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Robust prescribed performance tracking control for free-floating space manipulators with kinematic and dynamic uncertainty

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ABSTRACT

This paper investigates the task-space prescribed performance tracking control problem of free-floating space manipulators with kinematic and dynamic uncertainty. In order to formulate and solve this prescribed performance tracking problem on SE(3), we first select a suitable tracking error vector and prescribed performance bound which characterizes the minimum convergence rate and maximum overshoot of the tracking error vector. Then, two robust tracking controllers based on the prescribed performance bound are designed to solve the tracking control problem. Compared with the existing work on the guaranteeing prescribed performance control, a linear switching surface is incorporated into the controller design procedure, which makes it easy to cope with kinematic and dynamic uncertainty. A rigorous mathematical stability proof is given. Finally, numerical simulations are presented to demonstrate the effectiveness and robustness of the proposed controller.

1. Introduction

Free-Floating Space Manipulators (FFSMs) have increasingly been utilized to extend human manipulation in cost-expensive and hazardous space environments, such as capturing space debris, conducting on-orbit servicing, executing maintenance and construction of the International Space Station, etc [1,2]. Some well-known methods have been developed to solve kinematic and dynamic modeling problems of FFSMs, such as the generalized Jacobian matrix [3,4], the virtual manipulator approach [5], the dynamically equivalent manipulator approach [6], the endogenous configuration space approach [7], etc. There exist two significant differences between FFSMs and earth-based robots. On one hand, it is difficult to find a closed-form forward kinematics solution for FFSMs, because the attitude of the spacecraft depends not only on the current joint positions, but also on the path taken to reach the configuration [8]. On the other hand, if the spacecraft has a total mass close to the mass of the manipulator, there exists the high dynamic coupling between the manipulator and the base. The generalized Jacobian matrix of the FFSM depends not only on the kinematic parameters (e.g., link lengths, link twist angles, etc.), but also on the dynamic parameters (i.e., masses and inertias of rigid bodies). As a result, kinematic and dynamic equations of FFSMs will both be affected by dynamic parameter variations or uncertainty. Besides, results of [6] illustrate that the dynamic coupling decreases as the mass of the spacecraft increases, and if the mass of the manipulator arm is negligible compared to the spacecraft, the generalized Jacobian matrix of FFSMs can be best approximated by the fixed-based manipulator Jacobian. In these cases, the control algorithms applied to earth-based robots can be used for FFSMs.

When the coupling dynamic property of the space manipulator cannot be ignored, the task-space trajectory tracking control problem of FFSMs with dynamic uncertainty are different from the earth-based manipulator. For example, the adaptive tracking controllers developed in [9] for earth-base manipulators cannot be directly applied to FFSMs, because the dynamic equations of FFSMs cannot be linearly parameterized [10]. To overcome the nonlinearly parametric feature of the dynamics of FFSMs, the normal form augmentation approach is reported in [11]. However, the adaptive controller developed in [11] requires the measurement of the linear and angular accelerations of the spacecraft, which is critical from the viewpoint of practical implementation. To avoid the measurement of the spacecraft's acceleration, the adaptive controller in joint space [12], the pseudo-arm approach [13], the adaptive tracking controller based on the inverted chain approach [14] and the passivity based adaptive Jacobian tracking controller [15,16] have been proposed. In addition, the neural network has been applied

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Nomenclature

Ξ_I, Ξ_{B_0}, Ξ_T the inertia frame, the base frame and the tool frame, respectively;
$SO(3), SE(3)$ the special orthogonal group and the special Euclidean group, respectively;
$\mathfrak{so}(3), \mathfrak{se}(3)$ the Lie algebras of the Lie groups $SO(3)$ and $SE(3)$, respectively;
$\xi_j \in \mathbb{R}^6$ the twist coordinates associated with the joint J_j;
$R_{ib_0}, R_{it} \in SO(3)$ the rotation matrices of Ξ_{B_0} and Ξ_T with respect to Ξ_I, respectively;
$p_0, p_t \in \mathbb{R}^3$ the position vectors of the origins of Ξ_{B_0} and Ξ_T in Ξ_I, respectively;
$g_{ib_0}, g_{it} \in SE(3)$ the configurations of the base and the end-effector, respectively;
$V_{ij}^k \in \mathbb{R}^6$ the generalized velocity of Ξ_j with respect to Ξ_i, represented in Ξ_k, i.e. $V_{ij}^k = \left[\left(v_{ij}^k\right)^{\mathrm{T}}, \left(\omega_{ij}^k\right)^{\mathrm{T}}\right]^{\mathrm{T}}$;
$\Theta \in \mathbb{R}^n$ the joint angle vector, i.e. $\Theta = [\theta_1, \theta_2, \ldots, \theta_n]^{\mathrm{T}}$;
$\dot{\Theta} \in \mathbb{R}^n$ the joint angular velocity vector, i.e. $\dot{\Theta} = [\dot{\theta}_1, \dot{\theta}_2, \ldots, \dot{\theta}_n]^{\mathrm{T}}$;
Ψ_0 the initial momentum of the system;
$J_b, \Delta J_b \in \mathbb{R}^{6\times 6}$ the nominal term and the uncertainty of the Jacobian matrix of the base, respectively;
$J_m, \Delta J_m \in \mathbb{R}^{6\times n}$ the nominal term and the uncertainty of the Jacobian matrix of the manipulator, respectively;
$M_{bb}, \Delta M_{bb}$ the nominal term and the uncertainty of the generalized inertia matrix of the base, respectively;
$M_{bm}, \Delta M_{bm}$ the nominal term and the uncertainty of the coupled generalized inertia matrix of the base satellite and the manipulator, respectively;
$M_{mm}, \Delta M_{mm}$ the nominal term and the uncertainty of the generalized inertia matrix of the manipulator, respectively;

