L2 BACK-STEPPING CONTROL OF FREE-FLOATING SPACE ROBOT WITH FLEXIBLE JOINT BASED ON NONLINEAR DISTURBANCE OBSERVER

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ABSTRACT

The trajectory tracking control problem of flexible-joint space robot with uncontrolled base and uncertain parameters is discussed. With the relationships of the linear and angular momentum conversation, the dynamic equation of the space robot system is derived by the second Lagrange method. For the singular perturbation techniques can be applied in the flexible-joint space robot, a joint-flexible compensation is used to equally increase the system's stiffness. And then, singular perturbation method is used to decompose the whole system. As for the model error caused by the uncertain parameters, using a nonlinear disturbance observer observes and compensates the dynamic model. Finally, a L2 back-stepping controller is designed to track the desired trajectory in joint space. The proposed scheme doesn't need to linearly parameterize the dynamic equation of the system, and achieve the accurate tracking of the desired trajectory. A planar flexible-joint space robot with two links is simulated to verify the effectiveness of the proposed control scheme.

1 INTRODUCTION

As we all know, space robot can complete a series of harsh and complex space work, such as the construction, repair, maintenance of the satellites, and it plays a significant role in the outer environment, which appeals many researches[1~3]. We often assume it as a rigid system, but in reality, many space robots have flexible joint, which gives a disadvantage for the whole system's control. The flexibility which exists in the space robot's joint will make motor rotor angle deviation with manipulator, and cause the inharmonious of system's motion. Therefore, researches on the flexible-joint space robot have a very important and practical significance. And it has been paid attention by many researchers [4~7]. Liu Yechao [8] proposed a singular perturbation control for a flexible-joint robot based on flexibility compensation, but it aimed at the ground robot. Xie Limin [9] used a fuzzy sliding mode control and vibration suppression scheme to control the flexible-joint space robot, but it considers the inertia parameters are accurate.

In this paper, the control problem of coordinated motion of free-floating flexible-joint space robot with unknown parameter is discussed. Based on the conservation of the momentum and momentum, using the second Lagrange method derives the system dynamics. Due to the flexibility exists in the system, a joint-flexible compensation is used to equally increase the system stiffness, and it makes the application of the singular perturbation techniques convenient. And then, using a nonlinear disturbance observer [10] to observe and compensate the model error caused by the uncertain parameters. Finally, a L2 back-stepping control scheme for system is designed to track the desired motion. The proposed scheme does not need to deal with the inertia parameters of the system, and it does not need to know the accurate inertia parameters. The effectiveness of the proposed method is demonstrated by numerical simulations.

2 DYNAMIC MODELING

The structure of a flexible-joint space robot consists of a rigid base B_0, two rigid links (B_1, B_2), and two flexible-joints, as shown in the Figure 1. O_0 coincides with the mass center of B_0. O_{Ci} is the mass center of link B_i.

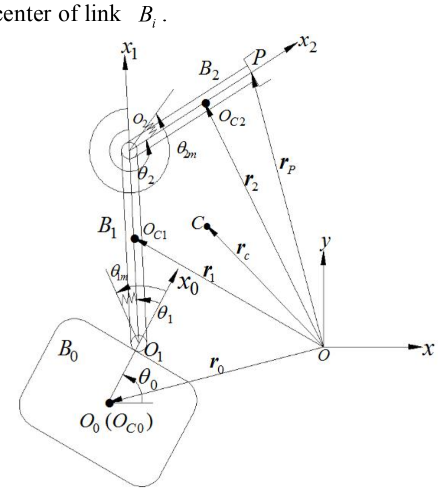

Figure 1: A flexible-joint space robot system

Assuming that both position and attitude of base for flexible-joint space robot is uncontrolled, and the whole system satisfies the laws of the linear momentum and angle momentum conservation. Therefore, the dynamic equation for the system is obtained by the Lagrange method as

$$\boldsymbol{J}_\theta \ddot{\boldsymbol{\theta}}_m + \boldsymbol{\tau}_\theta = \boldsymbol{\tau} \tag{1a}$$

