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Enabling strategies for safe proximity operations to uncooperative and non-collaborative objects in Low Earth Orbit

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Abstract. In-orbit servicing, transportation and removal activities are on the way to revolutionize the space economy and space exploitation. Particularly for the near-Earth environment these activities are considered important in the near- and long-term future to ensure the sustainability of space activities. In this paper one of the many challenges facing this new expanding field is addressed, namely the safe and robust design of proximity operations with non-collaborative and uncooperative objects. Guidance and control methods are developed to improve the safety of various proximity operations phases, starting from the far-range approach at tens of kilometres to closer approach distances of few tens of meters. Furthermore, a guidance and control method of a servicer platform to cope with the uncontrolled tumbling motion of the target object is proposed. Here a contactless control approach exploiting safe relative trajectories and the thruster plume impingement is used to reduce the angular motion of the uncontrolled target.

Introduction

Proximity operations play an important role in future mission architectures in the On-Orbit Servicing, Assembly and Manufacturing (OSAM) and Active Debris Removal (ADR) domain. A paradigm shift between monolithic one-use assets towards OSAM activities in space is recognised as both profitable and efficient for the future space economy by the global space community. Despite a rich heritage of Rendezvous and Proximity Operations (RPOs) to cooperative targets, advances in the design of operations to uncooperative and non-collaborative targets are instrumental for a systematic implementation of autonomous RPOs within OSAM activities in the future. An uncooperative target is defined as an object in space that is not capable of aiding the knowledge of its state to another active object, for example with an inter-satellite link. A non-collaborative target is defined as a space object which cannot change its state to aid the OSAM activities, i.e. control its attitude or orbit. One of the key enablers for autonomous proximity operations to uncooperative and non-collaborative targets is flight safety. In fact, any anomaly with respect to the nominal profile or any contingency at spacecraft level will cause the triggering of safety measures, ultimately leading to chaser s/c in safe mode, thus potentially endangering the platforms and/or the completion of the mission. Such situations are not unknown to past missions. In the JAXA robotic demonstration mission ETS-VII [1], anomalies during an experiment caused the spacecraft to abort operations and position itself at 2.5 km distance from the target while investigating the issue. In 2005 during DART mission, the chaser unexpectedly used all the on-board propellant and during the retirement manoeuvres a collision with the target was detected [2]. More recently in early 2022 ELSA-d demonstration failures in the thrusters' assembly caused the chaser to move away at a safe distance from the target and a consequent re-assessment and re-planning of rendezvous and docking demonstration operations [3].

This Ph.D. research stems from the challenges encountered in the proximity operations domain to develop novel strategies to enable the safe and systematic implementation of OSAM activities in the future. The main research question is:

"How can we improve safety and robustness of proximity operations design for systematic application in future mission applications?"

In the research activities, the following key drivers and requirements are considered:

- **Safety**: The strategies shall ensure the safety of the whole mission operations.
- **Autonomy**: The service shall be able to perform the operations in diminishing the dependency from ground support as much as possible.
- **Efficiency**: The strategies shall be cost effective, both from a mission architecture point of view and from a spacecraft in orbit resources (propellant) point of view.
- **Reliability**: The strategies shall be robust to orbit conditions.

The research focuses on the relative mission design and Guidance Navigation and Control (GNC) aspects of proximity operations, specifically in the conditions where the target is uncooperative and non-collaborative targets. The research is organized in three main blocks, shown in Figure 1, which are deemed as instrumental to a safe approach to an uncooperative and non-collaborative target:

I. Approach GNC design to uncooperative and non-collaborative objects
II. Management of target tumbling motion
III. Safe inspection planning

In the next sections the research performed or planned for each block is described .

