Attitude Stabilization of a Rigid Spacecraft with Two Controls[1)]

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Abstract Rigid spacecraft models with two controls can not be locally asymptotically stabilized by continuous pure-state feedbacks. Available stabilization methods include the method using time-varying feedbacks and the method using discontinuous feedbacks. Most of the existing time-varying control results suffer from the drawback that the designed control laws are very complex. Moreover, the control laws using smooth time-varying feedback do not stabilize the system at exponential convergence rate. A smooth time-varying controller is developed by introducing an assistant state variable and using feedback linearization technique. Besides the advantage of design simplicity, the states of the closed loop system converge at exponential rate. The validity of our method is demonstrated by simulation results.

Key words Rigid spacecraft, attitude control, smooth time-varying feedback, local stabilization, exponential convergence

1 Introduction

The control of underactuated mechanical systems, i. e., systems with fewer inputs than degrees of freedom, is an interesting problem. The interest may come from two aspects. One is the appeal for controlling a system with fewer actuators especially when failure of an actuator in a mechanical system occurs. The other aspect is that using fewer actuators to implement control of the same object allows to reduce cost, weight, as well as occurrence of component failures.

Due to the reduced dimension of the input space, the controllability of the system need to be studied. Moreover, even when the controllability is guaranteed, the stabilization problem for underactuated systems is usually more difficult. Thus, the control problem of underactuated mechanical systems has attracted growing attention in recent years. Examples of these systems are underactuated rigid spacecrafts with two controls[1~3], underactuated autonomous surface vessels[4], underactuated autonomous underwater vehicles[5], etc.

The underactuated rigid spacecraft system is one of the underactuated systems that have been intensely investigated. It is well known that if the system is fully actuated, i. e., in the case of three controls, then the attitude of this system is fully controlled and can be easily stabilized using smooth feedbacks[6]. The present paper focuses on the attitude stabilization of underactuated rigid spacecraft with only two controls. Obviously, to a space flight system, the control problem in an underactuated status is very important. However, if the system is underactuated, i. e., in the case of two controls, it has been pointed out that the system can not be locally asymptotically stabilized by means of smooth pure state feedback[1].

One of main solutions of tackling this problem is using time-varying feedbacks[1~3]. In [1], explicit smooth periodic time-varying feedbacks have been proposed by using center manifold theory, time-averaging and Lyapunov techniques. However, these time varying

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feedbacks using periodic signals produce very slow (non-exponential) convergence of system states. To yield exponential stabilization, two nonsmooth time-varying methods have been proposed respectively in [2] and [3] using homogeneous method and Lyapunov technique. Nevertheless, the designed control laws are very complex.

In [7~8], by using an assistant state variable method, smooth aperiodic time-varying exponentially convergent control laws have been developed for a class of nonholonomic systems including (extended) chained system, (extended) power form system, Brockett system, etc. In this paper, combining this method and feedback linearization technique together, we show that smooth aperiodic time-varying control laws with exponential convergence can be developed to locally asymptotically stabilize the attitude of rigid spacecraft to the equilibrium. Moreover, the design procedure is very simple. The validity of our method will be demonstrated by simulation results.

2 The rigid spacecraft model

The complete attitude motion of a rigid spacecraft can be described by the following kinematic and dynamic equations[1]:

$$\dot{R} = S(\omega)R, \quad J\dot{\omega} = S(\omega)J\omega + [\tau_1 \quad \tau_2 \quad 0]^{\mathrm{T}} \tag{1}$$

where $R \in SO(3)$ denotes the rotation matrix representing the attitude, $\omega = [\omega_1 \quad \omega_2 \quad \omega_3]^{\mathrm{T}}$ the angular velocity vector, $J = \mathrm{diag}(j_1, j_2, j_3)$ the inertia matrix of the spacecraft, j_1, j_2 and j_3 the principal moments of inertia, τ_1 and τ_2 the control torques applied to the rigid body, and $S = \begin{bmatrix} 0 & \omega_3 & -\omega_2 \\ -\omega_3 & 0 & \omega_1 \\ \omega_2 & -\omega_1 & 0 \end{bmatrix}$ the matrix representation of the cross product.

