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# Speed Trajectory Tracking Control for Free-Floating Space Robot with Uncertain Inertial Parameters

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**Abstract.** A speed trajectory tracking control (STTC) approach is proposed to optimize the end-effector trajectory tracking control for free-floating space robot (FFSR) with uncertain inertial parameters, where two stages controller are designed by the state dependent Riccati equation (SDRE). Firstly, the first-stage SDRE nominal optimization controller is designed by using the nominal system model. Next, by analyzing the error transfer process resulting from uncertain parameters under the nominal control law, the second-stage SDRE compensated controller is designed by the state dependent matrix (SDM) of the system state errors. Then, the optimization tracking control for the FFSR with uncertain inertial parameters is achieved by combining the first-stage SDRE nominal optimization controller and the second-stage SDRE compensated controller. Finally, numerical simulations are given to demonstrate the proposed approach which satisfies the precision of the tracking error and the optimization requirement of the input torque.

## 1. Introduction

With the development of human space activities, space robots has broad application prospect because of their ability to perform tasks in space environments that are too risky for humans. Space robots can be divided into two categories according to the base controlled or not, free-floating space robot (FFSR) and free-flying space robot. FFSR has the characteristics of the strong coupling, the dynamics of the singular, certain model parameters, and etc. FFSR has good orbit ability because it does not need additional energy to control the posture of the base, then FFSR has received much more attention in space robots field. Many researchers have given much attention on FFSR and obtained many excellent results, where the end-effector trajectory tracking control is the important problem to guarantee the space robot to accomplish orbit tasks <sup>[1-7]</sup>.

For the trajectory tracking control problem of FFSR, Umetani<sup>[1]</sup> proposed a generalized Jacobian matrix to achieve decomposition speed control by constructing the kinematics model of FFSR. Papadopoulos<sup>[2]</sup> constructed the dynamics model of FFSR and proposed the feedback control method based on the control torque. However, the control methods of [1] and [2] require a high degree of the model and the uncertainty of the system parameters is not considered.

In order to solve the uncertain parameters problem in the trajectory tracking control, Gu<sup>[3]</sup> *et al.* proposed an extended manipulator modeling approach and a nominal form extended adaptive control approach, but these approaches were very difficult to practical application due to the acceleration of the spacecraft in the system model. Because the reference trajectory cannot be achieved in the joint space by the dynamic coupling, the extended modeling approach for manipulator was modified in [7] by the fixed parameters approach of the nominal controller, but the approach required the acceleration of the manipulator joint.



The state dependent Riccati equation (SDRE) technique is an effective design method of nonlinear feedback controller of nonlinear systems<sup>[10]</sup>, and it has received considerable attention in the past two decades<sup>[11-13]</sup>. SDRE linearizes the nonlinear system by the state dependent coefficient matrix (SDC), and derives the feedback control law by solving the algebra Riccati equation (ARE). SDRE has been broadly applied in many fields including the satellite attitude control<sup>[14]</sup>, the under-water vehicle<sup>[15]</sup>, the tank control<sup>[16]</sup>, and the robotic manipulator<sup>[17]</sup>.

In the current paper, based on two stages controller with SDRE, a STTC approach is proposed to optimize the end-effector trajectory tracking control for FFSR with uncertain inertial parameters. The first-stage SDRE nominal optimization controller is designed according to the nominal system model. Considering uncertain parameters under the nominal control law, the second-stage SDRE compensated controller is designed by the SDC of the system state errors by analyzing the error transfer process. Then, the optimization tracking control for the FFSR with uncertain inertial parameters is achieved by the two stages controller. Furthermore, numerical simulations are given to demonstrate the effectiveness of the proposed approach.

