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Model predictive control for autonomous rendezvous and docking with a tumbling target

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A B S T R A C T

In this paper, we investigate the application of model predictive control (MPC) strategy for controlling a chaser spacecraft to dock with a tumbling target in space. The CW-based model is used to predict the proximity trajectory, while a receding prediction horizon is employed to complete the specific docking manipulation in finite time, and a 2-norm cost index about control input is used to minimize the fuel consumption of the chaser during docking. To ensure the implementation of the docking procedure, several engineering constraints such as control input saturation, collision avoidance, velocity constraint, and dock-enabling condition are considered simultaneously. A time-varying linear inequality constraint is used rather than the original quadratic constraint, to achieve the collision-avoidance requirement. Therefore, the constrained optimal rendezvous trajectory in the case of such a MPC framework can be obtained by solving a quadratic program subject to linear constraints. To verify the feasibility of the proposed MPC strategy, four AR&D scenarios are simulated. The simulation results show that MPC strategy can be an effective approach to achieve rendezvous and proximity maneuvering between a chaser spacecraft and a tumbling target while satisfying various constraints, and provide robustness to disturbances.

1. Introduction

Along with the rapid growth of space exploration, autonomous rendezvous and docking (AR&D) has become a growing necessity in recent years [1,3]. Especially, it has been thought as one of the key technologies for many foreseeable missions, such as space debris removing [2], on-orbit assembly, spacecraft repairing and/or upgrading, and spatial refueling [3]. Several space programs have been carried out as technology demonstration for servicing a cooperative spacecraft, including NASA's Demonstration for Autonomous Rendezvous Technology (DART) program [4], JAXA's Engineering Test Satellite-VII (ETS-VII) project [5], DARPA's Orbital Express (OE) program [6], and AFRL's Experimental Satellite System (XSS) [7] etc. In these programs, the targets are assumed to move in different Keplerian orbits without rapid attitude maneuver. However, AR&D with a non-cooperative target, such as a tumbling malfunctioning satellite or debris, is still an undemonstrated risky operation.

In the scope of this paper, we account for the on-orbit operations of controlling an active spacecraft (chaser) to approach and dock with a tumbling object (target). To enable this procedure, the position and velocity vectors of the chaser docking port and target one must be matched simultaneously. In addition, a collision avoidance constraint must be considered during final stage of rendezvous and docking. Usually, a certain "keep-out" zone which covers the outer surface of target is set to handle this constraint. Besides the collision avoidance constraint, several practical constraints such as control input saturation, velocity constraint etc., should also be included in this process. The autonomous docking operation under these constraints becomes a challenging task, and thus traditional rendezvous and docking strategies are unsuitable anymore.

Various guidance and path planning technologies have been investigated to deal with this problem in the past decades. In references [8–10], a guidance method based on Pontryagin minimum principle was proposed to formulate and solve the problem of minimum-energy and/or minimum-time optimal trajectory of rendezvous taking into account collision avoidance and dock-enabling condition as well. In reference [11], a fuel-optimal rendezvous trajectory was obtained by employing the Gauss pseudospectral method (GPM) to solve numerically the optimal con-

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trol problems. Besides collision avoidance and boundary condition, measure uncertainties were also concerned in this paper. Inverse dynamics-based trajectory planner was investigated in [12,13] for autonomous docking maneuver. The proposed planning method consisted of parameterizing the feasible rotational and translational trajectories via high-order polynomials, therefore the original optimal control problem was converted into a nonlinear programming problem. The method based on mixed-integer linear programming (MILP) was also proposed to find the fuel-optimal rendezvous trajectory for spacecraft subjected to avoidance requirements [14,15]. Both the binary variables and "big-M" method were investigated to ensure the safety of the docking trajectory. In references [16,17], the artificial potential function (APF) method combined with fuzzy logic was brought forward to drive a guidance control strategy for autonomous docking with a non-cooperative target, and Lyapunov theory was used to guarantee the stability of the guidance law.

In view of the nonlinear dynamics and kinematics in spacecraft orbit and attitude motions, several nonlinear control schemes have also been proposed in the case of proximity operations. In [18], a $\theta - D$ nonlinear optimal control technique was investigated to design a close-form control law. This proposed control law can minimize the tracking errors in relative position and attitude, and flexible structure vibrations simultaneously. Reference [19] proposed a coupled motion synchronization strategy for an active spacecraft and floating object in space. A nonlinear control law consisting of PID structure and feedback compensation term was designed in this paper to nullify position and attitude errors. A state-dependent Riccati equation (SDRE) technology was employed in [20] to design both position and attitude controllers. However, the SDRE must be solved repetitively at every integration step. In [21], a robust H_∞ controller was designed for spacecraft rendezvous in the presence of control input saturation, measurement error, model uncertainties, and thrust error. A fuzzy controller was proposed in reference [22] to achieve the requirements of AR&D with a non-cooperative target. Owing to the capability to deal with disturbances and uncertainties, sliding variable structure controllers were used to drive a chaser spacecraft to rendezvous with a tumbling target [23,24]. In addition, adaptive control technologies were also extensively employed to design robust controllers for spacecraft rendezvous and docking [25–28].