In order to control system (1), a preliminary step is to parametrize the attitude kinematics. Available parametrizations include Eulerian angles, Euler parameters (quaternion), and Cayley-Rodrigues parameters[1]. In contradistinction, the Cayley-Rodrigues parameters method not only can yield polynomial equations but also is a mininal parametrization method (using only three parameters), which is convenient for control and stabilization problems. The reader is referred to [1] for the detailed formulation of this parametrizations. Introducing Cayley-Rodrigues parameters to parametrization of the attitude kinematics equation of system (1), one obtains[1]:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \frac{1}{2}\left[\begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix} + \begin{bmatrix} 0 & \omega_3 & -\omega_2 \\ -\omega_3 & 0 & \omega_1 \\ \omega_2 & -\omega_1 & 0 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + (\omega_1 x_1 + \omega_2 x_2 + \omega_3 x_3)\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}\right] \tag{2}$$

$$\dot{\omega}_1 = c_1\omega_2\omega_3 + u_1, \quad \dot{\omega}_2 = c_2\omega_1\omega_3 + u_2, \quad \dot{\omega}_3 = c_3\omega_1\omega_2,$$

where x_1, x_2, and x_3 are Cayley-Rodrigues parameters, $u_1 = \tau_1/j_1$, $u_2 = \tau_2/j_2$, $c_1 = (j_2 - j_3)/j_1$, $c_2 = (j_3 - j_1)/j_2$, $c_3 = (j_1 - j_2)/j_3$.

It should be pointed out that under this parametrization the above derived equations are only local description of the attitude of the rigid spacecraft. It is natural to assume that $j_1 - j_2 \neq 0$, i.e., $c_3 \neq 0$, otherwise, system (2) is neither controllable nor stabilizable. Our task in this paper is to find smooth time-varying feedback control laws u_1 and u_2 which exponentially stabilize system (2).

3 Design of control laws

Let $x = [x_1 \quad x_2 \quad x_3]^{\mathrm{T}}$, $p = \omega_3(x_2 + x_1 x_3) + \omega_2(x_1 x_2 - x_3)$. After a suitable change of coordinates of the form

$$\bar{\omega}_1 = \omega_1(1 + x_1^2) + p, \quad \bar{u}_1 = (1 + x_1^2)(u_1 + c_1\omega_2\omega_3) + \omega_1 x_1 \bar{\omega}_1 + \dot{p} \tag{3}$$

i.e., $u_1 = -c_1\omega_2\omega_3 + (\bar{u}_1 - \omega_1 x_1 \bar{\omega}_1 - \dot{p})/(1 + x_1^2)$, $\omega_1 = (\bar{\omega}_1 - p)/(1 + x_1^2)$, system (2) can be written as

$$\dot{x}_1 = \frac{1}{2}\bar{\omega}_1, \quad \dot{\bar{\omega}}_1 = \bar{u}_1 \tag{4a}$$

$$\dot{x}_2 = \frac{1}{2}\left[\omega_2 - \omega_3 x_1 + \frac{\bar{\omega}_1}{1+x_1^2}x_3 + (\bar{\omega}^{\mathrm{T}}x)x_2 - \frac{px_3 + px_1x_2}{1+x_1^2}\right] \tag{4b}$$

$$\dot{\omega}_2 = c_2\frac{\bar{\omega}_1 - p}{1+x_1^2}\omega_3 + u_2 \tag{4c}$$

$$\dot{x}_3 = \frac{1}{2}\left[\omega_3 + \omega_2 x_1 - \frac{\bar{\omega}_1}{1+x_1^2}x_2 + (\bar{\omega}^{\mathrm{T}}x)x_3 + \frac{px_2 - px_1x_3}{1+x_1^2}\right] \tag{4d}$$

$$\dot{\omega}_3 = c_3\frac{\bar{\omega}_1 - p}{1+x_1^2}\omega_2 \tag{4e}$$

with $\bar{\omega} = [\bar{\omega}_1/(1+x_1^2) \quad \omega_2 \quad \omega_3]^{\mathrm{T}}$.

3.1 Control law for $\bar{u}_1$, u_1

Notice that the subsystem $(\bar{\omega}_1, x_1)$ in equation (4) is a controllable linear time-invariant system. Introducing an assistant state $x_0(t)$ such that $\dot{x}_0 = x_1$, one obtains:

$$\dot{x}_0 = x_1, \dot{x}_1 = \bar{\omega}_1/2, \dot{\bar{\omega}}_1 = \bar{u}_1 \tag{5}$$