$$\boldsymbol{D}(\boldsymbol{q}_3)\ddot{\boldsymbol{q}}_2 + \boldsymbol{H}(\boldsymbol{q}_3, \dot{\boldsymbol{q}}_2, \boldsymbol{\theta}_m, \dot{\boldsymbol{\theta}}_m) = \boldsymbol{\tau}_\theta \tag{1b}$$

$$\boldsymbol{\tau}_\theta = \boldsymbol{K}_m(\boldsymbol{\theta}_m - \boldsymbol{q}_2) \tag{1c}$$

Where $\boldsymbol{q}_3 = [\theta_0 \quad \theta_1 \quad \theta_2]^{\mathrm{T}}$ and $\boldsymbol{q}_2 = [\theta_1 \quad \theta_2]^{\mathrm{T}}$ are the vectors of generalized coordinate, $\boldsymbol{\theta}_m = [\theta_{m1} \quad \theta_{m2}]^{\mathrm{T}}$ is the vector of input motor's angle; $\boldsymbol{D}(\boldsymbol{q}_3) \in \boldsymbol{R}^{2\times 2}$ is system's positive and symmetric inertia matrix; $\boldsymbol{H}(\boldsymbol{q}_3, \dot{\boldsymbol{q}}_2, \boldsymbol{\theta}_m, \dot{\boldsymbol{\theta}}_m) \in \boldsymbol{R}^{2\times 1}$ represents the vector which consists of Coriolis and centrifugal forces; $\boldsymbol{\tau}_\theta \in \boldsymbol{R}^{2\times 1}$ represents the vector of input torques; $\boldsymbol{\tau} \in \boldsymbol{R}^{2\times 1}$ represents the vector of torques from motor; $\boldsymbol{K}_m = \mathrm{diag}(K_{m1} \ K_{m2})$ represents the flexible joint's stiffness matrix; $\boldsymbol{J}_\theta = \mathrm{diag}(J_{m1} \ J_{m2})$ is the motor's positive and symmetric inertia matrix.

Giving two order derivations to equation (1c), we obtain:

$$\boldsymbol{\theta}_m = \boldsymbol{K}_m^{-1}\boldsymbol{\tau}_\theta + \boldsymbol{q}_2 \Rightarrow \ddot{\boldsymbol{\theta}}_m = \boldsymbol{K}_m^{-1}\ddot{\boldsymbol{\tau}}_\theta + \ddot{\boldsymbol{q}}_2 \tag{2}$$

Substituting the equation (2) to the equation (1a), it can be expressed as

$$\boldsymbol{J}_\theta \boldsymbol{K}_m^{-1}\ddot{\boldsymbol{\tau}}_\theta + \boldsymbol{\tau}_\theta = \boldsymbol{\tau} - \boldsymbol{J}_\theta \ddot{\boldsymbol{q}}_2 \tag{3}$$

From the equation above, we can know that if the joint's stiffness $\boldsymbol{K}_m$ is big enough, we can use a small number α (where $\boldsymbol{K}_m = \boldsymbol{K}_1/\alpha^2$ and $\boldsymbol{K}_1$ has the same magnitude of the parameter matrix as $\boldsymbol{J}_\theta$) to realize the decomposition of the slow subsystem and the fast subsystem based on singular perturbation method. But the stiffness on the joints is too small to use it. Therefore, a kind of flexible compensator is used to equally improve joint's stiffness.

Define the control law of driving motor as

$$\boldsymbol{\tau} = \boldsymbol{K}_z\boldsymbol{\tau}_z + \boldsymbol{\tau}_c \tag{4}$$

Where $\boldsymbol{K}_z \in \boldsymbol{R}^{2\times 2}$ is a undetermined positive symmetric parameter matrix; $\boldsymbol{\tau}_z \in \boldsymbol{R}^{2\times 1}$ is a new controller; $\boldsymbol{\tau}_c \in \boldsymbol{R}^{2\times 1}$ is a joint flexible compensator to be introduced.

