2017 IEEE 56th Annual Conference on Decision and Control (CDC)
December 12-15, 2017, Melbourne, Australia

Task-Space Adaptive Dynamic Modularity Control of Free-Floating Space Manipulators

Hanlei Wang, Long Cheng, and Yongchun Xie

Abstract— **In this paper, we investigate the task-space adaptive control problem for free-floating space manipulators with uncertain kinematics and dynamics and with an unmodifiable inner joint control loop. The existence of an unmodifiable inner joint control loop makes most torque-based control algorithms in the literature inapplicable. We propose a dynamic modularity (DM) approach to resolve this problem, and this is hopeful for bridging the potential gap between the advanced control theory for (free-floating) space manipulators and practical engineering applications. Adaptive outer loop controllers are developed and shown to be able to guarantee the convergence of the task-space tracking errors. The performance of the proposed DM approach is shown by a numerical simulation.**

I. Introduction

The on-orbit servicing (OOS) with the aid of robot manipulators has recently become active in the space industry and academic community (see, e.g., [1], [2], [3]). The research on the system composed of a spacecraft and one or multiple manipulators mounted on it (known as space manipulator), however, dates back to the quite early years, covering the system kinematics, dynamics, and control (see, e.g., [4], [5], [6], [7]), and we may also note that the concept of space manipulator has already spread quite a lot (e.g., tethered space robots [8], [9]). The expectation of space manipulators to maneuver various classes of objects flexibly and intelligently motivates the sustaining research on developing adaptive controllers for space manipulators [10], [11], [12], [13], [14], [15], and the study of similar systems using adaptive algorithms also appears in the context of robots on a moving platform [16].

Dealing with the control of complex nonlinear systems is challenging, and one desirable situation that we may intuitively expect is the separation or relative independence of different system loops (i.e., achieving certain degree of modularity). One such case occurs in the adaptive control of fixed-base robots [17], [18]. Specifically, the kinematic and dynamic loops are separated and performance improvement is achieved in [17] by employing an adaptive kinematic regressor matrix and the inverse Jacobian feedback (unlike the results in [19], [20], [21], [22]), and a dynamic modularity (DM) approach is proposed in [18] to accommodate the users' needs and the interest of the robot manufacturers where the designs of the outer loop (for users) and the inner loop (for robot manufacturers) can be performed independently and more desirably the stability of the whole system can still be rigorously guaranteed. This motivates us to extend the DM approach in [18] to free-floating space manipulators (FFSMs), which have important applications in space activities and show particular advantages in terms of safe manipulation and energy conservation [5], [23]. The control scheme in [12] is torque-based and thus inapplicable to FFSMs that do not allow the torque input design [for instance, in many robotic applications, it is well known that the joint velocity (or position) command rather than joint torque can be directly specified]; in addition, the performance of the transpose Jacobian control used in [12] is not guaranteed to be satisfactory, as is stated in [24]. Due to the similar reason, the application of the inverse-dynamics-based adaptive controller in [14] to free-floating systems with a manipulator that does not admit the joint torque design is also challenging.

In this paper, we propose a DM approach for FFSMs with uncertain kinematics and dynamics, which can be considered as an extension of [25], [18] to the case of robots with a free-floating base. Specifically, we propose a design approach for the joint velocity (or position) command as well as parameter adaptation laws (which can also be referred to as adaptive outer loop controller) to address the dynamic effects and parametric uncertainties of the system consisting of both the manipulator and its free-floating base. It is shown that the proposed adaptive outer loop controllers can ensure the stability and convergence of the FFSM system with an inner unmodifiable PD/PID (proportional-derivative/proportional-integral-derivative) controller. In addition, the feedback control as well as the kinematic parameter adaptation law used here can be interpreted as adaptive inverse-Jacobian-like control (extending the results in [26], [27], [17] to address the case of a free-floating base), which tends to yield the improved performance in comparison with the adaptive transpose Jacobian controller in [12] (see, e.g., [17]). From an application perspective, thanks to the achieved dynamic modularity, the proposed approach can be applied to most engineering space robotic systems with an unmodifiable inner control loop (e.g., the ETS-VII space manipulator).

This work was supported by the National Natural Science Foundation of China under Grants 61374060, 61422310, 61333008, 61633016, and 61370032, the National Key Basic Research Program (973) of China under Grant 2013CB733100, and the China Scholarship Council.

H. Wang is with the Science and Technology on Space Intelligent Control Laboratory, Beijing Institute of Control Engineering, Beijing 100094, China (e-mail: hlwang.bice@gmail.com).

L. Cheng is with the State Key Laboratory of Management and Control for Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China, and also with the University of Chinese Academy of Sciences (e-mail: long.cheng@ia.ac.cn).

Y. Xie is with the Science and Technology on Space Intelligent Control Laboratory, Beijing Institute of Control Engineering, Beijing 100094, China, and also with Tianjin Key Laboratory of Microgravity and Hypogravity Environment Simulation Technology, Tianjin 330452, China (e-mail: xieyongchun@vip.sina.com).

978-1-5090-2872-6/17/$31.00 ©2017 IEEE

Furthermore, the proposed dynamic modularity control approach may seem more promising in that it would potentially decrease the cost of development of high-performance space robotic systems due to the dynamic modularity and that it might also help promote the commercialization of space robotic projects.

