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Robust model predictive control for multi-step short range spacecraft rendezvous

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Abstract

This work presents a robust model predictive control (MPC) approach for the multi-step short range spacecraft rendezvous problem. During the specific short range phase concerned, the chaser is supposed to be initially outside the line-of-sight (LOS) cone. Therefore, the rendezvous process naturally includes two steps: the first step is to transfer the chaser into the LOS cone and the second step is to transfer the chaser into the aimed region with its motion confined within the LOS cone. A novel MPC framework named after Mixed MPC (M-MPC) is proposed, which is the combination of the Variable-Horizon MPC (VH-MPC) framework and the Fixed-Instant MPC (FI-MPC) framework. The M-MPC framework enables the optimization for the two steps to be implemented jointly rather than to be separated factitiously, and its computation workload is acceptable for the usually low-power processors onboard spacecraft. Then considering that disturbances including modeling error, sensor noise and thrust uncertainty may induce undesired constraint violations, a robust technique is developed and it is attached to the above M-MPC framework to form a robust M-MPC approach. The robust technique is based on the chance-constrained idea, which ensures that constraints can be satisfied with a prescribed probability. It improves the robust technique proposed by Gavilan et al., because it eliminates the unnecessary conservativeness by explicitly incorporating known statistical properties of the navigation uncertainty. The efficacy of the robust M-MPC approach is shown in a simulation study.

Keywords: Short range spacecraft rendezvous; Multiple steps; Model predictive control; Chance-constrained approach

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1. Introduction

The spacecraft rendezvous has been recognized as one of the most important techniques in the current and future space engineering. It is the main step of many space missions including intercepting, repairing, saving, docking, large-scale structure assembling and satellite networking (Imani and Beigzadeh, 2016). Spacecraft rendezvous missions and experiments have been conducted by many countries such as Automated Transfer Vehicle (ATV) from European Space Agency (ESA) (De Pasquale, 2012), Orbital Express from the USA (Friend, 2008) and Tiangong-1/Shenzhou-8 from China (Zhou, 2012).

A typical rendezvous scenario involves two spacecraft: one is passively moving or actively maintaining a fixed orbit (which will be referred to as “the target”) and the other is actively controlled (which will be referred to as “the chaser”). Usually, the objective of a rendezvous problem is to determine control commands to transfer the chaser to reach a prescribed relative position with respect to the target with a safe terminal relative velocity while the fuel consumption is minimized (Hartley, 2015). A rendezvous process can be separated into several phases according to the range between the chaser and the target. The final phase, i.e. the short range phase, is the most

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important of all, for it is the key to the success of the whole rendezvous process and thus it raises high requirements on the controller design. Hence, most literatures hitherto pay attention to the controller design for the short range phase (Richards and How, 2003; Breger and How, 2008; Leomanni et al., 2014; Vazquez et al., 2017; Li and Zhu, 2017). In all of these works it is supposed that the chaser is initially within the line-of-sight (LOS) cone emanating from the docking port on the target. Although this initial condition is satisfied in typical rendezvous scenarios as the objective of the previous phase, exceptions exist in some specific cases. For example, the chaser and the target are originally the members of a satellite formation with the separation of several hundred meters before the chaser receives the ground instruction to rendezvous with the target. Such a scenario can be regarded as an incomplete rendezvous process that includes only the short range phase. In this scenario the chaser is not necessarily within the LOS cone initially. If so, the short range phase naturally includes two steps: the first step is to transfer the chaser into the LOS cone and the second step is to transfer the chaser into the aimed region with its motion confined within the LOS cone. As an example, the rendezvous experiment of the PRISMA mission (Noteborn et al., 2011) is in line with the description to some extent, but it is simpler since the LOS cone emanates from the chaser and thus the target can be covered by the LOS cone through the attitude control of the chaser. A feasible treatment on such a problem is to factitiously add extra conditions to separate the two steps, and then implement optimization for each step respectively. However, even if the controller designed in this way is optimal for each step, it is not necessarily optimal for the overall short range rendezvous process. As a result, it is useful to develop an approach capable of implement optimization for the two steps jointly without separating them, which is just the objective of this paper.

Model predictive control (MPC) is a now widely-used approach for the controller design for spacecraft rendezvous. The principle of MPC is that the optimal control inputs over a finite number of sampling instants, known as the “time horizon”, are computed at each instant, while only the first one of the optimal control sequence is executed and the optimization is re-implemented at the next instant when new measurement information is received (Weiss et al., 2015). The performance indices of interest like fuel consumption can be reduced by means of the rolling optimization mechanism of MPC compared with that obtained using traditional open-loop techniques which just force the chaser to track a pre-designed trajectory.

There have been lots of works about the application of MPC to spacecraft rendezvous. The most notable difference among them is the choice of MPC frameworks. There are mainly three types of MPC frameworks: Fixed-Horizon MPC (FH-MPC), Variable-Horizon MPC (VH-MPC) and Fixed-Instant MPC (FI-MPC). In a classical FH-MPC framework, the equilibrium input is calculated first which is defined as the input that enables the aimed terminal state to act as an equilibrium state. The cost function of FH-MPC penalizes the deviation of the real state from the aimed terminal state and the difference between the real input and the equilibrium input (Bemporad and Morari, 1999). A variation on the classical FH-MPC is proposed by Weiss et al. (2015) to avoid the need for a long horizon by introducing the virtual equilibrium input and the virtual equilibrium state as additional decision variables. The FH-MPC frameworks can stabilize the system, but that the aimed state is forced to be the equilibrium state can be too strict and not necessary in most spacecraft rendezvous scenarios (Richards and How, 2006). In addition, there are two disadvantages of FH-MPC: firstly, that its cost function penalizes the difference between the real input and the equilibrium input mismatches the true objective of minimizing fuel consumption, unless the equilibrium input exactly equals zero (such as V-bar approach on circular orbits); secondly, although the initial response can be tuned to be fast, its final convergence is asymptotic and it is very slow for the system to reach the aimed state (Hartley, 2015). To avoid the disadvantages of FH-MPC, the VH-MPC framework is proposed by Richards and How (2003). In the VH-MPC framework, some additional binary variables are introduced to signify when the rendezvous process is finished, so it can explicitly optimize the completion time as well as the fuel consumption. The aimed region or “box” that contains the aimed state must be defined to indicate the completion of rendezvous in VH-MPC, because the arrival at a particular state in finite time is impossible with disturbances existing. The limitation of VH-MPC is that it calls for solving a mixed integer linear programming (MILP) problem at each sampling instant, whose computation workload is relatively high and low-power spacecraft processors may not be qualified for the real-time computation. The third MPC framework is the FI-MPC framework, which is used by Larsson et al. (2006), and its efficacy has been validated on the real space mission PRISMA (Bodin et al., 2011). In the FI-MPC framework, the completion time is no longer the decision variable and instead is assigned in advance. In comparison with VH-MPC, what needs solving at each instant in the FI-MPC framework is just an easy-to-compute linear programming (LP) problem. The drawback of FI-MPC is its inability to optimize the completion time and that given in advance is usually conservative. The above MPC frameworks are all for a single-step rendezvous problem, and for a multi-step problem one can factitiously choose a relative position inside the LOS cone as the terminal state of the first step to separate the two steps and then apply one of the MPC frameworks to each step. However, the controller designed in this way is not necessarily optimal for the overall short range rendezvous process, even if it is optimal for each step. On the other hand, it is found in this work that the traditional VH-MPC framework can be naturally extended to multi-step rendezvous problems without separating the steps by introducing more binary variables. But it calls for solving a MILP problem at each sampling

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