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ADAPTIVE CONTROL OF SPACE ROBOT SYSTEM WITH AN ATTITUDE CONTROLLED BASE

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Abstract

In this paper, we discuss adaptive control of a space robot system with an attitude controlled base on which the robot is attached. We found that in joint space the dynamics can be linearized by a set of combined dynamic parameters, but in inertia space linear parameterization is impossible in general. Then we propose an adaptive control scheme in joint space which has been shown effective and feasible for the cases where unknown or unmodeled dynamics must be considered. Since most tasks are specified in inertia space, instead of joint space, we discuss the issues associated to adaptive control in inertia space and identify two potential problems, unavailability of joint trajectory since mapping from inertia space trajectory is dynamic dependent and subject to uncertainty, and nonlinear parameterization in inertia space. We approach the problem by making use of the proposed joint space adaptive controller and updating joint trajectory by the estimated dynamic parameters and given trajectory in inertia space. In the case study of a planar system, the linear parameterization problem is investigated, the design procedure of the controller is illustrated, and the validity and effectiveness of the proposed control scheme are demonstrated.

1 Introduction

Considerable research efforts have been directed to some primary functions of robots in space applications, such as material transport, simple manipulation, basic locomotion, inspection and maintenance of the space station and satellites [1, 2]. The adaptive control is critical for the robot system subject to dynamic uncertainty in these tasks. Our paper [6] discussed extensively the need of adaptive control due to various unmodeled dynamic effects in space applications.

This paper focuses on the robot system where the base attitude is controlled by thrust jets. When the attitude of the base is controlled, the orientation and position of both robot and base are no longer free, and the dynamic interaction between the base and robot results in the dynamic dependent kinematics, i.e., the kinematics is in relation to the mass property of the base and robot.

In this paper, based on linear momentum conservation law and Lagrangian dynamics, we at first formulate kinematics and dynamics equations of the space robot system with an attitude controlled base, in a systematic way. Based on the dynamic model developed, we study the linear parameterization problem, i.e., dynamics can be linearly expressed in terms of dynamic parameters. We have found that for the space robot system with an attitude control base, the linear parameterization is valid in joint space, while is not valid in inertia Cartesian space, or in short, inertia space.

Using the dynamic model, we propose an adaptive control scheme in joint space. The scheme does not need an acceleration measurement in joint space and a high feedback gain controller. Since in most applications, the tasks are specified in inertia space, instead of joint space, we discuss the issues in relation to implementation of adaptive control in inertia space and identify two main problems. The first problem occurs when the joint adaptive control is executed. The required joint trajectory cannot be generated by the given trajectory in inertia space due to the parameter uncertainty in the kinematic mapping which is dynamics dependent. The second problem is nonlinear parameterization in inertia space which make impossible to implement the same structured adaptive control as that in joint space. We approach this problem by making use of joint space adaptive controller and updating joint trajectory from identified kinematic mapping and the given trajectory in inertia space. This method has shown its effectiveness in simulation, and some issues associated to parameter estimation and updating time are discussed.

Finally, we study a planar robot system to investigate linear parameterization problem of robot system dynamics, and illustrate the validity and effectiveness of the proposed adaptive control schemes.

2 Dynamics of Space Robot System

In this section we discuss the dynamics of the space robot system when the orientation of the base is controlled and the translation of the base is free. As shown in Figure 1, a space robot system with an attitude controlled base can be modeled as a multibody chain composed of $n+1$ rigid bodies connected by n joints, which are numbered from 1 to n. Each body is numbered from 0 to n, and the base is denoted by B in particular. The mass and inertia of ith body are denoted by m_i and $\mathbf{I}_i$, respectively. A joint variable vector $\mathbf{q} = (q_1, q_2, \cdots, q_n)^T$ is used to represent those joint displacements. The orientation of the base is represented by a vector $\mathbf{q}_B = (q_{B1}, q_{B2}, q_{B3})^T$.

