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Closed-loop guidance for interplanetary CubeSats with indirect methods

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A new era in space is approaching fast. Soon, several miniaturized probes will permeate the inner Solar System. The space sector is enthusiastically embracing a new paradigm for space exploration, carried out by interplanetary CubeSats. Nevertheless, the current modus operandi can hamper this momentum: while the system development costs scale with its size, the same is not true for flight dynamics operations, which are still expensively performed from ground. According to the state of the art, during the complex process of trajectory design algorithm non-compliance with mission constraints are taken care by the operators on ground, manually. This process can take hours, if not days, and as of now it is not affordable autonomously by CubeSats.

Self-driving spacecraft are the solution: futuristic probes shall travel in a totally autonomous fashion, inferring their position from the surrounding environment and computing their guidance trajectory on board. If proven feasible, this technology will boost large missions as well. Yet, autonomous guidance and control is hazardous because robustness (convergence to a solution), optimality (cost function minimization), and sustainability (compatibility with available resources) must be met in trajectory re-design and correction maneuvers planning. Since the state of the art foresees these operations to be executed on ground, current techniques focus on optimality, and little attention is paid to designing robust and computationally simple algorithms. It is the case of indirect methods. These nonlinear programming algorithms compute the global optimum of an optimal control problem addressing it from the necessary conditions of optimality. However, they suffer from a small convergence region. Thus, they have been always considered to not ensure the robustness necessary for onboard computation - up to now.

In this work we present a new idea for the exploitation of indirect methods onboard in a closed-loop guidance scheme. The information on the nominal path of a spacecraft can be exploited to provide these methods an informed initial guess built to enlarge their convergence region. This information can be stored in the onboard computer, reducing the computational load required by the nonlinear programming computations to a mere memory access, and thus making these methods compatible with the reduced resources of CubeSats. If successful, this scheme will disrupt completely the state of the art of onboard guidance, and the way spacecraft are piloted towards their targets.

1 Introduction

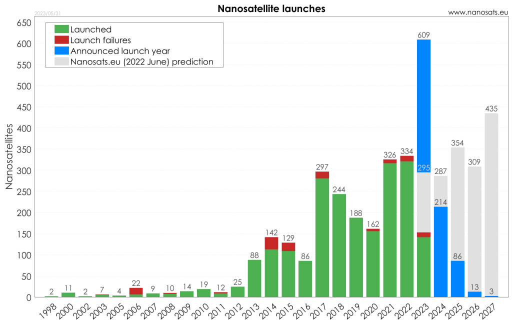

Fig. 1: Nanosatellites launches per year.[§]

Recent years have witnessed the space sector experiencing a thriving growth. According to [1], the number of nanosatellites launches doubled in 2021 and 2022 compared to 2020. For 2023 more than 600 launches are planned, confirming the involvement of a rising number of players in the space sector [§] (see Fig. 1). A considerable role in this growth is represented by the significant decrease in access costs to space. Investments in the field and technological advances led to a decrease in the budget needed to carry on a space mission. In particular CubeSats, miniaturized spacecraft, have enabled parties not supported by huge capitals (as universities or smaller private companies) to space thanks to their low design, manufacturing, and launch costs [2, 3]. By relying on off-the-shelf components, CubeSats also need less testing and validation procedures, cutting down costs and time-to-flight even more. It should be noted, however, that the space sector expansion was biased towards that part of space closer to the Earth. Only a tiny fraction of the

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[§] www.nanosats.eu Last access on 7th September 2023 total space launches targeted interplanetary orbits. As longer duration characterize deep-space missions, the great advantages brought by CubeSats technology are hindered by the extensive resources - both in terms of budget and human personnel - required to sustain the human-in-the-loop ground operations during multiple months or years. Moreover, no matter the available budget, ground slots for communications are scarce and are expected to saturate soon.

