Control of Space Robots with Unactuated Joints *

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Abstract: The underactuated free floating robot in space is nonlinear systems where velocity and acceleration constraints are both nonintegrable, therefore it is a second order nonholonomic system. In this paper, by investigating the system dynamics in depth, we propose a simple velocity-based method to control the unactuated joints and a multi-step composite strategy to implement orientation tracking tasks. The proposed algorithm is of significance in controlling space robots when some joints fail to function, or they are intentionally set to be passive for energy efficiency and safety purposes.

Key words: averaging control; nonholonomic control; underactuated robot

含有未驱动关节的空间机器人控制

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摘要：含有未驱动关节的自由漂浮空间机器人具有不可积分的速度和加速度约束，因而是一个二阶非完整系统.通过分析系统的动力学结构，本文设计了一种全新的基于速度控制的方法控制未驱动关节，然后采用多步混合控制策略实现空间机器人的定位跟踪.

关键词：空间机器人；欠驱动系统；非完整约束；平均系统

1 Introduction

The control of a free floating space robot with passive joints is an important problem in spacecraft maintenance, high efficiency control and fault tolerance design. It, however, has not been well adderssed in collections of the related work in [1,2]. Compared with other systems, it is one of the most general, and the most diffcult underactuated systems.

Most work on the nonholonomic control aim at the systems with only the first order nonholonomic constraints. In space robot control[3,4], people are only interested in kinematic planning without much dynamics consideration. Kolmanovsky and McClamroch[5] proposes an algorithm with a back-stepping method for planning and controlling a two-joint free-floating robot with fully actuated joints. An angular momentum conservation is considered in their paper. By using the designed feedback the subsystem of acceleration (torque) conrtol can be simplified to satisfy the condition of back-stepping method. But this is not feasible to our system where only partial joints are actuated. Morin and Samson[6] also proposes a back-stepping method to implement the stabilization of altitude of a spacecraft controlled by two control torques. Their model can also be simplified to two strictly cascaded systems. Based on the properties of homogeneous systems, the constructed time-varying controller guarantees the exponential stabilization. Petersen and Egeland's method[7] is similar to [6], except that a global coordinate transformation is constructed to allow the system to satisfy homogeneity. Their model of an underactuated surface vessel is a special case of systems with second order nonholonomic constraints, as the inertial matrix is constant and the second order constraint contains only velocities as variables.

As will be deliberated in the next section, the system we discuss here contains a second-order nonholonomic constraint in which the configuration variables can not be omitted. Therefore, the back-stepping torque control method can not be directly applied to our system.

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Moreover, the existence of drift terms destroys the equivalency between accessibility and controllability so the controllability analysis becomes extremely difficult. To attenuate the effect of drift terms, a high gain input is considered in [8], but it has limitation in engineering application. [9] proposes a control Lie bracket based method for velocity constraint with a drift, but it is difficult to generate the suitable control Lie bracket for our system in the torque control level. For the second order constrained systems (robot with passive joints), Nakamura[10] proposes a chaos analysis, Arai[11] presents a specific open loop planning method, Oriolo[12] suggests an homogeneous system (nilpotent) approximation algorithm. However, all of these approaches have limitation in dealing with practical problems.

In this paper, by investigating the system dynamics in depth, we propose a simple velocitybased method to control the unactuated joints and a multi-step composite strategy to implement orientation tracking tasks. The rest of this paper is organised as follows: Partial linearization and model simplification are presented in Sectin 2. The control strategy is proposed in Section 3. To demonstrate the feasibility of the proposed strategy, a simulation study is given in the following section.

2 System description

As shown in Fig. 1, a planar four-link space robotic system (a three-link robot mounted on a space vehicle) with one passive joint (the last one) is considered as an example to illustrate our method.

