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Coordinated trajectory planning of dual-arm space robot using constrained particle swarm optimization

Mingming Wang[a,b], Jianjun Luo[a,b,*], Jianping Yuan[a,*], Ulrich Walter[c]

[a] Science and Technology on Aerospace Flight Dynamics Laboratory, Northwestern Polytechnical University, 710072, Xi'an, China
[b] Research Institute of Northwestern Polytechnical University in Shenzhen, 518057, Shenzhen, China
[c] Institute of Astronautics, Technical University of Munich, 85748, Garching, Germany

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ABSTRACT

Application of the multi-arm space robot will be more effective than single arm especially when the target is tumbling. This paper investigates the application of particle swarm optimization (PSO) strategy to coordinated trajectory planning of the dual-arm space robot in free-floating mode. In order to overcome the dynamics singularities issue, the direct kinematics equations in conjunction with constrained PSO are employed for coordinated trajectory planning of dual-arm space robot. The joint trajectories are parametrized with Bézier curve to simplify the calculation. Constrained PSO scheme with adaptive inertia weight is implemented to find the optimal solution of joint trajectories while specific objectives and imposed constraints are satisfied. The proposed method is not sensitive to the singularity issue due to the application of forward kinematic equations. Simulation results are presented for coordinated trajectory planning of two kinematically redundant manipulators mounted on a free-floating spacecraft and demonstrate the effectiveness of the proposed method.

1. Introduction

In light of the space robots currently planned by world wild space agencies, an increase in the number and the capacity of robot applied in space missions will be a foregone conclusion in the coming future to fulfill the increasing demands of satellite maintenance, on-orbit assembly and space debris removal *etc* [1,2]. Space robot exhibits some special characteristics due to the dynamic coupling between the space manipulators and the spacecraft (base). Accordingly, particular trajectory planning techniques have to be developed to cope with the dynamic coupling issue of free-floating space robot.

Many methodologies and strategies of motion planning for single-arm space robot have been proposed in the literature. Torres and Dubowsky [3] derived the concept of Enhanced Disturbance Map (EDM) as a heuristic trajectory planning method; nevertheless, the EDM is hard to attain especially for the space robot with higher DOF. Yamada and Yoshikawa [4] introduced a method of Cyclic Arm Motion (CAM) using the feedback attitude error to regulate the base attitude continuously. Papadopoulos et al. [5] mapped the non-holonomic constraint to a space and employed polynomials to construct smooth and continuous trajectories for planar free-floating space manipulator. Xu et al. [6] presented a point-to-point path planning method using non-holonomic characteristic of free-floating space robot, while the base attitude and the end-effector's pose can be regulated synchronously. Afterwards, Abad et al. [7] designed an optimal control scheme for eliminating or minimizing base attitude disturbance, while the uncertainties in the initial and final boundary conditions were considered. In addition, in Ref. [8], Yoshida et al. employed the concept of Reaction Null-Space (RNS) based reactionless manipulation to remove the time loss and the velocity limit of manipulation both for kinematically non-redundant and redundant space manipulators. Moreover, the RNS-based trajectory planning method was also applied in Refs. [9,10] to capture a tumbling target by using the momentum conservation law. More recently, based on the constrained least-squares approach, a Least-Squares-Based Reaction Control (LSBRC) method [11] was introduced to locally minimize the dynamic disturbance transferred to the spacecraft during trajectory tracking maneuver.

The above mentioned studies focus mainly on the motion planinig with a single-arm robot. Nevertheless, when the orbital target does not possess a grapple, the interception and capture may be very difficult. In such cases, multi-arm robotic system which can increase the probality of grasp and provide dexterous manipulation will be a reasonable alternative. Accordingly, appropriate technical schemes have to be designed to coordinate their motions. A dual-arm robotic system was introduced in Ref. [12], where one of its arms tracks a pre-defined trajectory, while the other arm works for minimizing the base attitude

* Corresponding authors. Science and Technology on Aerospace Flight Dynamics Laboratory, Northwestern Polytechnical University, 710072, Xi'an, China.
E-mail addresses: mwang@nwpu.edu.cn (M. Wang), jjluo@nwpu.edu.cn (J. Luo), jyuan@nwpu.edu.cn (J. Yuan), walter@tum.de (U. Walter).