Substituting the equation (4) to the equation (3), we can obtain

$$\boldsymbol{J}_\theta \boldsymbol{K}_m^{-1}\ddot{\boldsymbol{\tau}}_\theta + \boldsymbol{\tau}_\theta = \boldsymbol{K}_z(\boldsymbol{\tau}_z - \boldsymbol{K}_z^{-1}\boldsymbol{J}_\theta \ddot{\boldsymbol{q}}_2) + \boldsymbol{\tau}_c \tag{5}$$

Where $\boldsymbol{K}_c \in \boldsymbol{R}^{2\times 2}$ is a positive and symmetric flexible compensation matrix, and $\boldsymbol{K}_z = \boldsymbol{I} + \boldsymbol{K}_c$, here $\boldsymbol{I} \in \boldsymbol{R}^{2\times 2}$ is a unit matrix.

Define flexible compensator $\boldsymbol{\tau}_c$ as

$$\boldsymbol{\tau}_c = -\boldsymbol{K}_c\boldsymbol{\tau} \tag{6}$$

Substituting the equation (4) to the equation (3), we can obtain

$$\boldsymbol{J}_\theta(\boldsymbol{K}_m\boldsymbol{K}_z)^{-1}\ddot{\boldsymbol{\tau}}_\theta + \boldsymbol{\tau}_\theta = \boldsymbol{\tau}_z - \boldsymbol{K}_z^{-1}\boldsymbol{J}_\theta \ddot{\boldsymbol{q}}_2 \tag{7}$$

Comparing the equation (3) with equation (7), we can find that if we properly choose the compensation matrix $\boldsymbol{K}_z$ (also $\boldsymbol{K}_c$), we can equally improve the system joint's stiffness, which simplifies the application of singular perturbation method.

According to the system described as equation (7), based on the singular perturbation method, we can divide the controller $\boldsymbol{\tau}_z$ into two sub-controllers:

$$\boldsymbol{\tau}_z = \boldsymbol{\tau}_{zs} + \boldsymbol{\tau}_{zf} \tag{8}$$

Where $\boldsymbol{\tau}_{zs} \in \boldsymbol{R}^{2\times 1}$ is the controller for slow subsystem; $\boldsymbol{\tau}_{zf} \in \boldsymbol{R}^{2\times 1}$ is the controller for fast subsystem.

3 DESIGN OF FAST SUBSYSTEM

According to the method proposed above, based on singular perturbation, we can define a very small number α, which satisfies $\boldsymbol{K}_m\boldsymbol{K}_z = \boldsymbol{K}_a/\alpha^2$, and $\boldsymbol{K}_a \in \boldsymbol{R}^{2\times 2}$ has a same magnitude of the parameter matrix as $\boldsymbol{J}_\theta$.

Combining with equation (8), equation (7) can be expressed as below

$$\alpha^2\boldsymbol{J}_\theta\ddot{\boldsymbol{\tau}}_\theta + \boldsymbol{K}_a\boldsymbol{\tau}_\theta = \boldsymbol{K}_a(\boldsymbol{\tau}_{zs} - \boldsymbol{K}_z^{-1}\boldsymbol{J}_\theta\ddot{\boldsymbol{\theta}}) + \boldsymbol{K}_a\boldsymbol{\tau}_{zf} \tag{9}$$

In order to simplify the control of equation (9), we can design the fast subsystem controller as follow

$$\boldsymbol{\tau}_{zf} = -\alpha\boldsymbol{K}_s\dot{\boldsymbol{\tau}}_\theta \tag{10}$$

Substituting the equation (10) to equation (9), we can obtain the dynamic model of fast subsystem as

$$\alpha^2\boldsymbol{J}_\theta\ddot{\boldsymbol{\tau}}_\theta + \alpha\boldsymbol{K}_a\boldsymbol{K}_s\dot{\boldsymbol{\tau}}_\theta + \boldsymbol{K}_a\boldsymbol{\tau}_\theta = \boldsymbol{K}_a(\boldsymbol{\tau}_{zs} - \boldsymbol{K}_z^{-1}\boldsymbol{J}_\theta\ddot{\boldsymbol{\theta}}) \tag{11}$$

Where the choice of $\boldsymbol{K}_s \in \boldsymbol{R}^{2\times 2}$ should guarantee the stability of equation (11).