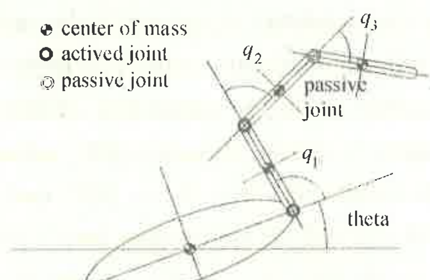

Fig. 1 Four-link space system

The system dynamics can be described as [2,12]

$$\begin{cases}\begin{pmatrix} m_{11}(q) & m_{12}(q) & m_{13}(q) \\ m_{21}(q) & m_{22}(q) & m_{23}(q) \\ m_{31}(q) & m_{32}(q) & m_{33}(q)\end{pmatrix}\begin{pmatrix}\ddot{q}_1 \\ \ddot{q}_2 \\ \ddot{q}_3\end{pmatrix} + n(q,\dot{q}) = \begin{pmatrix}\tau_1 \\ \tau_2 \\ 0\end{pmatrix}, \\ S_1(q)\dot{q}_1 + S_2(q)\dot{q}_2 + S_3(q)\dot{q}_3 = \dot{\theta}, \end{cases} \tag{1}$$

here $\theta \in \mathbb{R}$ is the orientation of the first body relative to the inertial coordinate system, $q = (q_1, q_2, q_3) \in \mathbb{R}^3$ and $\tau = (\tau_1, \tau_2, 0) \in \mathbb{R}^3$ represents the vector of joint coordinates and the vector of generalized forces respectively, $\{m_{ij}\}$ is the 3×3 inertial matrix, and n with dimension 3×1 is the centrifugal and Coriolis term. $\{m_{ij}\}$ and n are described in detail in Appendix of [13].

There are two nonholonomic constraints of different orders included in these equations. One is a constraint of first order (the velocity) which represents the relationship between the orientation and the shape of the space robot

$$\dot{\theta} = S_1(q)\dot{q}_1 + S_2(q)\dot{q} + S_3(q)\dot{q}_3. \tag{2}$$

Another constraint is that of the second order (the acceleration) which occurs during the robot motion

$$m_{31}(q)\ddot{q}_1 + m_{32}(q)\ddot{q}_2 + m_{33}(q)\ddot{q}_3 + n_3(q,\dot{q}) = 0. \tag{3}$$

Choosing the generalized forces τ such as

$$\begin{aligned}\tau_1 &= (m_{11} - m_{13}m_{33}^{-1}m_{31})u_1 + (m_{12} - \\ &\quad m_{13}m_{33}^{-1}m_{32})u_2 + n_1 - m_{13}m_{33}^{-1}n_3, \\ \tau_2 &= (m_{21} - m_{23}m_{33}^{-1}m_{31})u_1 + (m_{22} - \\ &\quad m_{23}m_{33}^{-1}m_{32})u_2 + n_2 - m_{23}m_{33}^{-1}n_3,\end{aligned} \tag{4}$$

with $u = (u_1, u_2) \in \mathbb{R}^2$ an auxiliary input vector, the above dynamic equations (1) can be re-expressed as a partially linearized one

$$\begin{cases}\dot{q}_1 = v_1, \quad \dot{q}_2 = v_2, \quad \dot{q}_3 = v_3, \\ \dot{\theta} = S_1(q)v_1 + S_2(q)v_2 + S_3(q)v_3, \\ \dot{v}_1 = u_1, \quad \dot{v}_2 = u_2, \\ \dot{v}_3 = C_1(q)u_1 + C_2(q)u_2 + C_3(q),\end{cases} \tag{5}$$

where $C_1(q)$, $C_2(q)$ and $C_3(q)$ are expressed in detail in Appendix.

The purpose of this paper is to drive the robot from one point to another with zero velocity at the desired point. This implies that the system is controlled to move from $(q(t_0), \dot{q}(t_0), \theta(t_0)) = (q^0, 0, \theta^0)$ to $(q(t_f), \dot{q}(t_f), \theta(t_f), \dot{\theta}(t_f)) = (q^f, 0, \theta^f, 0)$ with $q^0 \neq q^f$ and $\theta^0 \neq \theta^f$.