The main purpose of this paper is to achieve AR&D with a tumbling target using model predictive control (MPC). MPC has a long history in the field of control engineering. The ability to handle constraints in a multivariable control system makes this methodology attractive to researchers. A variety of papers (see e.g., [29–31] and references therein) have proposed the use of MPC for close-range rendezvous problem in the last decade. However, most of the previous researches focus only on the capture of a cooperative target, assuming that the docking port of the target is fixed in space. An application of MPC for spacecraft docking with a tumbling object was concerned in [31,32], where the target was assumed to rotate at a constant angular velocity in the orbital plane and the out-of-plane relative motion was neglected. Based on [31,32], this paper greatly expands the scope by considering the relative motion between a chaser and a tumbling target in three-dimensional space. Then, a fuel-optimal path-tracking MPC problem under constraints that accounts for collision avoidance, thrust constraint, and velocity constraints is formulated. In order to achieve online real-time computation, linear approximation is employed to handle the nonlinear constraints, hence the original MPC problem can be solved by using existed quadratic programming (QP) algorithms.

The remainder of the paper is organized as follows. In Section 2, the problem formulation is given including the relevant coordinate frames, relative motion dynamics, attitude dynamics of the target spacecraft, constraints modeling, and control objective. Section 3 gives the MPC controller designing procedure in detail. An overview of the prediction of the state and output variables, optimization index, linear inequality constraints, and QP procedure is included in this section. Simulation results with detailed discussions are presented in Section 4. Section 5 concludes the paper.

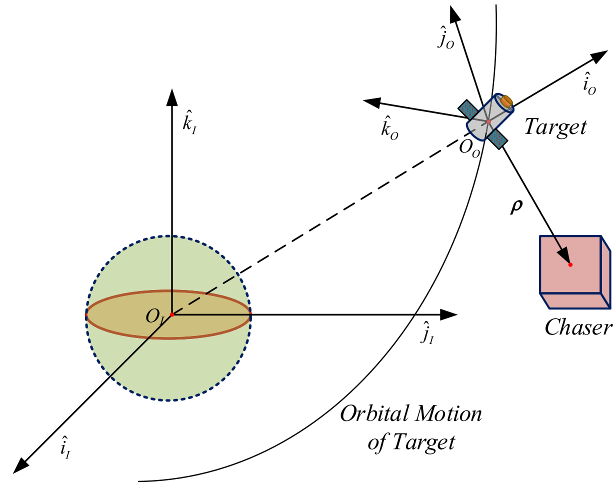

Fig. 1. Autonomous rendezvous and docking.

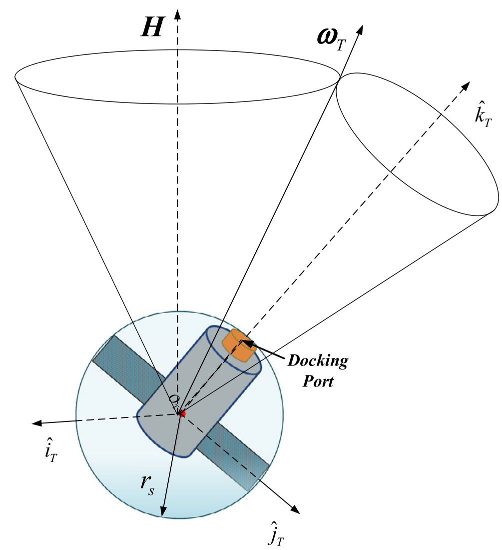

Fig. 2. The tumbling motion of target spacecraft.

2. Problem formulation

The problem concerned in this paper is to driving an active spacecraft autonomous docking with a tumbling target in space. The target is assumed to be an uncontrolled tumbling object, such as a malfunctioning satellite or a spent launcher's stage [41]. In order to achieve the docking mission, we assume that the state information of target can be obtained from chaser's observation and estimation [8–14,20–24,26]. This assumption is reasonable in practice, because many technologies have been brought forward to estimate the state information of a space target [33–35].

For close-proximity rendezvous problem, the following coordinate frames are defined as shown in Figs. 1 and 2.

1) The Earth-centered inertial coordinate frame is denoted as $\mathcal{F}_I : \{O_I, \hat{i}_I, \hat{j}_I, \hat{k}_I\}$ with the origin at the center of the Earth. The $\hat{i}_I$ axis points toward the vernal equinox, $\hat{k}_I$ axis is along the North Pole, and $\hat{j}_I$ completes the triad.