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Effective motion planning strategy for space robot capturing targets under consideration of the berth position

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ABSTRACT

Although many motion planning strategies for missions involving space robots capturing floating targets can be found in the literature, relatively little has discussed how to select the berth position where the spacecraft base hovers. In fact, the berth position is a flexible and controllable factor, and selecting a suitable berth position has a great impact on improving the efficiency of motion planning in the capture mission. Therefore, to make full use of the manoeuvrability of the space robot, this paper proposes a new viewpoint that utilizes the base berth position as an optimizable parameter to formulate a more comprehensive and effective motion planning strategy. Considering the dynamic coupling, the dynamic singularities, and the physical limitations of space robots, a unified motion planning framework based on the forward kinematics and parameter optimization technique is developed to convert the planning problem into the parameter optimization problem. For getting rid of the strict grasping position constraints in the capture mission, a new conception of grasping area is proposed to greatly simplify the difficulty of the motion planning. Furthermore, by utilizing the penalty function method, a new concise objective function is constructed. Here, the intelligent algorithm, Particle Swarm Optimization (PSO), is worked as solver to determine the free parameters. Two capturing cases, i.e., capturing a two-dimensional (2D) planar target and capturing a three-dimensional (3D) spatial target, are studied under this framework. The corresponding simulation results demonstrate that the proposed method is more efficient and effective for planning the capture missions.

1. Introduction

Recently, much attention has been paid to the unmanned on-orbit servicing (OOS) technology [1] because of its merit of substituting the astronauts to execute the extra-vehicular activities (EVA). Space robots are regarded as the most promising technology for OOS missions, such as inspecting the environment, repairing and maintaining satellites, and cleaning orbital debris [2]. Some successful space robots, e.g., Canadarm and Canadarm-2 [3], have been well applied in constructing and servicing the international space station (ISS). Some well-known OOS technology demonstrations, such as the ETS-VII satellite [4] and Orbital Express [5] also verified that the current technologies can handle the cooperative targets well. However, the increasing amount of human-launched materials has aggravated the build-up of human-generated space debris [6], which will seriously threaten the security of on-orbit spacecrafts. In 2009, the Kosmos-Iridium collision event [7] changed world opinion; thus, it is necessary to capture and remove these threatening debris for maintaining a stable and secure space environment.

A space robotic system usually consists of a spacecraft base and one or more robotic manipulators; such a system exhibits completely different kinematic and dynamic characteristics from base-fixed robots [8]. One of the most distinctive features is the dynamic coupling between the manipulator and the spacecraft base, i.e., the motion of the manipulator will induce the motion of the base, and the coupling motion of the base will deteriorate the positioning accuracy and operational dexterity of the manipulator [9]. Space robots usually have two working modes: the free-flying mode (the position and attitude of the base are actively controlled) and the free-floating mode (neither of position and attitude is controlled) [10,11]. For most missions of capturing targets, in the first step, the space robot operates in free-flying mode to reach the rendezvous zone, and then it will change the free-flying mode into the free-floating mode for safely capturing with saving the energy consumption of the gas-jet thrusters. However, the space robot in free-floating mode is an under-actuated system [12,13], and its non-holonomic behaviour [14] indicates that the motion control of the manipulator not only relies on the current joint position but also relies on the current joint velocity. More specifically speaking, the robot only

