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Enhancing autonomy for close-proximity operations: the MSCA-funded project CASTOR

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Abstract

The space industry is rapidly growing with missions planned for the future, both in commercial ventures and scientific exploration. As demand for space-based services and deep space exploration increases, autonomous deep-space probes are needed. Reliance on ground-based personnel for spacecraft operations poses challenges in terms of cost, scalability, and communication delays. Autonomous probes with guidance and control capabilities would simplify operations, reduce costs, and facilitate space exploration. However, current spacecraft autonomy is limited, and on-board trajectory optimization algorithms face computational constraints. The CASTOR (Challenging Autonomous Spacecraft through Trajectory Optimization with Robustness) project, funded under Marie Skłodowska-Curie Actions, aims to develop a framework for robust autonomous guidance and control for spacecraft operating near minor bodies, considering on-board power and computational limitations. It includes an autonomous guidance algorithm with sequential convex programming and polynomial chaos expansion for uncertainty propagation. The algorithm will be implemented on spacecraft-compatible hardware and tested in RAFFAELLO, a laboratory environment simulating conditions near a minor body. The successful implementation of CASTOR will have significant implications for space operations, enabling cost reduction, enhancing scientific exploration, and democratizing space for new operators.

1. Introduction

The space economy is experiencing significant growth, with numerous space missions planned for the near future. These missions include both commercial ventures in near-Earth orbit and scientific exploration activities in deep space. Artificial constellations composed of thousands of spacecraft are becoming a reality, revolutionizing access to space-based services[1], while the focus on exploring planets, moons, asteroids, and comets, is growing, as they hold the potential to reveal the origin of life, provide insights into the evolution of our solar system, and offer resources for sustainable development[2]. This momentum is additionally fostered by CubeSats and other emerging low-cost small-scale platforms. Miniaturized probes will soon pervade the solar system, pushed by their lower cost and easier implementation[3]. To meet these demands, there is a need for more autonomous deep-space probes. In fact, currently, spacecraft flight operations heavily rely on ground-based personnel to plan spacecraft trajectories, determine their state, and steer their course, i.e., to perform guidance, navigation, and control (GNC) tasks. However, the cost and scalability of these operations become challenging for small satellites, while communication delays and on-gournd resource limitations can limit the scientific exploration. Therefore, autonomous probes with GNC capabilities would enable cost reduction, simplify operations, and facilitate future space exploration and exploitation.

Currently, spacecraft autonomy is limited to only a few subsystems, and autonomous guidance, navigation, and control tasks are typically confined to specific, time-limited, non-critical operations. In normal situations, GNC routines are carried out on the ground due to the substantial human effort involved. Orbital maneuvers, which are determined by GNC functions, undergo meticulous planning and thorough simulation to understand their effects on spacecraft dynamics. This cautious approach is justified by the high costs associated with traditional space assets, and it typically takes some days to be completed[4]. Additionally, conventional methods for optimizing the trajectories, such as guidance algorithms used by on-ground teams, are not suitable for on-board use. They either require solving large-scale optimization problems or lack the ability to guarantee convergence. Thus, a simpler introduction on-board of current algorithms is not suitable to grant autonomy to spacecraft.

Moreover, currently, most of the Guidance and Control (G&C) alogrithms focuses solely on the nominal trajectory. However, spacecraft always deviate from the nominal trajectory due to uncertainties in dynamics, state observation, and actuation. These uncertainties are more pronounced in miniaturized platforms with limited control capabilities and less mature components, and in highly non-linear environments. As a matter of fact, in highly non-linear environments like the vicinity of asteroids, it is useful to consider the entire stochastic range of possible trajectories when performing GNC tasks. This is necessary to avoid unflyable[5] or excessively costly trajectories[6]. As a result, robust trajectory optimization techniques have been recently introduced for preliminary on-ground guidance[7, 8]. These methods aim to reduce propellant requirements while satisfying stochastic constraints, although they can take several minutes on multicore clusters to provide a solution. Implementing robust trajectory optimization on autonomous probes would be advantageous as it would enable G&C functions that are optimal, resilient to uncertainties, and compliant with constraints. Nevertheless, performing robust trajectory optimization on board presents significant challenges as computational and time-consuming tasks must be executed within limited resources and time constraints.

