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Author: Dr. Omer Burak Iskender
Nanyang Technological University, Singapore, Republic of, iske0001@e.ntu.edu.sg

ONLINE LEARNING & OPTIMIZATION FOR AUTONOMOUS SPACE SERVICING MISSIONS

Abstract

This paper presents a Learning-Based Model Predictive Control approach to address 6-Degrees-of-Freedom spacecraft guidance & control problem in the presence of dynamic uncertainties. One of the key challenges of automated space missions is the accurate representation of spacecraft dynamics that covers the entire performance envelope which is highly nonlinear, and rendering them is impractical for control systems. Particularly, this paper focuses on the fuel or propellant sloshing problem that can deteriorate the accuracy of translational and rotational motion control for future space servicing missions such as capture of space debris that requires agile, autonomous, and precise maneuvers. The fundamental idea is to use the well-known translational and rotational dynamics in-orbit as the base, constrained optimization problem formulation to address safety and performance constraints while minimizing the fuel use, and online learning by benefiting from the data obtained in real-time to refine the dynamic model for the improved performance.

There are a number of studies which investigate fuel sloshing but the knowledge of the motion in a micro-gravity environment still requires in-depth studies. Today, one of the most precise ways to simulate fuel sloshing is to conduct computational fluid dynamics (CFD) analysis based on the Navier-Stokes equations. However, this method is demanding in terms of time and computation resources and cannot be executed in real-time as a full scale CFD simulation could take many days. Furthermore, it is well-known that data driven, and optimization-based algorithms have the bottle neck of high computation power demand. On that note, the second objective is to employ industrial grade simulation models that can be adapted to real-time simulation environments and use space-based radiation hardened processors such as LEON3 to enable more realistic simulation practice.

The performance of the algorithm is presented in the scope of a potential future mission and of the available equipment for rendezvous and docking towards space servicing missions, both in circular and elliptical orbits by employing Clohessy-Whiltshere and Yamanaka-Ankersen Equations respectively. The results also cover a comparison between the proposed algorithms with Linear–quadratic regulator (LQR) based control law and Linear-MPC formulation with integral action to highlight the clear advantages of the Learning-based MPC formulation. It was demonstrated that when compared with aforementioned controllers, the proposed controller can achieve better control accuracy with 1) less pointing error, 2) lower settling time & overshoot, 3) less actuator use; therefore, fuel use. Later, Monte-Carlo simulations were run to evaluate the performance for different initial conditions, sensor & actuator errors, and for magnitude uncertainty of the fuel slosh. The Processor in the Loop experiments demonstrate that the proposed strategy is a promising candidate for future space servicing missions because 1) the learning-based algorithm shows additional robustness to sensor errors and critical uncertainties like fuel slosh, 2) the algorithm is real-time implementable on low power space processors as convex programming offers deterministic convergence properties and guarantees finite time solutions, 3) critical physical and geometrical constraints can be addressed in the safety critical systems.