In this framework, deep space is and will be a prerogative of a few more prominent stakeholders and agencies. The EXTREMA project (Engineering Extremely Rare Events in Astrodynamics for Deep-Space Missions in Autonomy) [4] aims to steer from such a future scenario by triggering a paradigm shift, enabling deep-space CubeSats with autonomous guidance, navigation, and control (GNC) capabilities. The project, awarded a five-year grant from the European Research Council, is planned to last until 2025, and it is based on three fundamental pillars:

- **Pillar I: Autonomous Navigation**: focuses on the development of navigation algorithms to enable CubeSats to locate themselves in deep space in complete autonomy by exploiting information in the surrounding environment.
- **Pillar II: Autonomous Guidance and Control**: aims to directly shift the current guidance paradigm. As of today, trajectory planning is performed on ground due to the limited computational resources available on board. Correction maneuvers have to be planned from ground too, employing a great amount of resources in terms of time and human personnel. EXTREMA aims to develop lightweight and robust closed-loop low-thrust guidance algorithms, exploiting the knowledge of the spacecraft position to compute a new trajectory to achieve mission objectives in complete autonomy.
- **Pillar III: Autonomous Ballistic Capture**: the limited resources characterizing CubeSats systems represent a bottleneck in achieving specific mission objectives as, for instance, expensive orbit insertion maneuvers. Because of this, EXTREMA aims to further develop the autonomy of deep-space probes by engineering ballistic capture, exploiting the multi-body dynamics of the Solar System to remain in the proximity of the target body for a prolonged period of time.

The outcome of each pillar will be integrated into a series of experiments and, brought together in the EXTREMA Simulation Hub (ESH) [5]: a hardware-in-the-loop (HIL) testing facility that will allow testing integrated GNC (Fig. 2). The facility under construction in the DART Laboratory [¶] will integrate three different facilities under a comprehensive HIL simulation framework:

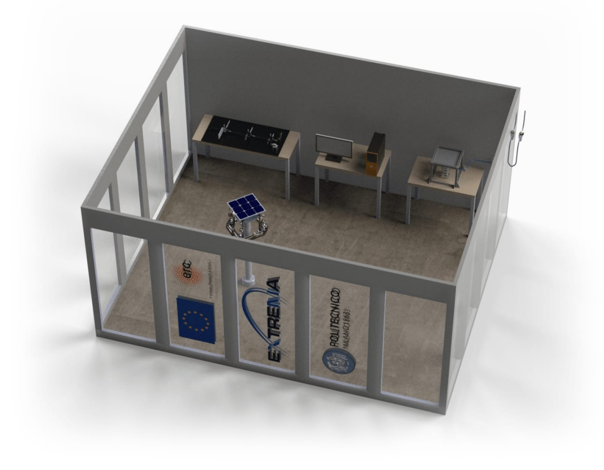

Fig. 2: ESH 3D rendering.

- **RETINA:** the Realistic Experimental facility for vision-based NAvigation [6] is an optical facility that will simulate the light pattern as received by the spacecraft optical camera through a set of lenses and screens. The output image will be employed to test and validate optical navigation algorithms based on image processing of deep-space starfields.
- **ETHILE:** the EXTREMA THruster In the Loop Experiment [7] is a cold-gas thrust test bench that will mimic the thruster in the spacecraft. In order to allow the simulation of multiple types of thrusters, a scaling framework based on dynamic similarity is employed to map the physical parameters of ETHILE to the ones of the target thruster.
- **STASIS:** the SpacecrafT Attitude SImulation System [8] is an air-bearing platform used to simulate the attitude evolution of a spacecraft in deep space. STASIS will also host the board representing the onboard computer of the spacecraft and the set of attitude sensors and actuators to be employed on the spacecraft. It features a set of moving masses, a wireless power generation system, and a set of additional attitude actuators to compensate for the difference in inertial properties between the platform and the spacecraft.