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Nomenclature

J_i	Joint i
C_i	Center of mass (CoM) of the body i
$\sum_\mathrm{I}$, $\sum_i$	Inertia frame and the body i frame
$\sum_\mathrm{B}$, $\sum_\mathrm{E}$	Base frame and the end effector frame
$\sum_\mathrm{T}$, $\sum_\mathrm{TH}$	Target frame and the target handle frame
$\boldsymbol{a}_i$, $\boldsymbol{b}_i$	Position vectors from J_i to C_i and from C_i to J_{i+1}
$\boldsymbol{d}_\mathrm{E}$	Position vector from $\sum_\mathrm{B}$ to $\sum_\mathrm{E}$
$\boldsymbol{r}_\mathrm{g}$	Position vector of the whole space robot CoM
$\boldsymbol{r}_\mathrm{B}$, $\boldsymbol{r}_i$	Position vectors of the base CoM and C_i
$\boldsymbol{P}_i$, $\boldsymbol{P}_\mathrm{E}$	Position vectors of J_i and $\sum_\mathrm{E}$
$\boldsymbol{P}_\mathrm{TH}$	Position vectors of the target handle
$\boldsymbol{H}_\mathrm{B}$	Inertia matrix of the base
$\boldsymbol{H}_\mathrm{M}$	Inertia matrix of the manipulator
$\boldsymbol{H}_\mathrm{BM}$	Coupling matrix between the base and manipulator
$\boldsymbol{v}_\mathrm{B}$, $\dot{\boldsymbol{v}}_\mathrm{B}$	Linear velocity and acceleration vectors of the base
$\boldsymbol{\omega}_\mathrm{B}$, $\dot{\boldsymbol{\omega}}_\mathrm{B}$	Angular velocity and acceleration vectors of the base
$\dot{\boldsymbol{x}}_\mathrm{B}$, $\ddot{\boldsymbol{x}}_\mathrm{B}$	Generalized velocity and acceleration vectors of the base
$\boldsymbol{\theta}$, $\dot{\boldsymbol{\theta}}$, $\ddot{\boldsymbol{\theta}}$	Joint position, velocity, and acceleration vectors
$\boldsymbol{c}_\mathrm{B}$, $\boldsymbol{c}_\mathrm{M}$	Velocity dependent non-linear term of the base and the manipulator
$\boldsymbol{F}_\mathrm{B}$, $\boldsymbol{F}_\mathrm{E}$	External forces applied on the base and the manipulator
$\boldsymbol{\tau}$	Joint torque of the manipulator
$\boldsymbol{J}_\mathrm{B}$, $\boldsymbol{J}_\mathrm{M}$	Jacobian matrices of the base and the manipulator
$\boldsymbol{v}_\mathrm{E}$	Linear velocity vector of the end effector
$\boldsymbol{\omega}_\mathrm{E}$	Angular velocity vector of the end effector
$\dot{\boldsymbol{x}}_\mathrm{E}$	Generalized velocity vector of the end effector
$\boldsymbol{H}_\mathrm{MC}$	Motion-coupling matrix between the manipulator and the base
$\boldsymbol{H}_\mathrm{MCv}$, $\boldsymbol{H}_\mathrm{MC\omega}$	Sub-motion-coupling matrices corresponding to the linear and angular velocity terms of the base
$\boldsymbol{J}_\mathrm{G}$	Generalized Jacobian Matrix (GJM) of the space robot in free-floating mode
$\boldsymbol{J}_\mathrm{Gv}$, $\boldsymbol{J}_\mathrm{G\omega}$	Sub-GJMs corresponding to the linear and angular velocity terms of the end effector
t_0, t_f	Initial and terminal time
$\boldsymbol{r}_\mathrm{B}$	Berth position vector of the base
$\Delta\boldsymbol{P}_\mathrm{E}$	Position displacement of the end effector
$\boldsymbol{\psi}_\mathrm{E}$, $\boldsymbol{\psi}_\mathrm{B}$	X-Y-Z Euler angles of the end effector and the base
$\boldsymbol{\psi}_\mathrm{TH}$	X-Y-Z Euler angles of the target handle
$\dot{\boldsymbol{\psi}}_\mathrm{E}$, $\dot{\boldsymbol{\psi}}_\mathrm{B}$	X-Y-Z Euler angle rate of the end effector and the base
$\boldsymbol{R}_\mathrm{E}$, $\boldsymbol{R}_\mathrm{B}$	Rotation matrices of $\sum_\mathrm{E}$ and $\sum_\mathrm{B}$ with respect to $\sum_\mathrm{I}$
$\Delta\boldsymbol{P}_\mathrm{ETH}$	Position vector from $\sum_\mathrm{E}$ to $\sum_\mathrm{TH}$
D_S	Minimum safe distance
$\hat{\boldsymbol{r}}_\mathrm{B}$	Hypothetical berth position vector
$\hat{\boldsymbol{\psi}}_\mathrm{E}$	End effector Euler angles based on $\hat{\boldsymbol{r}}_\mathrm{B}$
$\hat{\boldsymbol{P}}_\mathrm{E}$	End effector position vector based on $\hat{\boldsymbol{r}}_\mathrm{B}$
	Joint trajectory function vector
$\theta_i(t)$	Trajectory function of joint i
$\boldsymbol{D}$	Grasping area function
$\Delta\boldsymbol{r}_\mathrm{B}$	Adjustable variable of the berth position
Γ_C	Objective function based on the conventional method
$\delta\boldsymbol{p}_\mathrm{E}$, $\delta\boldsymbol{\psi}_\mathrm{E}$	Grasping position and attitude error vectors
$\boldsymbol{\lambda}_\mathrm{p}$, $\boldsymbol{\lambda}_\psi$	Weight coefficient matrices of grasping accuracy
ℓ	Penalty function
Γ_N	Objective function based on the proposed method
τ	Normalized time
T	Total execution time
f_{ik}	Coefficient of the joint i polynomial function
$\boldsymbol{f}_\mathrm{P}$	Undetermined parameter vector of the joint trajectories
$\bar{\boldsymbol{x}}_i$	Position of the particle i in PSO
$\bar{\boldsymbol{v}}_i$	Velocity of the particle i in PSO
ϖ	Inertia weight in PSO
Iter	Current iteration number in PSO
${}^i(\cdot)$	Pre-superscript i denoting the vector defined in $\sum_i$
$S(\cdot)$	Skew-symmetric matrix of the vector
$\Vert\cdot\Vert$	Norm of the vector
$\vert\cdot\vert$	Absolute value of the scalar