II. Kinematics and Dynamics of Free-Floating Space Manipulators

Consider a FFSM with zero initial linear and angular momenta. Let $x \in R^n$ be the position of the end-effector of the FFSM in the task space (e.g., Cartesian space or image space), and it is relevant to the manipulator joint position and spacecraft attitude via a nonlinear mapping (see, e.g., [5], [28]). The end-effector velocity $\dot{x}$ can be written as [5], [28]

$$\dot{x} = J_b(\epsilon_b, q_m)\omega_b + J_m(\epsilon_b, q_m)\dot{q}_m \tag{1}$$

where $q_m \in R^n$ is the manipulator joint position, $\epsilon_b \in R^4$ is the Euler parameter vector that corresponds to the spacecraft attitude matrix (see, e.g., [29]), $\omega_b \in R^3$ is the angular velocity of the spacecraft with respect to the inertial frame expressed in the spacecraft frame, and $J_b(\epsilon_b, q_m) \in R^{n\times 3}$ and $J_m(\epsilon_b, q_m) \in R^{n\times n}$ are the Jacobian matrices. For conciseness, $J_b(\epsilon_b, q_m)$ and $J_m(\epsilon_b, q_m)$ are denoted by J_b and J_m in the sequel, respectively. The kinematics (1) has the following linearity-in-parameters property [19], [26].

Property 1: The kinematics (1) depends linearly on a constant kinematic parameter vector a_k, which gives rise to

$$J_b\psi_1 + J_m\psi_2 = Z(\epsilon_b, q_m, \psi)a_k \tag{2}$$

where $\psi_1 \in R^3$, $\psi_2 \in R^n$, $\psi = \left[\psi_1^T, \psi_2^T\right]^T$, and $Z(\epsilon_b, q_m, \psi)$ is the kinematic regressor matrix.

The equations of motion of the FFSM taking into consideration the actuator model can be written as [10], [30]

$$M(q_m)\ddot{q} + C(q_m, \dot{q})\dot{q} + \begin{bmatrix} 0_3 \\ B\dot{q}_m \end{bmatrix} = \begin{bmatrix} 0_3 \\ Ku \end{bmatrix} \tag{3}$$

where $\dot{q}_m$ is the manipulator joint velocity, $\dot{q} = \left[\omega_b^T, \dot{q}_m^T\right]^T$, $M(q_m) = \begin{bmatrix} M_{bb} & M_{bm} \\ M_{bm}^T & M_{mm} \end{bmatrix}$ is the inertia matrix, $C(q_m, \dot{q}) = \begin{bmatrix} C_{bb} & C_{bm} \\ C_{mb} & C_{mm} \end{bmatrix}$ is the Coriolis and centrifugal matrix, $M_{bb} \in R^{3\times 3}$ is the inertia matrix of the spacecraft, $M_{bm} \in R^{3\times n}$ is the coupled inertia matrix between the spacecraft and the manipulator, $M_{mm} \in R^{n\times n}$ is the inertia matrix of the manipulator, $C_{bb} \in R^{3\times 3}$ is the Coriolis and centrifugal matrix of the spacecraft, $C_{bm} \in R^{3\times n}$ is the coupled Coriolis and centrifugal matrix between the spacecraft and the manipulator, $C_{mb} \in R^{n\times 3}$ is the coupled Coriolis and centrifugal matrix between the manipulator and the spacecraft, $C_{mm} \in R^{n\times n}$ is the Coriolis and centrifugal matrix of the manipulator, $B \in R^{n\times n}$ is a diagonal positive definite matrix, $K \in R^{n\times n}$ is a diagonal positive definite matrix, and $u \in R^n$ is the armature voltage. Three well-recognized properties associated with (3) are listed as follows (see, e.g., [5], [10], [31]).

Property 2: The inertia matrix $M(q_m)$ is symmetric and uniformly positive definite.

Property 3: The Coriolis and centrifugal matrix $C(q_m, \dot{q})$ can be suitably chosen so that $\dot{M}(q_m) - 2C(q_m, \dot{q})$ is skew-symmetric.

Property 4: The dynamics (3) depends linearly on a constant dynamic parameter vector a_d, which yields

$$\begin{aligned} &M_{bb}\dot{\zeta}_1 + M_{bm}\dot{\zeta}_2 + C_{bb}\zeta_1 + C_{bm}\zeta_2 \\ &= Y_b(q_m, \dot{q}, \zeta, \dot{\zeta})a_d \end{aligned} \tag{4}$$

$$\begin{aligned} &M_{bm}^T\dot{\zeta}_1 + M_{mm}\dot{\zeta}_2 + C_{mb}\zeta_1 + C_{mm}\zeta_2 + B\zeta_2 \\ &= Y_m(q_m, \dot{q}, \zeta, \dot{\zeta})a_d \end{aligned} \tag{5}$$

where $\zeta_1 \in R^3$ and $\zeta_2 \in R^n$ are differentiable vectors, $\zeta = \left[\zeta_1^T, \zeta_2^T\right]^T$, $\dot{\zeta}$ is the derivative of ζ, and $Y_b(q_m, \dot{q}, \zeta, \dot{\zeta})$ and $Y_m(q_m, \dot{q}, \zeta, \dot{\zeta})$ are regressor matrices.

III. Adaptive Outer Loop Control

In this section, we investigate the adaptive outer loop controller design for the FFSM system given by (1) and (3) with u being specified by the PD control action (the case of PID control is discussed later)

$$u = -K_D(\dot{q}_m - \dot{q}_{mc}) - K_P(q_m - q_{mc}) \tag{6}$$

where q_{mc} and $\dot{q}_{mc}$ act as the joint position and velocity commands, respectively, and K_D and K_P are diagonal positive definite matrices and typically unknown to the user. This is a major difference between our work and most results in the literature (e.g., [11], [12], [13], [14]), and it is well known that an inner PD or PID controller is typically adopted in most industrial/commercial robots (see, e.g., [32], [33]) and in most space robotic applications (e.g., the ETS-VII space manipulator). The control objective is to realize the asymptotic end-effector trajectory tracking, i.e., $x - x_d \to 0$ as $t \to \infty$, where $x_d \in R^n$ denotes the desired trajectory and it is assumed that x_d, $\dot{x}_d$, and $\ddot{x}_d$ are all bounded. For facilitating the controller design in the sequel, we rewrite (6) as

$$u = -K_D\left[(\dot{q}_m - \dot{q}_{mc}) + \mathcal{K}_P(q_m - q_{mc})\right] \tag{7}$$

where $\mathcal{K}_P = K_D^{-1}K_P = \mathrm{diag}[w_P]$ with w_P being an n-dimensional vector.