The aim of the ESH is to perform HIL simulations of interplanetary transfers under an accelerated framework. To do so, the onboard computer on STASIS platform runs the autonomous guidance algorithm and

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[¶] dart.polimi.it Last access on 7th September 2023 sends the computed thrusting profile to ETHILE. The computation of the spacecraft control profile is a task traditionally performed on ground, where computational resources are extensive and human intervention is possible. Thus, classical trajectory optimization algorithms are not designed to be performed completely and autonomously on board. In this work, a set of necessary high-level requirements for autonomous guidance are identified. Then the focus shifts on the main drawbacks of the application of these requirements to an approach based on indirect formulation, and on the design of an algorithm capable of fulfilling them.

The paper is structured as follows. Section 2 discusses the main requirements necessary for onboard guidance, and the drawbacks related to their application to an indirect formulation of the low-thrust space trajectory optimization problem. Section 3 describes the idea of a closed-loop indirect guidance scheme capable of overcoming these difficulties. From this analysis, sections 6, 4, and 5 detail the three research threads we are focusing on to develop this scheme. Finally, Section 7 draws conclusions on the work.

2 Onboard Guidance

Computing the thrusting profile for a deep-space CubeSat implies the solution of a low-thrust trajectory optimization problem, considered as a specialization of the optimal control problems for systems continuous in time. No analytic solutions involving an acceptable level of assumptions exist for this kind of problems, even under the two-body dynamics. For this reason, several numerical techniques have been developed. State-of-the-art divides these guidance techniques into indirect and direct approaches [9, 10]. Direct methods [11, 12, 13, 14] transform the continuous optimal control problem into a parameter optimization problem discretizing the time domain, and then transcribing the dynamics and the other constraints in a set of equality constraints. Indirect methods [15, 16] employ the necessary conditions equations obtained from the calculus of variation, requiring an explicit computation of them. Due to the nature of these equations, indirect methods leads to the exact solution of the optimal control problem. They are therefore characterized by high precision, but they have a very small convergence domain, meaning that if they are fed with a poor initial guess, they hardly converge.

To run both these methods on board poses several mandatory challenges. The requirements for a suitable real-time guidance algorithm include (Fig. 3):

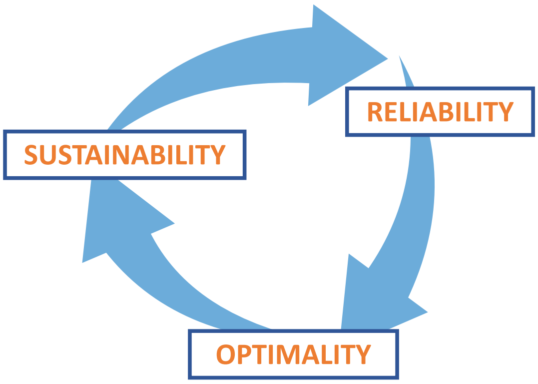

Fig. 3: The three characteristics of an onboard guidance algorithm.

- **reliability**, the capability of converging even when poor initial guesses are provided and to deliver a solution nevertheless the state of the spacecraft,
- **sustainability on board**, due to the limited resources, especially for CubeSats, which translates in stringent constraints,
- and **optimality**, the ability of finding the trajectory consuming the minimum fuel, respecting the aforementioned constraints.

Having a wider converge region, direct methods are more reliable then indirect ones, even if to fully capture the dynamics of the problem they usually require tons of variables, becoming, on the other hand, not sustainable for onboard applications. However, among direct methods, convex optimization [17, 18] represents an interesting approach as it ensures robustness and computational affordability at the same time. For this reason it is usually selected for autonomous guidance algorithms [19, 20, 21, 22, 23, 24, 25]. Note that none of those involves deep-space scenarios, as the development for this area is still in its infancy. However, the use of convex optimization comes at costs of an approximated solution: it is not able to catch a perfect bang-bang thrusting profile for a fuel optimal problem, meaning that they usually catch a sub-optimal solution which later has to be post-processed. On the other hand, indirect methods provide the correct solution of the problem, but their use in onboard applications is hindered. In particular, historically there are three major difficulties slowing down their development [9]. Namely these are:

- the **difficult derivation** of the equation expressing the necessary conditions for optimality,
- the **mandatory knowledge of an preconceived structure** of the constrained and of the unconstrained arcs if paths constraints are present,
- and the **necessity of a good initial guess** for the great sensitivity of the problem to it.