3 Control strategy

Because of the existence of two constraints with two different orders , it is very diffcult to implement the point-to-point control directly. We propose the following strategy to handle this case. The control strategy will be divided into three phases:

1) Actuated joint control phase: control the actuated joint 1 and joint 2 to move and stay at their own desired positions at time t_1;

2) Shape phase: design a control algorithm to control the unactuated joint 3 to move and stay at its desired position at time $t_2 (t_1 < t_2 < t_f)$ and let joint 1 and joint 2 go back to their desired positions at t_2;

3) Orientation phase: design another algorithm to move the orientation angle θ to its desired position θ^f at time t_f and let the three joints go back to their desired positions at this time. The whole procedure can be described more clearly as

$$\begin{pmatrix} t = t_0 \\ q_1(0) = q_1^0 \\ q_2(0) = q_2^0 \\ q_3(0) = q_3^0 \\ v(0) = 0 \\ \theta(0) = \theta^0 \end{pmatrix} \Rightarrow \begin{pmatrix} t = t_1 \\ q_1(t_1) = q_1^f \\ q_2(t_1) = q_2^f \\ q_3(t_1) = q_3(t_1) \\ v(t_1) = 0 \\ \theta(t_1) = \theta(t_1) \end{pmatrix} \Rightarrow$$

$$\Rightarrow \begin{pmatrix} t = t_2 \\ q_1(t_2) = q_1^f \\ q_2(t_2) = q_2^f \\ q_3(t_2) = q_3^f \\ v(t_2) = 0 \\ \theta(t_2) = \theta(t_2) \end{pmatrix} \Rightarrow \begin{pmatrix} t = t_f \\ q_1(t_f) = q_1^f \\ q_2(t_f) = q_2^f \\ q_3(t_f) = q_3^f \\ v(t_f) = 0 \\ \theta(t_f) = \theta^f \end{pmatrix}.$$

With the partially linearized model (5), the first phase can be implemented easily by using some simple controllers. For example, a linear feedback of the form

$$\begin{cases} u_1^{(1)} = -k_{11} v_1 - k_{12}(q_1 - q_1^f), \\ u_2^{(1)} = -k_{21} v_2 - k_{22}(q_2 - q_2^f), \end{cases} \tag{6}$$

with $k_{ij} > 0, i,j = \{1,2\}$ is a suitable choice for this phase. For the other two control phases, we will present two different control strategies to be discussed below.

3.1 Shape control phase

In this phase, the unactuated joint is controlled to its desired target with zero velocity, while the two actuated joints are controlled back to their own positions, from which motion starts at the beginning of this phase. By the end of this phase, the shape of the space robot has changed to its desired shape configuration. As mentioned in the first section of this paper, the control of nonlinear systems with second-order nonholonomic constraints has not been addressed extensively. Limited cases discussed in publications lack generality in implementation. Therefore, we first study the system model to investigate whether the existing methods can solve our problem.

For the reason of simplicity, we treat the system in this phase in a reduced oredr form

$$\begin{cases} \dot{q}_1 = v_1, \quad \dot{q}_2 = v_2, \quad \dot{q}_3 = v_2, \\ \dot{v}_1 = u_1, \quad \dot{v}_2 = u_2, \\ \dot{v}_3 = C_1(q)u_1 + C_2(q)u_2 + C_3(q,v). \end{cases} \tag{7}$$

It is easy to find in the Appendix that $C_1(q)$ and $C_2(q)$ contain the variables q alone (exclusion of v), which implies that with the control vectors

$$g_1 = \frac{\partial}{\partial v_1} + C_1(q)\frac{\partial}{\partial v_3}, \quad g_2 = \frac{\partial}{\partial v_2} + C_2(q)\frac{\partial}{\partial v_3},$$

it is impossible to construct a conrtol Lie bracket containing only the component in $\frac{\partial}{\partial v_3}$ direction. Therefore many existing nonholonomic control techniques can not be extended to this second order nonholonomic system directly. As to the hybrid control method which has showed some promise for some systems [14, 15], it seems difficult to generalize it to this system. This can be explained by investigating the drift term $C_3(q,v)$ in the two-order nonholonomic constraint which is a motion equation of the system. As expressed in the Appendix, $C_3(q,v)$ can be further decomposed into

$$C_3(q,v) = C_{31}(q)v_1^2 + C_{32}(q)v_2^2 + C_{33}(q)v_3^2 + C_{34}(q)v_1 v_2. \tag{8}$$

