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Manipulability measure of dual-arm space robot and its application to design an optimal configuration

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ABSTRACT

Coupling effect exists among different arms and the base in a multi-arm space robot. The manipulability measure of one arm can be affected by the base and the other arms, which has important effects on the configuration optimization, the singularity avoidance and the compliant control. The manipulability measure for a multi-arm space robot is more complex than that of a single-arm space robot. At present, the manipulability measure of a multi-arm space robot has not been studied. In the paper, a new concept of manipulability measure is applied to analyze the manipulability measure for a dual-arm space robot, especially for the manipulability measure of the mission arm subjecting to the influence from coupling effect of auxiliary arm and the base. Based on the manipulability measure of mission arm, a performance index is introduced and used to design and choose an optimization configuration for a dual-arm space robot. Finally, a plane dual-arm space robot is simulated, which is illustrated the influence of joint angles and the base attitude on mission arm's manipulability measure. Simulation results show that the proposed manipulability measure is useful for a multi-arm space robot and optimal configuration can be extended and applied to the coordinated soft rendezvous and docking and the target capture in the field of on-orbit servicing.

1. Introduction

With the merit of enhanced efficiency and reduced risk for astronauts, space robots will play an increasingly important role in the future space activities, such as satellite repairing, large space structures construction, space debris removal. Comparing with a single-arm space robot, a dual-arm robotic system has much more dexterity, and can be used to complete more complex tasks [1–3]. With the complexity and flexibility of the on-orbit servicing, multi-arm space robot is being studied. For example, the space robots Dexter [4] and Robonaut2 [5] both have two arms, which are well-known space robot systems launched to the international space station. Moreover, The Defense Advanced Research Projects Agency (DARPA) is carrying out the SUMO/FREND project to investigate the feasibility of using three robotic arms to grapple an existing cooperative or non-cooperative satellite [6].

For a multi-arm space robot system, one or more arms are called mission arms, which perform the on-orbit servicing mission, other arms are called auxiliary arms, which can be used to stabilize the base or follow the movement of the mission arm for visual measurement during the whole mission and so on [7]. Designing a multi-arm space robot and choosing its appropriate configurations to carry out several on-orbit tasks are a challenging issue. Manipulability measure, condition number, dexterity, et al are useful to evaluate a configuration, avoidance of singularity and compliant control algorithm and others [8], which is contribute to design better configurations. In particularly, the manipulability measure is one of the hot spots in the robot field [9–12]. For a single-arm space robot, Yoshida [13] analyzed the manipulability of space robot, pointed out that because of the coupling effect between the manipulator and its base in a space robot, the manipulability measure of arm mounted on satellite is different from ground manipulator. When the parameters are fixed, the manipulability can be used to evaluate the quality of the space robot's different configuration. Nenchev etc [14] proposed the inverse kinematic solutions of the space robotic system, and presented a FAR manipulability measure which was able to evaluate space redundant manipulator from the view point of minimum spacecraft attitude disturbance. Al-Dois etc [15] proposed a direct search

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non-gradient design optimization method to determine the optimal task time and optimal parameters of single serial robot manipulators. Lee introduced task-orient manipulability measure (TOMM) and task-orient dual-arm manipulability measure (TODAMM) [16], then applied the TODAMM to the optimization of dual redundant arm joint configurations.

When a multi-arm space robot performs different tasks [17], the configuration of its arms need to be carefully designed. As above mentioned, manipulability measure is a key factor to design a better configuration. Analysis of manipulability measure is the premise of designing an optimal configuration. However, it is known that the coupling effect such as reaction exists among the mission arm, auxiliary arm and base in a dual-arm space robot, so the manipulability measure of mission arm is affected more seriously by the base and other arms than a single-arm space robot. But this problem has not been studied. In the paper, firstly a new concept of manipulability measure is introduced and applied to analyze the manipulability measure of dual-arm space robot, especially for the mission arm's manipulability measure. Then it proposes an approach about how to choose a better dual-arm posture from the candidate configurations based on the proposed manipulability measure. Finally, the reaction effect on manipulability measure is analyzed by simulation experiments. Some numerical simulation results indicate that new concept of manipulability measure is useful to design and choose an optimization configuration for dual-arm space robot.