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disturbance and optimizing the operational torque of the robotic system. Miyabe et al. [13], used the hybrid position/force control and the vibration suppression control and employed two flexible manipulators to capture a spinning object in space. Alternatively, an equivalent balance arm and its corresponding Dynamic Balance Control (DBC) scheme [14] were designed to reduce the attitude disturbance induced by the mission arm. Xu et al. [15] presented the coordinated motion planning of a dual-arm space robot for capturing a target in space. Shah et al. [16] proposed the strategy for point-to-point reactionless manipulation of the spacecraft mounted with the dual-arm robotic system. More recently, Wang et al. [17] presents a synthesis method of minimizing attitude disturbance, where DBC and RNS were integrated into the framework of task-priority based solution using the redundancy resolution of a space robot. James et al. [18] synthesized the rapidly exploring random trees (RRT) with control-based sampling and timescaling methods to construct reactionless maneuvering of a space robot in pre-capture phase. It is worth noting that in the aforementioned works, the existing coordinated motion planning methods of space robot could be categorized as follows: 1) the generalized Jacobian matrix (GJM) is employed without multi-objective optimization; 2) applying pseudo-inverse of coupling inertia matrix to generate reactionless manipulation; 3) reconstruction the task-level reactionless constraints in terms of end-effector velocities, but with the expense of the tracking error for dependent variables; 4) synthesizing searching and timescaling methods to generate reactionless manipulation. While the coordinated trajectory planning of multi-arm space robot in joint-space with multiple objectives is least explored in the literature.

The main motivation for this paper is to obtain a new coordinated joint trajectory planning method for kinematically redundant manipulators while cope with joint limits and anti-collision constraints with different objectives. The reason for choosing kinematically redundant manipulator is the existence of infinite solutions which can be employed to fulfil additional constraints, such as minimizing base attitude disturbance, or collision avoidance, and so on. Bézier curve for its simplicity and normalization is chosen to represent the shape of joint trajectory and limit the values of joint range, velocity and acceleration. Constrained PSO with adaptive inertia weight and stagnation handling is implemented to search the optimal solution for constructing the shape of the Bézier curve. The original contribution of this paper is the construction of coordinated trajectory planning framework for dual-arm space robot. Moreover, the present work is easily to extend to different kinds of robots, like fixed-base manipulator, planar manipulator, kinematically redundant multi-arm space robot, etc.

The paper is organized as follows: In Sec. 2 we formulate the trajectory planning problem of the space robot as an optimization issue under certain constraints. Kinematics and dynamics of dual-arm space robot are introduced. In Sec. 3, cost functions and constraints employed in coordinated trajectory planning issue are formulated. Moreover, parameterization of joint trajectory using Bézier curve is presented and integrated into the non-linear optimization issue. Sec. 5 shows the simulation results of the proposed coordinated trajectory planning method applied to kinematically redundant dual-arm. Finally, the conclusive remarks are made in Sec. 6 at the end of this paper.

2. Problem formulation

The objective of coordinated trajectory planning for dual-arm space robot is to generate applicable joint motion laws $\theta(t)$ without violating the imposed constraints to complete the desired manipulator tasks. Normally, it can be formulated as a non-convex optimization issues, i.e. minimize a specific objective $\Gamma(\theta)$ subject to a list of inequality constraints $g_i(\theta)$ and equality constraints $h_i(\theta)$:

Table 1
Kinematic and dynamic symbols used in the paper.

symbols	representation
J_i, C_i	joint i and mass center of link i
$\boldsymbol{a}_i$, $\boldsymbol{b}_i \in \mathbb{R}^3$	position vector from J_i to C_i and from C_i to J_{i+1}
$\boldsymbol{r}_{C_i} \in \mathbb{R}^3$	position vector of mass center of link i
$\boldsymbol{r}_b$, $\boldsymbol{r}_e \in \mathbb{R}^3$	position vector of base and end-effector
ω_b, $\omega_e \in \mathbb{R}^3$	angular velocity of base and end-effector
$m_i \in \mathbb{R}$, $\mathbf{I}_i \in \mathbb{R}^{3\times3}$	mass and inertia matrix of link i
$\mathbf{H}_b \in \mathbb{R}^{6\times6}$	inertia matrix of the base
$\mathbf{H}_{bm} \in \mathbb{R}^{6\times n}$	coupling inertia matrix
$\mathbf{H}_m \in \mathbb{R}^{n\times n}$	inertia matrix of the manipulator
$\boldsymbol{c}_b \in \mathbb{R}^6$, $\boldsymbol{c}_m \in \mathbb{R}^n$	velocity dependent non-linear terms
$\boldsymbol{f}_b$, $\boldsymbol{f}_e \in \mathbb{R}^6$	force and moment exert on base and end-effector
$\tau \in \mathbb{R}^n$	torque exert on manipulator joints

$$\begin{aligned} &\text{minimize} \quad \Gamma(\theta(t)) \\ &\text{subject to: } g_i(\theta(t)) < 0, \quad i = 1,2,\cdots,n_{ieq} \\ &\quad h_i(\theta(t)) = 0, \quad i = 1,2,\cdots,n_{eq} \end{aligned} \tag{1}$$