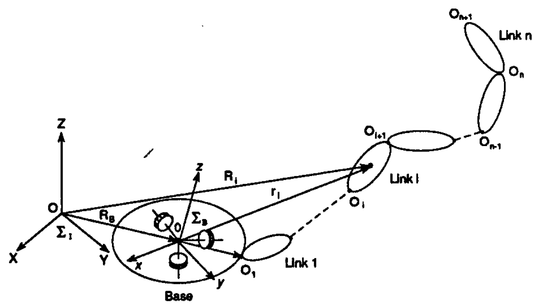

Figure 1 Space robot system with an attitude controlled base

Two coordinate frames are defined, the inertia coordinate $\sum_I$ on the orbit, and the base coordinate $\sum_B$ attached on the base body with its origin at the centroid of the base. As shown in Figure 1, let $\mathbf{R}_i$ and $\mathbf{r}_i$ be the position vectors pointing the centroid of ith body with reference to $\sum_I$ and $\sum_B$ respectively, then

$$\mathbf{R}_i = \mathbf{r}_i + \mathbf{R}_B \tag{1}$$

where $\mathbf{R}_B$ is the position vector pointing the centroid of the base with reference to $\sum_I$. Let $\mathbf{V}_i$ and $\mathbf{\Omega}_i$ be linear and angular velocities of ith body with respect to $\sum_I$, $\mathbf{v}_i$ and ω_i with respect to $\sum_B$. Then we have

$$\begin{aligned} \mathbf{V}_i &= \mathbf{v}_i + \mathbf{V}_B + \mathbf{\Omega}_B \times \mathbf{r}_i \\ \mathbf{\Omega}_i &= \omega_i + \mathbf{\Omega}_B \end{aligned} \tag{2}$$

where $\mathbf{V}_B$ and $\mathbf{\Omega}_B$ are linear and angular velocities of the centroid of the base with respect to $\sum_I$, and operator '$\times$' represents outer product of R^3 vector. The velocities $\mathbf{v}_i$ and ω_i in base coordinates can be represented by

$$\mathbf{v}_i = \mathbf{J}_{Li}(\mathbf{q})\dot{\mathbf{q}} \tag{3}$$

$$\omega_i = \mathbf{J}_{Ai}(\mathbf{q})\dot{\mathbf{q}} \tag{4}$$

where $\mathbf{J}_{Li}(\mathbf{q})$ and $\mathbf{J}_{Ai}(\mathbf{q})$ are the submatrices of Jacobian of the ith body representing linear part and angular part respectively. The motion rate relationship between joint space and inertia space has been derived [6] as follows.

$$\begin{bmatrix} \mathbf{\Omega}_B \\ \mathbf{V}_E \end{bmatrix} = \mathbf{N} \begin{bmatrix} \mathbf{\Omega}_B \\ \dot{\mathbf{q}} \end{bmatrix}, \qquad \mathbf{N} = \begin{bmatrix} \mathbf{U}_3 & \mathbf{O}_3 \\ \mathbf{J}_{rr} & \mathbf{J}_{rE} \end{bmatrix} \tag{5}$$

where $\mathbf{N}$ is the generalized Jacobian, $\mathbf{V}_E$ is the velocity of the robot end-effector in inertia space, $\mathbf{O}_3$ is a 3×3 zero matrix, and $\mathbf{U}_3$ is a 3×3 unity matrix. $\mathbf{J}_{rr} = [(\mathbf{r}_c - \mathbf{r}_E)\times]$, and $\mathbf{J}_{rE} = \mathbf{J}_E - \mathbf{J}_c$

The total system kinetic energy can be represented by [6]

$$\mathbf{T} = 1/2\dot{\theta}^T \mathbf{M}(\theta)\dot{\theta} \tag{6}$$

where $\theta = [\mathbf{q}_B, \mathbf{q}]^T$, $\mathbf{M}$ is the inertia matrix of the system.