In order to face these challenges, the European Union selected the project CASTOR to be funded under the Marie Skłodowska-Curie Actions. CASTOR (Challenging Autonomous Spacecraft through Trajectory Optimization with Robustness) is a research project fostering autonomous guidance and control for future spacecraft in close proximity operations, foreseeing the collaboration of Politecnico di Milano with NASA's Jet Propulsion Laboratory and the GNC Section of ESA. CASTOR aims to develop a framework for implementing robust autonomous guidance and control for limited control spacecraft, flying in highly perturbed environments, subject to significant uncertainties in dynamics, navigation, and control, while considering the power and computational limitation on board a typical spacecraft.

This work presents the project CASTOR, its methodology, and its expected results. Additionally, the future development and the potential outcomes are shown to provide a full overview of the project in all its 28-months span.

2. Overview of the project

The primary focus of the CASTOR project revolves around a significant research question:

To what extent can a miniaturized spacecraft autonomously fly close to a minor body?

To tackle this question, three specific objectives have been set within the project:

1. Develop an efficient methodology for autonomous guidance and control that can handle uncertainties. This involves creating a new algorithm capable of guiding a self-driving spacecraft along hyperbolic arcs around a minor body. The algorithm should consider stochastic properties, adhere to engineering and scientific constraints (e.g., position tags and close approach distance), and pave the way for autonomous close-proximity operations.

2. Implement the robust guidance algorithm on spacecraft-compatible hardware. While closed-loop guidance is a well-established field, existing algorithms are typically designed to run on ground-based systems with ample computational power. This project aims to enable on-board execution, making the most of limited computational resources. The goal is to deploy the robust G&C algorithm on hardware mimicking the one used on spacecraft.

3. Test the methodology in a laboratory environment that simulates the conditions near a minor body. While numerical simulations play a crucial role in astrodynamics for testing and validating specific solutions, Hardware-in-the-Loop (HIL) simulations increase the fidelity and allows better performance evaluations. For this reason, CASTOR will leverage the EXTREMA Simulation Hub at Politecnico di Milano [9] and the Robotic Arm Facility For Autonomous cubesat ExpLoration in cLose proximity Operations (RAFFAELLO) (Fig. 1), a hardware-in-the-loop testbench within the COSMICA project, funded by the Italian Ministry of University and Research. This facility simulates satellite-environment interaction near an asteroid. The target is to validate the hardware-software set in a relevant laboratory setting.

By accomplishing these specific objectives, the CASTOR project will push the boundaries of autonomous guidance and control around minor celestial bodies, forming another building block for self-driving spacecraft.

3. Methodology

This project addresses the challenge of achieving autonomous closed-loop guidance during close-proximity operations (CPOs) through a combination of traditional methods and innovative techniques. The objective is to enable on-board hardware-based implementation of G&C using robust trajectory optimization.

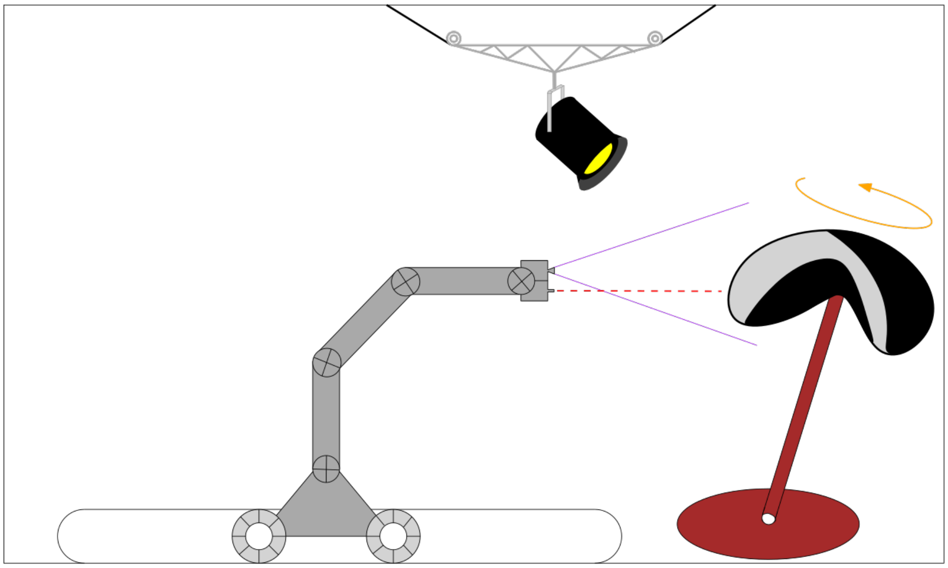

Fig. 1. Schematics of the RAFFAELLO facility. The robotic arm simulates the dynamics of the spacecraft, while the lamp creates realistic illumination conditions.