As the number α is very small, if $\alpha \to 0$, we know that $\boldsymbol{K}_m\boldsymbol{K}_z \to \infty$, which means that system's joints can be regarded as rigid joints. And then, we can approximate that $\boldsymbol{\theta}_m \approx \boldsymbol{q}_2, \dot{\boldsymbol{\theta}}_m \approx \dot{\boldsymbol{q}}_2, \ddot{\boldsymbol{\theta}}_m \approx \ddot{\boldsymbol{q}}_2$, and get the dynamic model of slow subsystem:

$$\overline{\boldsymbol{D}}(\boldsymbol{q}_3)\ddot{\boldsymbol{q}}_2 + \overline{\boldsymbol{H}}(\boldsymbol{q}_3, \dot{\boldsymbol{q}}_2) = \boldsymbol{\tau}_{zs} \tag{12}$$

Where $\overline{\boldsymbol{D}}(\boldsymbol{q}_3) = \boldsymbol{D}(\boldsymbol{q}_3) + \boldsymbol{K}_z^{-1}\boldsymbol{J}_m$ is slow subsystem's inertia matrix; $\overline{\boldsymbol{H}}(\boldsymbol{q}_3, \dot{\boldsymbol{q}}_2) \in \boldsymbol{R}^{2\times 1}$ is the vector while $\boldsymbol{\theta}_m \approx \boldsymbol{q}_2, \dot{\boldsymbol{\theta}}_m \approx \dot{\boldsymbol{q}}_2, \ddot{\boldsymbol{\theta}}_m \approx \ddot{\boldsymbol{q}}_2$ is substituted into the vector of $\boldsymbol{H}_{2\theta}(\boldsymbol{q}_3, \dot{\boldsymbol{q}}_2, \boldsymbol{\theta}_m, \dot{\boldsymbol{\theta}}_m)$.

As $\boldsymbol{K}_z^{-1}\boldsymbol{J}_m$ is also a positive and symmetric matrix, $\overline{\boldsymbol{D}}(\boldsymbol{q}_3)$ still has the characteristic of positive and symmetric; and the matrix $\dot{\overline{\boldsymbol{D}}}(\boldsymbol{q}_3) - 2\overline{\boldsymbol{H}}(\boldsymbol{q}_3, \dot{\boldsymbol{q}}_2)$ is still skew-symmetric.

4 DESIGN OF SLOW SUBSYSTEM

As the unknown inertia parameter exists in the system, the real model should be presented as follow

$$\hat{\bar{D}}(q_3)\ddot{q}_2 + \hat{\bar{H}}(q_3,\dot{q}_2) = \tau_{zs} + d \qquad (13)$$

Where $\hat{\bar{D}}(q_3) \in R^{2\times2}$ and $\hat{\bar{H}}(q_3,\dot{q}_2) \in R^{2\times1}$ are the estimated matrix of $\bar{D}(q_3)$ and $\bar{H}(q_3,\dot{q}_2)$, $d \in R^{2\times1}$ is the model error, it can be seen as system disturbance and satisfied

$$d = -\left[\bar{D}(q_3) - \hat{\bar{D}}(q_3)\right]\ddot{q}_2 - \left[\bar{H}(q_3,\dot{q}_2) - \hat{\bar{H}}(q_3,\dot{q}_2)\right]$$

To ensure the accuracy of the whole system's motion, eliminating the disturbance d is the primary problem. Therefore, a nonlinear disturbance observer is used to approximately observe d , and gets high accuracy value to eliminate the model error before the design of controller, which reduces the adverse impact on the system.

