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Robust coordinated control of a dual-arm space robot

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ABSTRACT

Dual-arm space robots are more capable of implementing complex space tasks compared with single arm space robots. However, the dynamic coupling between the arms and the base will have a serious impact on the spacecraft attitude and the hand motion of each arm. Instead of considering one arm as the mission arm and the other as the balance arm, in this work two arms of the space robot perform as mission arms aimed at accomplishing secure capture of a floating target. The paper investigates coordinated control of the base's attitude and the arms' motion in the task space in the presence of system uncertainties. Two types of controllers, i.e. a Sliding Mode Controller (SMC) and a nonlinear Model Predictive Controller (MPC) are verified and compared with a conventional Computed-Torque Controller (CTC) through numerical simulations in terms of control accuracy and system robustness. Both controllers eliminate the need to linearly parameterize the dynamic equations. The MPC has been shown to achieve performance with higher accuracy than CTC and SMC in the absence of system uncertainties under the condition that they consume comparable energy. When the system uncertainties are included, SMC and CTC present advantageous robustness than MPC. Specifically, in a case where system inertia increases, SMC delivers higher accuracy than CTC and costs the least amount of energy.

1. Introduction

Free-Flying Space Robots (FFSRs) have the potential to perform on-orbit servicing missions autonomously or telerobotically instead of time-consuming, risky and expensive astronaut Extra Vehicular Activities (EVA). Distinguished from fixed-base robots, the manipulator motion will disturb the unrestricted spacecraft base and any motion design without the provision of this reaction motion will result in task failure. Many literature have addressed the coordinated control schemes for a single space manipulator and the spacecraft, as reviewed in Ref. [1]. The solutions can be classified into two types. One type comes from the idea of analyzing the dynamic coupling effect and minimizing or restricting the disturbance generated by the manipulator motion at the base by performing path planning for the manipulator motion [2–9]. The other can be referred as active control of the base attitude in comparison to the first solution [10–16]. In addition to the stiff connection capture, flexible connection capture including net capture [17–21] and tethered space robots [22,23] have been extensively studied [24].

To extend the dexterity and flexibility of space robots, a dual-arm or multi-arm space robot can be employed to complete more complex tasks. In Ref. [25], Yoshida et al. provided the detail derivation of the model of a space robot with multiple arms based on its geometric features and momentum conservative property of the system. Also, the authors implemented both independent control of each arm and dual-arm coordinated control for the robot. Both methods were developed by assuming an accurate space robot model. Papadopoulos and Moosavian compared the performance of model-based control algorithms to that of a transposed Jacobian algorithm [26] for a multi-arm space robot. The latter was shown to yield acceptable performance with reduced computational burden though the model-based control approach can give smaller errors and smaller required torques. Ref. [27] presented a visual servoing controller based on a task redundancy approach for a dual-arm space robot which can realize coordination of the end-effector's motion and the spacecraft attitude. Such controller has been extended to achieve reactionless visual servoing for a space robot with more arms to implement other space tasks [28].

Xu et al. addressed two cases of coordinated motion planning of a dual-arm space robot in Ref. [29]. The first case involved a spacecraft with two mission arms whereas the base is left free-floating. In the second case, one arm acts as a mission arm, and the other serves as a balanced arm. The desired path was generated by analyzing the linear momentum constraints and angular momentum constraints separately. Motion planning of a dual-arm space robot using the same concept that one arm is used to implement the desired task and the other performs as a balance arm to keep the base inertially fixed was also discussed in Refs. [30] and [31]. The manipulability measure of the mission arm subjected to the

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influence of the balanced arm and the base was investigated in Ref. [32], which helps to determine an optimal configuration for a dual-arm space robot. Two control strategies, which can compensate the flexibility excitation of the solar panels mounted on the base, were presented for a dual-arm space robot in Ref. [33]. Motion control of dual-arm ground robots have been investigated in Refs. [34–37].