2.1. Kinematics and dynamics of space robot

Before discussion dual-arm space robot in detail, some symbols and variables applied in the following sections are listed in Table 1. As shown in Fig. 1, a dual-arm space robotic system is composed of a spacecraft body (base) and two kinematically redundant manipulators both with n DOF, there being $2n+1$ bodies in total. Many investigations have been conducted in the field of multi-body dynamics. Refer to [19,20], the dynamic equations of a space robotic system using the Lagrangian mechanism can be expressed as follows:

$$\begin{bmatrix} \mathbf{H}_b & \mathbf{H}_{bm}^a & \mathbf{H}_{bm}^b \\ \mathbf{H}_{bm}^{a\mathrm{T}} & \mathbf{H}_m^a & 0_n \\ \mathbf{H}_{bm}^{b\mathrm{T}} & 0_n & \mathbf{H}_m^b \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{x}}_b \\ \ddot{\theta}^a \\ \ddot{\theta}^b \end{bmatrix} + \begin{bmatrix} \boldsymbol{c}_b \\ \boldsymbol{c}_m^a \\ \boldsymbol{c}_m^b \end{bmatrix} = \begin{bmatrix} \boldsymbol{f}_b \\ \tau_m^a \\ \tau_m^b \end{bmatrix} + \begin{bmatrix} \mathbf{J}_b^{a\mathrm{T}} & \mathbf{J}_b^{b\mathrm{T}} \\ \mathbf{J}_e^{a\mathrm{T}} & 0_{n\times6} \\ 0_{n\times6} & \mathbf{J}_e^{b\mathrm{T}} \end{bmatrix} \begin{bmatrix} \boldsymbol{f}_e^a \\ \boldsymbol{f}_e^b \end{bmatrix} \tag{2}$$

where $\ddot{\boldsymbol{x}}_b \in \mathbb{R}^6$ is the vector of linear and angular accelerations of the base, $\ddot{\theta}^a \in \mathbb{R}^n$ and $\ddot{\theta}^b \in \mathbb{R}^n$ represent joint accelerations of manipulator a and b. For definiteness and without loss of generality, variables with superscripts a and b denote that they are respectively related to the manipulator a and b. For a free-floating space robotic system, there is no external force and torque applied to the end-effectors ($\boldsymbol{f}_e^a = \boldsymbol{f}_e^b = 0$) and to the base ($\boldsymbol{f}_b = 0$). The motions of the manipulators are governed only by the internal torque on their joints. Hence, according to the momenta conservation law, the linear momentum $\boldsymbol{P}_0$ and angular momentum $\boldsymbol{L}_0$ of the whole robotic system are conserved which can be expressed by:

$$\begin{bmatrix} \boldsymbol{P}_0 \\ \boldsymbol{L}_0 \end{bmatrix} = \mathbf{H}_b \dot{\boldsymbol{x}}_b + \mathbf{H}_{bm}^a \dot{\theta}^a + \mathbf{H}_{bm}^b \dot{\theta}^b \tag{3}$$

Suppose the initial linear and angular momentum $\boldsymbol{P}_0 = \boldsymbol{L}_0 = 0$, since $\mathbf{H}_b$ is always invertible, the motion of the base can be described by

$$\dot{\boldsymbol{x}}_b = \begin{bmatrix} \dot{\boldsymbol{r}}_b \\ \omega_b \end{bmatrix} = \mathbf{J}_a \dot{\theta} = [-\mathbf{H}_b^{-1}\mathbf{H}_{bm}^a \quad -\mathbf{H}_b^{-1}\mathbf{H}_{bm}^b] \begin{bmatrix} \dot{\theta}^a \\ \dot{\theta}^b \end{bmatrix} \tag{4}$$

By substituting Eq. (4) into the kinematic mapping of the end-effector a, $\dot{\boldsymbol{x}}_e^a = \mathbf{J}_b^a \dot{\boldsymbol{x}}_b + \mathbf{J}_e^a \dot{\theta}^a$, and end-effector b, $\dot{\boldsymbol{x}}_e^b = \mathbf{J}_b^b \dot{\boldsymbol{x}}_b + \mathbf{J}_e^b \dot{\theta}^b$, the motion of the end-effectors can be given as follows

$$\begin{bmatrix} \dot{\boldsymbol{x}}_e^a \\ \dot{\boldsymbol{x}}_e^b \end{bmatrix} = \begin{bmatrix} \mathbf{J}_g^a \\ \mathbf{J}_g^b \end{bmatrix} \dot{\theta} = \begin{bmatrix} \mathbf{J}_e^a - \mathbf{J}_b^a \mathbf{H}_b^{-1} \mathbf{H}_{bm}^a & -\mathbf{J}_b^a \mathbf{H}_b^{-1} \mathbf{H}_{bm}^b \\ -\mathbf{J}_b^b \mathbf{H}_b^{-1} \mathbf{H}_{bm}^a & \mathbf{J}_e^b - \mathbf{J}_b^b \mathbf{H}_b^{-1} \mathbf{H}_{bm}^b \end{bmatrix} \begin{bmatrix} \dot{\theta}^a \\ \dot{\theta}^b \end{bmatrix} = \mathbf{J}_g \dot{\theta} \tag{5}$$

where $\mathbf{J}_g$ is termed Generalized Jacobian Matrix (GJM) which was first derived in Ref. [21] for single space manipulator. From Eqs. (4) and (5),