## 2. Infinite-time SDRE tracking controller

Consider the nonlinear system with affine input as

$$\begin{aligned}\dot{x} &= f(x) + g(x)u \\ y &= h(x)\end{aligned}\quad (1)$$

where  $x \in R^n$ ,  $u \in R^m$ ,  $f(x) \in C^k$ ,  $g(x) \in C^k$ ,  $k \geq 1$ , and  $f(0) = 0$ ,  $g(x) \neq 0$ ,  $\forall x$ . Then, (1) can be rewritten as State Dependent Coefficient (SDC) form

$$\begin{aligned}\dot{x}(t) &= A(x)x(t) + B(x)u(t), x(0) = x_0 \\ y(t) &= C(x)x(t)\end{aligned}\quad (2)$$

where  $f(x) = A(x)x(t)$ ,  $B(x) = g(x)$  and  $h(x) = C(x)x$ , and  $A(x), B(x), C(x)$  are SDC matrices. Generally speaking, there are not only one group SDC matrices.

Let  $y_r(t)$  is the expected output trajectory, then the infinite-time trajectory tracking index as

$$\min J = \frac{1}{2} \int_0^\infty e^T Q(x) e + u^T R(x) u dt \quad (3)$$

where  $e(t) = y_r(t) - C(x)x(t)$ ,  $Q(x)$  and  $R(x)$  are positive definite symmetric matrices. And

$$u = -R^{-1}(x)B^T(x)[P(x)x - S(x)] \quad (4)$$

$$S(x) = -\left([A(x) - B(x)R^{-1}B^T(x)P(x)]^T\right)^{-1} C(x)^T Q y_r(t) \quad (5)$$

where  $P(x)$  satisfies the algebraic Riccati equation

$$C^T(x)Q(x)C(x) + P(x)A(x) + A^T(x)P(x) - P(x)B(x)R(x)^{-1}B(x)^T P(x) = 0 \quad (6)$$

## 3. SDRE based two stages tracking controller

In this section, the nominal optimization controller is designed according to the nominal dynamic model of the space robot. Next, the state errors between the practical system and the nominal system can be obtained, and then the state error equation is presented. Then, the compensated controller is designed to achieve the trajectory tracking. Figure 1 gives the system schematic of the controller.

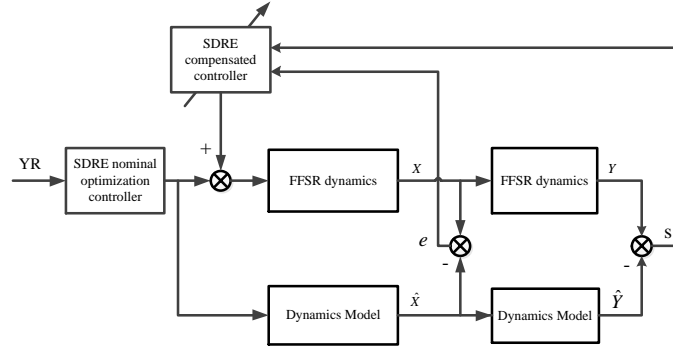


Figure 1. The system schematic of the controller

### 3.1. The kinematics and dynamic model of space robots

The kinematics and dynamic model of  $n$  degree-of-freedom space robots can be described as

$$\begin{aligned} M(q_b, q_m) \ddot{q}_m + L(q_b, q_m, \dot{q}_b, \dot{q}_m) \dot{q}_m &= \tau \\ \dot{y} &= J^*(q_b, q_m) \dot{q}_m \end{aligned} \quad (7)$$

where  $q_b \in R^{3 \times 1}$  represents the base angles,  $q_m \in R^{n \times 1}$  is the manipulator angles,  $\tau \in R^{n \times 1}$  represents the manipulator torque,  $y \in R^{n \times n}$  is the end-effector trajectory,  $M = M(q_b, q_m) \in R^{n \times n}$  represents a symmetric definite inertial matrix,  $L(q_b, q_m, \dot{q}_b, \dot{q}_m) \in R^{n \times n}$  is the matrix consists of terms due to the centrifugal and Coriolis force,  $\dot{M} - 2L$  is a anti-symmetric matrix, and  $J^*(q_b, q_m) \in R^{n \times n}$  represents a generalized Jacobian matrix.

