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Tube-based robust model predictive control for spacecraft proximity operations in the presence of persistent disturbance

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ABSTRACT

Rendezvous and Proximity Operations (RPOs) of two autonomous spacecraft have been extensively studied in the past years, taking into account both the strict requirements in terms of spacecraft dynamics variations and the limitations due to the actuation system. In this paper, two different Model Predictive Control (MPC) schemes have been considered to control the spacecraft during the final phase of the rendezvous maneuver in order to ensure mission constraints satisfaction for any modeled disturbance affecting the system. Classical MPC suitably balances stability and computational effort required for online implementation whereas Tube-based Robust MPC represents an appealing strategy to handle disturbances while ensuring robustness. For the robust scheme, the computational effort reduction is ensured adopting a time-varying control law where the feedback gain matrix is evaluated offline, applying a Linear Matrix Inequality approach to the state feedback stabilization criterion. An extensive verification campaign for the performance evaluation and comparison in terms of constraint satisfaction, fuel consumption and computational cost, i.e. CPU time, has been carried out on both a three degrees-of-freedom (DoF) orbital simulator and an experimental testbed composed by two Floating Spacecraft Simulators reproducing a quasi-frictionless motion. Main conclusions are drawn with respect to the mission expectations.

1. Introduction

Automated rendezvous and docking (RVD) missions have been widely studied in the last ten years. During these missions, controlled trajectories, in which a Chaser spacecraft tries to reach and dock a Target spacecraft, are guaranteed by a control system, able to handle uncertainties and external environment disturbances. Different control techniques have been proposed in literature, including feedback-linearization-based approach [1], Riccati equation techniques [2], sliding-mode control (SMC) [3], and other control setups in [4,5]. In [1] the problem of motion synchronization of free-flying robotic spacecraft and serviceable floating objects in space is considered, but a limitation of this approach is that the linear system can be different from the nonlinear one, due to the cancellation of nonlinearities. The Riccati equation techniques (as in [2]) are simple, numerically stable and competitive in computational effort with other known methods. However, only small parametric uncertainties are included. In [3] SMC strategies are proposed for thruster control, even if it is deemed to lead to excessive fuel consumption, due to switching on/off thrusters at high frequency. Even if a fuel-efficient algorithm is proposed, a high consumption is verified to track the docking port. As clearly explained in [4], a model predictive control approach for spacecraft proximity maneuvering which could effectively handle the constraints on thrust magnitude, line-of-sight, and approach velocity, and can be more effective than other controllers in terms of fuel consumption.

For this reason, in this research, special attention has been reserved to the adoption of MPC, for its ability to deal with the constraints that typically characterize this maneuver, both in terms of relative position and velocity, as well as actuation system limitations. The approach proposed here moves along the lines of previous works employing MPC schemes for RVD. A Linear Quadratic MPC (LQMPC) has been adopted to enforce thrust magnitude limitation, line of sight (LOS) constraints, and velocity constraints for soft docking in [6]. In [7], a low-complexity MPC scheme for three degree-of-freedom (DoF) spacecraft system is developed for the low-thrust rendezvous and proximity operations.

However, in all of these approaches, orbital perturbations, disturbances, and model errors are not taken into account. In [8],

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the improved performance of a robust MPC in the presence of disturbances, compared with a classical one, are highlighted solving the spacecraft rendezvous problem. In the last years, focusing on robust approach, a new appealing approach has been introduced, called Tube-based Robust MPC (TRMPC), which focuses on two main goals: (i) the robustness to additive disturbances and (ii) the computational efficiency of a classical MPC. Moreover, this algorithm is split in two parts: (i) an offline evaluation of the constraints to ensure the uncertain future trajectories lie in sequence of sets, known as *tubes*, and (ii) the online MPC scheme applied to the nominal trajectories, representing the center of the tube itself as in [9].

The main ideas of this paper are to evaluate the performance of a robust MPC controller, both in simulations and on an experimental setup, and to demonstrate the real-time effectiveness of the proposed robust approach. Moreover, this proposed MPC controller is able to handle uncertainties due to external disturbances and additive noise, according to the recent trend in literature [10]. Starting from the approach proposed in [11], our idea is to evaluate for the first time the performance of this controller within the space rendezvous scenario both in simulation, for a three degree-of-freedom (DoF) orbital simulator, and in an experimental setup, i.e. in a three DoF air-bearing spacecraft testbed. Hence, a real-time implementation of the TRMPC approach is here proposed to test the effectiveness of the controller on board.

In order to reach a reasonable computational effort for the robust approach, a time-varying control law is adopted where the feedback gain matrix is evaluated offline. A Linear Matrix Inequalities (LMI) approach is applied to the state feedback stabilization criterion for the stability analysis and the evaluation of the feedback matrix. As explained in [12] and in [13], the proposed method improves the computational efficiency of a robust MPC even using low-thrust propulsion, typically adopted in the final phase of RVD maneuver, as in the proposed case-study. Furthermore, due to the presence of parametric physical uncertainties and discrepancies between the mathematical model and the actual dynamics of the physical system in operation, as non linearities and neglected high-order dynamics, the LMI approach is able to reduce the computational effort required by other robust controller, guaranteeing the stability of the system and improving real-time implementation feasibility. The modeled uncertainties are related to the model linearization of the Hill–Clohessy–Wiltshire (HCW) equations, in which the coupling between the position and speed variables and the quadratic terms related to the distance between the Target and the chaser are neglected. In detail, all the terms $o(\rho^2/R^2)$ are not considered, with ρ the distance between the two spacecraft and R the distance between the Target and the Earth [14]. Moreover, the uncertainties of the control matrix are related to the mass and inertia variation due to the fuel consumption. The LMI approach applied to the Edge Theorem, generalization of the Kharitonov Theorem, allows the offline definition of the feedback gain matrix, which is adopted to define the time-varying control law. Further information of both Edge Theorem and Kharitonov Theorem can be found in [16]. Finally, the robust TRMPC is compared with a classical LQMPC in terms of computational cost, fuel consumption, and constraints satisfaction when the system is affected by persistent bounded uncertainties. The LQMPC, proposed in this paper, was deeply validated in [15], in which a LQMPC and inverse dynamics in the virtual domain (IDVD) guidance methods are combined.

