sgn}(s) + \left(s^T Lg(x) - \frac{\dot{\hat{u}}_d}{\eta}\right)\tilde{u}_d + \left(s^T Lg(x) - \dot{\hat{k}}\Gamma^{-1}\right)\tilde{k}
\end{aligned}$$

Substituting adaptive law (9) and (10) into the above equation, one obtains

$$\dot{V}(x) \leq -\rho_1 s^2 - \rho_2 s \leq 0 \tag{13}$$

Since here $\rho_1 > 0$, $\rho_2 > 0$, Equation (13) only as $s = 0$, $\dot{V}(x) \equiv 0$. As $s \neq 0$, $\dot{V}(x) < 0$.

Thus the stability of the overall system is proved and $\dot{V}(x) = 0$ only if $s = 0$, which ends the proof of Theorem 3.1.

Remark 3.2. *In order to eliminate chattering generated by the sliding mode switching,* $\text{sgn}(s)$ *function will be taken place of saturation function* $\text{sat}(s)$ *in the above controller*

(8):

$$\mathrm{sat}(s) = \begin{cases} 1, & s_i > \delta_i \\ \dfrac{s_i}{\delta_i}, & |s_i| \le \delta_i \\ -1, & s_i < -\delta_i \end{cases} \tag{14}$$

where $\delta_i > 0$ $(i = 1, 2)$ *are constants.*

Remark 3.3. *The control law is presented by* $\dot{u}$ *in (8), which may generate new noises and increase calculation amount, so here its integral form is adopted. Thus, the proposed control law is given in this paper by (15).*

$$\dot{u} = P^{-1} \int_0^t \left\{ -\rho_1 s - \rho_2 \mathrm{sat}(s) - L \left[f(x) + g(x) \left(\hat{K} u + \hat{u}_d \right) \right] + L \ddot{q}_d \right\} d\tau \tag{15}$$

Remark 3.4. *Consider the structural damage of system (4), the proposed adaptive dynamic sliding mode damage-tolerant controller (8)-(10) and (15) can compensate the uncertainties or disturbances completely and also has the tolerant ability under the fault tolerant control system of actuator fault.*

4. **Experiments.** In order to verify the effectiveness of the proposed method, we take the simulation experiment on the dynamics equation of the double joint manipulator. Related simulation parameters are as follows:

$$M(q) = \begin{pmatrix} 3.66 + 1.74 \cos q_2 & 0.76 + 0.87 \cos q_2 \\ 0.76 + 0.87 \cos q_2 & 0.76 \end{pmatrix}$$

$$C(q, \dot{q}) = \begin{pmatrix} -0.87 \dot{q}_2 \sin q_2 & -0.87 (\dot{q}_1 + \dot{q}_2) \sin q_2 \\ 0.87 \dot{q}_1 \sin q_2 & 0 \end{pmatrix}$$

$$G(q) = \begin{pmatrix} 3.04 g \cos q_1 + 0.87 g \cos(q_1 + q_2) \\ 0.87 g \cos(q_1 + q_2) \end{pmatrix}$$

Let system initial state be $q_0 = [0.5, 0]$, and tracked signals $q_d = [\cos \pi t, \sin \pi t]$ and $u_d(t) = [0.5 \cos \pi t, 0.5 \sin \pi t]$. Faulty factor $K = diag\{0.6, 0.5\}$, and control torques u_1, u_2 have fault in $t = 30s$, $t = 25s$ respectively. $L = diag\{-1\}$, $P = diag\{5\}$, $\rho_1 = \rho_2 = 3$, $g = 9.8$.

The experimental results and analysis are as follows: it can be seen from Figures 2 and 3 without fault existing only when the external disturbance, and the responses of joint position using the proposed control schemes can track the desired signals in a very short time, also for the external disturbance it owns strong robustness.

It can be seen that from Figures 4-5 the responses of joints-1 with actuator fault at 30s can be asymptotically stable and the desired signals can be tracked fast. Meanwhile, joint-2 with actuator fault at 25s, the system stability and fast tracking can also be achieved by regulation time within 3s.