When the parameters of the system are uncertain, (7) can be rewritten as

$$\begin{aligned} \hat{M}(q_b, q_m) \ddot{q}_m + \hat{L}(q_b, q_m, \dot{q}_b, \dot{q}_m) \dot{q}_m + \tilde{M}(q_b, q_m) \ddot{q}_m + \tilde{L}(q_b, q_m, \dot{q}_b, \dot{q}_m) \dot{q}_m &= \tau \\ \dot{y} &= \hat{J}^*(q_b, q_m) \dot{q}_m + \tilde{J}^*(q_b, q_m) \dot{q}_m \end{aligned} \quad (8)$$

where

$$\begin{aligned} M(q_b, q_m) &= \hat{M}(q_b, q_m) + \tilde{M}(q_b, q_m) \\ L(q_b, q_m, \dot{q}_b, \dot{q}_m) &= \hat{L}(q_b, q_m, \dot{q}_b, \dot{q}_m) + \tilde{L}(q_b, q_m, \dot{q}_b, \dot{q}_m) \\ J^*(q_b, q_m) &= \hat{J}^*(q_b, q_m) + \tilde{J}^*(q_b, q_m) \end{aligned}$$

and  $\hat{M}(q_b, q_m)$  represents the nominal inertial matrix,  $\tilde{M}(q_b, q_m)$  is the inertial error matrix due to the uncertain parameters,  $\hat{L}(q_b, q_m, \dot{q}_b, \dot{q}_m)$  is the matrix consists of terms due to the centrifugal and Coriolis force with uncertain parameters,  $\hat{J}^*(q_b, q_m)$  is the nominal generalized Jacobian matrix, and  $\tilde{J}^*(q_b, q_m)$  represents the generalized Jacobian matrix errors due to the uncertain parameters.

### 3.2. The SDRE-based end-effector speed trajectory tracking controller

Let  $\tau_r$  represents the output of the nominal controller and  $\tau_d$  is the equivalent compensated of the control torque of the modeling error due to the uncertain parameters, that is

$$\begin{aligned} \tau_d &= \tilde{M}(q_b, q_m) \ddot{q}_m + \tilde{L}(q_b, q_m, \dot{q}_b, \dot{q}_m) \dot{q}_m \\ \tau_r &= \hat{M}(q_b, q_m) \ddot{q}_m + \hat{L}(q_b, q_m, \dot{q}_b, \dot{q}_m) \dot{q}_m \end{aligned}$$

When the input torque of the FFSR system is  $\tau = \tau_r + \tau_d$ , the dynamic model with uncertain parameters is

$$\begin{aligned}\ddot{q}_m &= -\hat{M}(q_b, q_m)^{-1} \hat{L}(q_b, q_m, \dot{q}_b, \dot{q}_m) \dot{q}_m + \hat{M}(q_b, q_m)^{-1} (\tau_r + \tau_d) \\ \dot{y} &= \hat{J}^*(q_b, q_m) \dot{q}_m + \tilde{J}^*(q_b, q_m) \dot{q}_m\end{aligned}\quad (9)$$

Let the state variable of the system is  $X = \dot{q}_m$  and the output variable is  $Y = \dot{y}$ , then (9) is

$$\begin{aligned}\dot{X} &= f(x) + g(x)(\tau_r + \tau_d) \\ Y &= J^*(q_b, q_m)X\end{aligned}\quad (10)$$

where  $f(x) = -\hat{M}^{-1} \hat{L}X$ ,  $g(x) = \hat{M}^{-1}$ . When  $X = 0$ , one has  $f(0) = 0$ ,  $g(0) \neq 0$ . It is assumed that  $q_b$  and  $q_m$  can be real-time obtained, then

$$\begin{aligned}\dot{X} &= \hat{A}(x)X + \hat{B}(x)(\tau_r + \tau_d) \\ Y &= C(x)X\end{aligned}\quad (11)$$

where  $\hat{A}(x) = -\hat{M}^{-1} \hat{L}$ ,  $\hat{B}(x) = \hat{M}^{-1}$ ,  $C(x) = J^*$ .