We first define a spacecraft reference velocity ω_{br} by

$$\hat{M}_{bb}\dot{\omega}_{br} + \hat{M}_{bm}\ddot{q}_{mr} + \hat{C}_{bb}\omega_{br} + \hat{C}_{bm}\dot{q}_{mr} = K_b(\omega_b - \omega_{br}) \tag{8}$$

where K_b is a symmetric positive definite matrix, $\dot{q}_{mr}$ and $\ddot{q}_{mr}$ will be defined later, and the matrices $\hat{M}_{bb}$, $\hat{M}_{bm}$, $\hat{C}_{bb}$, and $\hat{C}_{bm}$ are obtained by replacing the parameter a_d in M_{bb}, M_{bm}, C_{bb}, and C_{bm} with its estimate $\hat{a}_d$, respectively. The definition of ω_{br} given by (8) is based on [12], and the difference is that here the estimated transpose Jacobian feedback is no longer needed. The interesting point may lie in the fact that the above definition, although for the case of task-space trajectory tracking, is the same as the one for the case of joint-space trajectory tracking in [34]. Using ω_{br} defined by (8), we define a sliding vector

$$s_b = \omega_b - \omega_{br}. \tag{9}$$

Next, following [12], we define a manipulator joint reference velocity

$$\dot{q}_{mr} = \hat{J}_m^{-1}(\dot{x}_r - \hat{J}_b\omega_{br}) \tag{10}$$

where $\dot{x}_r = \dot{x}_d - \alpha\Delta x$ with α being a positive design constant and $\Delta x = x - x_d$, and $\hat{J}_b$ and $\hat{J}_m$ are the estimated Jacobian matrices and are obtained by replacing a_k in J_b and J_m with its estimate $\hat{a}_k$, respectively. Differentiating (10) with respect to time yields

$$\ddot{q}_{mr} = \hat{J}_m^{-1}(\ddot{x}_r - \hat{J}_b\dot{\omega}_{br} - \dot{\hat{J}}_b\omega_{br} - \dot{\hat{J}}_m\dot{q}_{mr}). \tag{11}$$

We now define a sliding vector

$$s_m = \dot{q}_m - \dot{q}_{mr}. \tag{12}$$

From (9) and (12) and using (1), (10), and Property 1, we have that

$$\begin{aligned} J_b s_b + J_m s_m =& \dot{x} - J_m\dot{q}_{mr} - J_b\omega_{br} \\ =& \Delta\dot{x} + \alpha\Delta x + Z(\epsilon_b, q_m, \dot{q}_r)\Delta a_k \end{aligned} \tag{13}$$

and equation (13) can further be written as

$$\Delta\dot{x} = -\alpha\Delta x - Z(\epsilon_b, q_m, \dot{q}_r)\Delta a_k + Js \tag{14}$$

where $\dot{q}_r = \left[\omega_{br}^T, \dot{q}_{mr}^T\right]^T$, $s = \left[s_b^T, s_m^T\right]^T$, $\Delta a_k = \hat{a}_k - a_k$, and $J = \begin{bmatrix} J_b & J_m \end{bmatrix}$. The formulation (13) and (14) is made by introducing a kinematic regressor matrix $Z(\epsilon_b, q_m, \dot{q}_r)$ that depends on the reference velocity $\dot{q}_r$ (in contrast to [12]), which extends the results in [26], [27], [17] to consider the case of a free-floating base.

The joint velocity command is given as

$$\begin{aligned} \dot{q}_{mc} + \hat{\mathcal{K}}_P q_{mc} =& \dot{q}_{mr} + \hat{\mathcal{K}}_P q_{mr} + \mathrm{diag}[\hat{w}_i, i = 1, \ldots, n] \\ &\times [Y_m(q_m, \dot{q}, \dot{q}_r, \ddot{q}_r)\hat{a}_d] \end{aligned} \tag{15}$$

where

$$q_{mr} = q_{mr}(0) + \int_0^t \dot{q}_{mr}(\sigma)d\sigma, \tag{16}$$

$\hat{w}_i$ is the estimate of the inverse of the i-th diagonal entry of $K_D^* = KK_D$ which is denoted by w_i, $i = 1, \ldots, n$, and $\hat{\mathcal{K}}_P = \mathrm{diag}[\hat{w}_P]$ with $\hat{w}_P$ being the estimate of w_P. w_i can be explicitly expressed as $w_i = (k_{ii}k_{D,ii})^{-1}$ with k_{ii} denoting the i-th diagonal entry of K and $k_{D,ii}$ denoting the i-th diagonal entry of K_D, $i = 1, \ldots, n$. The adaptation laws for the estimated parameters $\hat{a}_k$, $\hat{a}_d$, $\hat{w} = [\hat{w}_1, \ldots, \hat{w}_n]^T$, and $\hat{w}_P$ are given as

$$\dot{\hat{a}}_k = \Gamma_k Z^T(\epsilon_b, q_m, \dot{q}_r)\Delta x \tag{17}$$

$$\dot{\hat{a}}_d = -\Gamma_d Y^T(q_m, \dot{q}, \dot{q}_r, \ddot{q}_r)s \tag{18}$$

$$\dot{\hat{w}} = -\Lambda \mathrm{diag}[Y_m(q_m, \dot{q}, \dot{q}_r, \ddot{q}_r)\hat{a}_d]s_m \tag{19}$$

$$\dot{\hat{w}}_P = \Lambda_P \mathrm{diag}[q_{mc} - q_{mr}]s_m \tag{20}$$

where Γ_k and Γ_d are symmetric positive definite matrices, Λ and Λ_P are diagonal positive definite matrices, $s = \left[s_b^T, s_m^T\right]^T$, and

$$Y(q_m, \dot{q}, \dot{q}_r, \ddot{q}_r) = \begin{bmatrix} Y_b^T(q_m, \dot{q}, \dot{q}_r, \ddot{q}_r) & Y_m^T(q_m, \dot{q}, \dot{q}_r, \ddot{q}_r) \end{bmatrix}^T.$$