$$\mathbf{M}(\theta) = \begin{bmatrix} \mathbf{M}_{11} & \mathbf{M}_{12} \\ \mathbf{M}_{21} & \mathbf{M}_{22} \end{bmatrix} \tag{7}$$

$$\mathbf{M}_{11} = \mathbf{I}_c + \sum_{i=1}^{n} \mathbf{D}(\mathbf{r}_i) m_i - \sum_{i=1}^{n}\sum_{j=1}^{n} R_{ij} m_i m_j / m_c \tag{8}$$

$$\mathbf{M}_{22} = \mathbf{H}_q + \sum_{i=1}^{n}\sum_{j=1}^{n} Q_{ij} m_i m_j / m_c \tag{9}$$

$$\mathbf{M}_{12} = \sum_{i=1}^{n} \mathbf{I}_i \mathbf{J}_{Ai} + \sum_{i=1}^{n} [\mathbf{r}_i]\mathbf{J}_{Li} m_i + \sum_{i=1}^{n}\sum_{j=1}^{n} S_{ij} m_i m_j / m_c \tag{10}$$

where the matrices $[\mathbf{r}_i]\mathbf{J}_{Li}$, $\mathbf{J}_{Ai}$, R_i, Q_i, S_i are only functions of geometric parameters, i.e., independent of dynamic parameters. The above formulations imply that the inertia matrix can be linearly represented by a set of combination of dynamic parameters, m_k, $\mathbf{I}_k$, $m_i m_j / m_c$, $i, j, k = 0, 1, \cdots, n$.

The property of linear parameterization to dynamic parameters is one of prerequisite conditions under which most adaptive and nonlinear dynamic control schemes are developed. It has been shown [5] that the problem of parameterization linearity in dynamics can be reduced to the problem of parameterization linearity in inertia matrix. Therefore, in order to study whether linear parameterization is valid for the space robot system with an attitude controlled base, we need to show whether the inertia matrix M can be linearly represented by a set of properly chosen combinations of dynamic parameters.

From the kinetic energy formulation, we can derive dynamics equation by Lagrangian dynamics.

$$\mathbf{M}\ddot{\theta} + \mathbf{B}(\theta, \dot{\theta})\dot{\theta} = \tau \tag{11}$$

where

$$\mathbf{B}(\theta, \dot{\theta})\dot{\theta} = \dot{\mathbf{M}}\dot{\theta} - \frac{\partial}{\partial \theta}\left(\frac{1}{2}\dot{\theta}^T \mathbf{M}\dot{\theta}\right) \tag{12}$$

The corresponding dynamic equation in inertia space is

$$\mathbf{H}\ddot{\mathbf{x}} + \mathbf{C}(\mathbf{x}, \dot{\mathbf{x}})\dot{\mathbf{x}} = \mathbf{F} \tag{13}$$

where

$$\mathbf{H} = \mathbf{N}^{-T}\mathbf{M}\mathbf{N}^{-1} \tag{14}$$

$$\mathbf{C} = \mathbf{N}^{-T}\mathbf{B}\mathbf{N}^{-1} - \mathbf{H}\dot{\mathbf{N}}\mathbf{N}^{-1} \tag{15}$$

N is a generalized Jacobian matrix and is dynamics depenedent for the space robot system. The inertia space dynamic equation can be linearly expressed in terms of dynamic parameters if and only if the inertia matrix **H** can be linearly parameterized [5] since

$$\mathbf{C}(\mathbf{x},\dot{\mathbf{x}})\dot{\mathbf{x}} = \dot{\mathbf{H}}\dot{\mathbf{x}} - \frac{\partial}{\partial \mathbf{x}}(\frac{1}{2}\dot{\mathbf{x}}^T\mathbf{H}\dot{\mathbf{x}}) \tag{16}$$

We suppose $\mathbf{N}^{-1}$ exists, and

$$\mathbf{N}^{-1} = \frac{\mathbf{N}^*}{det(\mathbf{N})} \tag{17}$$

where $\mathbf{N}^*$ and $det(\mathbf{N})$ are the adjoint and determinant of the matrix **N**, then

$$\mathbf{H} = \frac{\mathbf{N}^{*T}\mathbf{M}\mathbf{N}^*}{[det(\mathbf{N})]^2} \tag{18}$$

In the above equation, $[det(\mathbf{N})]^2$ appears as the denominator. From derivation procedure of **N** in the last section, it is clear that the **N** is time-varying and highly coupled by dynamic parameters, i.e., mass/inertia. For such a complicated nonlinear, time-varying function combining with dynamic parameters and time-varying joint angles, it is impossible that every element of $\mathbf{N}^{*T}\mathbf{M}\mathbf{N}^*$ has the common factor $[det(\mathbf{N})]^2$ at every instant.