The novel improvements in indirect methods development have made the first and the second points not problematic for onboard applications. Nowadays automatic differentiation tools are easily exploited to derive the equations for the necessary conditions for optimality. Moreover, the preconceived knowledge of the constrained arcs is not necessary, as switching-detection techniques have been developed to accurately locate time instants in which path constraints activate or deactivate [26, 27, 28]. Still, indirect methods suffer from a very low reliability, or robustness, as to converge they require to start an iterative root-finding process in the basin of attraction (from now on called **convergence region**) of a solution of the low-thrust optimal control problem. Obviously, this is a dog-chasing-his-own-tail issue, as the solution is the unknown indirect methods attempt to locate. Moreover, the initialization is not straightforward as the physical meaning of the involved variable is not straightforward as well, and as the convergence region is notoriously small, and it shrinks as the complexity of the problem increases. However, when an indirect method is provided with the *right* initial guess, their convergence is very rapid.

For these reasons, the exploitation of indirect methods is nowadays confined to on-ground mission design. Their development for onboard applications is rarely taken into account, and thus:

- they have **never been deployed on GNC boards** representative of spacecraft onboard capabilities,
- they have **never** been studied to **foresee operational constraints**,
- the **convergence region** of the solutions to the low-thrust optimal control problem have **never been assessed**,
- and attempts to stick to this region, reaching the **necessary reliability**, have never been proposed.

In the following sections, we detail the design of an autonomous guidance scheme based on an optimal indirect method foreseeing the development of these features, showing in the meantime the preliminary results of the research.

3 Closed–Loop Sustainability

The low reliability of indirect methods is still an open point that prevents them from being used onboard. However, the peculiar conformation of the autonomous guidance application could in part mitigate the issue. Differently from the on-ground mission design, the onboard application is characterized by the preconceived knowledge of a nominal flyable interplanetary transfer (dark blue line in Fig. 4). This trajectory is computed previously the beginning of the mission, since the whole operational life of the satellite is designed upon it. However, during the mission, divergences from the nominal trajectory always occur. These are mainly due to approximations in the dynamical models, disalignment and inconsistencies in the thrust actuation, and unmodeled perturbations. Thus, the spacecraft, supposed to fly a certain transfer, at a certain time instant will be on a different trajectory, the real one (orange line in Fig. 4). Historically, it is duty of the flight dynamic operations team on ground to periodically acquire the estimated real state from the spacecraft sensors, compute the deviation from the nominal trajectory, and calculate and upload the maneuvers to correct the satellite state. This approach, highly dependent on the pre-determined nominal trajectory and on contact with the ground, is known as the **fly-the-wire method** (Fig. 4).

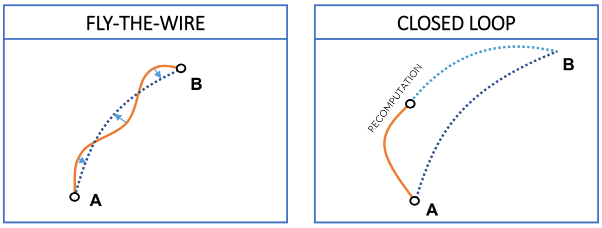

Fig. 4: Fly-the-wire vs closed-loop approach.

Nowadays, the fly-the-wire method is opposed to the newer **closed-loop** approach, according to which a new nominal trajectory is computed every time the spacecraft departs from the pre-determined one. Obviously, this method leads to a more optimal solution, as the spacecraft is not forced to follow a trajectory optimal for an old state, but a new one, updated on the current state estimation. For this reason, this is the current paradigm for deep-space low-thrust missions [29] and the one chosen here to develop the guidance scheme.