The above experiment result shows that the presented scheme when the joints have a fault-free is able to guarantee the stability of the system and the external disturbance has very strong robustness. When the joint fault occurs, the proposed fault tolerant control scheme can tolerate fault, and in a shorter time to adjust fault, it enables the system to be stable and fast track the desired signal.

5. **Conclusion.** In this paper, a fault-tolerant control design scheme is proposed for the problems of actuator fault of space manipulator. Firstly, the dynamic model of the double joint space manipulator is introduced, and the model of the actuator fault is established. Secondly, the design of the sliding mode basic controller and the design of the adaptive sliding mode fault-tolerant controller are carried out for the actuator

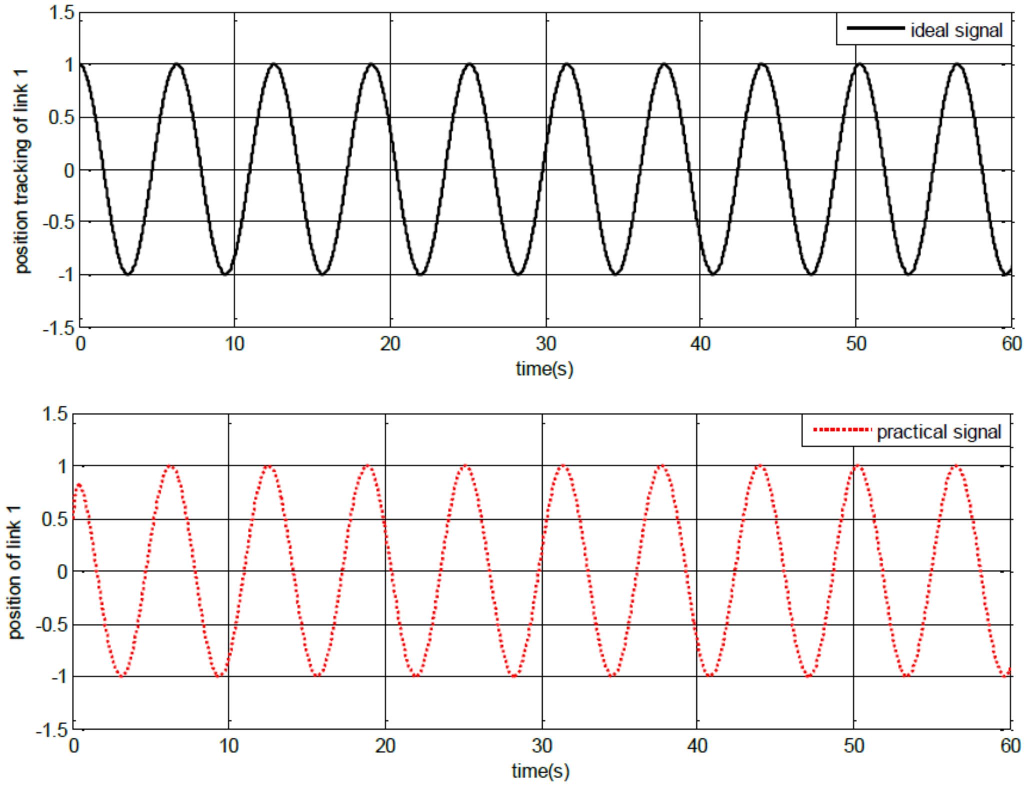

FIGURE 2. Fault free joint-1 trajectory tracking curve

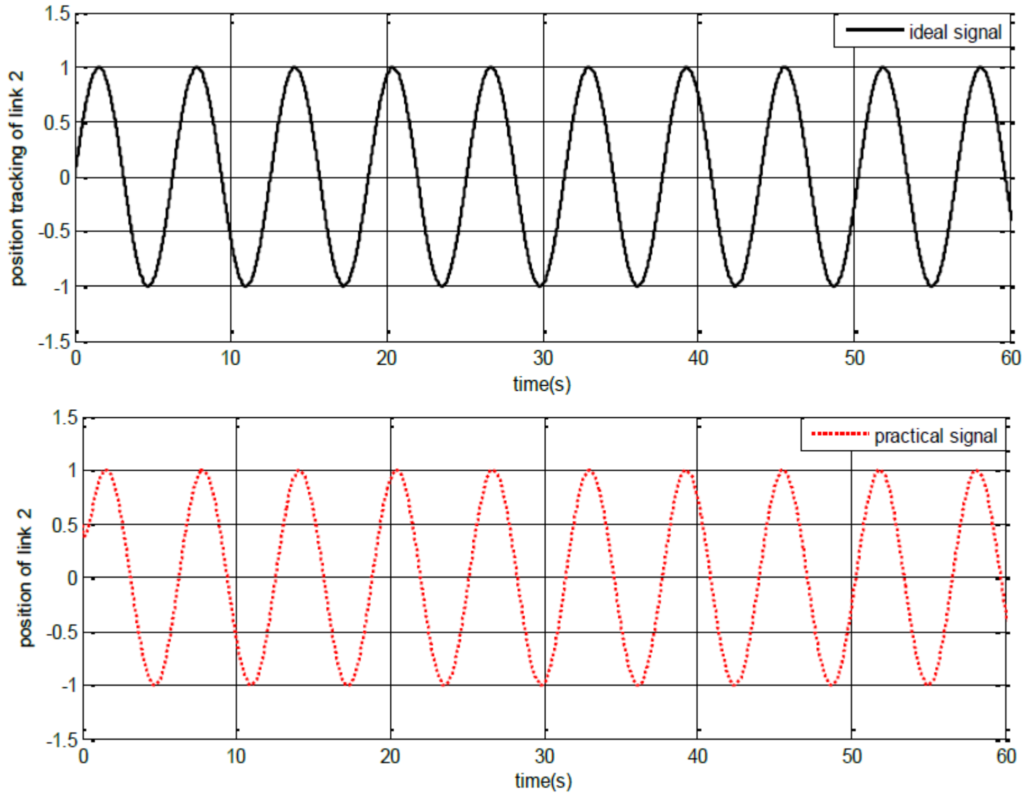

FIGURE 3. Fault free joint-2 trajectory tracking curve