4.1 Design of Nonlinear Disturbance Observe

Assuming that the change rate of disturbance d satisfies $\|\dot{d}\| \le \beta_d$, here β_d is a positive constant. Combining with system's model of equation (13), using following nonlinear disturbance observer :

$$\dot{\hat{d}} = L(q_3,\dot{q}_2)\left[\hat{\bar{D}}(q_3)\ddot{q}_2 + \hat{\bar{H}}(q_3,\dot{q}_2) - \tau_{zs}\right] - L(q_3,\dot{q}_2)\hat{d} \qquad (14)$$

Where $\hat{d}$ is the estimated value of system's disturbance d ; $L(q_3,\dot{q}_2)$ is a gain matrix.

Define e_d as observe error:

$$e_d = d - \hat{d} \qquad (15)$$

According to the reference [11], we know that the observe error $e_d(\infty)$ will asymptotically converge to a closed sphere with a finite radius, and the radius satisfies the following condition:

$$\beta = \max\left\{\frac{\beta_d}{L_i(q_3,\dot{q}_2)}, i = 1,2\right\} \qquad (16)$$

As for the unknown positive constant β_d , we always can choose a matrix $L(q_3,\dot{q}_2)$ to satisfy the following equation:

$$\|e_d\| < \|\beta_d\| \qquad (17)$$

Here $\beta = [\beta_{1d} \quad \beta_{2d}]^{\mathrm{T}}$. The detail process of proof can be found in the literature [12].

Through the compensation of the nonlinear disturbance observer, equation (13) can be written as

$$\hat{\bar{D}}(q_3)\ddot{q}_2 + \hat{\bar{H}}(q_3,\dot{q}_2) = \tau_{sD} + e_d \qquad (18)$$

Here τ_{sD} is the needed torque after the compensation of nonlinear disturbance observer and it satisfies $\tau_{zs} = \tau_{sD} - \hat{d}$.

The dynamic equation (18) of the slow subsystem can also be rewritten as

$$\ddot{q}_2 = \hat{\bar{D}}(q_3)^{-1}\left[\tau_{sD} + e_d - \hat{\bar{H}}(q_3,\dot{q}_2)\right] \qquad (19)$$

Obviously, it is a second-order MIMO nonlinear system.

4.2 Design of L2 Back-stepping Controller

The main idea of L_2 disturbance suppression is defining a performance index J_t related with system's disturbance signal e_d and evaluation signal z_P , and designing a control input τ to make J_t as small as possible, which will make the whole system asymptotically stable. It is equivalent to solve a dissipative inequality problem based on the theory of *Lyapunov* stability, which is

$$H = \dot{V} - \frac{1}{2}(\gamma^2\|e_d\|^2 - \|z_P\|^2) \qquad (20)$$

Here γ is an interference suppression level factor; V is a positive *Lyapunov* function; z_P is an evaluation function, and it can be set as the linear relationship with system's motion error, which is $z_P = pe$.

From the equation (17), we know that $\|e_d\| < \|\beta_d\|$, and we can use the method of L_2 disturbance suppression to eliminate the disturbance, and ensure system's accurate tracking.

Step 1 Assuming the desire trajectories of the joints are:

$$q_d = [\theta_{1d} \quad \theta_{2d}]^{\mathrm{T}} \qquad (21)$$

Where θ_{1d}、θ_{2d} represents θ_1、θ_2 desired trajectory respectively.

The tracking error e between q_2 and q_d is:

$$e = q_2 - q_d \qquad (22)$$

Differentiating the equation (22), we can get the derivation of tracking error e :

$$\dot{e} = \dot{q}_2 - \dot{q}_d \qquad (23)$$

Define the intermediate dummy variable z_1 as:

$$z_1 = \dot{e} + c_1 e \qquad (24)$$

Here $c_1 \in R^{2\times2}$ is a symmetric and positive constant matrix.