2. Kinematic modeling of dual-arm space robot

Space robot is a spacecraft system that equips one or more robotic arms. A dual-arm space robot is shown in Fig. 1, which is made up of base, $arm-a$ and $arm-b$. The $arm-a$ is a n_a – DOF serial link manipulator, the $arm-b$ is a n_b – DOF serial link manipulator.

2.1. Definitions and assumptions

The symbols appearing in Fig. 1 and next sections are defined as follows. Note that $k \in \{a, b\}$. B_0 is the base of the space robot. B_i^k is the ith link. J_i^k is the ith joint of $arm-k$. C_0 is the centroid of B_0. C_i^k is the centroid of B_i. ΣI is the inertia coordinate system. Σi is the fixed coordinate system of B_i^k. $\boldsymbol{a}_i^k \in \boldsymbol{R}^{3\times1}$ and $\boldsymbol{b}_i^k \in \boldsymbol{R}^{3\times1}$ are the vectors from J_i^k to C_i^k and from C_i^k to J_{i+1}^k respectively. $\boldsymbol{l}_i^k \in \boldsymbol{R}^{3\times1}$ is the vector from J_i^k to J_{i+1}^k. $\boldsymbol{r}_i^k \in \boldsymbol{R}^{3\times1}$ is the position vector of C_i^k in ΣI. $\boldsymbol{r}_0 \in \boldsymbol{R}^{3\times1}$ is the position vector of base centroid. $\boldsymbol{r}_g \in \boldsymbol{R}^{3\times1}$ is the position vector of system centroid. $\boldsymbol{p}_i^k \in \boldsymbol{R}^{3\times1}$ is the position vector of J_i in ΣI. $\boldsymbol{p}_e^k \in \boldsymbol{R}^{3\times1}$ is the end-effector position vector of $arm-k$. $\boldsymbol{k}_i^k \in \boldsymbol{R}^{3\times1}$ is the unit vector of rotation direction of joint. $\boldsymbol{v}_0 \in \boldsymbol{R}^{3\times1}$ and $\omega_0 \in \boldsymbol{R}^{3\times1}$ are the linear velocity and angular velocity of base, and $\dot{\boldsymbol{x}}_b = \left[\boldsymbol{v}_0^{\mathrm{T}}, \omega_0^{\mathrm{T}}\right]$. m_0 is the mass of base. m_i^k is the mass of B_i^k. $\boldsymbol{I}_0 \in \boldsymbol{R}^{3\times3}$ is the rotary inertia of base. $\boldsymbol{I}_i^k \in \boldsymbol{R}^{3\times3}$ is the rotary inertia of B_i^k. θ_i^k is the ith joint angle of $arm-k$. $\boldsymbol{\Theta}^k \in \boldsymbol{R}^{S\times1}$ is the joint angle matrix, S is the number of joints in $arm-k$. In this paper, for a vector $\boldsymbol{r} = [x, y, z]$, the operator $(\tilde{\cdot})$ is defined as follow,

$$\tilde{\boldsymbol{r}} = \begin{bmatrix} 0 & -z & y \\ z & 0 & -x \\ -y & x & 0 \end{bmatrix}$$

Besides, the following assumption are made,

(a) The system is composed by rigid bodies, and the mass of body B_i^k is consisted of the ith link and the $(i+1)$th joint in $arm-k$.

(b) The entire system is free-floating, and all motion is generated only by the joint actuation. In such a case, the conservation of momentum holds true.