Substituting (8) into the upper portion of (3) and using Property 4 gives

$$\begin{aligned} &M_{bb}\dot{s}_b + M_{bm}\dot{s}_m + C_{bb}s_b + C_{bm}s_m \\ &= -K_b s_b + Y_b(q_m, \dot{q}, \dot{q}_r, \ddot{q}_r)\Delta a_d \end{aligned} \tag{21}$$

where $\Delta a_d = \hat{a}_d - a_d$. Combining (15), (7), and the lower portion of (3) gives (using Property 4)

$$\begin{aligned} &M_{bm}^T\dot{s}_b + M_{mm}\dot{s}_m + C_{mb}s_b + C_{mm}s_m \\ &= -(K_D^* + B)s_m - K_P^*\left[\int_0^t s_m(\sigma)d\sigma + \delta_0\right] \\ &\quad + K_D^*\mathrm{diag}[\Delta w]Y_m(q_m, \dot{q}, \dot{q}_r, \ddot{q}_r)\hat{a}_d \\ &\quad - K_D^*\mathrm{diag}[q_{mc} - q_{mr}]\Delta w_P \\ &\quad + Y_m(q_m, \dot{q}, \dot{q}_r, \ddot{q}_r)\Delta a_d \end{aligned} \tag{22}$$

where $\delta_0 = q_m(0) - q_{mr}(0)$ is a constant vector, $\Delta w = \hat{w} - w$ with $w = [w_1, \ldots, w_n]^T$, $\Delta w_P = \hat{w}_P - w_P$, and $K_P^* = KK_P$. Let us write (21) and (22) compactly as

$$\begin{aligned} &M(q_m)\dot{s} + C(q_m, \dot{q})s \\ &= -K^*s - \left[0_3^T, \left[K_P^*\left(\int_0^t s_m(\sigma)d\sigma + \delta_0\right)\right]^T\right]^T \\ &\quad + \left[0_3^T, (K_D^*\mathrm{diag}[\Delta w]Y_m(q_m, \dot{q}, \dot{q}_r, \ddot{q}_r)\hat{a}_d)^T\right]^T \\ &\quad - \left[0_3^T, (K_D^*\mathrm{diag}[q_{mc} - q_{mr}]\Delta w_P)^T\right]^T \\ &\quad + Y(q_m, \dot{q}, \dot{q}_r, \ddot{q}_r)\Delta a_d \end{aligned} \tag{23}$$

where $K^* = \mathrm{diag}\left[K_b, K_D^* + B\right]$.

We are presently ready to formulate the following theorem.

Theorem 1: Suppose that $\hat{\mathcal{K}}_P$ is uniformly positive definite. Then the adaptive outer loop controller given by (15), (17), (18), (19), and (20) for the FFSM system given by (1) and (3) under the inner PD controller (6) ensures the convergence of the task-space tracking errors, i.e., $\Delta x \to 0$ and $\Delta\dot{x} \to 0$ as $t \to \infty$.

Proof: Consider the Lyapunov-like function candidate

$$\begin{aligned} V_1 =& \frac{1}{2}s^T M(q_m)s + \frac{1}{2}\left[\int_0^t s_m(\sigma)d\sigma + \delta_0\right]^T K_P^* \\ &\times \left[\int_0^t s_m(\sigma)d\sigma + \delta_0\right] + \frac{1}{2}\Delta w^T K_D^*\Lambda^{-1}\Delta w \\ &+ \frac{1}{2}\Delta w_P^T K_D^*\Lambda_P^{-1}\Delta w_P + \frac{1}{2}\Delta a_d^T\Gamma_d^{-1}\Delta a_d \end{aligned} \tag{24}$$

and its derivative along the trajectories of (23), (18), (19), and (20) can be written as (using Property 3)

$$\dot{V}_1 = -s^T K^* s \leq 0. \tag{25}$$

This leads us to immediately obtain that $s \in \mathcal{L}_2 \cap \mathcal{L}_\infty$, $\int_0^t s_m(\sigma)d\sigma \in \mathcal{L}_\infty$, $\hat{w} \in \mathcal{L}_\infty$, $\hat{w}_P \in \mathcal{L}_\infty$, and $\hat{a}_d \in \mathcal{L}_\infty$.

Due to the well-recognized fact that J is bounded, we obtain that $Js \in \mathcal{L}_2$. Hence, there must exist a positive constant ℓ_M such that $\int_0^t s^T(\sigma)J^T(\sigma)J(\sigma)s(\sigma)d\sigma \leq \ell_M$ for $\forall t \geq 0$. Consider the following quasi-Lyapunov function candidate

$$V_2 = \frac{1}{2}\Delta x^T \Delta x + \frac{1}{2}\Delta a_k^T \Gamma_k^{-1} \Delta a_k + \frac{1}{2\alpha}\left[\ell_M - \int_0^t s^T(\sigma) J^T(\sigma) J(\sigma) s(\sigma) d\sigma\right] \quad (26)$$

where the use of the last term in V_2 follows the standard practice (see, e.g., [35, p. 118]). Differentiating V_2 with respect to time along the trajectories of (14) and (17) yields

$$\dot{V}_2 = -\alpha \Delta x^T \Delta x + \Delta x^T J s - \frac{1}{2\alpha} s^T J^T J s. \quad (27)$$