To comprehend how to apply the closed-loop approach to an indirect-based algorithm, hereafter a brief recap on how a generic indirect method works is reported (refer to [26] for an extensive mathematical demonstration, which is beyond the scope of this work). Being the state and costate vector $\mathbf{y} = [\mathbf{x}, \boldsymbol{\lambda}]$, the optimal control problem attempts to find the optimal initial value of the costate $\boldsymbol{\lambda}_i^{opt}$ such that

$$\mathbf{y}(t_f) = \boldsymbol{\varphi}([\mathbf{x}_i, \boldsymbol{\lambda}_i^{opt}], t_i, t_f) = \overline{\mathbf{y}_f} \tag{1}$$

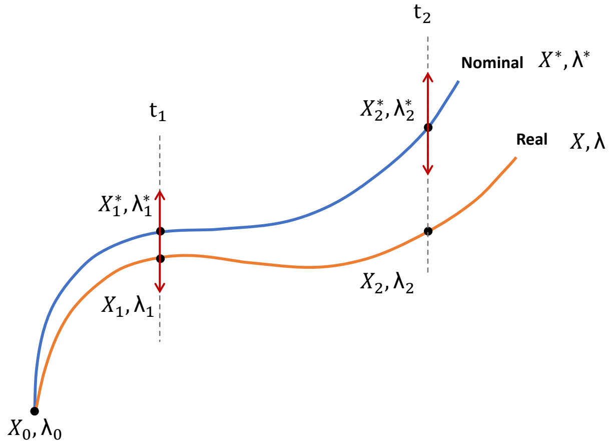

Fig. 5: Representation of the peculiar situation of onboard application for indirect method.

where t_i and t_f are the prescribed initial and final time instant, $\boldsymbol{\varphi}$ is the flow of the trajectory computed integrating the dynamics of both state and costates, and $\overline{\mathbf{y}_f}$ is the prescribed final boundary condition. This is known as a two point boundary value problem, solved through a root-finding process which iterates on $\boldsymbol{\lambda}_i$ (with a Newton-based algorithm) to find for which value $\mathbf{y}(t_f) - \overline{\mathbf{y}_f} = \mathbf{0}$.

According to this formulation, once $\boldsymbol{\lambda}_i^{opt}$ is known at each time instant t when the state of the spacecraft is sampled and estimated, both the real state $\mathbf{x}$ and the costate related to the previous nominal trajectory $\boldsymbol{\lambda}^*$ are known as well (refer to Fig. 5). Depending on the magnitude of the perturbations involved in the trajectory, and according to the closed-loop approach, two situations can arise:

- the couple made of the new state $\mathbf{x}$ and old costate $\boldsymbol{\lambda}^*$ is inside the convergence region. Referring to time instant t_1 in Fig. 5, this means that feeding the indirect algorithm with the new state $\mathbf{x}_1$ and the old costate $\boldsymbol{\lambda}_1^*$ as initial guess, it is able to converge to a new solution.
- the couple made of the new state $\mathbf{x}$ and old costate $\boldsymbol{\lambda^*}$ is outside the converge region. Referring to time instant t_2 in Fig. 5, this means that providing the new state $\mathbf{x}_2$ and the old costate $\boldsymbol{\lambda}_2^*$, the convergence is not reached.

