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Pre-impact trajectory planning for minimizing base attitude disturbance in space manipulator systems for a capture task

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Abstract Aimed at capture task for a free-floating space manipulator, a scheme of pre-impact trajectory planning for minimizing base attitude disturbance caused by impact is proposed in this paper. Firstly, base attitude disturbance is established as a function of joint angles, collision direction and relative velocity between robotic hand and the target. Secondly, on the premise of keeping correct capture pose, a novel optimization factor in null space is designed to minimize base attitude disturbance and ensure that the joint angles do not exceed their limits simultaneously. After reaching the balance state, a desired configuration is achieved at the contact point. Thereafter, particle swarm optimization (PSO) algorithm is employed to solve the pre-impact trajectory planning from its initial configuration to the desired configuration to achieve the minimized base attitude disturbance caused by impact and the correct capture pose simultaneously. Finally, the proposed method is applied to a 7-dof free-floating space manipulator and the simulation results verify the effectiveness.

1. Introduction

The importance of capturing operations by a space manipulator has been increasing in recent years. A whole capture mission contains three specific phases: target chasing control phase, impact phase between the target and robotic hand and stabilization control phase of tumbling motion.[1] During the first phase, which is also called pre-impact phase, trajectory tracing or optimization sometimes is needed. And during the impact phase, due to control and sensing errors, there remain certain amounts of relative velocities between the robotic hand and the contact point of the target. Thus a force impulse is generated, which may damage the manipulator or the target if its magnitude is too large and disturb the base due to dynamic coupling. Therefore, the minimization of impact force impulse and the minimization of base attitude disturbance caused by the impact become two major problems for a capture task. In some cases, particularly when either (or both) manipulator and target are fragile or expensive, it is desired

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that the manipulation be as gentle as possible. Special attention needs to be paid to the minimization of impact force impulse. Regarding this issue, many scholars[2–6] proposed their own solutions, and also our previous work.[7,8] In other cases, especially when the manipulator moment of inertia is not negligible in comparison to the base, obvious base attitude disturbance will affect the communication with the ground and power supply for space manipulator, and compensating the disturbance using the attitude control system will consume large fuel which is limited in space. Therefore, proposing a method for minimizing base attitude disturbance caused by impact is the aim of the present study.

So far, there have been some studies on the minimization of base attitude disturbance. The base attitude disturbance can be compensated by utilizing moment compensation system, for example, base-mounted reaction wheels, which apply moments to the base to cancel moments induced by the impact.[9–11] Dimitrov and Yoshida[12,13] proposed the idea of preloading bias momentum in the chaser's manipulator, which is with equal magnitude and opposite direction to the one in the target. In this case, the momentum of the entire system at the end of the pre-impact phase is equal to zero, and after contact, the target momentum "entering" the chaser could be canceled out with the one preloaded in manipulator. Therefore, the momentum of the whole capture system can be stored in reaction wheels. And this idea can also be seen in Refs.[14,15]. Using a balance arm to compensate the base attitude is another way. Based on linear and angular momentum conservation law, the dynamics coupling between the base and its multi-arm manipulators are analyzed. On this basis, the base attitude disturbance can be minimized by controlling the balance arm.[16,17] However, these kinds of compensation system may have several drawbacks. Firstly, they add significant mass to a system. Secondly, their capacity to compensate base disturbance is limited. Thirdly, they increase the complexity of the system, which is not preferred in control scheme. Therefore, methods to plan manipulator motion to minimize the base attitude disturbance are more interesting.

Gattupalli et al.[18] used holonomic distribution to reach closer to the target and task-level constraints to finally get to the capture point; during the point-to-point maneuvre, no reaction moment gets transferred to the base. Kaigom et al.[19] also achieved minimized base disturbance based on the reaction null space and the constrained particle swarm optimization (PSO). However, the disturbance caused by impact is not considered in both methods. Nguyen-Huynh and Sharf[20] presented an adaptive algorithm to generate reactionless motion for a space manipulator when capturing the target. Focused on the unstable motion of space manipulator due to the impact effect, Dong and Chen[21] designed a robust adaptive compound control algorithm to suppress the unstable motion. They focused on the control strategy at the post-impact stage, which may affect the existing compliance control capability of space robot regarding both implementation and operation. Nenchev and Yoshida[22] presented impact dynamic analysis of a free-floating space robot subject to a force impulse at the hand, especially focused on the study of the joint reaction and the base reaction, and the change of the respective partial momenta of the space robot. They showed that preferable directions of the impulsive force exist, such that impact momentum transfer toward the base can be minimized. Based on the idea, Cong and Sun[23] introduced "straight arm capture" concept. In the methods, there will be no attitude disturbance neither during the impact nor after it, when all link centroid and the base centroid are aligned, and the force impulse direction is along that line. This is the most favorable condition, but it is a little hard to be obtained for plane robot, not to say space robot. Huang et al.[24] suggested to find an optimal path for a space robot in joint space to minimize the base disturbance forces and momenta transmissed from the end-effector to the base. Cocuzza et al.[25] presented an angular-acceleration-level solution based on constrained least-squares approach for the inverse kinematics of redundant space manipulators, which is aimed at locally minimizing the dynamic disturbances transferred to the base during trajectory tracking. And for capturing a free-tumbling object, Flores-Abad et al.[26] presented an optimal control strategy for a space robot under the conditions of having minimal impact on the base satellite during the capturing operation.

In this paper, a scheme of pre-impact trajectory planning in space manipulator systems is proposed for a capture task. It is a combination of null space and PSO algorithm, where null space is used to search for the best configuration for capture and PSO algorithm is responsible for achieving the trajectory from initial state to the desired state. By this scheme, a pre-impact trajectory of space manipulator can be obtained to achieve the minimized base attitude disturbance caused by impact and the correct capture pose at the same time.

2. Base attitude disturbance caused by impact

2.1. Collision assumption

The following assumptions are made in establishing the base attitude disturbance function.[8]

(1) The duration of contact is so short that the interaction forces act instantaneously.
(2) The changes in position and orientation during impact are negligible and effects of other forces except the impact force can be disregarded.
(3) From above assumptions (1) and (2), the inertia term of dynamic equation is dominant and other terms are less important.
(4) Impulsive forces as well as moments are induced on an act-react principle at the single-point of contact.

2.2. Base attitude disturbance function

Fig. 1 shows a general model of a free-floating space manipulator which is composed of $n+1$ parts, and they are connected with revolute joints, where $\Sigma_{\rm I}$ is the inertial frame, $\Sigma_{\rm E}$ the end-effector frame, Σ_i the ith joint frame $(i = 1, 2, \ldots, n)$, n the joint number, $\boldsymbol{r}_{\rm o}$ the vector from origin of $\Sigma_{\rm I}$ to base center, $\boldsymbol{r}_{\rm g}$ the vector from origin of $\Sigma_{\rm I}$ to total mass center of the system, $\boldsymbol{r}_{\rm og}$ the vector from base center to total mass center of the system, and $\boldsymbol{r}_{{\rm o}i}$ the vector from base center to the ith link center.

The equations governing the motion of a free-floating space manipulator as a multibody system are in general expressed in the following form:[27]