From the standard result concerning the basic inequalities, we have that

$$\Delta x^T J s \leq \frac{\alpha}{2}\Delta x^T \Delta x + \frac{1}{2\alpha} s^T J^T J s, \quad (28)$$

using which, we obtain from (27) that

$$\dot{V}_2 \leq -\frac{\alpha}{2}\Delta x^T \Delta x \leq 0. \quad (29)$$

The result given by (29) immediately yields the conclusion that $\Delta x \in \mathcal{L}_2 \cap \mathcal{L}_\infty$ and $\hat{a}_k \in \mathcal{L}_\infty$. From (10), we obtain that $\hat{J}_b \omega_{br} + \hat{J}_m \dot{q}_{mr} = \dot{x}_r \in \mathcal{L}_\infty$. Due to the result that $\hat{J}_b s_b + \hat{J}_m s_m \in \mathcal{L}_\infty$, we then obtain that $\hat{\dot{x}} = \hat{J}_b \omega_b + \hat{J}_m \dot{q}_m \in \mathcal{L}_\infty$ where $\hat{\dot{x}}$ is the estimate of $\dot{x}$. According to [6], the angular momentum conservation equation can be written as $R_b(M_{bb}\omega_b + M_{bm}\dot{q}_m) = 0$ with R_b being the attitude matrix of the spacecraft with respect to the inertial frame, and then we obtain that $\hat{\dot{x}} = (\hat{J}_m - \hat{J}_b M_{bb}^{-1} M_{bm})\dot{q}_m$. If the matrix $\hat{J}_m - \hat{J}_b M_{bb}^{-1} M_{bm}$ is nonsingular, $\dot{q}_m = (\hat{J}_m - \hat{J}_b M_{bb}^{-1} M_{bm})^{-1} \hat{\dot{x}} \in \mathcal{L}_\infty$ and thus $\omega_b \in \mathcal{L}_\infty$ based on the above angular momentum conservation equation. From the kinematics (1), we obtain that $\dot{x} \in \mathcal{L}_\infty$ and hence $\Delta \dot{x} \in \mathcal{L}_\infty$ and $\ddot{x}_r \in \mathcal{L}_\infty$. Therefore, Δx is uniformly continuous. From the properties of square-integrable and uniformly continuous functions [36, p. 232], we obtain that $\Delta x \to 0$ as $t \to \infty$.

The fact that $\dot{q} \in \mathcal{L}_\infty$ and $s \in \mathcal{L}_\infty$ implies that $\dot{q}_r \in \mathcal{L}_\infty$. Then, we obtain from (17) that $\dot{\hat{a}}_k \in \mathcal{L}_\infty$, giving rise to the boundedness of $\dot{\hat{J}}_b$ and $\dot{\hat{J}}_m$. Equations (8) and (11) can be rewritten compactly as

$$\underbrace{\begin{bmatrix} \hat{M}_{bb} & \hat{M}_{bm} \\ \hat{J}_b & \hat{J}_m \end{bmatrix}}_{H} \begin{bmatrix} \dot{\omega}_{br} \\ \ddot{q}_{mr} \end{bmatrix} = \begin{bmatrix} -\hat{C}_{bb}\omega_{br} - \hat{C}_{bm}\dot{q}_{mr} + K_b s_b \\ \ddot{x}_r - \dot{\hat{J}}_b \omega_{br} - \dot{\hat{J}}_m \dot{q}_{mr} \end{bmatrix} \quad (30)$$

From the standard matrix theory, the invertibility of H is equivalent to that of $H^* = \begin{bmatrix} \hat{M}_{bb} & \hat{M}_{bm} \\ 0_{n\times 3} & \hat{J}_m - \hat{J}_b \hat{M}_{bb}^{-1} \hat{M}_{bm} \end{bmatrix}$ and further that of $\hat{M}_{bb}$ and $\hat{J}_m - \hat{J}_b \hat{M}_{bb}^{-1} \hat{M}_{bm}$. Therefore, if $\hat{M}_{bb}$ and $\hat{J}_m - \hat{J}_b \hat{M}_{bb}^{-1} \hat{M}_{bm}$ are invertible, we obtain from (30) that $\dot{\omega}_{br} \in \mathcal{L}_\infty$ and $\ddot{q}_{mr} \in \mathcal{L}_\infty$. Equation (15) can further be written as

$$\dot{q}_{mc} - \dot{q}_{mr} + \hat{\mathcal{K}}_P(q_{mc} - q_{mr}) = \text{diag}[\hat{w}_i, i = 1, \ldots, n] Y_m(q_m, \dot{q}, \dot{q}_r, \ddot{q}_r)\hat{a}_d \quad (31)$$

and since $\hat{\mathcal{K}}_P$ is uniformly positive definite and bounded, we obtain that $q_{mc} - q_{mr} \in \mathcal{L}_\infty$ and $\dot{q}_{mc} - \dot{q}_{mr} \in \mathcal{L}_\infty$ from the standard linear system theory. On the other hand, $\int_0^t s_m(\sigma) d\sigma = q_m - q_m(0) - [q_{mr} - q_{mr}(0)] \in \mathcal{L}_\infty$ and therefore $q_m - q_{mr} \in \mathcal{L}_\infty$, which then implies that $q_m - q_{mc} \in \mathcal{L}_\infty$. Due to the result that $\dot{q}_{mr} \in \mathcal{L}_\infty$, we obtain that $\dot{q}_{mc} \in \mathcal{L}_\infty$. From (23) and using Property 2, we obtain that $\dot{s} \in \mathcal{L}_\infty$, and consequently, $\dot{\omega}_b \in \mathcal{L}_\infty$ and $\ddot{q}_m \in \mathcal{L}_\infty$. This immediately leads to the result that $\ddot{x} \in \mathcal{L}_\infty$ according to the differentiation of the kinematics (1). Thus, $\Delta \ddot{x} \in \mathcal{L}_\infty$, implying that $\Delta \dot{x}$ is uniformly continuous. According to Barbalat's Lemma [31], we obtain the result that $\Delta \dot{x} \to 0$ as $t \to \infty$. ■