Even if the above statement is true, there is still possibility to linearly parameterize **H**, provided that the numerator can be linearly parameterized and the denominator can be expressed as a product of two scalar functions with only one containing dynamic parameters, i.e.,

$$det(\mathbf{N}) = f_1(m_i, I_i)f_2(\theta_i) \tag{19}$$

where f_1 is a function of dynamic parameters which are unknown but constant, f_2 is a function independent of any dynamic parameters. This, unfortunately, is impossible in general due to high coupling between dynamic parameters and joint variables. For example, two DOF generalized Jacobian may contain the following simple terms

$$det(\mathbf{N}) = m_1 sin(\theta_1) + m_2 cos(\theta_2) \tag{20}$$

Even for such a simple form, $det(\mathbf{N})$ cannot be decomposed as a product of two functions with one containing m_1 and m_2 only, and nor can $[det(\mathbf{N})]^2$. Therefore, in general for a space robot with an attitude controlled base, dynamics can be linearly parameterized in terms of dynamic parameters in joint space, but it cannot in inertia space. More regerous proof can be found in our paper [3].

3 Adaptive Control Scheme

From previous discussion, we have learned that the dynamics of the space robot system in joint space is linear in terms of a set of combinations of dynamic parameters. Therefore, this set of new combined parameters can be used in the design of our adaptive controller. This leads us to propose an adaptive control algorithm in joint space. Since a unique solution may be found from inverse kinematics of the robot system *with the attitude controlled base*, adaptive control algorithm in joint space is feasible.

We define a composite error **s** in joint space

$$\mathbf{s} = \dot{\mathbf{e}}_p + \zeta \mathbf{e}_p \tag{21}$$

$$\mathbf{e}_p = \theta_d - \theta \tag{22}$$

and we also define modified joint velocity

$$\theta' = \dot{\theta} + \mathbf{s} \tag{23}$$

and modified joint acceleration

$$\theta'' = \frac{d}{dt}\theta' + \mathbf{s} = \ddot{\theta}_d + (\zeta+1)\dot{\mathbf{e}}_p + \zeta\mathbf{e}_p = \ddot{\theta}_d + \mathbf{s} + \zeta\dot{\mathbf{e}}_p \tag{24}$$

If we apply the following control law in joint space,

$$\tau = \hat{\mathbf{M}}\theta'' + \hat{\mathbf{B}}\theta' \tag{25}$$

then from Equation (11) we have

$$\mathbf{M}\ddot{\theta} = -\mathbf{B}(\theta,\dot{\theta})\dot{\theta} + \hat{\mathbf{M}}\theta'' + \hat{\mathbf{B}}\theta' \tag{26}$$

Defining $\tilde{\mathbf{M}} = \hat{\mathbf{M}} - \mathbf{M}$, $\tilde{\mathbf{B}} = \hat{\mathbf{B}} - \mathbf{B}$, we have

$$\mathbf{M}\ddot{\mathbf{e}}_p = -\mathbf{Y}(\theta,\dot{\theta},\theta_d,\dot{\theta}_d,\ddot{\theta}_d)\tilde{\mathbf{a}} - (\mathbf{M}+\mathbf{B})\mathbf{s} - \mathbf{M}\zeta\dot{\mathbf{e}}_p$$

where

$$\mathbf{Y}\tilde{\mathbf{a}} = \tilde{\mathbf{M}}\theta'' + \tilde{\mathbf{B}}\theta' \tag{27}$$

$$\tilde{\mathbf{a}} = \hat{\mathbf{a}} - \mathbf{a} \tag{28}$$

and $\hat{\mathbf{a}}$ is an estimation of the unknown dynamic parameters of the space robot system including the robot, the base, and the payload.