has the precise differential kinematics (i.e., kinematics at velocity level).

In past several decades, many research studies on the kinematic analysis and motion planning on capturing targets have made great achievements. Vafa and Dubowsky [15] proposed the Virtual Manipulator (VM) technique to analyse the work space and the inverse kinematics of space robots in the case of a controllable attitude system. Umetani and Yoshida [16] proposed the Generalized Jacobian Matrix (GJM) to describe the differential kinematics, in which, under the assumption that GJM was nonsingular, a method based on resolving the inverse of GJM was applied to plan the joint trajectories. Papadopoulos, and Dubowsky [17] investigated the singularities of GJM and found that the singularities of GJM were related to not only the geometry parameters but also the inertia parameters of space robots; such singularities are also called dynamic singularities. Different from kinematic singularities, dynamic singularities do not form static manifolds and thus it is difficult to determine the singular distributions, which is a serious problem for planning and controlling the manipulator of space robots [18]. Furthermore, the concepts of Path Dependent Workspace (PDW) and Path Independent Workspace (PIW) [17] were proposed to avoid dynamic singularities. However, trajectory planning in PIW will narrow the motion scope of the manipulator, which is not an optimal or effective method. To completely avoid dynamic singularities, Agrawal and Xu [19] proposed a method based on the optimal control theory and the forward integration scheme to plan the global optimum trajectory. For capturing stationary targets, some methods based on the forward kinematics and parameter optimization algorithms (e.g., Sequential Quadratic Programming (SQP) [13], Genetic Algorithm (GA) [20], Particle Swarm Optimization (PSO) [21,22], and Differential Evolution (DE) [23]) have been successfully employed to plan the optimal joint trajectories with various objective functions. For capturing tumbling targets, Aghili [24] proposed an optimal controller based on the requirement of zero relative velocity when the end effector contacts the grasping point on the target to minimize the impact force. Lampariello and Hirzinger [25] proposed a method based on nonlinear optimization to plan the feasible trajectories for grasping the tumbling targets in a useful time. An optimal grasping configuration that makes the direction of the relative velocity pass through the center of mass (CoM) of the whole space robot system is proposed to minimize the base attitude disturbance, which allows the nonzero relative velocity between the end effector and the grasping point [26].

To conclude, most motion planning of capturing missions can be regarded as point-to-point trajectory optimizations, and the primary task is steering the end effector to meet the grasping constraints at the grasping instant, which contain the grasping position, grasping attitude, and grasping velocity (for the tumbling targets) [24]. Two major methods are adopted to solve optimal motion planning problems: one is based on the optimal control theory to plan the joint trajectories [19,24,26]; the other is the parameter optimization technique, which converts the planning problem into the parameter optimization problem [13,20–23,25]. The first technique is an elegant approach to solve the optimal time and the discontinuous joint torque; however, sometimes the planned joint trajectories are not smooth enough. By contrast, the second technique can easily obtain more smooth joint trajectories with satisfying other planning objectives simultaneously; however, the numerical iterations may take an excessive amount of time. From the