Remark 1: The proposed controller requires that the estimated inertia matrix $\hat{M}_{bb}$, the estimated generalized Jacobian matrices $\hat{J}_m - \hat{J}_b M_{bb}^{-1} M_{bm}$ and $\hat{J}_m - \hat{J}_b \hat{M}_{bb}^{-1} \hat{M}_{bm}$ (i.e., the estimated versions of the generalized Jacobian matrix in, e.g., [4], [6]), and the estimated Jacobian matrix $\hat{J}_m$ are all invertible, which is the same as the case in [12]. The parameter projection algorithms [37] can be adopted to fulfill this requirement in the adaptation process (see, e.g., [38], [19], [20]). Furthermore, the condition that $\hat{\mathcal{K}}_P$ is uniformly positive definite can also be straightforwardly guaranteed by using the projection algorithms [37] since $\hat{\mathcal{K}}_P$ is diagonal.

IV. Adaptive Outer Loop Control With an Inner PID Controller

In this section, we present the adaptive outer loop controller design as an inner PID controller is embedded in the space robotic system. In this case, the armature voltage u takes the following form

$$u = -K_D(\dot{q}_m - \dot{q}_{mc}) - K_P(q_m - q_{mc}) - K_I \int_0^t [q_m(\sigma) - q_{mc}(\sigma)] d\sigma \quad (32)$$

where K_D, K_P, and K_I are diagonal positive definite matrices. Due to the incorporation of the integral action, the previous outer loop controller generally cannot ensure the stability of the system. To this end, we introduce the following quantity based on the joint reference velocity given by (10)

$$\dot{q}_{mr}^* = \dot{q}_{mr} - K_c(q_m - q_{mr}) \quad (33)$$

where K_c is a diagonal positive definite matrix. The joint velocity command is now defined as

$$\dot{q}_{mc} + \hat{\mathcal{K}}_P q_{mc} + \hat{\mathcal{K}}_I \int_0^t [q_{mc}(\sigma) - q_{mr}(\sigma)] d\sigma = \dot{q}_{mr}^* + \hat{\mathcal{K}}_P q_{mr} + \text{diag}[\hat{w}_i, i = 1, \ldots, n] \times [Y_m(q_m, \dot{q}, \dot{q}_r^*, \ddot{q}_r^*)\hat{a}_d] \quad (34)$$

where $\dot{q}_r^* = \left[\omega_{br}^T, \dot{q}_{mr}^{*T}\right]^T$, $\ddot{q}_r^*$ is the derivative of $\dot{q}_r^*$, and $\hat{\mathcal{K}}_I = \text{diag}[\hat{w}_I]$ with $\hat{w}_I$ being an n-dimensional vector. The adaptation laws for $\hat{a}_d$, $\hat{w}$, $\hat{w}_P$, and $\hat{w}_I$ are given as

$$\dot{\hat{a}}_d = -\Gamma_d Y^T(q_m, \dot{q}, \dot{q}_r^*, \ddot{q}_r^*)\xi \quad (35)$$

$$\dot{\hat{w}} = -\Lambda \mathrm{diag}[Y_m(q_m, \dot{q}, \dot{q}_r^*, \ddot{q}_r^*)\hat{a}_d]\xi_m \quad (36)$$

$$\dot{\hat{w}}_P = \Lambda_P \mathrm{diag}[q_{mc} - q_{mr}]\xi_m \quad (37)$$

$$\dot{\hat{w}}_I = \Lambda_I \mathrm{diag}\left[\int_0^t [q_{mc}(\sigma) - q_{mr}(\sigma)]d\sigma\right]\xi_m \quad (38)$$

where $\xi_m = \dot{q}_m - \dot{q}_{mr}^* = s_m + K_c\left[\int_0^t s_m(\sigma)d\sigma + \delta_0\right]$, $\xi = \left[s_b^T, \xi_m^T\right]^T$, and Λ_I is a diagonal positive definite matrix. The adaptation law for $\hat{a}_k$ remains the same as (17).

Theorem 2: Suppose that K_c is chosen so that $\mathcal{M} = (K_D + K^{-1}B)K_c + K_P - K_I K_c^{-1}$ is positive semidefinite and that the system

$$\ddot{z}^* + \hat{\mathcal{K}}_P \dot{z}^* + \hat{\mathcal{K}}_I z^* = 0 \quad (39)$$

with $z^* \in R^n$ is uniformly exponentially stable. Then the adaptive outer loop controller given by (34), (17), (35), (36), (37), and (38) for the FFSM system given by (1) and (3) under the inner PID controller (32) ensures the convergence of the task-space tracking errors, i.e., $\Delta x \to 0$ and $\Delta \dot{x} \to 0$ as $t \to \infty$.

Following similar steps as in [18] and in the proof of Theorem 1, we can complete that of Theorem 2.

V. Simulation Results

In this section, we use the simulation example in [14] [i.e., a two-DOF (degree-of-freedom) space manipulator moving in a plane] to show the system performance under the proposed adaptive outer loop control. We here consider the case of using an inner PD controller. The sampling periods for the inner and outer loops are set as 0.5 ms (fast) and 20 ms (slow), respectively.