Take the following feedback control law

$$\bar{u}_1 = -k_0x_0 - k_1x_1 - k_2\bar{\omega}_1 \tag{6}$$

where the gain vector $K_1 = [k_0 \quad k_1 \quad k_2]$ is chosen such that the eigenvalues of the closed-loop system (5~6) are assigned to be three different negative real numbers $-l_0, -l_1, -l_2$ with $l_2 > l_1 > l_0 > 0$. Then states $x_0(t), x_1(t)$ and $\bar{\omega}_1(t)$ can be expressed in the following form

$$\begin{aligned} x_0(t) &= m_0e^{-l_0t} + m_1e^{-l_1t} + m_2e^{-l_2t} \\ x_1(t) &= -l_0m_0e^{-l_0t} - l_1m_1e^{-l_1t} - l_2m_2e^{-l_2t} \\ \bar{\omega}_1(t) &= 2(l_0^2m_0e^{-l_0t} + l_1^2m_1e^{-l_1t} + l_2^2m_2e^{-l_2t}) \end{aligned} \tag{7}$$

where m_0, m_1, and m_2 are some real constants which are determined by k_2, k_1, k_0 and the initial values of system states $x_0(0), x_1(0)$, and $\bar{\omega}_1(0)$. Moreover, m_0 is given by

$$m_0 = \frac{1}{2(l_2 - l_0)(l_1 - l_0)}[2l_1l_2x_0(0) + 2(l_1 + l_2)x_1(0) + \bar{\omega}_1(0)] \tag{8}$$

The results show that by introducing an assistant state variable and using augmented state feedback described by equation (6), we can make the augmented closed loop system (5~6) asymptotically stable. Given initial values of $x_1(0)$ and $\bar{\omega}_1(0)$, to make $x_1(t)$ and $\bar{\omega}_1(t)$ converge at definite exponential rate e^{-l_0t}, i. e., the coefficients of e^{-l_0t} in the descriptions of $x_0(t), x_1(t)$, and $\bar{\omega}_1(t)$ in equation (7) are non-zero, requires $m_0 \neq 0$ according to equation (7). This requirement can not be satisified through linear feedback consisting of only states $x_1(t)$ and $\bar{\omega}_1(t)$ but can be satisified through selecting a suitable initial value of the assistant state $x_0(t)$. Observing equation (8), one can find that given any fixed initial values $x_1(0)$ and $\bar{\omega}_1(0)$, states $x_1(t)$ and $\bar{\omega}_1(t)$ can always be set to converge at definte exponential rate if we choose suitable $x_0(0)$. For example, selecting $x_0(0)$ such that

$$x_0(0) \neq -[2(l_1 + l_2)x_1(0) + \bar{\omega}_1(0)]/(2l_1l_2) \tag{9}$$

can make m_0 nonzero and $x_1(t)$ and $\bar{\omega}_1(t)$ converge to zero at definte exponential rate e^{-l_0t}.

Remark 1. For any bounded initial states $x_1(0)$ and $\bar{\omega}_1(0)$, we can always choose an $x_0(0)$ independent of $x_1(0)$ and $\bar{\omega}_1(0)$ to make $m_0 \neq 0$. Assume that, for instance, $|x_1(0)| \leqslant q_1$, $|\bar{\omega}_1(0)| \leqslant q_2$, where $q_1 > 0, q_2 > 0$ are some known constants; then from (8) we know that $m_0 \neq 0$ if we choose $x_0(0)$ such that $|x_0(0)| > \frac{1}{2l_1l_2}[2(l_1 + l_2)q_1 + q_2]$.

Here, let us consider the slow converging mode in states $x_1(t)$ and $\bar{\omega}_1(t)$. To this end, let $z(t) = m_0l_0e^{-l_0t}$ and we have $\dot{z}(t) = -l_0z(t)$. Substituting $z(t)$ into equation (7) yields

$$x_1(t) = [-1 + f_1(t)]z(t), \quad \bar{\omega}_1(t) = [2l_0 + f_2(t)]z(t) \tag{10}$$

where

$$f_1(t) = -\frac{m_1 l_1}{m_0 l_0} e^{-(l_1 - l_0)t} - \frac{m_2 l_2}{m_0 l_0} e^{-(l_2 - l_0)t}, \quad f_2(t) = 2\left(\frac{m_1 l_1^2}{m_0 l_0} e^{-(l_1 - l_0)t} + \frac{m_2 l_2^2}{m_0 l_0} e^{-(l_2 - l_0)t}\right).$$