This equation shows that, for the lack of gravitationlike term, after the transition ($v_{1,2,3} = 0$), the drift term $C_3(q,v)$ will approach zero exactly. This limits the use of hybrid method. While, the special form of drift $C_3(q,v)$ also inspires us that by producing cyclic motion of q_1 and q_2 with suitable control u_1 and u_2, after each cycle, $u_{1,2} = 0$ and $v_{1,2} = 0$, the system does have a pure motion along the direction of v_3 which is generated by v_1^2, v_2^2 and $v_1 v_2$ and can be approximately expressed by

$$v_3(T) - v_3(0) \approx C_{31}\int_0^T v_1^2 dt + C_{32}\int_0^T v_2^2 dt + C_{33}\int_0^T v_1 v_2 dt. \tag{9}$$

Therefore, it is possible to control the unactuated joint 3 by moving the actuated joints in circle-like trajectories. We study the problem below using an averaging method[16].

Substitute C_3 with (8), we have the motion equation of joint 3

$$\dot{v}_3 = C_1(q)u_1 + C_2(q)u_2 + C_{31}(q)v_1^2 + C_{32}(q)v_2^2 + C_{33}(q)v_3^2 + C_{34}(q)v_1v_2 \quad (10)$$

Similarly to [12], within one cycle $t\in[0,T]$, for joint $i=1,2$, we select the input as

$$u_i^{(2)} = \begin{cases} A_i\cos4\pi t/T, & t\in[0,T), \\ A_i\cos4\pi(t-T/2)/T, & t\in[T/2,T], \end{cases} \quad (11)$$

such that

$$v_i(T) - v_i(0) = \int_0^T u_i(t)\mathrm{d}t = 0,\ i = 1,2,$$

$$q_i(T) - q_i(0) = \int_0^T\int_0^t u_i(\tau)\mathrm{d}\tau\mathrm{d}t = 0,$$

then we have

$$\int_0^T v_i^2(t)\mathrm{d}t = \int_0^T\left(\int_0^t u_i(\tau)\mathrm{d}\tau\right)^2\mathrm{d}t = \frac{T^3}{8\pi^2}A^2,$$

$$\int_0^T v_1v_2\mathrm{d}t = \int_0^T\left(\int_0^t u_1(\tau)\mathrm{d}\tau\right)\left(\int_0^t u_2(\tau)\mathrm{d}\tau\right)\mathrm{d}t = \frac{T^3}{8\pi^2}A_1A_2. \quad (12)$$

Average(10), we obtain

$$\frac{1}{T}\int_0^T\dot{v}_3\mathrm{d}t = \frac{1}{T}\int_0^T C_1(q)u_1\mathrm{d}t + \frac{1}{T}\int_0^T C_2(q)u_2\mathrm{d}t + \frac{1}{T}\int_0^T C_{31}(q)v_1^2\mathrm{d}t + \frac{1}{T}\int_0^T C_{32}(q)v_2^2\mathrm{d}t + \frac{1}{T}\int_0^T C_{33}(q)v_3^2\mathrm{d}t + \frac{1}{T}\int_0^T C_{34}(q)v_1v_2\mathrm{d}t,$$

according to integral mean value theorems, by setting T small enough, we can obtain the averaged behavior of v_3, expressed by $\bar{v}_3$, as

$$\dot{\bar{v}}_3 = \frac{T^2}{8\pi^2}C_{31}(\bar{q})A_1^2 + \frac{T^2}{8\pi^2}C_{32}(\bar{q})A_2^2 + C_{33}(\bar{q})\bar{v}_3^2 + \frac{T^2}{8\pi^2}C_{34}(\bar{q})A_1A_2, \quad (13)$$

here $\bar{q}$ represents the average of q over [0,T].