Consider the *Lyapunov* function V_1 as

$$V_1 = \frac{1}{2}e^{\mathrm{T}}e \qquad (25)$$

Differentiating equation (25), we can obtain

$$\dot{V}_1 = e^{\mathrm{T}}\dot{e} = e^{\mathrm{T}}z_1 - e^{\mathrm{T}}c_1 e \qquad (26)$$

From the equation (26), we know that if $z_1 = 0$, and then $\dot{V}_1$ can be regarded as the system trajectory error vector of the two type function, and it satisfies $\dot{V}_1 \le 0$. Therefore, a next step design is needed to make $z_1 = 0$.

Step 2 Differentiating the equation (24)

$$\dot{z}_1 = \ddot{q}_2 - \ddot{q}_d + c_1\dot{e} \qquad (27)$$

Substituting the equation (19) to (27), we can obtain

$$\dot{\boldsymbol{z}}_1 = \hat{\bar{\boldsymbol{D}}}(\boldsymbol{q}_3)^{-1}\left[\boldsymbol{\tau}_{sD} + \boldsymbol{e}_d - \hat{\bar{\boldsymbol{H}}}(\boldsymbol{q}_3,\dot{\boldsymbol{q}}_2)\right] - \ddot{\boldsymbol{q}}_{\mathrm{d}} + \boldsymbol{c}_1\boldsymbol{e} \tag{28}$$

Consider the *Lyapunov* function V_2 as

$$V_2 = V_1 + \frac{1}{2}z_1^{\mathrm{T}}\hat{\bar{\boldsymbol{D}}}(\boldsymbol{q}_3)z_1 \tag{29}$$

Differentiating the equation (22), and combining equation (26) and (28), we can obtain

$$\begin{aligned}\dot{V}_2 &= \dot{V}_1 + z_1^{\mathrm{T}}\hat{\bar{\boldsymbol{D}}}(\boldsymbol{q}_3)\dot{z}_1 + \frac{1}{2}z_1^{\mathrm{T}}\dot{\hat{\bar{\boldsymbol{D}}}}(\boldsymbol{q}_3)z_1 \\ &= \boldsymbol{z}_1^{\mathrm{T}}\left\{\boldsymbol{\tau}_{sD} + \boldsymbol{e}_d - \hat{\bar{\boldsymbol{H}}}(\boldsymbol{q}_3,\dot{\boldsymbol{q}}_2) - \hat{\bar{\boldsymbol{D}}}(\boldsymbol{q}_3)\ddot{\boldsymbol{q}}_{\mathrm{d}} + \hat{\bar{\boldsymbol{D}}}(\boldsymbol{q}_3)\boldsymbol{c}_1\boldsymbol{e}\right\} \\ &\quad + \frac{1}{2}\boldsymbol{z}_1^{\mathrm{T}}\dot{\hat{\bar{\boldsymbol{D}}}}(\boldsymbol{q}_3)\boldsymbol{z}_1 + \boldsymbol{e}^{\mathrm{T}}\boldsymbol{z}_1 - \boldsymbol{e}^{\mathrm{T}}\boldsymbol{c}_1\boldsymbol{e}\end{aligned} \tag{30}$$

According to the equation (30), we can design the control law as follow

$$\begin{aligned}\boldsymbol{\tau}_{sD} &= \hat{\bar{\boldsymbol{H}}}(\boldsymbol{q}_3,\dot{\boldsymbol{q}}_2) + \hat{\bar{\boldsymbol{D}}}(\boldsymbol{q}_3)\ddot{\boldsymbol{q}}_{\mathrm{d}} - \hat{\bar{\boldsymbol{D}}}(\boldsymbol{q}_3)\boldsymbol{c}_1\boldsymbol{e} \\ &\quad - \boldsymbol{e} - \frac{1}{\gamma^2}\boldsymbol{z}_1 - \hat{\bar{\boldsymbol{H}}}(\boldsymbol{q}_3,\dot{\boldsymbol{q}}_2)\boldsymbol{z}_1\end{aligned} \tag{31}$$