Currently, G&C is predominantly managed from ground-based systems. However, the constant supervision required for spacecraft operations is not feasible for low-cost missions. Therefore, adapting the G&C pipeline for on-board, supervisor-free implementation becomes necessary. Additionally, accurate trajectory planning must consider future stochastic paths arising from the spacecraft's current position in perturbed environments. This approach reduces propellant requirements and mitigates risks, especially for platforms with limited control capabilities like CubeSats.

To address these challenges, CASTOR exploits Close-Operations closed-Loop Autonomous Guidance (COLAG) algorithm. COLAG consists of two layers (Fig. 2): an outer layer based on sequential convex programming (SCP) and an inner layer employing polynomial chaos expansion (PCE) for uncertainty propagation. The outer layer utilizes sequential convex programming tailored to the specific needs and hardware constraints of the project. This optimization method has proven effective for solving orbital problems in deep-space low-thrust missions[10], to deal with linear uncertainties and CPOs[11]. During the project, it is adapted to handle nonlinear uncertainties, a goal-oriented approach for scientific requirements, and the ability to run on limited hardware. The inner layer incorporates polynomial chaos expansion, a nonlinear uncertainty propagation technique capable of retrieving complete probability distribution functions[12]. This method is necessary due to the increased uncertainty associated with low-cost platforms and the highly perturbed environments encountered in the project. By approximating quantities of interest using orthogonal polynomials, PCE computes the series coefficients through stochastic integration. To address the computational challenge posed by the curse of dimensionality, sparse optimal quadrature grids are implemented in CASTOR's uncertainty propagation for orbital motion.

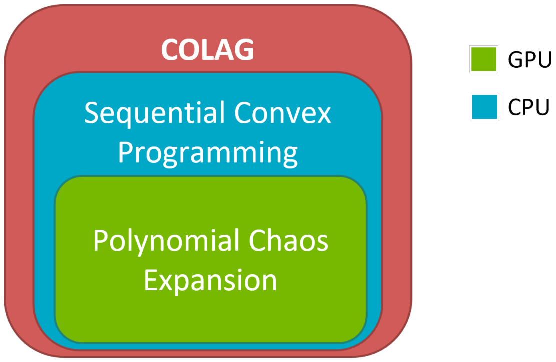

Fig. 2. Two-layer strategy for CASTOR autonomous G&C algorithm.

This two-layer method sets the stage for the next generation of autonomous spacecraft for minor bodies, ensuring both convergence and execution speed. To maximize performance, minimize runtime, and minimize power demand, suitable hardware is essential. The inner layer, which requires thousands of sample integrations and tensor operations for PCE coefficient computation, necessitates a System-on-a-Chip (SoC) integrating a CPU and GPU. The parallel architecture and tensor operation efficiency of GPUs significantly enhance the performance of the inner layer, while the main processor characteristics benefit the outer layer. While GPUs have primarily been utilized in vision-based applications in the space sector[13], their potential for G&C tasks, including COLAG, can also be effectively harnessed.

The implementation of SW and selection of HW are interdependent to ensure optimal utilization of the SoC's capabilities and a hardware-software fit. Special attention is given to quantifying and adapting the algorithm's computational requirements to the available hardware. In order to emulate similar modules and vary computational resources to better match the software demands, the nVidia Jetson Orin Dev Kit[·] is exploited by CASTOR.

At the end of the project, the hardware-software set, known as the Autonomous Guidance Computer (AGC), will be tested in the RAFFAELLO facility. Two case studies are proposed:

Case Study 1 involves a CubeSat operating close to Apophis during its flyby, utilizing a low-thrust thruster to perform trajectories for imaging targets at various distances and illumination conditions, similar to SATIS CubeSat [14];

Case Study 2 focuses on a SmallSat conducting CPOs around a medium-size asteroid using electric low-thrust propulsion, reproducing a mission scenario common in literature [15].

These scenarios will validate the AGC under heterogeneous conditions.

4. Conclusions

The outcomes of this project will have a profound impact on the future of space operations. The primary objective is to develop an advanced algorithm for autonomous trajectory optimization that caters to the limited capabilities of satellites operating in close proximity to minor bodies. This algorithm will be complemented by a dedicated on-board system to execute it effectively. The developed solution will empower spacecraft to efficiently plan their future trajectories while adhering to scientific and technological constraints based on an estimated state. The research results will be delivered as a comprehensive software and hardware package, already tested in a relevant environment (TRL 4). Moreover, this solution can be easily adapted to various scenarios, including high-density areas like low-Earth orbits, where collision risks are significant. By simplifying spacecraft traffic management, it will reduce the reliance on human-in-the-loop flight dynamics tasks, streamline operations, and eliminate the turnaround time required for ground-based control computations. Consequently, the cost of operations will be significantly reduced. The potential savings will enable new players such as small enterprises and universities to enter the space market. They can leverage miniaturized probes to offer cost-effective communication services or conduct close observations of celestial bodies like the Moon. This will contribute to democratizing space exploration and facilitating the deployment of low-cost spacecraft for various applications.