Suppose $C_{31}(\bar{q}) \neq 0$, $C_{32}(\bar{q}) \neq 0$, let

$$A_i = \alpha_i\frac{2\sqrt{2}\pi}{T}\sqrt{\left|\frac{S(\bar{v}_3,\bar{q}^3,q_3^d)}{C_{31}(\bar{q})}\right|},\quad i = 1,2, \quad (14)$$

here

$$S(\bar{v}_3,\bar{q}_3,q_3^d) = -k_1\bar{v}_3 - k_2(\bar{q}_3 - q_3^d) - C_{33}(\bar{q})\bar{v}_3^2,$$

$$\alpha_1 = \begin{cases} 1, & SC_{31} > 0, \\ 0, & SC_{31} < 0. \end{cases} \quad (15)$$

$$\alpha_2 = \begin{cases} 1, & \alpha_1 = 0 \text{ and } SC_{32} > 0, \\ 0, & \alpha_1 = 1 \text{ or } SC_{32} < 0. \end{cases}$$

It is found that when $\alpha_1+\alpha_2=1$, substituting(15), (14) and (11) into (13), q_3 in the averaged system (13) will converge to q_3^d exponentially, implying we have constructed a control strategy in the average sense for the shape phase. We may conclude:

Proposition 3.1 For system (5) in the shape phase, with α_1,α_2 defined as (15), if $\alpha_1+\alpha_2\neq0$, the system (7) is controllable, and furthermore, the control laws (11), (14), (15) ensure its exponential convergence in the average sense, and meanwhile keep the final values of q_1, q_2 unchanged.

Now let's consider the difference between the averaged behavior of v_3 (13) and it's original one (10). From (11), (14), (15), it can be deduced that the control magnitude, A_i, will approach zero when $\bar{q}_3 \longrightarrow q_3^d$ and $\bar{v}_3 \longrightarrow 0$, which have been guaranteed by Proposition 3.1. This implies the magnitude of u_i and v_i will approach zero as well. Then what is left in equation (10) will be

$$\dot{v}_3 = C_{33}(q)v_3^2. \quad (16)$$

If $v_3 \neq 0$, the above equation means v_3 will change monotonously, which is contradictory to $\bar{v}_3 = 0$. So v_3 will approach zero, which means $q_3 \longrightarrow \bar{q}_3 \longrightarrow q_3^d$. This can be concluded as:

Proposition 3.2 For system (5) in the shape phase, with α_1,α_2 defined as (15), if $\alpha_1+\alpha_2\neq0$, the system (7) is controllable, and furthermore, the control laws (11), (14), (15) ensure the convergence of q_3 to q_3^d, and meanwhile keep the final values of q_1, q_2 unchanged.

Remark From (15) and (13), it is easy to find that $\alpha_1+\alpha_2\neq0$ gives a sufficient controllability condition. If it is satisfied, then $\alpha+\alpha_2\equiv1$, i.e., there is only one joint being actuated at a time. Therefore α_i defines a control switcher between joint 1 and joint 2. After a careful study of (14), we can even better define α_i in (15) so that a suitable joint can be selected to produce a smaller control amplitude. When the sufficient controllability condition $\alpha_1 + \alpha_2 \neq 0$ is not satisfied, the system can slide without any control till it reaches the region where $SC_{31} > 0$ or $SC_{32} > 0$.