Substituting the equation (31) to (30), it can be expressed as

$$\dot{V}_2 = -\boldsymbol{e}^{\mathrm{T}}\boldsymbol{c}_1\boldsymbol{e} + \boldsymbol{z}_1^{\mathrm{T}}\left(\boldsymbol{e}_d - \frac{1}{\gamma^2}\boldsymbol{z}_1\right) \tag{32}$$

Discussing the L_2 disturbance suppression of system, that is

$$\begin{aligned}H &= \dot{V}_2 - \frac{1}{2}(\gamma^2\|\boldsymbol{e}_d\|^2 - \|z_P\|^2) \\ &= -\boldsymbol{e}^{\mathrm{T}}\boldsymbol{c}_1\boldsymbol{e} + \boldsymbol{z}_1^{\mathrm{T}}\boldsymbol{e}_d - \frac{1}{\gamma^2}\boldsymbol{z}_1^{\mathrm{T}}\boldsymbol{z}_1 - \frac{1}{2}(\gamma^2\|\boldsymbol{e}_d\|^2 - p^2\|\boldsymbol{e}\|^2) \\ &\le -(\boldsymbol{c}_1 - p^2)\|\boldsymbol{e}\|^2 - \frac{1}{2\gamma^2}\boldsymbol{z}_1^{\mathrm{T}}\boldsymbol{z}_1 \\ &\le 0\end{aligned} \tag{33}$$

From the above equation, we know that system's gain is less than γ.

5 EXPERIMENTAL SIMULATION

In order to prove the performance of the proposed controller, a simulation is carried out on a planar flexible-joint space robot with two links, as shown in Fig.1. The actual parameters of system are as follows:

$m_0 = 60.0\text{kg}$, L_0=1.5 m, J_0=30.0kg • m^2,
m_1=6.0 kg, L_1=3.0 m, a_1=1.5 m, a_2=1.5m,
J_1=3kg • m^2, m_2=6.0 kg, L_2=3.0 m,
J_2=3kg • m^2, J_{m1}=0.08kg • m^2, J_{m2}=0.08kg • m^2。

The estimated values of system are as follows:

$\hat{m}_0 = 50.0\text{kg}$, $\hat{L}_0 = 1.5$ m, $\hat{J}_0 = 25.0$kg • m^2,
$\hat{m}_1 = 6.0$ kg, $\hat{L}_1 = 3.0$ m, $\hat{a}_1 = 1.5$ m, $\hat{J}_1 = 3$kg • m^2,
$\hat{m}_2$=5.0 kg, $\hat{L}_2$=2.5 m, $\hat{a}_2$=1.5m, $\hat{J}_2$=3kg • m^2。

The desired trajectories of the arm joints are:

$$\theta_{1d} = \cos(0.2\pi t)\,,\ \theta_{2d} = \sin(0.2\pi t)\ .$$

And the unit is radian.

The parameters used in the simulation are:

$$\boldsymbol{c}_1 = \mathrm{diag}(1.2,1.2),\quad \gamma^2 = 0.04\,.$$

The initial states of the space robot system are as follows:

$$\theta_0 = 0.2,\quad \theta_1 = 0.1,\quad \theta_2 = 0.5$$

And the unit is radian. The time taken for the simulation is 10.0 seconds.