3.2 Control law for u_2

Since the control law for $\bar{u}_1(t)$ has been designed, states $x_0(t)$, $x_1(t)$, and $\bar{\omega}_1(t)$ now can be taken as time functions. Introducing the following substitutions

$$y_1 = x_2, \; y_2 = \omega_2, \; y_3 = x_3/z, \; y_4 = \omega_3/z \tag{11}$$

to the reduced system which consists of coordinates $(x_2(t), x_3(t), \omega_2(t), \omega_3(t))$, one obtains from equation (4),

$$\dot{y}_1 = \frac{1}{2}\left[y_2 - x_1 z y_4 + \frac{\bar{\omega}_1 z}{1 + x_1^2} y_3 + (\bar{\omega}^{\mathrm{T}} x) y_1 - \frac{p z y_3 + p x_1 y_1}{1 + x_1^2}\right] \tag{12a}$$

$$\dot{y}_2 = c_2 \frac{\bar{\omega}_1 - p}{1 + x_1^2} z y_4 + u_2 \tag{12b}$$

$$\dot{y}_3 = l_0 y_3 + \frac{1}{2}\left[y_4 + y_2 \frac{x_1}{z} - \frac{\bar{\omega}_1}{z(1 + x_1^2)} y_1 + (\bar{\omega}^{\mathrm{T}} x) y_3 + \frac{p y_1 - p x_1 z y_3}{z(1 + x_1^2)}\right] \tag{12c}$$

$$\dot{y}_4 = l_0 y_4 + c_3 \frac{\bar{\omega}_1}{z(1 + x_1^2)} y_2 - c_3 \frac{p}{z(1 + x_1^2)} y_2 \tag{12d}$$

Here p can be rewritten as $p = z\bar{p}$ where $\bar{p} = y_4(y_1 + x_1 z y_3) + y_2(x_1 y_1/z - y_3)$. $\bar{\omega}^{\mathrm{T}} x$ can also be rewritten as $\bar{\omega}^{\mathrm{T}} x = \frac{(\bar{\omega}_1 - p)x_1}{1 + x_1^2} + y_1 y_2 + z^2 y_3 y_4$. Denote $y = [y_1 \quad y_2 \quad y_3 \quad y_4]^{\mathrm{T}}$. Under a suitable partition, system (12) can be rewritten as a linear time-varying system with a high order perturbation as follows:

$$\dot{y} = (A + A_1(t))y + Bu_2 + f(t, y) \tag{13}$$

where

$$A = \begin{bmatrix} 0 & \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -l_0 & -\frac{1}{2} & l_0 & \frac{1}{2} \\ 0 & 2c_3 l_0 & 0 & l_0 \end{bmatrix}, \quad A_1(t) = \begin{bmatrix} \frac{x_1 \bar{\omega}_1}{2(1 + x_1^2)} & 0 & \frac{z\bar{\omega}_1}{2(1 + x_1^2)} & -\frac{x_1 z}{2} \\ 0 & 0 & 0 & \frac{c_2 \bar{\omega} z}{1 + x_1^2} \\ l_0 - \frac{\bar{\omega}_1}{2(1 + x_1^2)z} & \frac{1}{2} + \frac{x_1}{2z} & \frac{x_1 \bar{\omega}_1}{2(1 + x_1^2)} & 0 \\ 0 & \frac{c_3 \bar{\omega}_1}{(1 + x_1^2)z} - 2c_3 l_0 & 0 & 0 \end{bmatrix},$$

$$B = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \quad f(t, y) = \begin{bmatrix} \frac{1}{2}[(y_1 y_2 + z^2 y_3 y_4) y_1 - (z^2 \bar{p} y_3 + x_1 z \bar{p} y_1)/(1 + x_1^2)] \\ -c_2 z^2 \bar{p} y_4/(1 + x_1^2) \\ \frac{1}{2}[(y_1 y_2 + z^2 y_3 y_4) y_3 + (\bar{p} y_1 - x_1 z \bar{p} y_3)/(1 + x_1^2)] \\ -c_3 \bar{p} y_2/(1 + x_1^2) \end{bmatrix}.$$

It can be verified that (A, B) is a controllable pair if $l_0 c_3 \neq 0$, which has been presumed to be satisfied in Section 2. The control law for u_2 is designed as follows

$$u_2(t) = -k_3 y_1 - k_4 y_2 - k_5 y_3 - k_6 y_4 \tag{14}$$

where the gain vector $K_2 = [k_3, k_4, k_5, k_6]$ is selected such that the matrix $A - BK_2$ is a Hurwitz matrix.