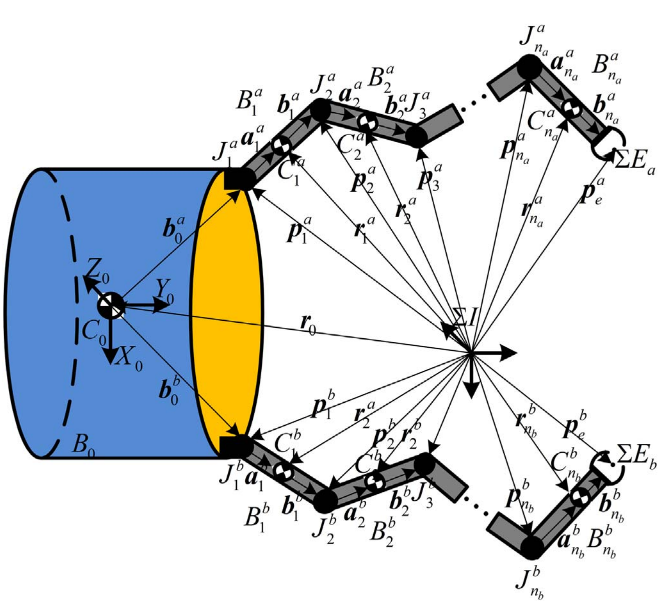

Fig. 1. A dual-arm space robot.

2.2. Kinematic equations of dual-arm space robot

In the dual-arm space robot, the centroid position of B_i^k and the tip position of $arm-k$ are expressed as (1) and (2),

$$\boldsymbol{r}_i^k = \boldsymbol{r}_0 + \boldsymbol{b}_0^k + \sum_{j=1}^{i-1}\left(\boldsymbol{a}_j^k + \boldsymbol{b}_j^k\right) + \boldsymbol{a}_i^k \tag{1}$$

$$\boldsymbol{p}_e^k = \boldsymbol{r}_0 + \boldsymbol{b}_0 + \sum_{j=1}^{n_k}\left(\boldsymbol{a}_j^k + \boldsymbol{b}_j^k\right) \tag{2}$$

The centroid linear velocity of B_i^k and the tip linear velocity of $arm-k$ are expressed as (3) and (4),

$$\boldsymbol{v}_i^k = \dot{\boldsymbol{r}}_i^k = \boldsymbol{v}_0 + \omega_0 \times \left(\boldsymbol{r}_i^k - \boldsymbol{r}_0\right) + \sum_{j=1}^{i}\left[\boldsymbol{k}_j^k \times \left(\boldsymbol{r}_i^k - \boldsymbol{p}_j^k\right)\right]\dot{\theta}_j^k \tag{3}$$

$$\boldsymbol{v}_e^k = \dot{\boldsymbol{p}}_e^k = \boldsymbol{v}_0 + \omega_0 \times \left(\boldsymbol{p}_e^k - \boldsymbol{r}_0\right) + \sum_{j=1}^{n_k}\left[\boldsymbol{k}_j^k \times \left(\boldsymbol{p}_e^k - \boldsymbol{p}_j^k\right)\right]\dot{\theta}_j^k \tag{4}$$

The centroid angular velocity of B_i^k and the tip angular velocity of $arm-k$ are expressed as (5) and (6),

$$\omega_i^k = \omega_0 + \sum_{j=1}^{i}\boldsymbol{k}_j^k\dot{\theta}_j^k \tag{5}$$

$$\omega_e^k = \omega_0 + \sum_{j=1}^{n_k}\boldsymbol{k}_j^k\dot{\theta}_j^k \tag{6}$$

From (4) and (6), the tip velocity of $arm-k$ are represented by

$$\dot{\boldsymbol{x}}_e^k = \begin{bmatrix} \boldsymbol{v}_e^k \\ \omega_e^k \end{bmatrix} = \boldsymbol{J}_b^k \begin{bmatrix} \boldsymbol{v}_0 \\ \omega_0 \end{bmatrix} + \boldsymbol{J}_m^k\dot{\boldsymbol{\Theta}}^k \tag{7}$$

where $\boldsymbol{J}_b^k$ and $\boldsymbol{J}_m^k$ are Jacobian matrices for satellite motion and manipulator motion respectively.