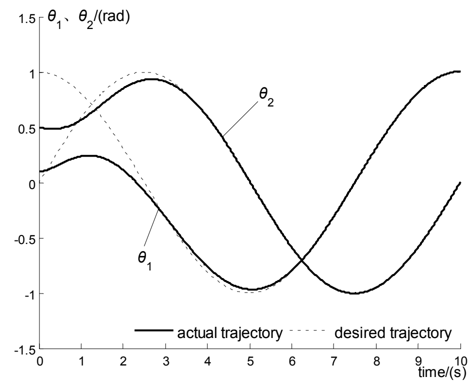

Figure 2: Tracking trajectory of the arm joints

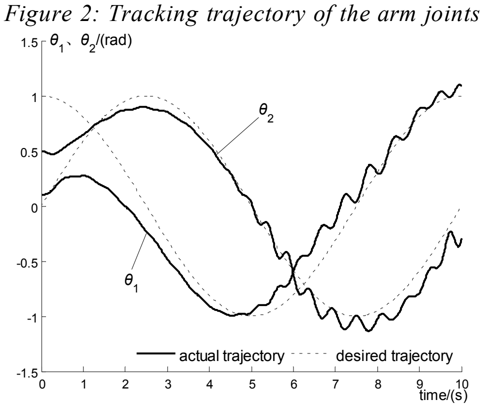

Figure 3: Tracking trajectory of the arm joints (without flexible compensator)

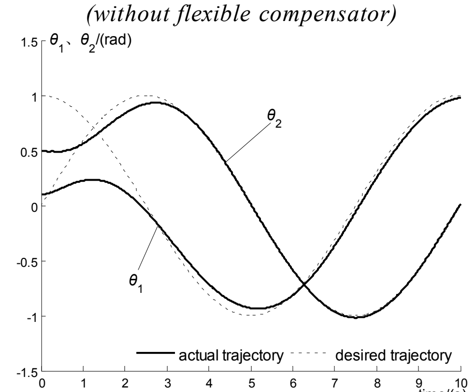

Figure 4: Tracking trajectory of the arm joints (without disturbance observer)

Fig.2 shows the trajectory tracking of system's arm joints under the proposed controller. Fig.3 and Fig.4 show the trajectory tracking of system's arm joints while controller is without flexible compensator or nonlinear disturbance observe respectively. Comparing these 3 figures, we can conclude that only combining with the flexible compensator and nonlinear disturbance observe can the system realize the stable and accurate tracking.

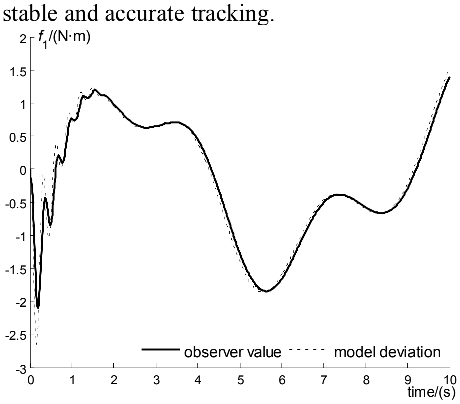

Figure 5: The observer value and the real model deviation (1)

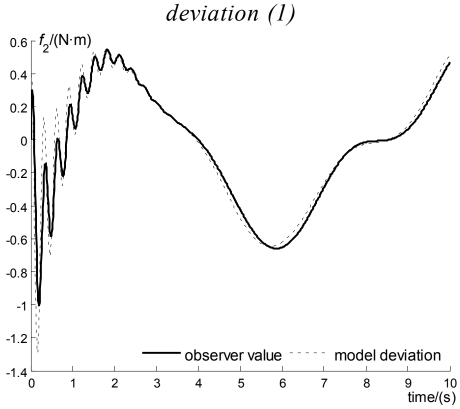

Figure 6: The observer value and the real model deviation (2)

Fig.5 and Fig.6 show the observation of the nonlinear disturbance observer and the system's dynamic model deviation. From these two figures, we can find that the observer value can change with the model deviation, which shows the effectiveness of the nonlinear disturbance observer.

6 CONCLUSION

The paper discusses a L2 back-stepping control scheme based on the disturbance observe and flexible compensator for the flexible-joint space robot with uncontrolled base's position and attitude. With the observation and compensation of the nonlinear disturbance observer, the system's model error is eliminated, and using a L2 back-stepping controller realizes the accurate tracking of system and ensures the whole system's stability. The proposed scheme does not need to linearly parameterize the inertia parameters of the system, and it does not need to know the accurate inertia parameters. The simulation verifies the feasibility and efficiency of the proposed control scheme.

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