Obviously, in the second case a *good* guess must be guaranteed: if this happens, the optimization towards a new nominal solution is possible, and the issue related to the reliability of indirect methods is solved. This is the main direction we are working towards to develop a closed-loop guidance law for deep-space CubeSat mission leveraging on indirect methods. In particular, our endeavour is focusing on:

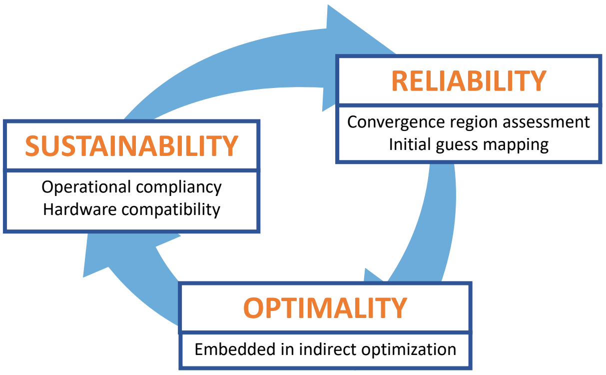

Fig. 6: Addressing of the three characteristics of the onboard guidance indirect algorithm.

- the **assessment of the convergence region**, as up to now it has be known to be small, but has never be assessed,
- the **creation of a mapping** of the known costates of the previous nominal trajectory to a good initial guess for the real trajectory to be used whenever the new state falls beyond the convergence region,
- and finally, the **sustainability within a CubeSat mission** of the algorithm is considered as well, implying both the possibility of the deployment on hardware as well as the fulfillment by the algorithm of the operational constraints (i.e. the imposition of coasting arcs during the transfer to ensure the state estimation),

In this way all the three requirements required for onboard algorithm are addressed. Being the **optimality** embedded in the indirect formulation, the **sustainability** ensured by the operational compliant constraints contained in the algorithm and by the compatibility with the CubeSat hardware, and the **reliability** guaranteed by the characterization of the convergence region and the map to a good initial guess.

4 Convergence Region Characterization

It is common knowledge and concern that indirect methods are characterized by a restricted convergence region [9, 30]. This means that to reach the solution for the low-thrust optimal control problem, they need an initial guess close to the solution itself to start the iteration of the root-finding process. Obviously, being in general the solution the unknown, the selection of a good initial guess is not straightforward. Moreover, differently from

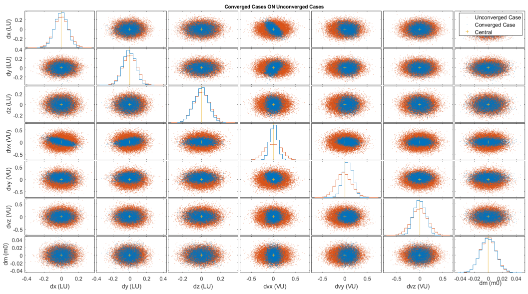

Fig. 7: Convergence region estimation with higher perturbations.

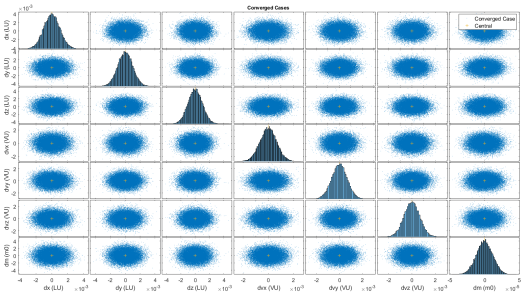

Fig. 8: Convergence region estimation with lower perturbations.

direct formulations which solve a transcribed problem where the unknowns are the physical variables of the problem, and thus methods to approximate a plausible initial guess exist (as shaped-based models [31], or a simple integration with a lower level and a constant direction for the thrust), indirect formulations attempt to locate the optimal initial values of the costates of the problem, which have a not immediate physical meaning [32]. They have been developed methods for the initialization of costates [33], but they are are not always effective, and it is not clear in which cases they are.

The same problem, in a reduced extent, exists in the onboard implementations of indirect methods. Even if in this case a nominal solution is known and pre-loaded in the GNC board, it has never been addressed to what extent the in flight perturbations can affect the state before the nominal costate trajectory lies beyond the convergence region of an indirect method. In a few word, the extent of this convergence region, for how small, has never been assessed. To make a guidance algorithm flyable, indirect- or direct-based, it has to be not only compatible with the right hardware, but also verifiable. It is clear then that without a clear assessment of the region of convergence an autonomous guidance algorithm based on indirect methods is basically not feasible.