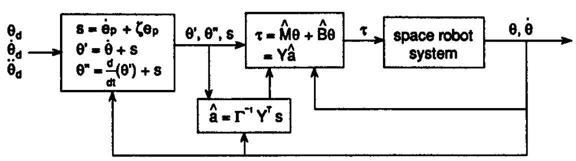

Figure 2 Block diagram of adaptive controller in joint space

We now design our adaptive control algorithm using Lyapunov function candidate

$$V = 1/2\mathbf{s}^T\mathbf{M}\mathbf{s} + 1/2\tilde{\mathbf{a}}^T\Gamma\tilde{\mathbf{a}} \tag{29}$$

where the matrix Γ is diagonal and positive definite. This yields

$$\dot{V} = -\mathbf{s}^T\mathbf{M}\mathbf{s} + 1/2\mathbf{s}^T(\dot{\mathbf{M}} - 2\mathbf{B})\mathbf{s} + \tilde{\mathbf{a}}^T(\Gamma\dot{\hat{\mathbf{a}}} - \mathbf{Y}^T\mathbf{s}) \leq 0$$

if

$$\dot{\hat{\mathbf{a}}} = \Gamma^{-1}\mathbf{Y}^T\mathbf{s} \tag{30}$$

due to the fact that the matrix $\dot{\mathbf{M}} - 2\mathbf{B}$ is skew-symmetric, and **M** is positive definite. Therefore, the system is stable in the sense of Lyapunov [6]. A PID type adaptive control scheme has also been studied in [6]. A block diagram of the proposed control algorithm with PD type s is shown in Figure 2. The proposed adaptive controller is conceptually simple and easy to implement. This approach does not require the use of joint accelerations and inversion of inertia matrix. Its computational cost is low because it can be implemented through the use of Newton-Euler recursive formulation, which can be seen from Equation (25).

4 Adaptive Control in Inertia Space

Conceptually, for most applications, the desired robot hand trajectory (i.e., position, velocity and acceleration) must be specified in inertia space. For example, let's consider catching a moving object by a space robot. The desired trajectory after catching depends upon the tasks and the motion trajectory of the object before catching, and thus must be specified in inertia space. Fortunately, the mapping from robot hand position in inertia space to displacements in joint space can be uniquely determined for a space robot system when the base is attitude controlled. For a complete free-flying space robot system, this mapping is not uniquely determined [5].

However, the unique kinematics relationship can only be determined when dynamic parameters are given, for this relationship is indeed dynamic dependent. When some dynamic parameters are unknown, which is indeed the reason why we come to adaptive control, the mapping is not determined! Therefore, the primary difficulty of extending our approach from joint space to inertia space is that the desired trajectory in inertia space cannot be transformed to the desired trajectory in joint space because some dynamic parameters are unknown. In previous discussion, we have utilized a desired trajectory in joint space, as other researchers have done [4], without giving any explanation about how the trajectory is generated. The problem is not significant if the objective is to identify dynamic parameters, but is important if the objective is to control the system.

The problem can be resolved if the same structured adaptive control scheme can be implemented in inertia space. This, however, is not feasible because the proposed adaptive control scheme in joint space requires the linear parameterization of the dynamic model which is not valid for the inertia space representation.

We approach the problem in the following way. First, given trajectory in inertia space, we use an initial estimation of dynamic parameters to compute initial joint trajectory. Then the initial joint trajectory and dynamic parameters are used in the proposed joint space adaptive control algorithms. After a certain period of time we update the system dynamic parameters by using new estimated ones in the outer loop of our controller. We can then specify more precise joint space trajectory based on these new parameters and the inertia space trajectory. Since the inertia space trajectory is uniquely determined by the joint space trajectory and dynamic parameters, it can be shown from the Jacobian relationship that position errors in inertia space converges to a given boundary if position errors in joint space and parameter errors are bounded, provided that the robot is not in its singularity configuration. The control scheme is illustrated in Figure 3.