3.2 Orientation control phase

In the orientation control phase, i.e., phase 3, we suppose joint 3 has moved to its desired angle. Without considering joint 3, by setting $v_3 = 0$, the system can be simplified as another reduced order form below

$$\begin{cases} \dot{q}_1 = v_1, \quad \dot{q}_2 = v_2, \\ \dot{\theta} = S_1(q)v_1 + S_2(q)v_2, \\ \dot{v}_1 = u_1, \quad \dot{v}_2 = u_2. \end{cases} \tag{17}$$

This is similar to a fully actuated three-link freefloating space robot. These models have been investigated extensively in publications [3,4,9]. It is easy to consider v_1 and v_2 as control variables for much more simplicity. With the control vectors

$$p_1 = \frac{\partial}{\partial q_1} + S_1 \frac{\partial}{\partial \theta}, \quad p_2 = \frac{\partial}{\partial q_2} + S_2 \frac{\partial}{\partial \theta},$$

the cycle movement of v_1 and v_2 will generate a pure move of θ in the direction of the control Lie bracket

$$[p_1, p_2] = \left(\frac{\partial S_2}{\partial q_1} - \frac{\partial S_1}{\partial q_2}\right)\frac{\partial}{\partial \theta}. \tag{18}$$

Here in this paper, for the reason of brevity, we propose a controller for the system (17) without proof, which can be done easily from (18).

Proposition 3.3 For the system (17), suppose

$$H(q) = \frac{\partial S_2}{\partial q_1} - \frac{\partial S_1}{\partial q_2} \neq 0, \tag{19}$$

with $\varepsilon > 0$ small enough, the control law below

$$\begin{cases} u_1^{(3)} = \mathrm{sgn}\left(\frac{-(\bar{\theta} - \theta^d)}{H(\bar{q})}\right)\sqrt{\left|\frac{-(\bar{\theta} - \theta^d)}{H(\bar{q})}\right|} \sin\frac{1}{\varepsilon}t, \\ u_2^{(3)} = \mathrm{sgn}\left(\frac{-(\bar{\theta} - \theta^d)}{H(\bar{q})}\right)\sqrt{\left|\frac{-(\bar{\theta} - \theta^d)}{H(\bar{q})}\right|} \cos\frac{1}{\varepsilon}t, \end{cases} \tag{20}$$

ensures the attractivity of θ^d asymptotically, and meanwhile keeps q_1, q_2 unchanged in an average sense.

This proposition shows that suitable cycle moves of joint 1 and joint 2 may produce a desired change of the orientation of the robot. However, the move may also generate undesired changes of the shape of the robot. It is because the velocities of joint 1 and joint 2 will unavoidably appear in (9) or (13), which trigger the move of joint 3. For the control of joint 1 and joint 2 in the form (20), from (12), (13), we can find that they generate movement of v_3 in the scale of $O(\varepsilon^2)$. Compared with the scale of movement $O(T^2)$ of v_3 generated by $u_i^{(2)}$, the undesired shape deformation can be compensated by the composite control $u_i^{(3c)} = u_i^{(2)} + u_i^{(3)}$ with $T \gg \varepsilon$. Conversely, the compensate control $u_i^{(2)}$ in $u_i^{(3c)}$ will not change the orientation of the robot. This is because the control switcher of (15) will allow only $u_1^{(2)}$ or $u_2^{(2)}$ active at one time, that will never generate any movement along the Lie bracket direction (18). Therefore we may have the following proposition which can be called orientation without shape deformation.

Proposition 3.4 The composite control strategy

$$u_i^c = u_i^{(2)} + u_i^{(3)}, \quad i = 1,2,$$

where $u_i^{(2)}$ and $u_i^{(3)}$ are defined by (11), (14), (15) and (20) separately, with $T \gg \varepsilon$, ensures the attractivity of θ^d for θ asymptotically in the orientation control phase, and meanwhile keeps q_1, q_2 and q_3 unchanged in an average sense.

Proof of this proposition can be implemented by using singular perturbation and averaging methods[16] based on the discussion above.

Remark we can even consider the composite law

$$u_i^c = u_i^{(1)} + u_i^{(2)} + u_i^{(3)}$$

to control the system, i.e., control the system in three different time scales t, Tt and εt. In fact, we use this strategy in simulation to deal with the error accumulation which may drive the system diverge from the desired position.