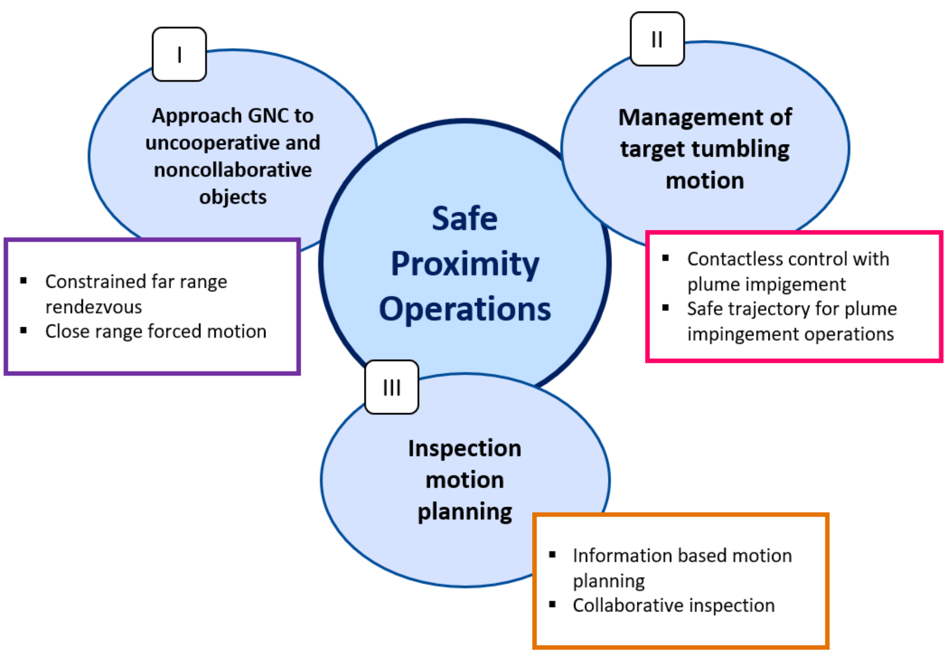

Figure 1. Schematic block diagrams of the Ph.D. activities.

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Approach to Guidance Navigation and Control

The activities in the approach GNC design focus mainly on the guidance and control aspects of the approach trajectory. Specifically, two phases of the approach are identified as:

- **Far-range approach**: from the first detection of the target with the onboard sensors up, approximately around 30-50 km.
- **Close-range approach**: starting at around few hundred meters when the chaser is required to final approach the target condition in the target body.

In the far range a guidance and control strategy were developed to enhance the performance of the Angles Only (AO) navigation filter, and published in [4]. In fact, from very far distances the chaser often has to rely only on Line Of Sight (LOS) measurements for its navigation solution, which result in a system with very poor observability. A guidance scheme optimising the propellant consumption and the observability enhancement feature is developed which improved the navigation solution and thus the control errors of the approach actuated in a Model Predictive Control (MPC) fashion.

In the close-range approach, novel formulation of safety constraints are developed extending the concept of Eccentricity and Inclination (E/I) vector separation to ensure passive abort safety ensuring more challenging scenarios. The work was presented in [5]. In proximity flight in the range of few meters, more complex trajectory final condition requirements, such as synchronization or complex reconfiguration, prevent the trajectory to be designed with a stringent geometry requirement such as the spiral approach. The conditions are formulated in function of ROEs, which are able to guarantee both a implementation advantage in the optimisation procedure used and a increased level of safety of flight. The safety measure is expressed for conditions of safety at time a given time ti as follows:

- **Point-Wise Safety (PWS):** Chaser's trajectory at time ti is said to be PWS safe if it is outside a geometrical KOZ defined around the target only at the time instant ti.
- **Passive Abort Safety (PAS):** Chaser's trajectory at ti is said to be PAS safe for a time interval ΔT if it is outside a geometrical KOZ around the target at time ti, and it will remain outside such KOZ also after a ΔT time interval of uncontrolled flight starting at ti.
- **Active Collision Safety (ACS) :** Chaser's trajectory at ti is said to be ACS safe if at time ti is outside a geometrical KOZ around the target, and it will remain outside such KOZ even for a $\Delta TACS + \Delta T$ time interval after ti . The intervals $\Delta TACS$ and ΔT are respectively the controlled collision avoidance portion and the uncontrolled portion of the trajectory after ti.

The safety constraints are expressed explicitly in function of the ROE state and included in a guidance scheme based on a Sequential Convex Programming (SCP) algorithm. The latter methods have been developed thanks to its efficiency in solving nonlinear programming problem with limited amount of computational resources, useful for an onboard implementation of the algorithm. In Figure 3 are shown the trajectories designed considering the novel ROE based safety constraints with respect to a purely fuel optimal trajectory for a test case of synchronization to a rotating target. The target hold point angular velocity to synchronise the chaser with was considered in this example as 0.5 deg/s. In Figure 4 it is shown the projection in the RN plane of motion of the failure trajectories stemming from the nominal trajectory. This demonstrate the efficacy of the algorithm to grant PAS in terms of RN separation.