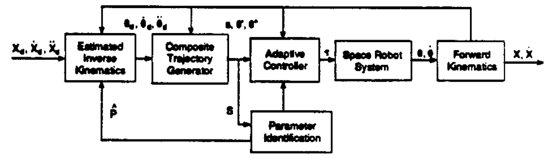

Figure 3 Block diagram of adaptive control strategy in inertia space

It is worthwhile to discuss two issues in the implementation of the proposed control scheme. First, to accurately estimate unknown parameters, a persistent excitation (PE) trajectory is required to drive the robot joints. PE trajectories in joint space and that in inertia space are not equivalent due to nonlinear kinematic transformation. Therefore, it is of importance to carefully choose initial trajectory in inertia space such that the resultant trajectory in joint space is of PE. If the PE condition is not satisfied, parameter identification error occurs, although the joint space position errors may still converge.

Second, the updating time for inverse kinematics using the estimated parameters in the outer loop must be slow enough to maintain the system stable. The outer loop, as shown in Figure 3, is used to update the inverse kinematics and thereby the desired joint trajectory that is used in joint space adaptive controller. A fast updation may not guarantee the convergence of parameter errors. In the simulation, the updating time for inverse kinematics is set to 10 seconds. Simulation results have shown that position errors in inertia space converge to zero as errors in joint space converge to zero and estimated parameters converge to their true values.

5 Simulation Study

In this section, we conduct a case study to show the computation of the proposed algorithms and their feasibility. A two-DOF revolute manipulator with link length given by l_1 and l_2 (l_1=l_2=l) is considered as a lumped-parameter model with point mass m_1 and m_2 at the end of each link. For simplicity, we assume that the base attitude can be successfully controlled so that we need only consider the control of the robot itself. The system model for simulation study is shown in Figure 4.

At initialization, m_c and $\mathbf{R}_c$ are computed, and they remain unchanged unless a load is added.

$$m_c = m_0 + m_1 + m_2 \tag{31}$$

$$m_c\mathbf{R}_c = m_0\mathbf{R}_0 + m_1\mathbf{R}_1 + m_2\mathbf{R}_2 \tag{32}$$

$$\mathbf{R}_1 = \mathbf{R}_0 + \mathbf{r}_1 \tag{33}$$

$$\mathbf{R}_2 = \mathbf{R}_0 + \mathbf{r}_2 \tag{34}$$

The generalized Jacobian is

$$\mathbf{N} = \frac{l}{m_c}\begin{bmatrix} -(m_1+m_2)s_1 - m_2 s_{12} & -m_2 s_{12} \\ (m_1+m_2)c_1 + m_2 c_{12} & m_2 c_{12} \end{bmatrix} \tag{35}$$

The system dynamics has the following form,

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{B}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} = \tau \tag{36}$$

where

$$\mathbf{M} = p_1\mathbf{R}_1 + p_2\mathbf{R}_2 + p_3\mathbf{R}_3 \tag{37}$$

$$p_1 = \frac{m_0 m_1}{m_c}, \quad p_2 = \frac{m_1 m_2}{m_c}, \quad p_3 = \frac{m_0 m_2}{m_c} \tag{38}$$

$$\mathbf{R}_1 = l^2\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \quad \mathbf{R}_2 = l^2\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \tag{39}$$

$$\mathbf{R}_3 = l^2\begin{bmatrix} 2(1+c_2)1 & (1+c_2)1 \\ (1+c_2)1 & 1 \end{bmatrix} \tag{40}$$