When  $\tau_d = 0$ , i.e. there is no uncertain parameter, then the nominal system is

$$\begin{aligned}\dot{\hat{X}} &= \hat{A}(\hat{x})\hat{X} + \hat{B}(\hat{x})\tau_r \\ \hat{Y} &= \hat{C}(\hat{x})\hat{X}\end{aligned}\quad (12)$$

By (4) and (5), one can see that the control law

$$\tau_r = -R_r^{-1}(\hat{x})\hat{B}^T(\hat{x})\{P_r(\hat{x})\hat{X} - l_r(\hat{x})\}\quad (13)$$

with

$$l_r(\hat{x}) = -\left(\left[\hat{A}(\hat{x}) - \hat{B}(\hat{x})R_r^{-1}\hat{B}^T(\hat{x})P_r(\hat{x})\right]^T\right)^{-1} \hat{C}(\hat{x})^T Q_r Y_r(t)$$

satisfies

$$\min J = \frac{1}{2} \int_0^\infty E_1^T Q_r(x) E_1 + \tau_r^T R_r(x) \tau_r dt\quad (14)$$

where  $E_1 = Y_r - \hat{Y}$ ,  $Y_r(t)$  is the expected end-effector speed trajectory, and  $P_r(\hat{X})$  satisfies

$$\hat{C}^T(\hat{x})Q_r(\hat{x})\hat{C}(\hat{x}) + P(\hat{x})\hat{A}(\hat{x}) + \hat{A}^T(\hat{x})P_r(\hat{x}) - P_r(\hat{x})\hat{B}(\hat{x})R_r(\hat{x})^{-1}\hat{B}(\hat{x})^T P_r(\hat{x}) = 0\quad (15)$$

Consider that  $\hat{M}(q_b, q_m)$  is symmetric, one can see that  $\hat{B}(\hat{x}) = \hat{M}^{-1}(q_b, q_m)$  is a symmetric and definite matrix. Let the weight matrix

$$Q_r(\hat{x}) = \text{diag}\{q_1, q_2\}, q_1, q_2 > 0$$

$$R_r(\hat{x}) = \text{diag}\{r_1, r_2\}, r_1, r_2 > 0$$

Then

$$\text{rank}[\hat{B}, \hat{A}\hat{B}, \dots, \hat{A}^{n-1}\hat{B}] = n$$

$$\text{rank}[Q^{1/2}_r, Q^{1/2}_r \hat{A}, \dots, Q^{1/2}_r \hat{A}^{n-1}]^T = n$$

and  $P_r(\hat{x})$  is only one.

When  $\tau_d \neq 0$ , i.e. the system parameters are uncertain, then

$$\dot{X} - \hat{X} = \hat{A}(x)X - \hat{A}(\hat{x})\hat{X} + [\hat{B}(x) - \hat{B}(\hat{x})]\tau_r + \hat{B}(x)\tau_d\quad (16)$$

$$\dot{E} = \hat{A}(\hat{x})E + \hat{B}(x)U\quad (17)$$

$$\tilde{C}(E)X = S - \hat{C}(x)E \quad (18)$$

where  $U = \tau_d + \hat{B}(x)^{-1} \tilde{A}(E)X + \hat{B}(x)^{-1} \tilde{B}(E)\tau_r$ . Let the expected error output is

$$Y_{er} = S - \hat{C}(\hat{x})E \quad (19)$$

and

$$Y_e = -\hat{C}(\hat{x})E \quad (20)$$

where the state error is  $E = \dot{X} - \dot{\hat{X}}$ , the model error is  $\tilde{A}(E) = \hat{A}(x) - \hat{A}(\hat{x})$ ,  $\tilde{B}(E) = \hat{B}(x) - \hat{B}(\hat{x})$ ,  $\tilde{C}(E) = C(x) - \hat{C}(\hat{x})$ , and the output error is  $S = Y - \hat{Y}$ . Then, the SDRE control law can be designed as