The performance of controllers developed based on accurate space robot model will be deteriorated in the presence of model uncertainties. Ref. [38] proposed an indirect adaptive control scheme devoted to trajectory tracking of a dual-arm space robot when it manipulates a target with unknown inertia parameters. The controller was developed based on the reduced-order model of the constrained system and was able to control the pose of both the spacecraft base and the target. Chen and Guo [39] realized linear parameterization of the dual-arm space robot model based on an under-actuated model and the idea of augmentation approach. Adaptive control scheme was then developed to achieve the coordinated control of the base's attitude and arm's motion in the joint space. In combination with neural networks, an adaptive RBF neural network control method was proposed by the same authors in Ref. [40], which eliminates the need of linear parameterization and accurate knowledge of the model. By regulating the positive values of the coefficient of sliding condition, a chattering-free sliding mode controller was developed in Ref. [41] for a multi-arm space manipulator. The controller can coordinate the arms' motion in the joint space.

However, for many space missions, the desired hand trajectory is specified in the inertial space. Though the joint motion can be accurately controlled, the precise motion control of the end-effectors can not be guaranteed since the mapping from joint space to task space depends on the inaccurate parameters. Therefore, in this paper, coordinated control of the base's attitude and the manipulator motion in the inertial space is addressed. The dynamic equations of a dual-arm FFSR with actuating reaction wheels are formulated. The strong nonlinearities and existing system uncertainties of this Multiple-Input-Multiple-Output (MIMO) system complicate the controller design. By utilizing a diagonalization method, the strongly coupled problem is transformed into multiple single-input problems by introducing virtual torques. Two types of controllers, i.e. the Sliding Mode Controller (SMC) developed by the same authors in Ref. [42] and the Model Predictive Controller (MPC), are extended in this paper to coordinate the motion of the space robot arms and attitude of the spacecraft. It has been shown through numerical simulation that MPC achieves higher accuracy than SMC in trajectory tracking under the premise of an accurate system model. However, SMC presents better robustness than MPC in the presence of system uncertainties.

The paper is organized into five sections. Section 2 systematically formulates the kinematic and dynamic equations of a dual-arm space robot. In Section 3, decoupling of this MIMO system into several single-input systems is performed before proceeding to the controller design. Then two control approaches, namely smooth sliding mode control and model predictive control, are developed to finally implement spacecraft attitude regulation and simultaneous manipulator trajectory tracking in the task space. Estimation of the bounds of system uncertainties is discussed in this section. Section 4 presents the simulation results and compares the performance of the two types of controllers with a conventional computed-torque controller. Section 5 concludes the work.

2. Space robot model

2.1. Scenario description

A scenario where a space robot approaches a target in close proximity is considered in this paper. Such scenario can represent a typical operation of on-orbit servicing task. Specifically, the space robot has two arms mounted on its base and each arm comprises three links connected by revolute joints, as shown in Fig. 1. The motions of the arms will potentially result in base rotation in the $x_I - y_I$ plane.

Throughout the paper, symbols with superscript ${}^{0}\{\}$, ${}^{i}\{\}$, ${}^{t}\{\}$ and ${}^{a}\{\}$ represent variables expressed in the body frame, link frame, target frame and inertial frame, respectively. Vectors or matrices without any indicated superscripts in the following sections can mean variables with reference to the inertial frame or those that can be transformed into the inertial frame. The symbols appearing in Fig. 1 are defined as follows.

$\mathsf{L}_i^{(k)}$ link i of arm k
$\mathsf{J}_i^{(k)}$ joint i of arm k
${}^{a}\boldsymbol{r}_g \in \mathbb{R}^3$ position vector of Center of Mass (CM) of the space robot
${}^{a}\boldsymbol{r}_0 \in \mathbb{R}^3$ position vector of CM of the base
${}^{a}\boldsymbol{r}_i^{(k)} \in \mathbb{R}^3$ position vector of CM of $\mathsf{L}_i^{(k)}$
${}^{a}\boldsymbol{r}_e^{(k)} \in \mathbb{R}^3$ position vector of the end-effector of arm k
$\boldsymbol{b}_{001}^{(k)} \in \mathbb{R}^3$ position vector from CM of the base to $\mathsf{J}_1^{(k)}$
$a_i^{(k)}, b_i^{(k)} \in \mathbb{R}^1$ length from $\mathsf{J}_i^{(k)}$ to CM of $\mathsf{L}_i^{(k)}$ and from CM of $\mathsf{L}_i^{(k)}$ to $\mathsf{J}_{i+1}^{(k)}$
$l_i^{(k)} = a_i^{(k)} + b_i^{(k)}$
$\boldsymbol{I}_0, \boldsymbol{I}_i^{(k)} \in \mathbb{R}^{3\times 3}$ inertia matrix of the spacecraft base and $\mathsf{L}_i^{(k)}$
$m_0, m_i^{(k)} \in \mathbb{R}^1$ mass of the spacecraft base and $\mathsf{L}_i^{(k)}$
${}^{a}\boldsymbol{r}_t \in \mathbb{R}^3$ position vector of CM of the target
${}^{t}\boldsymbol{p}^{(k)} \in \mathbb{R}^3$ position vector of the fixture corresponding to arm k with respect to the CM of the target