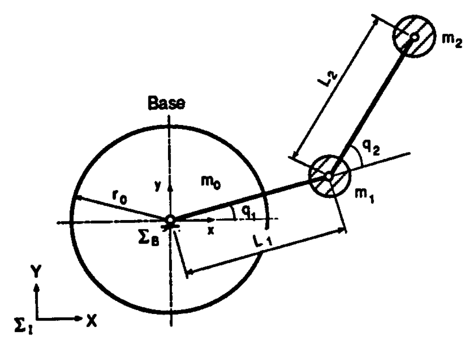

Figure 4 Planar space robot system model

It is noted that $\mathbf{M}$ is linear in terms of the combined dynamic parameters p_1, p_2 and p_3. This is an example to show that dynamics of the space robot system can be linearly parameterized in joint space when the base attitude is controlled. We also note that m_0, m_1 and m_2 can be uniquely determined by p_1, p_2 and p_3,

$$m_1 = p_1 p_2\left(\frac{1}{p_1} + \frac{1}{p_2} + \frac{1}{p_3}\right) \tag{41}$$

$$m_2 = p_2 p_3\left(\frac{1}{p_1} + \frac{1}{p_2} + \frac{1}{p_3}\right) \tag{42}$$

$$m_0 = p_1 p_3\left(\frac{1}{p_1} + \frac{1}{p_2} + \frac{1}{p_3}\right) \tag{43}$$

The matrix $\mathbf{B}$ is determined by

$$\mathbf{B} = \frac{m_0 m_2}{m_c}\begin{bmatrix} -2l^2 s_2\dot{q}_2 & -l^2 s_2 \dot{q}_2 \\ l^2 s_2 \dot{q}_1 & 0 \end{bmatrix} = p_3\mathbf{R}_4 \tag{44}$$

Our adaptive control law is

$$\tau = \hat{\mathbf{M}}\mathbf{q}'' + \hat{\mathbf{B}}\mathbf{q}' = \mathbf{Y}\hat{\mathbf{a}} \tag{45}$$

$$\mathbf{Y} = \begin{bmatrix} \mathbf{R}_1\mathbf{q}'' & \mathbf{R}_2\mathbf{q}'' & \mathbf{R}_3\mathbf{q}'' + \mathbf{R}_4\mathbf{q}' \end{bmatrix} \tag{46}$$

$$\hat{\mathbf{a}} = [\hat{p_1}, \hat{p_2}, \hat{p_3}]^T \tag{47}$$

with the following adaptation law

$$\dot{\hat{\mathbf{a}}} = [\gamma_1 \mathbf{s}^T\mathbf{R}_1\mathbf{q}'', \gamma_2 \mathbf{s}^T\mathbf{R}_2\mathbf{q}'', \gamma_3 \mathbf{s}^T(\mathbf{R}_3\mathbf{q}'' + \mathbf{R}_4\mathbf{q}')]^T \tag{48}$$

To study the proposed adaptive algorithms, we use the following common set of conditions:

$$q_{1d} = \frac{\pi}{180}(54 + 6(sin(t) + cos(4t))) \tag{49}$$

$$q_{2d} = \frac{\pi}{180}(-126 + 6(sin(2t) + cos(6t))) \tag{50}$$

$$\zeta = 10 \tag{51}$$

In the first case we used the mass parameters below, $m_0 = 41kg$, $m_1 = 5kg$, $m_2 = 4kg$, and the initial guess of all three parameters is set to 50% of their true values. It can be found from Figure 5 that joint errors converge to zero and all parameters converge to their true values 4.1, 0.4, and 3.28 (with small errors 1.2%, 2.1%, 2.5%, respectively) after a transient period (approximately 10 seconds). Figure 6 shows identification of combined parameters p_1, p_2, and p_3, and the resultant mass m_1, m_2, and m_0. From Figure 6 we found that estimation of all parameters m_1, m_2, and m_0 are very close to their true values. For inertia space adaptive controller, an initial guess of the updating parameters is set to 80% of the true value. The inertia space trajectory and joint space trajectory employed in the simulation are shown in Figure 7. We used 10 seconds as updating time for inverse kinematics. The effectiveness of this adaptive scheme has been verified by the tracking errors shown in Figure 8. It is found that position errors in inertia space converge to zero as errors in joint space converge to zero and estimated parameters converge to their true values. More results can be found in our paper [6].

6 Conclusions

In this paper, we have discussed adaptive control of a space robot system with an attitude controlled base on which the robot is attached. We showed that the system dynamics in joint space can be linearly parameterized, i.e., the dynamics can be linearized in joint space by a set of combined dynamic parameters, while the same conclusion is not true in inertia space.