The gains for the inner PD controller are set as $K_D = 10.0I_2$ and $K_P = 20.0I_2$, and the diagonal matrices K and B are set as $K = \mathrm{diag}[100.0, 60.0]$ and $B = \mathrm{diag}[12.0, 6.0]$, respectively. The controller parameters for the outer control loop are chosen as $K_b = 200.0$, $\alpha = 15.0$, $\Lambda = 0.001I_2$, $\Lambda_P = 500.0I_2$, $\Gamma_d = 120.0I_{10}$, and $\Gamma_k = 160.0I_4$. The initial kinematic and dynamic parameter estimates are set as $\hat{a}_k(0) = [0.6, 1.2, 2.8, 2.9]^T$ and $\hat{a}_d(0) = [1.8, 1.8, 1.8, 1.8, 1.8, 155.0, 50.0, 10.0, 0.0, 0.0]^T$, and the initial values of $\hat{w}$ and $\hat{w}_P$ are set as $\hat{w}(0) = [0, 0]^T$ and $\hat{w}_P(0) = [1.0, 1.0]^T$, respectively. The desired trajectory in the task space is given as $x_d = [2.85 + 0.25\cos(0.8\pi t), -0.38 + 0.25\sin(0.8\pi t)]^T$. The simulation results are shown in Fig. 1 and Fig. 2.

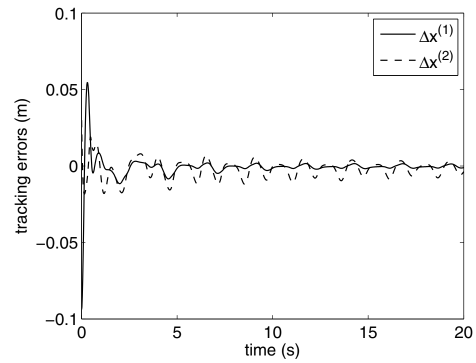

Fig. 1. Position tracking errors.

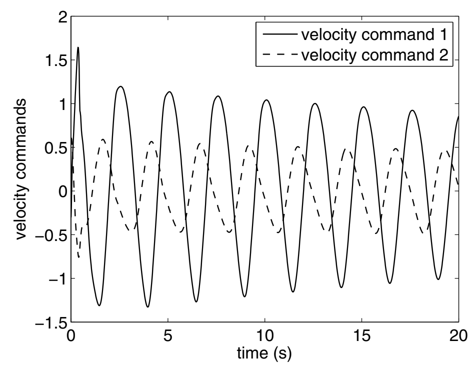

Fig. 2. Joint velocity commands.

VI. Conclusion

The purpose of our study here is to develop task-space adaptive outer loop controllers for free-floating space manipulators with uncertain kinematics and dynamics so as to approach the objective of dynamic modularity for space robotic systems. The proposed outer loop controllers are in the form of joint velocity (or position) command, which is dynamically and adaptively generated to address both the dynamic effects of the system and the parametric uncertainties, and the inner joint servoing controller is assumed to take the form of PD or PID control. It is shown that the task-space tracking errors converge to zero asymptotically. The performance of the proposed control approach is shown by numerical simulation results.

References

[1] A. Flores-Abad, O. Ma, K. Pham, and S. Ulrich, "A review of space robotics technologies for on-orbit servicing," *Progress in Aerospace Sciences*, vol. 68, pp. 1–26, Jul. 2014.

[2] D. Barnhart, B. Sullivan, R. Hunter, J. Bruhn, E. Fowler, L. Hoag, S. Chappie, G. Henshaw, B. Kelm, T. Kennedy, M. Mook, and K. Vincent, "Phoenix project status 2013," in *AIAA SPACE 2013 Conference and Exposition: AIAA 2013-5341*, San Diego, CA, 2013, pp. 1–17.

[3] W. Xu, B. Liang, B. Li, and Y. Xu, "A universal on-orbit servicing system used in the geostationary orbit," *Advances in Space Research*, vol. 48, no. 1, pp. 95–119, Jul. 2011.

[4] Y. Umetani and K. Yoshida, "Resolved motion rate control of space manipulators with generalized Jacobian matrix," *IEEE Transactions on Robotics and Automation*, vol. 5, no. 3, pp. 303–314, Jun. 1989.

[5] E. Papadopoulos, "On the dynamics and control of space manipulators," Ph.D. dissertation, Massachusetts Institute of Technology, Cambridge, MA, 1990.

[6] E. Papadopoulos and S. Dubowsky, "On the nature of control algorithms for free-floating space manipulators," *IEEE Transactions on Robotics and Automation*, vol. 7, no. 6, pp. 750–758, Dec. 1991.

[7] Z. Vafa and S. Dubowsky, "On the dynamics of space manipulators using the virtual manipulator, with applications to path planning," *The Journal of Astronautical Sciences*, vol. 38, no. 4, pp. 441–472, Oct.-Dec. 1990.

[8] M. Nohmi and S. Yoshida, "Experimental analysis for attitude control of a tethered space robot under microgravity," in *54th International Astronautical Congress of the International Astronautical Federation: IAC-03-A.6.07*, Bremen, Germany, 2003.

[9] P. Huang, J. Cai, Z. Meng, Z. Hu, , and D. Wang, "Novel method of monocular real-time feature point tracking for tethered space robots," *Journal of Aerospace Engineering*, vol. 27, no. 6, pp. 04 014 039–1–04 014 039–14, Nov. 2014.

[10] Y. Xu, H.-Y. Shum, T. Kanade, and J.-J. Lee, "Parameterization and adaptive control of space robot systems," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 30, no. 2, pp. 435–451, Apr. 1994.

[11] Y.-L. Gu and Y. Xu, "A normal form augmentation approach to adaptive control of space robot systems," in *Proceedings of the IEEE International Conference on Robotics and Automation*, Atlanta, GA, 1993, pp. 731–737.