$$U = -R_d^{-1} \hat{B}^T(x) \{P_d E - l_d\} \quad (21)$$

Satisfies

$$\min J = \frac{1}{2} \int_0^\infty S^T Q_2(x) S + U^T R_2(x) U dt \quad (22)$$

where

$$l_d = - \left( \left[ \hat{A}(\hat{x}) - \hat{B}(x) R_d^{-1} \hat{B}^T(x) P_d \right]^T \right)^{-1} [-\hat{C}(x)^T Q_d Y_{er}] \quad Q_d = \text{diag}\{q_{d1}, q_{d2}\}, q_{d1}, q_{d2} > 0$$

$$R_d = \text{diag}\{r_{d1}, r_{d2}\}, r_{d1}, r_{d2} > 0$$

and  $P_d$  is a solution of the equation

$$\hat{C}^T(x) Q_d \hat{C}(x) + P_d \hat{A}(\hat{x}) + \hat{A}^T(\hat{x}) P_d - P_d \hat{B}(x) R_d^{-1} \hat{B}^T(x) P_d = 0$$

Then, one has

$$\tau_d = U - \hat{B}(x)^{-1} \tilde{A}(E)X - \hat{B}(x)^{-1} \tilde{B}(E)\tau_r \quad (23)$$

### 3.3. Stability analysis

It is assumed that the expected end-effector speed trajectory  $Y_r(t)$  can be determined by the following linear observable system

$$\begin{aligned} \dot{z}(t) &= Fz(t), z(0) = 0 \\ Y_r(t) &= Hz(t) \end{aligned} \quad (24)$$

where  $\{F, H\}$  is full observable. Let

$$\begin{aligned} \bar{X} &= \begin{bmatrix} \hat{X} \\ z \end{bmatrix}, \quad \bar{A} = \begin{bmatrix} \hat{A}(\hat{x}) & O \\ O & F \end{bmatrix}, \quad \bar{B} = \begin{bmatrix} \hat{B}(\hat{x}) \\ O \end{bmatrix} \\ \bar{Q} &= \begin{bmatrix} \hat{C}(\hat{x})^T Q_r \hat{C}(\hat{x}) & -\hat{C}(\hat{x})^T Q_r H \\ -H^T Q_r \hat{C}(\hat{x}) & H^T Q_r H \end{bmatrix} \end{aligned}$$

Then, by the optimal control theory, the tracking problem (14) can be transfer into the following SDRE regulator problem

$$\dot{\bar{X}}(t) = A(\bar{x}) \bar{X} + \bar{B} \tau_r^* \quad (25)$$

$$\min J = \frac{1}{2} \int_0^\infty \bar{X}^T \bar{Q}(x) \bar{X} + \tau_r^{*T} R_r(x) \tau_r^* dt \quad (26)$$

Due to  $\text{rank}[\hat{B}, \hat{A}\hat{B}, \dots, \hat{A}^{n-1}\hat{B}] = n$ , one can see that

a) If (24) is asymptotically stable,  $\{\bar{A}(x), \bar{B}(x)\}$  is stable.

b) If (24) is not asymptotically stable, it is assumed that the non-asymptotically stable of  $Y_r(t)$  is a zero input response of (14). In this case,  $Y_r(t)$  can be rewritten as

$$\begin{aligned} \begin{bmatrix} \dot{z}_s(t) \\ \dot{z}_{ns}(t) \end{bmatrix} &= \begin{bmatrix} F_s & O \\ O & \hat{A}(\hat{x}) \end{bmatrix} \begin{bmatrix} z_s(t) \\ z_{ns}(t) \end{bmatrix} \\ Y_r(t) &= \hat{C}(\hat{x}) z_{ns} + H_s z_s(t) \\ \bar{X}^* &= \begin{bmatrix} \hat{X} - z_{ns} \\ z_s \end{bmatrix}, \quad \bar{A}^* = \begin{bmatrix} \hat{A}(x) & O \\ O & F_s \end{bmatrix} \\ \bar{B}^* &= \begin{bmatrix} B(x) \\ O \end{bmatrix} \end{aligned}$$

and (14) can be transfer into a regulator problem. In above equation, the real parts of the eigenvalues of  $F_s$  all are negative. Then,  $\{\bar{A}^*(x), \bar{B}^*(x)\}$  can be point-wise stable. For  $Q$ , it satisfies

$$\bar{Q}^{1/2} = \begin{bmatrix} Q_r^{1/2} \hat{C}(\hat{x}) & -Q_r^{1/2} H \\ O & O \end{bmatrix}$$