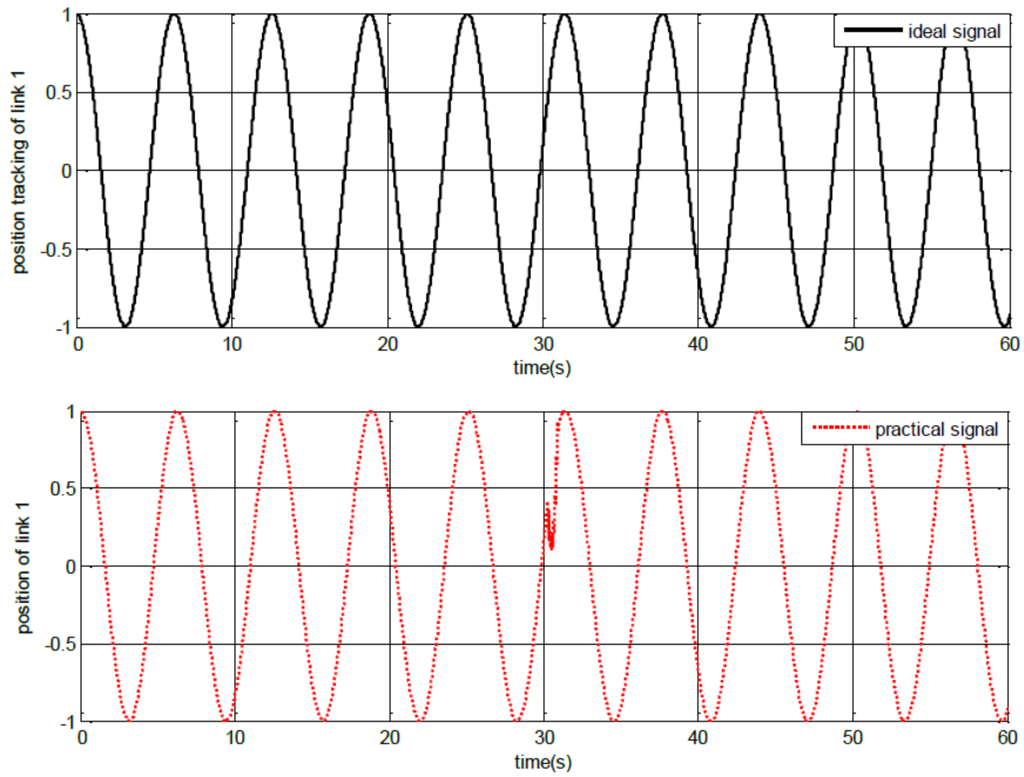

Figure 4. Fault tolerant control joint-1 trajectory tracking curve

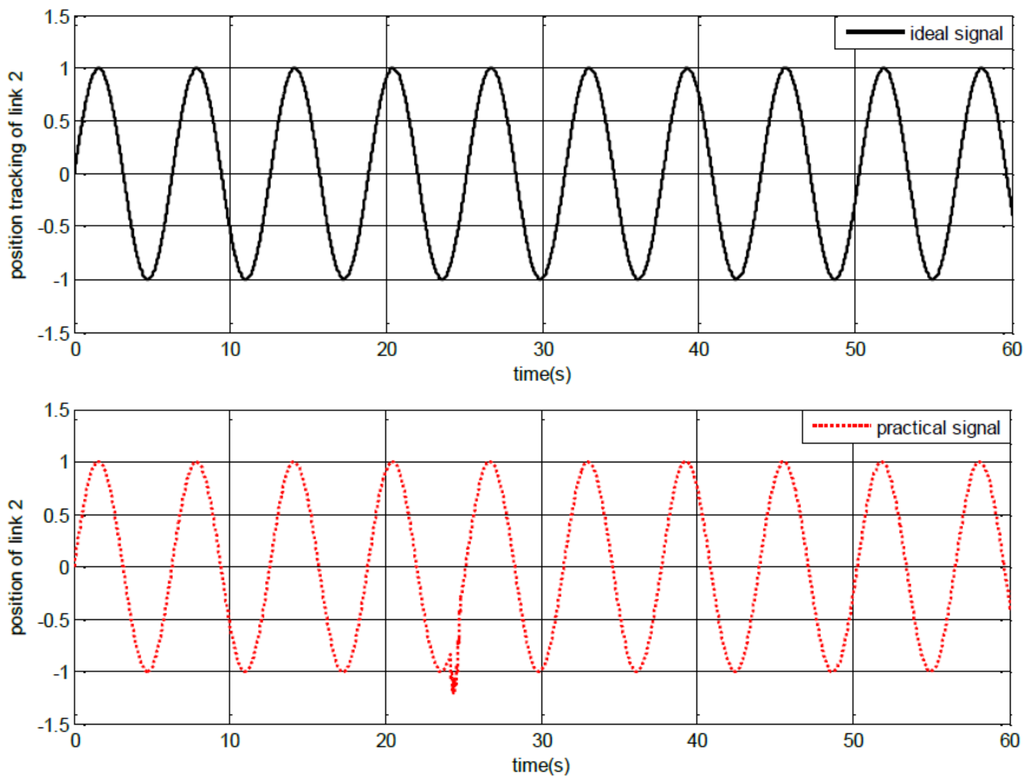

Figure 5. Fault tolerant control joint-2 trajectory tracking curve

fault. Finally, the experimental results and the analysis show that the proposed scheme is effective for actuator faults and external disturbances. We will study fault diagnosis and fault tolerance on sensor fault for manipulator in the future.

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