Rewriting equations (6) and (14) with coordinates of system (2), one thus obtains the feedback control laws for system (2)

$$u_1 = -\frac{k_0 x_0 + k_1 x_1 + (k_2 + \omega_1 x_1)[\omega_1(1 + x_1^2) + p] + \dot{p}}{1 + x_1^2} - c_1 \omega_2 \omega_3 \tag{15}$$

$$u_2(t) = -k_3 x_2 - k_4 \omega_2 - k_5 x_3/z - k_6 \omega_3/z \tag{16}$$

Lemma 1[7]**.** Consider a linear time-varying system $\dot{x} = (A + A_1(t))x + (B + B_1(t))u$. Suppose the system satisfies the following properties:

1) (A, B) is a stabilizable pair,

2) $\int_0^\infty \| A_1(t) \| \mathrm{d}t < \infty$, $\int_0^\infty \| B_1(t) \| \mathrm{d}t < \infty$, $\lim_{t\to\infty} A_1(t) = 0$, $\lim_{t\to\infty} B_1(t) = 0$.

Then there exists a state feedback $u = -Kx$ which makes the closed system uniformly exponentially stable, where K is selected such that $A - BK$ is a Hurwitz matrix.

Lemma 2[9]**.** Consider a nonlinear system $\dot{x} = A(t)x + f(t, x)$ with $f(t,x): C[I \times R^n, R^n]$, and $f(t,x) \equiv x$ if and only if $x = 0$. If the system satisfies one of the following conditions

a) for each $\forall \varepsilon > 0$, there exists $\sigma(\varepsilon) > 0$ such that

$$\| f(t,x) \| < \varepsilon \| x \|, \ \forall x \in D = [x \mid \| x \| < \sigma], \ t \in [t_0, +\infty),$$

b) $\| f(t,x) \| / \| x \| \to 0, \forall t \geq 0$, as $\| x \| \to 0$,

then we can conclude that the nonlinear system is locally exponentially stable if the associated system $\dot{x} = A(t)x$ is exponentially stable.

Theorem 1. System (1) can be locally asymptotically exponentially stabilized by (15~16).

Proof. From the design procedure of u_1, one can easily know that states $x_1(t)$ and $\bar{\omega}_1(t)$ are all made globally convergent at a fixed exponential decay rate, i. e, $e^{-l_0 t}$, if the initial value of assistant state $x_0(t)$ is selected according to equation (9). By taking a coordinate transformation $y_1 = x_2, y_2 = \omega_2, y_3 = x_3/z, y_4 = \omega_3/z$ to the reduced system, the transformed system (12) can be rewritten as system (13) which is a linear time-varying system with a high order perturbation. System (13) satisfies the following properties: (A, B) is a controllable pair and $\int_0^\infty \| A_1(t) \| \mathrm{d}t < \infty$, $\lim_{t\to\infty} A_1(t) = 0$.

According to Lemma 1, the control law (14) can exponentially stabilize the associated system of (13), i. e. , $\dot{y} = (A + A_1(t))y + Bu_2$. Note that the components of $f(t,y)$ in (13) consist of y_1, y_2, y_3, y_4 of degrees no less than 3 and bounded time functions $z, x_1, \bar{\omega}_1$. It can be easily verified that $\| f(t,x) \| / \| x \| \to 0, \forall t \geq 0$, as $\| x \| \to 0$, which means the satisfaction of the condition of Lemma 2. So system (13) is locally exponentially stable due to Lemma 2. Thus, $(x_2, \omega_2, x_3, \omega_3)$ converge locally to zero with exponential decay. According to (3), one obtains that $\omega_1(t)$ also locally converges to zero with exponential decay. The theorem is thus proved. □

Remark 2. From Eqs. (7)~(9), one might find that $z(t)$ equals to $\frac{l_0}{2(l_2 - l_0)(l_1 - l_0)} [2 l_1 l_2 x_0(t) + 2(l_1 + l_2) x_1(t) + \bar{\omega}_1(t)]$, which can substitute for $z(t)$ for the convenience of physical realization of the control system. This also means the final control laws may only consist of system states and the assistant state $x_0(t)$, without time t in the explicit expression.

4 Simulation results

We illustrate the results of the paper with a simulation example of a rigid spacecraft with two independent control torques. The model parameters are given by $j_1 = 300\mathrm{kg \cdot m^2}$, $j_2 = 200\mathrm{kg \cdot m^2}$, and $j_3 = 100\mathrm{kg \cdot m^2}$, respectively , so that $c_1 = 0.33$, $c_2 = -1$, $c_3 = 1$. The results of the simulation for a sample initial condition given by $x_1(0), x_2(0), x_3(0) = -1.0, 0.2, 0.5$, $\omega_1(0), \omega_2(0), \omega_3(0) = -1.5, -1.6, -0.6$ rad/m are shown in Figs. 1~3. Here select $x_0(0) = 2$. The gain vector K_1 was chosen to be $K_1 = [8.96 \quad 18.88 \quad 5.6]$, which implies $l_0, l_1, l_2 = 2.8, 2.0, 0.8$, $m_0 = 2.31$. $K_2 = [-22.2 \quad 7 \quad 29.4 \quad 29.23]$ which locates the eigenvalues of the matrix $A - BK_2$ at $-2.0, -1.6, -1.2, -0.6$. The controls laws given by Eqs. (15~16) were used. The time responses of the states of the closed loop are shown in Figs. 1 and 2. The control torques τ_1 and τ_2 are shown in Fig. 3.