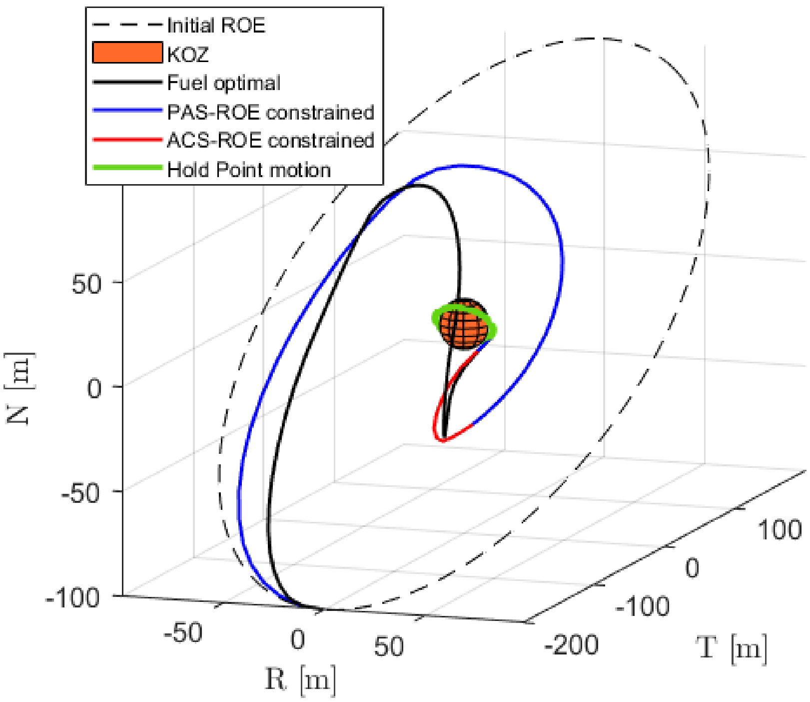

Figure 2. Trajectories in RTN of the fuel optimal and safety constrained case of a synchronisation test case. In blue and red are respectively the PAS and ACS section of the safety constrained solution, while the fuel optimal solution is displayed in black.

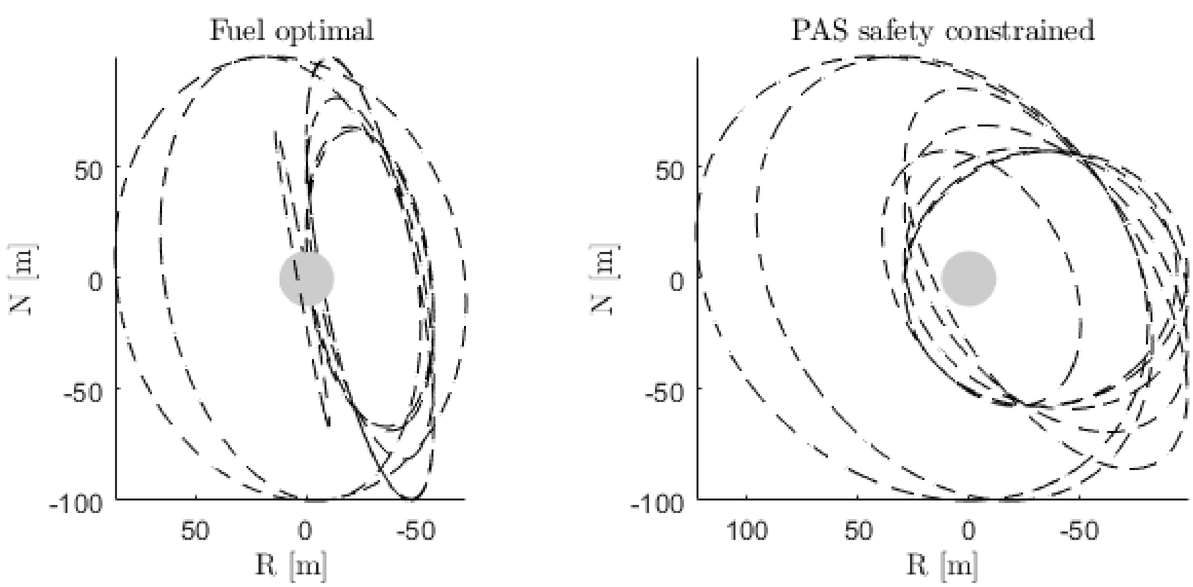

Figure 3. RN projection of the future uncontrolled trajectories correspondent to the ROE of PAS constrained nodes for synchronisation test case. The fuel optimal solution (left) and the safety constrained solution (right) are reported.

Management of the tumbling motion

When planning close-proximity operations the tumbling motion of the target is very influential in granting the possibility of performing the servicing/capture task. However, for targets with fast tumbling rates the energetic level of the synchronisation trajectory required, and the collision risks due to appendages quickly rotating pose great risk to the feasibility of operations. In this block of the Ph.D. research a strategy to detumble a target spacecraft using the plume impingement of the chaser's thruster [5]. A tool for simulating the impingement actions of a monopropellant plume was developed and a guidance and control algorithm developed for the damping of the residual rotational angular momentum by controlling the thruster pointing and firing. In the example shown in Figure X, the study proved the feasibility of damping the tumbling rate below 0.1 deg/s for tumbling rates as fast as 11 deg/s for a constellation satellite with a 1 N hydrazine thruster. This will enable the management of the dangerous tumbling motion for further operations, by simply using the thrusters' already onboard the platform.