An adaptive control scheme in joint space is proposed to cope with dynamic uncertainties based on the dynamic model developed. The scheme is effective and feasible for space robot applications by eliminating the use of joint acceleration measurement, inversion of inertial matrix, high gain feedback, and considerable computation cost.

Concerning that the tasks in space are specified in inertia space in most applications, we discussed the issues of adaptive control of the robot for the tasks that must be filfull in inertia space. Two main problems have been identified. If the joint adaptive control is implemented, the desired joint trajectory cannot be generated from the given inertia space trajectory since kinematic mapping is dynamics dependent, and thus is subjected to uncertainty in parameters. Moreover, the same structured adaptive control as in joint space is not feasible for inertia space due to nonlinear parameterization in inertia space. We approached this problem by making use of the proposed joint space adaptive controller while updating joint trajectory by using the estimated dynamic parameters and the given trajectory in inertia space. This method has shown its effectiveness in simulation.

References

[1] A.K. Bejczy and B. Hannaford. Man-machine interaction in space telerobotics. In *Proceedings of the International Symposium of Teleoperation and control 1988*, 1988.

[2] G. Butler (edited). *The 21st century in space: adavances in the astrountical sciences.* American Astronautical Society, 1988.

[3] Y.-L. Gu and Y. Xu. Internal dynamics and adaptive control of a space robot system. *(submitted to IEEE Transactions on Robotics and Automation)*, 1991.

[4] M.W. Walker and L-B. Wee. An adaptive control strategy for space based robot manipulators. In *Proceedings of IEEE Conference on Robotics and Automation*, 1991.

[5] Yangsheng Xu and Heung-Yeung Shum. Dynamic control of a space robot system with no thrust jets controlled base. Technical Report CMU-RI-TR-91-34, The Robotics Institute, Carnegie-Mellon University, 1991.

[6] Yangsheng Xu, Heung-Yeung Shum, Ju-Jang Lee, and Takeo Kanade. Adaptive control of a space robot system with an attitude controlled base. Technical Report CMU-RI-TR-91-14, The Robotics Institute, Carnegie-Mellon University, 1991.

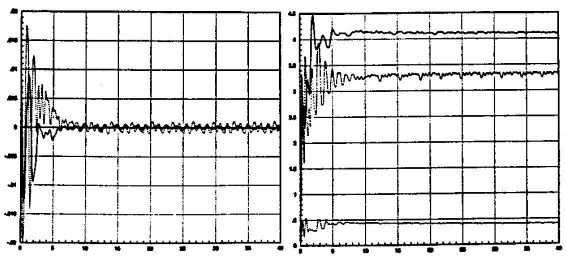

Figure 5 Tracking errors and parameter estimations using joint space adaptive control

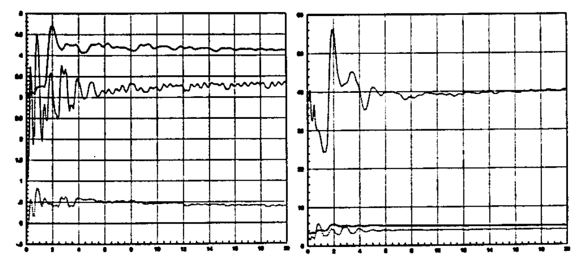

Figure 6 Illustration of combined dynamic parameter identification

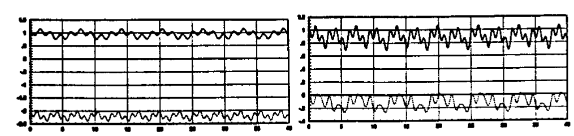

Figure 7 Trajectories in joint space and in inertia space using inertia space adaptive controller

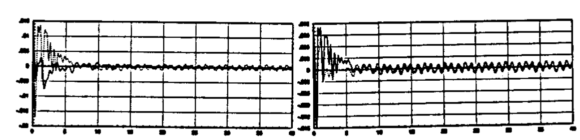

Figure 8 Tracking errors in joint space and in inertia space using inertia space adaptive controller