An extensive verification campaign, both in simulation and in an experimental testbed, has been accomplished to validate the performance of the TRMPC. Its compatibility for real-time implementation and constraint satisfaction has been verified when the system is affected by bounded additive disturbances. As said before, the simulations are carried out on a three DoF orbital simulator. Instead, the experimental verification has been carried out using two spacecraft that float over a polished granite monolith surface reproducing a quasi-frictionless motion in Spacecraft Robotics Laboratory at the Naval Postgraduate School [17].

The paper is organized as follows. In Section 2 and 3 the model setup, both of the simulation environment (three DoF) and of the experimental testbed are presented. The control objective and the system dynamics are explained in detail in Section 4. In Section 5 the MPC design is described, focusing on the theory of the TRMPC and how the concept of Tube is introduced and defined, according to a constraint tightening approach. The simulation results obtained with the three DoF orbital simulator are presented in Section 6 while experimental results are described in Section 7, together with a comparison of the performance of LQMPC and TRMPC. Main conclusions are drawn in Section 8.

Notation: The notation employed is standard. Blackboard boldface letters (e.g., $\mathbb{X}$) denote sets. Bold letters, e.g., $\mathbf{u}_k = [u_{0|k} \cdots u_{N-1|k}]$, are used to denote the stack vector of N predicted values. Positive (semi)definite matrices $\boldsymbol{A}$ are denoted as $\boldsymbol{A} \succ 0$ ($\boldsymbol{A} \succeq 0$), whereas negative (semi)definite matrices are denoted as $\boldsymbol{A} \prec 0$ ($\boldsymbol{A} \preceq 0$). The set $\mathbb{I}_{\geq 0}$ denotes the positive integers, including 0. We use x_k for the (measured) state at time k and $\mathrm{x}_{i|k}$ for the state predicted i steps ahead at time k. $A \oplus B$ and $A \ominus B$ denotes the Minkowski sum and Pontryagin set difference, respectively.

2. Model of the translational three DoF relative orbital maneuver

The nominal relative motion of the two spacecraft in neighboring orbits can be described through HCW linearized equations in the typical continuous-time state-space formulation as $\dot{\mathrm{x}} = \boldsymbol{A}\mathrm{x} + \boldsymbol{B}\mathrm{u}$, where $\mathrm{x} = [x, y, z, \dot{x}, \dot{y}, \dot{z}]$ is the state vector representing the 3-position and 3-velocity components of the Chaser with respect to the Target in the local coordinate system (Local Vertical Local Horizontal (LVLH) frame), $\mathrm{u} = [F_x, F_y, F_z]$ is the control vector, expressed in the body reference frame, represented by the control force components applied to the spacecraft through the actuation system. As described in [18], the LVLH coordinate system is centered on the center of mass (CoM) of the Target and the axes are defined as follows: the X axis (V_{bar}) is in the direction of the orbital velocity vector, the Y axis (H_{bar}) is in the opposite direction of the angular momentum vector of the orbit, while the Z axis (R_{bar}) is radial from the spacecraft center of mass to the CoM Earth. The Chaser has the goal to arrive in the proximity of the Target vehicle, considering a V-bar approach within a cone corridor. $\boldsymbol{A}$ and $\boldsymbol{B}$, the state and control matrices respectively, are defined as in [19] as a function of the angular velocity of the orbit (known and constant) with respect to the inertial frame ω_0 and the wet mass of the Chaser m_{CV}.

Due to the space environment, external disturbances in terms of forces and moments, such as the J2, the gravity gradient, and the solar radiation pressure, could affect the vehicle performance and drive the chaser to violate the constraints. If these additive noises are included in the spacecraft dynamics, the following continuous-time uncertain system shall be considered

$$\dot{\mathrm{x}} = \boldsymbol{A}\mathrm{x} + \boldsymbol{B}\mathrm{u} + \boldsymbol{B}_w\mathrm{w}, \tag{1}$$

where w is the vector of persistent noise, mainly related to the external environment and can be modeled as a random and bounded noise. In particular, the disturbance sequence is the realization of a stochastic process where $\mathrm{w} \in \mathbb{W}$ is a random variable with known distribution, and the set $\mathbb{W}$ is a compact and convex set, containing the origin in its interior. Then, a discrete-time representation of system (1) is derived as follows

$$\mathrm{x}_{k+1} = \boldsymbol{A}_d\mathrm{x}_k + \boldsymbol{B}_d\mathrm{u}_k + \boldsymbol{B}_{w_d}\mathrm{w}_k, \tag{2}$$