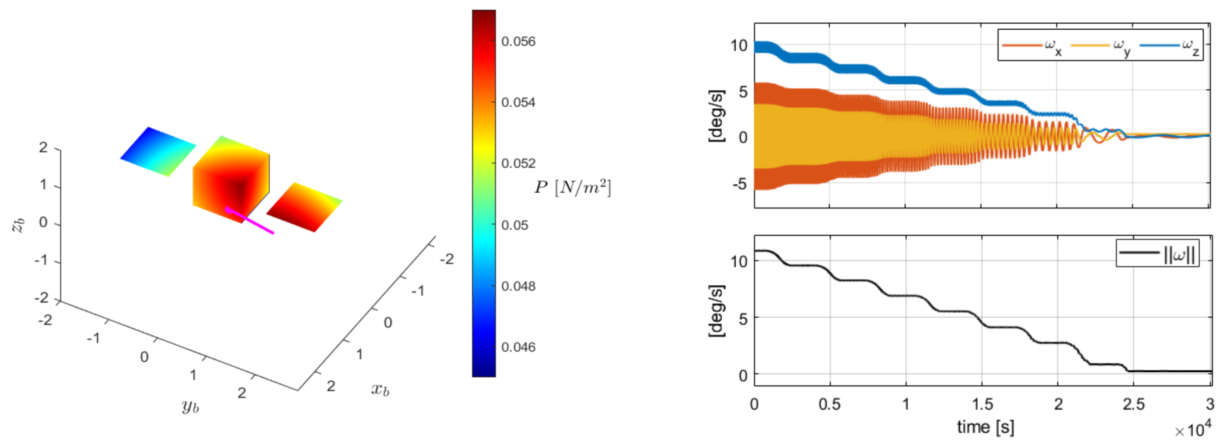

Figure 4. Pressure field on the target satellite due to a 1 N hydrazine thruster. Angular rate history of the target subject to the plume impingement control.

Safe inspection planning

In this block of the research the design of the trajectory guidance for an optimized inspection phase is developed. An inspection phase is the phase of a OSAM or ADR mission where the chaser performs inspection of the target satellite to characterize fully its state, orbital and rotational, and its physical status, i.e. damages or features. This block will be part of the 3rd PhD year and will focus on the design of trajectories for inspection to optimise the information gained during the observations. The ROE framework will be used to design a sequence of fly-around trajectory that fulfil the safety requirements described in the previous sections, but at the same time maximise the observation output of the onboard sensors.

Conclusions

The output of this Ph.D. project is the advancement in the safe and systematic design of proximity operations for future in-orbit servicing and removal mission in Low Earth Orbit (LEO). The results of the first two year provided advanced strategy to cope with trajectory safety using novel formulations in relative orbital elements, and strategy to manage the tumbling motion of a non-collaborative target. As a future step, the inspection phase will be designed with focus on the safety of operations.

Acknowledgments

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References

[1] Kawano, I., Mokuno, M., Kasai, T., and Suzuki, T., “Result of Autonomous Rendezvous Docking Experiment of Engineering Test Satellite-VII,” Journal of Spacecraft and Rockets, Vol. 38, No. 1, 2001, pp. 105–111. https://doi.org/10.2514/2.3661

[2] “Overview of the DART Mishap Investigation Results For Public Release, URL : http://www.nasa.gov/pdf/148072main_DART_mishap_overview.pdf

[3] https://astroscale.com/astroscales-elsa-d-mission-successfully-completes-complex-rendezvousoperation/

[4] Borelli, G., Gaias, G., and Colombo, C., “Rendezvous and proximity operations design of an active debris removal service to a large constellation fleet,”Acta Astronautica,Vol. 205, 2023, pp. 33–46. https://doi.org/10.1016/j.actaastro.2023.01.021

[5] Borelli, G., Gaias, G., and Colombo, C., “SAFETY IN FORCED MOTION GUIDANCE FOR PROXIMITY OPERATIONS BASED ON RELATIVE ORBITAL ELEMENTS“, AAS/AIAA 33rd Space Flight Mechanics Meeting, Austin, TX, US.

[6] Borelli, G., Gaias, G., and Colombo, C., “ROTATIONAL CONTROL WITH PLUME IMPINGEMENT TO AID THE RIGID CAPTURE OF AN UNCOOPERATIVE FAILED SATELLITE“, 2020 AAS/AIAA Astrodynamics Specialist Conference, Lake Tahoe, CA, US.