4 Simulation

In this section, we will mainly demonstrate the efficiency of the velocity based control method proposed in section 3.1. The example of a space robot is a four-link planar robot with the same dimension and mass parameters as used in [5]. The control task is to move the unactuated joint 3 from ($q_3(0) = 1, \dot{q}_3(0) = 0$) to its desired point ($q_3^f = 0, \dot{q}_3^f = 0$), with the actuated joint 1 and joint 2 moving in cyclic path and returning back to their initial position ($q_1 = -\pi/4, q_2 = \pi/4$) at the completion of a task. A composite controller

$$u_i^{(2c)} = u_i^{(1)} + u_i^{(2)}, \quad i = 1,2$$

is implemented in the simulation study. Here $u_i^{(1)}$ and $u_i^{(2)}$ are defined by (6) and (11) with parameters selected as

$k_{11}, k_{12} = 2,3;\quad k_{21}, k_{22} = 1.5,2;\quad k_1, k_2 = 4,1.$ From Fig.2 and Fig.3, we can see that joint 3 con-

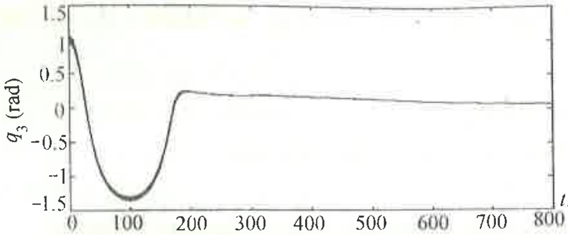

Fig. 2 Position of joint 3 (unactuated)

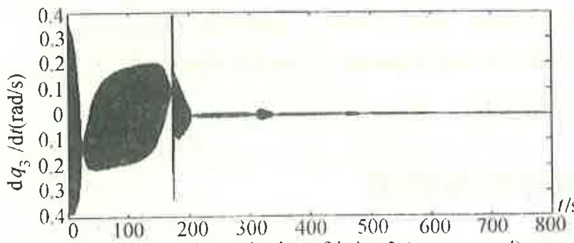

Fig. 3 Angular velocity of joint 3 (unactuated)

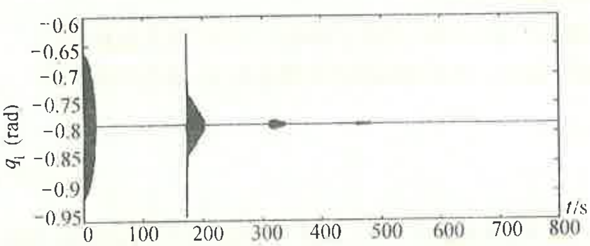

Fig. 4 Position of joint 1 (actuated)

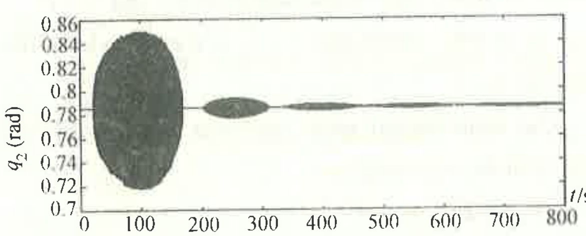

Fig. 5 Position of joint 2 (actuated)

verges well to its desired value, in both averaged system and real system. Compare Fig.4 with Fig.5, it is easy to show that our control switcher triggers joint 1 and joint 2 in turn. This verifies the results discussed in the remarks of Proposition 3.2.

5 Discussion and Conclusion

We have proposed a strategy to implement the point-to-point motion control of an underactuated free-floating robot. As an example, we have investigated extensively the system with two joints actuated and one joint free. Because its specific structure of the system, this system contains both the first-order and the second-order nonholonomic constraints, and thus is difficult to be stabilized by the existing nonholonomic control methods. Based on our analysis of the drift term in the system, a simple velocity-based method is designed to control the unactuated joint. Then a three step conrtol strategy is constructed for the whole control task. The proposed method can be extended easily to other types of space robots. The simulation study has verified the feasibility of the proposed method.

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