[12] H. Wang and Y. Xie, "Passivity based adaptive Jacobian tracking for free-floating space manipulators without using spacecraft acceleration," *Automatica*, vol. 45, no. 6, pp. 1510–1517, Jun. 2009.

[13] S. Abiko and G. Hirzinger, "Adaptive control for a torque controlled free-floating space robot with kinematic and dynamic model uncertainty," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, St. Louis, MO, 2009, pp. 2359–2364.

[14] H. Wang and Y. Xie, "Prediction error based adaptive Jacobian tracking for free-floating space manipulators," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 48, no. 4, pp. 3207–3221, Oct. 2012.

[15] H. Wang and S. Xu, "On the adaptive zero reaction control of free-floating space manipulators," in *Proceeding of the 11th World Congress on Intelligent Control and Automation*, Shenyang, China, 2014, pp. 4600–4605.

[16] K.-D. Nguyen and H. Dankowicz, "Adaptive control of underactuated robots with unmodeled dynamics," *Robotics and Autonomous Systems*, vol. 64, pp. 84–99, Feb. 2015.

[17] H. Wang, "Adaptive control of robot manipulators with uncertain kinematics and dynamics," *IEEE Transactions on Automatic Control*, vol. 62, no. 2, pp. 948–954, Feb. 2017.

[18] H. Wang, W. Ren, C. C. Cheah, Y. Xie, and S. Lyu, "Dynamic modularity approach to adaptive inner/outer loop control of robotic systems," *arXiv preprint arXiv:1603.05557*, 2017.

[19] C. C. Cheah, C. Liu, and J.-J. E. Slotine, "Adaptive tracking control for robots with unknown kinematic and dynamic properties," *The International Journal of Robotics Research*, vol. 25, no. 3, pp. 283–296, Mar. 2006.

[20] ——, "Adaptive Jacobian tracking control of robots with uncertainties in kinematic, dynamic and actuator models," *IEEE Transactions on Automatic Control*, vol. 51, no. 6, pp. 1024–1029, Jun. 2006.

[21] C. Liu, C. C. Cheah, and J.-J. E. Slotine, "Adaptive Jacobian tracking control of rigid-link electrically driven robots based on visual task-space information," *Automatica*, vol. 42, no. 9, pp. 1491–1501, Sep. 2006.

[22] H. Wang, "Adaptive visual tracking for robotic systems without image-space velocity measurement," *Automatica*, vol. 55, pp. 294–301, May 2015.

[23] G. Hirzinger, K. Landzettel, B. Brunner, M. Fischer, C. Preusche, D. Reintsema, A. Albu-Schäffer, G. Schreiber, and B.-M. Steinmetz, "DLR's robotics technologies for on-orbit servicing," *Advanced Robotics*, vol. 18, no. 2, pp. 139–174, 2004.

[24] J. J. Craig, *Introduction to Robotics: Mechanics and Control*, 3rd ed. Upper Saddle River, NJ: Prentice-Hall, 2005.

[25] H. Wang, W. Ren, C. C. Cheah, and Y. Xie, "Dynamic modularity approach to adaptive inner/outer loop control of robotic systems," in *Proceedings of the Chinese Control Conference*, Chengdu, China, 2016, pp. 3249–3255.

[26] B. Ma and W. Huo, "Adaptive control of space robot system with an attitude controlled base," in *Proceedings of the IEEE International Conference on Robotics and Automation*, Nagoya, Japan, 1995, pp. 1265–1270.

[27] L. Cheng, Z.-G. Hou, and M. Tan, "Adaptive neural network tracking control for manipulators with uncertain kinematics, dynamics and actuator model," *Automatica*, vol. 45, no. 10, pp. 2312–2318, Oct. 2009.

[28] E. Papadopoulos and S. Dubowsky, "Dynamic singularities in free-floating space manipulators," *Journal of Dynamic Systems, Measurement, and Control*, vol. 115, no. 1, pp. 44–52, Mar. 1993.

[29] O. Egeland and J.-M. Godhavn, "Passivity-based adaptive attitude control of a rigid spacecraft," *IEEE Transactions on Automatic Control*, vol. 39, no. 4, pp. 842–846, Apr. 1994.

[30] M. W. Spong, S. Hutchinson, and M. Vidyasagar, *Robot Modeling and Control*. New York: Wiley, 2006.

[31] J.-J. E. Slotine and W. Li, *Applied Nonlinear Control*. Englewood Cliffs, NJ: Prentice-Hall, 1991.

[32] F. Caccavale and P. Chiacchio, "Identification of dynamic parameters and feedforward control for a conventional industrial manipulator," *Control Engineering Practice*, vol. 2, no. 6, pp. 1039–1050, Dec. 1994.

[33] J. Swevers, W. Verdonck, and J. D. Schutter, "Dynamic model identification for industrial robots," *IEEE Control Systems Magazine*, vol. 27, no. 5, pp. 58–71, Oct. 2007.

[34] H. Wang and Y. Xie, "On the recursive adaptive control for free-floating space manipulators," *Journal of Intelligent & Robotic Systems*, vol. 66, no. 4, pp. 443–461, Jun. 2012.

[35] R. Lozano, B. Brogliato, O. Egeland, and B. Maschke, *Dissipative Systems Analysis and Control: Theory and Applications*. London, U.K.: Springer-Verlag, 2000.

[36] C. A. Desoer and M. Vidyasagar, *Feedback Systems: Input-Output Properties*. New York: Academic Press, 1975.

[37] P. A. Ioannou and J. Sun, *Robust Adaptive Control*. Englewood Cliffs, NJ: Prentice-Hall, 1996.

[38] W. E. Dixon, "Adaptive regulation of amplitude limited robot manipulators with uncertain kinematics and dynamics," *IEEE Transactions on Automatic Control*, vol. 52, no. 3, pp. 488–493, Mar. 2007.