to approximate the model uncertainty and external disturbance [17,18]. Direct image-based optimal control scheme is also designed to solve the tracking control problem of FFSMs in the task space [19]. In [20], the effect of the nonzero initial angular momentum on the free-floating space manipulator system has been studied. The transverse function approach in [21] can be used to solve the kinematic control problem of FFSMs, because the angular momentum conservation condition is a nonholonomic kinematic constraint.

The present work is inspired by the work in [22,23], in which the transient performance of the tracking error is characterised as inequality constraints, and the error transformation technique is proposed to transform the 'constrained' system to an equivalent 'unconstrained' one. This technique has been utilized in the force/position tracking control for robots [24,25], and in the tracking control for flexible joint robots [26]. However, the above work can only guarantee the uniformly ultimate boundedness of the tracking errors. In this article, we will utilize the modified error transformation technique proposed in [27] to ensure the tracking error to converge to zero. Different from the back-stepping control scheme reported in [27], a novel robust control scheme based on the sliding mode is designed in this paper to solve the task-space prescribed performance tracking control problem of FFSMs with kinematic and dynamic uncertainty. Moreover, the proposed controller can also guarantee certain predefined minimum convergence rate, maximum steady-state error as well as overshoot concerning the tracking error. However, the proposed robust controller requires the information on the bound of the lumped disturbance. As a result, we need to choose a large design parameter to ensure robust stability of the closed-loop system, which will result in substantial chattering of the control effort. In order to eliminate the chattering phenomenon and resolve the overestimating problem, an adaptive-gain super-twisting disturbance observer is designed to estimate the upper bound of the uncertainty and external disturbance. The rest of this paper is organised as follows: Section 2 describes the task-space prescribed performance tracking control problem for FFSMs. In Section 3, two robust tracking controllers with guaranteed prescribed performance are designed. After that, numerical simulations for a 2 degrees of freedom (DOF) planar free-floating space manipulator are presented in Section 4 to validate the proposed control laws. Finally, we conclude the paper in Section 5.

2. Problem formulation

2.1. Kinematics and dynamics of free-floating space manipulators

We consider a free-floating space manipulator in the inertial frame Ξ_I as shown in Fig. 1. An n DOF serial manipulator with revolute or prismatic joints is mounted on the free-floating satellite base. Let Ξ_{B_0} denote the base frame which is attached at the center of mass of the satellite. The configuration of the base is defined as the following homogeneous matrix

$$g_{ib_0}(t) = \begin{bmatrix} R_{ib_0} & p_0 \\ O_{1\times 3} & 1 \end{bmatrix} \in SE(3), \tag{1}$$

where $R_{ib_0} \in SO(3)$ is the rotation matrix of the base frame relative to the inertial frame, $p_0 \in \mathbb{R}^3$ is the position of the center of mass of the base in the inertial frame. We can also denote $g_{ib_0} \in SE(3)$ by the order pair $\left(R_{ib_0}, p_0\right)$. The body velocity of the base $V_{ib_0}^{b_0}$ can be given by

$$V_{ib_0}^{b_0} = \begin{bmatrix} v_{ib_0}^{b_0} \\ \omega_{ib_0}^{b_0} \end{bmatrix} = \begin{bmatrix} R_{ib_0}^{\mathrm{T}} \dot{p}_0 \\ \left(R_{ib_0}^{\mathrm{T}} \dot{R}_{ib_0}\right)^{\vee} \end{bmatrix}, \tag{2}$$

where $v_{ib_0}^{b_0} \in \mathbb{R}^3$ and $\omega_{ib_0}^{b_0} \in \mathbb{R}^3$ are the body linear velocity and body angular velocity of the base, respectively. The *vee* map $(\cdot)^{\vee}: \mathfrak{so}(3) \to \mathbb{R}^3$ is given by

$$\begin{bmatrix} 0 & -x_3 & x_2 \\ x_3 & 0 & -x_1 \\ -x_2 & x_1 & 0 \end{bmatrix}^{\vee} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}. \tag{3}$$

Let Ξ_T denote the tool frame attached at the end-effector of the manipulator. The configuration of the end-effector is represented as

$$g_{it}(t) = \begin{bmatrix} R_{it} & p_t \\ O_{1\times 3} & 1 \end{bmatrix} \in SE(3), \tag{4}$$

where R_{it} is the rotation matrix of the end-effector relative to the inertial frame, $p_t \in \mathbb{R}^3$ is the position of the origin of the tool frame in the inertial frame. According to our early work reported on [28], g_{it} can be obtained by the product of exponentials formula (see Appendix A for full details)

$$g_{it} = g_{ib_0} e^{\hat{\xi}_1 \theta_1} \cdots e^{\hat{\xi}_n \theta_n} g_{b_0 t}(0), \tag{5}$$