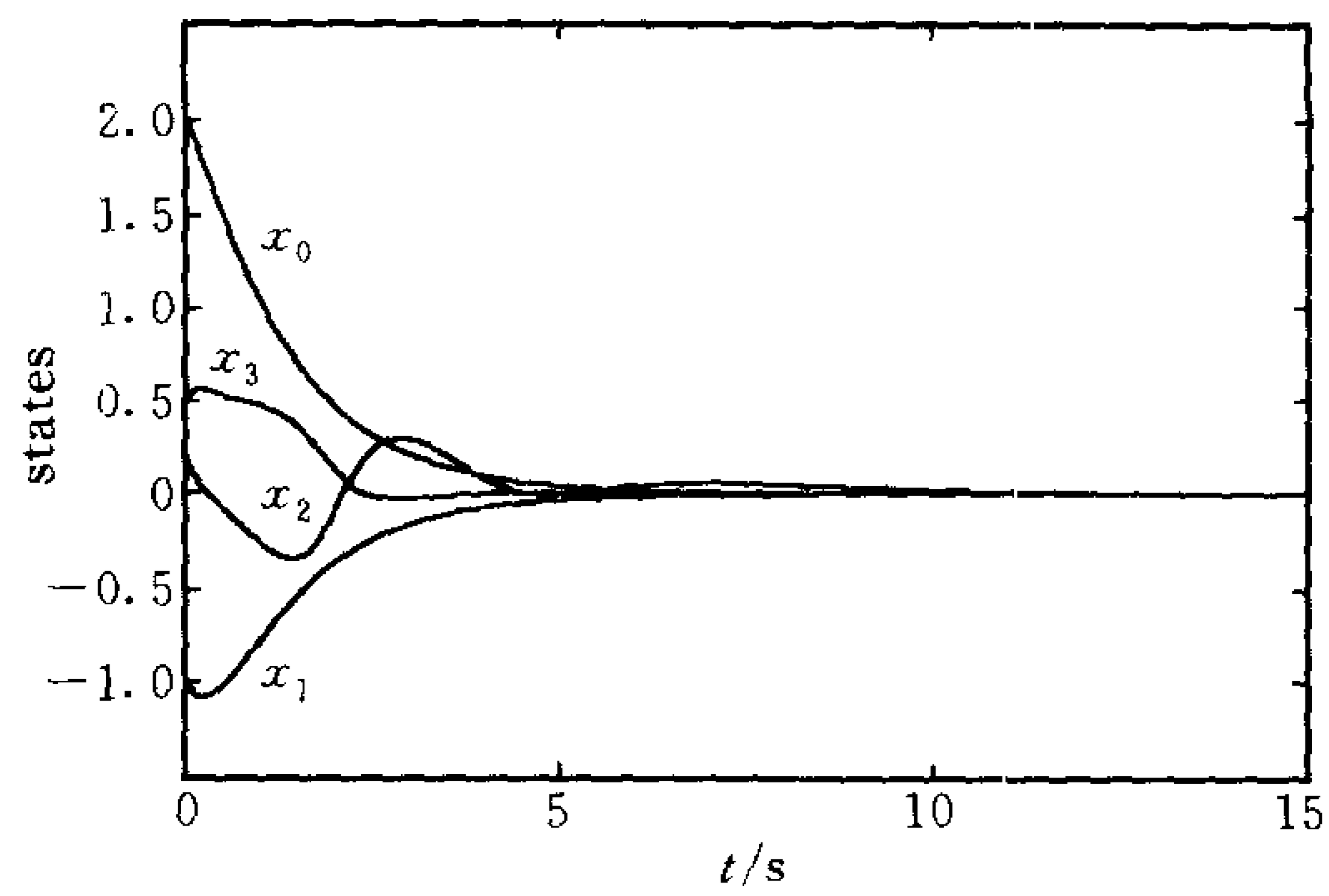

Fig. 1 Time responses of state variables x_0, x_1, x_2, x_3

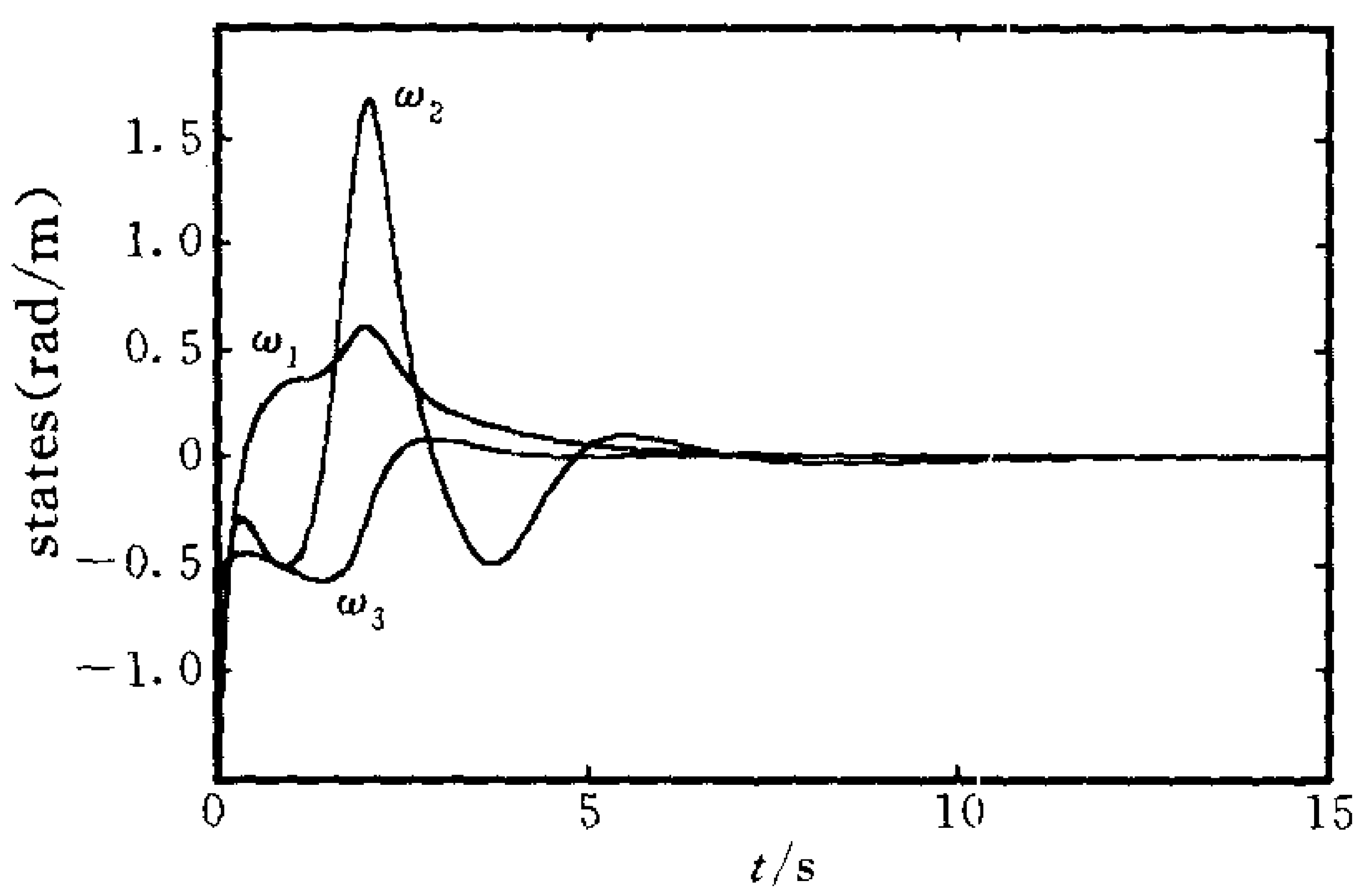

Fig. 2 Time responses of state variables $\omega_1, \omega_2, \omega_3$

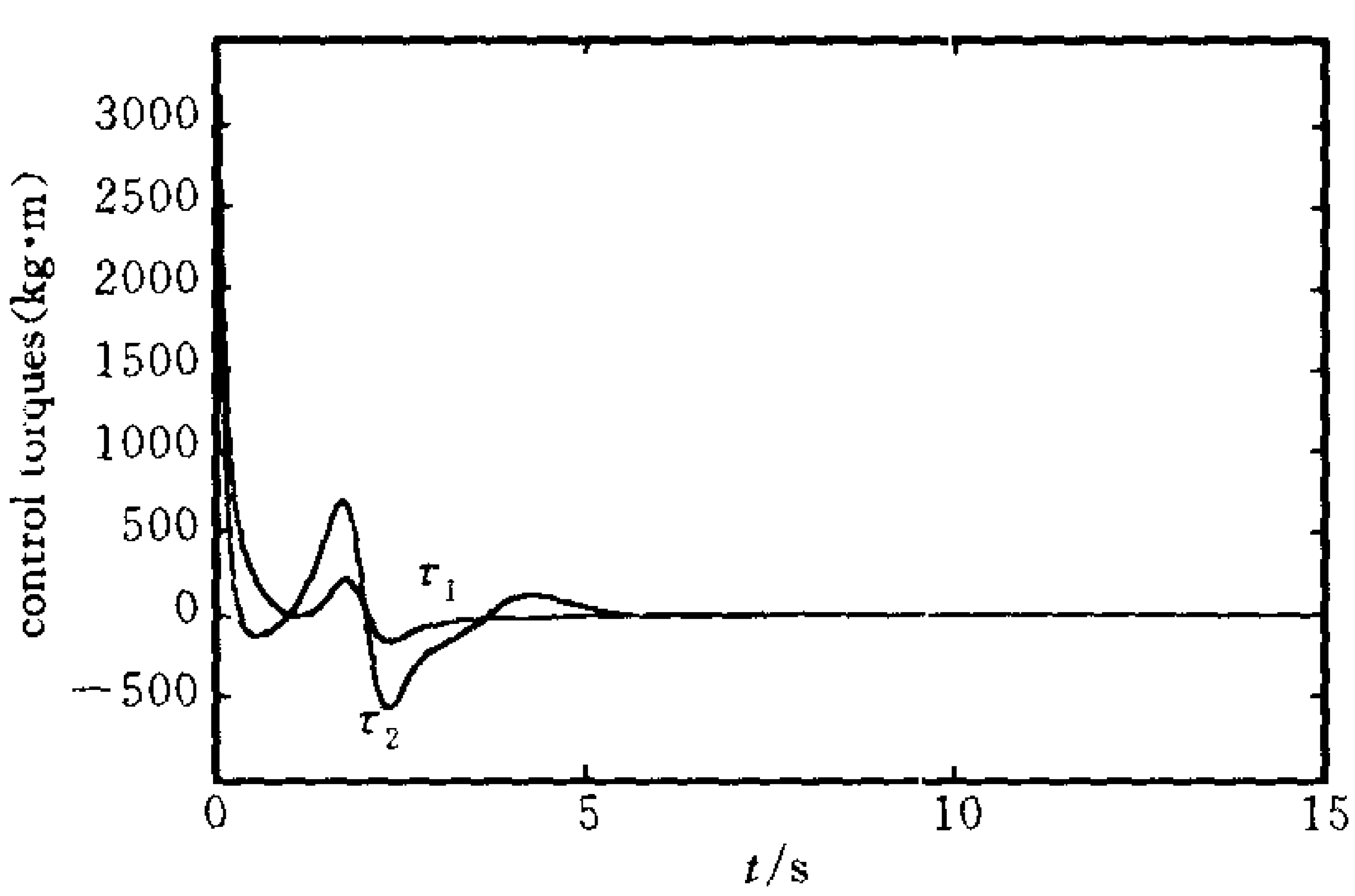

Fig. 3 Control torques τ_1, τ_2

5 Conclusions

The attitude stabilization problem of a rigid spacecraft using two controls has been considered. The results of this paper show that smooth time-varying controllers with exponential decay can be developed to stabilize the states of the closed loop system to the equilibrium by introducing an assistant state and using the feedback linearization technique. The design procedure is simple and convenient. The effectiveness of the proposed feedback control laws has been illustrated through a simulation example.

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带两控制器刚体飞行器的姿态镇定

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摘 要 已知带两控制器的刚体飞行器系统不能被连续的纯状态反馈局部渐近镇定.有效的解决方法包括时变反馈镇定方法和非连续反馈镇定方法.现有的时变反馈镇定方法设计均较为复杂.已有的光滑时变反馈方法是非指数收敛的.本文通过引入辅助变量以及采用反馈线性化技术设计出光滑时变的控制器.该方法设计简单且保证闭环系统状态是指数收敛的.仿真结果证明了本文方法的有效性.

关键词 刚体飞行器,姿态控制,光滑时变反馈,局部镇定,指数收敛

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