Consider that  $\{F, H\}$  is full observable and

$$\text{rank}[Q^{1/2}_r, Q^{1/2}_r \hat{A}, \dots, Q^{1/2}_r \hat{A}^{n-1}]^T = n$$

one can see that, if  $\{\hat{A}(\hat{x}), \hat{C}(\hat{x})\}$  is point-wise full observable,  $\{\bar{A}(x), \bar{Q}^{1/2}(x)\}$  is point-wise full observable. From the Theorem 2 of [13], there exists a control law

$$\tau_r^* = -R_r^{-1}(\hat{x}) \hat{B}^T(\hat{x}) \bar{P}(\hat{x}) \hat{X}$$

such that (25) is closed-loop local asymptotically stable.

By the optimal control theory,  $\tau_r^* = \tau_r$  when  $Y_r(t)$  is known; that is, the control law is independent of  $F, H$ . Then, there exist a control law (13) such that  $t \rightarrow \infty, E_1 = Y_r - \hat{Y} \rightarrow 0$ . Similarly, there exist a control law (21) such that  $t \rightarrow \infty, S = Y - \hat{Y} \rightarrow 0$ . Due to the FFSR end-effector speed tracking error  $E2 = Y_r - Y$  and  $E2 = E1 - S$ , then there exist the control law  $\tau_r + \tau_d$  such that  $t \rightarrow \infty, E2 \rightarrow 0$ ; that is, the stabilized tracking of the practical FFSR end-effector speed trajectory is achieved.

#### 4. Simulations

In this section, a space robot manipulator system is analyzed to demonstrate the effectiveness of the proposed approach. Figure 2 shows the sketch map of the space robot manipulator system which consists of a spacecraft (Sc) and two flexible link arms (A1 represents Arm 1 and A2 represents Arm 2), where the arms are regarded as flexible bodies and the spacecraft body is considered as rigid body. The inertial parameters of the reference model of the space robot manipulator system are given in Table 1.

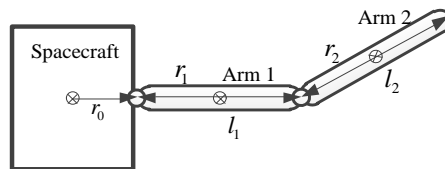


Figure 2. The space robot manipulator system

Table 1. The inertial parameters of the nominal model

Part	$l_i / m$	$r_i / m$	$m_i / kg$	$J_i / (kg \cdot m^2)$
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Sc	0.5	0.5	40	6.667
A1	0.5	0.5	4	0.333
A2	0.5	0.5	3	0.250

Consider the fuel consumption when the space robot manipulator system works on the orbit, then the inertial parameters of the system are changed and the practical inertial parameters is given as Table 2.

Table 2. The practical inertial parameters of the model

Part	$l_i / m$	$r_i / m$	$m_i / kg$	$J_i / (kg \cdot m^2)$
Sc	0.5	0.5	5	0.340
A1	0.5	0.5	4	0.333
A2	0.5	0.5	30	2.50

Let the expected end-effector speed trajectory is

$$x = 0.04\pi \sin(t), y = 0.04\pi \cos(t)$$

with the weight matrices are

$$Q_r = \text{diag}\{210, 350\}, Q_d = \text{diag}\{210, 350\}, R_r = \text{diag}\{0.01, 0.01\}, R_d = \text{diag}\{0.01, 0.01\}$$

The simulation time length is 6.5s and the simulation results are shown from Figure 3 to Figure 5. The joint torque is given in Figure 3, Figure 4 shows the tracking trajectory of the end-effector speed and Figure 5 presents the tracking errors of the end-effector speed.