To implement capture of the target, the space robot is expected to approach two fixture points of the target with the corresponding end-effector. Simultaneously, the spacecraft needs to be controlled at a desired orientation throughout the process to maintain stable communication with ground stations and sustainable energy accumulation from the Sun; whereas its translation is left free to save fuel. Therefore, thrusters are not fired during the operation. Instead, three orthogonally mounted reaction wheels are assumed to generate attitude control torques along roll, pitch and yaw axes in the base frame.

2.2. Kinematics and dynamics

Basic equations originated from geometric features of the system, as illustrated in Fig. 1 can be described as follows:

$$\boldsymbol{r}_i^{(k)} = \begin{cases} \boldsymbol{r}_0 + {}^{a}\boldsymbol{A}_0 {}^{0}\boldsymbol{b}_{01}^{(k)} + {}^{a}\boldsymbol{A}_i^{(k)i}\boldsymbol{a}_i^{(k)}, & \text{for } i = 1, \\ \boldsymbol{r}_0 + {}^{a}\boldsymbol{A}_0 {}^{0}\boldsymbol{b}_{01}^{(k)} + \sum_{j=1}^{i-1} {}^{a}\boldsymbol{A}_j^{(k)j}\boldsymbol{l}_j^{(k)} + {}^{a}\boldsymbol{A}_i^{(k)i}\boldsymbol{a}_i^{(k)}, & \text{for } i = 2, 3, \end{cases} \tag{1}$$

where ${}^{a}\boldsymbol{A}_0$ is the rotation matrix from the base frame to the inertial frame, ${}^{a}\boldsymbol{A}_i^{(k)}$ denotes the rotation matrix from the frame of $\mathsf{L}_i^{(k)}$ to the inertial frame.

One major characteristic of space robots which distinguishes them from ground-fixed ones is the lack of a fixed base [43]. In the micro-gravity environment, the motions of the space manipulator to a target induce undesirable disturbances to the spacecraft base. To express the motion parameters of the space robot in the inertial frame, the space robot coordinate frame ΣG is introduced and thus an additional equation arises according to the geometrical definition of CM of the space robot as,

$$m_0\boldsymbol{r}_0 + \sum_{k=1}^{2}\sum_{i=1}^{3} m_i^{(k)}\boldsymbol{r}_i^{(k)} = \boldsymbol{r}_g\left(m_0 + \sum_{k=1}^{2}\sum_{i=1}^{3} m_i^{(k)}\right). \tag{2}$$

Since there is no external forces applied to the system, $\boldsymbol{r}_g$ remains constant. Further, by localizing the origin of the inertial coordinate at CM of the system, $\boldsymbol{r}_g \equiv 0$ holds true. Substituting $\boldsymbol{r}_g \equiv 0$ and Eq. (1) into Eq. (2), $\boldsymbol{r}_0$ can be expressed based on the geometric parameters as,

$$\boldsymbol{r}_0 = -\frac{1}{m_g}\sum_{k=1}^{2}\left(\sum_{i=1}^{3} m_i^{(k)a}\boldsymbol{A}_0 {}^{0}\boldsymbol{b}_{01}^{(k)} - \sum_{i=1}^{3}\mu_i^{(k)a}\boldsymbol{A}_i^{(k)i}\boldsymbol{a}_i^{(k)} + \sum_{i=1}^{2}\mu_{i+1}^{(k)a}\boldsymbol{A}_i^{(k)i}\boldsymbol{b}_i^{(k)}\right), \tag{3}$$