Furthermore, the enhanced responsiveness of spacecraft will significantly expand the range of flyable trajectories and enhance the scientific output of missions. This research project marks a significant milestone in the progression towards autonomous spacecraft, enabling extensive robotic exploration of the solar system.

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References

[1] S. Bandyopadhyay, R. Foust, G. P. Subramanian, S.-J. Chung, and F. Y. Hadaegh, "Review of formation flying and constellation missions using nanosatellites," *Journal of Spacecraft and Rockets*, vol. 53, no. 3, pp. 567–578, 2016.

[2] A. M. Hein, M. Saidani, and H. Tollu, "Exploring potential environmental benefits of asteroid mining," *arXiv preprint arXiv:1810.04749*, 2018.

[3] R. Walker *et al.*, "Deep-space cubesats: Thinking inside the box," *Astronomy & Geophysics*, vol. 59, no. 5, pp. 5–24, 2018.

[4] J. A. Starek, B. Açıkmeşe, I. A. Nesnas, and M. Pavone, "Spacecraft autonomy challenges for next-generation space missions," *Advances in Control System Technology for Aerospace Applications*, pp. 1–48, 2016.

[·] See https://www.nvidia.com/en-us/autonomous-machines/embedded-systems/jetson-orin/ (last accessed: August 25, 2024).

[5] D. A. Dei Tos, M. Rasotto, F. Renk, and F. Topputo, "LISA Pathfinder mission extension: A feasibility analysis," *Advances in Space Research*, vol. 63, no. 12, pp. 3863–3883, 2019.

[6] C. Bottiglieri, F. Piccolo, C. Giordano, F. Ferrari, and F. Topputo, "Applied Trajectory Design for CubeSat Close-Proximity Operations around Asteroids: The Milani Case," *Aerospace*, vol. 10, no. 5, p. 464, 2023.

[7] C. Greco, S. Campagnola, and M. Vasile, "Robust space trajectory design using belief optimal control," *Journal of Guidance, Control, and Dynamics*, vol. 45, no. 6, pp. 1060–1077, 2022.

[8] C. Giordano, F. Topputo, *et al.*, "Analysis and Optimization of Robust Trajectories in Cislunar Environment with Application to the LUMIO Cubesat," in *33rd AAS/AIAA Space Flight Mechanics Meeting*, 2023, pp. 1–19.

[9] G. Di Domenico *et al.*, "The ERC-Funded EXTREMA Project: Achieving Self-Driving Interplanetary CubeSats," in *Modeling and Optimization in Space Engineering: New Concepts and Approaches*, Springer, 2022, pp. 167–199.

[10] A. C. Morelli, C. Hofmann, and F. Topputo, "Robust low-thrust trajectory optimization using convex programming and a homotopic approach," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 58, no. 3, pp. 2103–2116, 2021.

[11] K. Oguri and J. W. McMahon, "Robust spacecraft guidance around small bodies under uncertainty: Stochastic optimal control approach," *Journal of Guidance, Control, and Dynamics*, vol. 44, no. 7, pp. 1295–1313, 2021.

[12] B. A. Jones, A. Doostan, and G. H. Born, "Nonlinear propagation of orbit uncertainty using non-intrusive polynomial chaos," *Journal of Guidance, Control, and Dynamics*, vol. 36, no. 2, pp. 430–444, 2013.

[13] L. Kosmidis, J. Lachaize, J. Abella, O. Notebaert, F. J. Cazorla, and D. Steenari, "GPU4S: Embedded GPUs in space," in *2019 22nd Euromicro Conference on Digital System Design (DSD)*, IEEE, 2019, pp. 399–405.

[14] R. Walker, "Overview of ESA Lunar & Interplanetary CubeSat Missions," in *Interplanetary Small Satellite Conference*, 2023.

[15] A. Rizza, F. Topputo, and S. D'Amico, "Goal-oriented asteroid mapping under uncertainties using sequential convex programming," in *AIAA Scitech 2024 Forum*, 2024, p. 1990.