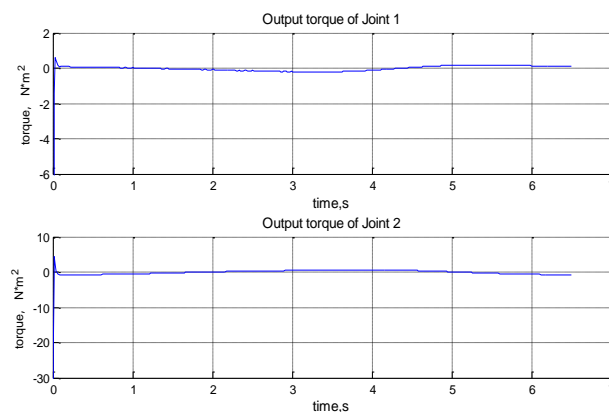


Figure 3. The outputs of the joint torque

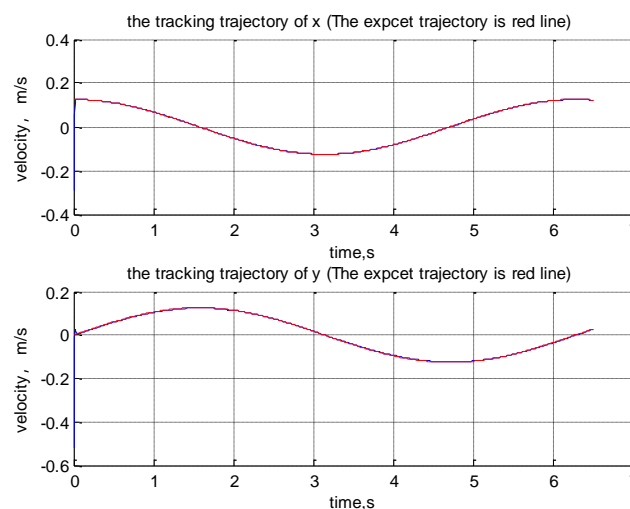


Figure 4. The tracking trajectory of the end-effector speed



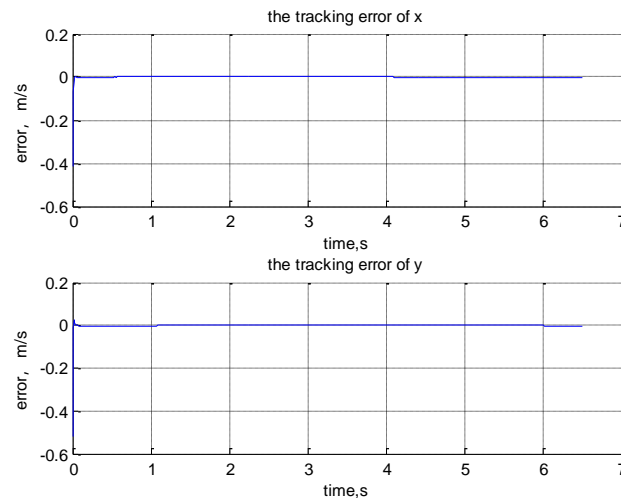


Figure 5. The tracking errors of the end-effector speed

From the simulation results, the end-effector speed of the space robot manipulator system with uncertain parameters is tracked by the proposed STTC approach based on two stages controller with SDRE. Meanwhile, the energy consumption of the joint torque is considered in the process of the designing controller. Therefore, the outputs of the joint torque are very small and the energy optimization can be achieved.

## 5. Conclusions

In this paper, a STTC approach based on two stages controller with SDRE (the first-stage SDRE nominal optimization controller and the second-stage SDRE compensated controller) is proposed to optimize the end-effector trajectory tracking control for FFSR with uncertain inertial parameters. The energy consumption is considered in the process of the end-effector trajectory tracking control. The proposed approach is applied to track the end-effector speed trajectory, and then the problem that the joint space trajectory is limited due to the coupling can be solved. Moreover, the practical generalized Jacobian matrix is not needed to be invertible and it only needs the nominal generalized Jacobian matrix is invertible, and then it is easily achieved in practical engineering.

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