For this reason we are working on the pre-characterization of the convergence region of the closed-loop guidance indirect algorithm. A Monte Carlo simulation applying a Gaussian distribution of perturbations centred on the state at the first time instant of the solution to a fuel optimal problem with a simple two-body dynamics have been performed to estimate the convergence region. The results are reported in Fig. 7. In this case, the perturbations considered are quite high: 0 mean, 0.2 AU of standard deviation for position, 0.05 VU for velocity and 0.3 initial masses for the spacecraft mass. The cases in which the indirect solver was not able to converge given the nominal costate and the new perturbed state (orange dots in Fig. 7) are clearly present - and expected. What we found interesting is that in between the converged cases (blue dots in Fig. 7), even if not clearly visible in the plots, there was some unconverged case, i.e. the statement that beyond a certain threshold of perturbation the convergence is ensured is simply not correct. The convergence region shows a complex and **fractal nature** typical of iterative root-finding methods. Moreover, there is a clear dependence on the trend of the region with the direction of the perturbations, especially in the coupling with the velocity along the x-direction, i.e. there is a coupling in the way the various perturbations affect the convergence of the method which should be further investigated.

The same analysis has been performed with lower standard deviation values in the Gaussian distribution (reduced of three order of magnitude) and the results are reported in Fig. 8. In this case the totality of the cases converged. It is clear thus that, even if the burden of the convergence region has a fractal nature, there exists an inside zone, the convergence region, where the convergence can be always ensured. The clear assessment of the extent of this region, makes then the algorithm verifiable, while the proof that the perturbations experienced by the spacecraft do not exceed it, makes the algorithm reliable. The typical values of deviations of a deep-space trajectory as the one proposed remains indeed inside the boundaries stated in the second Monte Carlo simulation [34]. Obviously, for each mission a verification of these boundaries must be performed. Moreover, if these boundaries are not respected, an enlargement of the convergence region can be performed through the exploitation of a mapping of the nominal and known costates to a good initial guess for the new, real trajectory, as discussed in the next Section.

5 Mapping of the Initial Guess

Whenever it is necessary, i.e. when the perturbations experienced by the spacecraft along the interplanetary transfer exceed the convergence region depicted in Fig. 8, the convergence of the algorithm must be ensured with the feeding of a proper initial guess able to lead to convergence to a new thrusting profile for the real state of the spacecraft. This should be achieved through a map pre-loaded on board able to compute a new costate initial guess starting from the nominal one, enlarging the convergence region of the algorithm.

Several studies have been performed over the last years to this aim, the majority of them exploiting high order expansion of the nominal trajectories in order to exploit their embedded information. They can effectively handle the non-linearity of the space environment, being also computationally light to be run onboard. High-order methods include state state transition tensors (STTs), higher order versions of the classical state transition matrix [35, 36, 37]. However, the calculation of STTs requires the computation of increasingly complex partial derivatives of the system. Differential algebraic (DA) techniques [38] enable instead the computation of those derivatives through an high-order expansion, creating a Taylor polynomial map. They have been efficiently exploited to build guidance algorithms for the arbitrary order expansion of the solution of a fuel-optimal problem [39, 40] and recently to formulate time-optimal guidance laws [41]. However, they have never been studied for onboard applications, but only on theoretical on ground applications.

For this reason we are developing our DA map, able to update on board the initial costates at each switching time of the thrusting arc, for deviations in the typical order for an interplanetary mission. The map is based on a 4th order expansion Taylor of a nominal trajectory. The results, applied to a CubeSat trajectory from the Earth to the asteroid 2014 YD have been reported in Figs. 9 and 10, where the corrected trend of the in-plane and out-of-plane angles are reported.

The DA map is able to correct the trajectory up to the final thrust arc, where issues related to the small amount of time available to correct the trajectory arise. Developments of the DA map are part of on-going and future work.

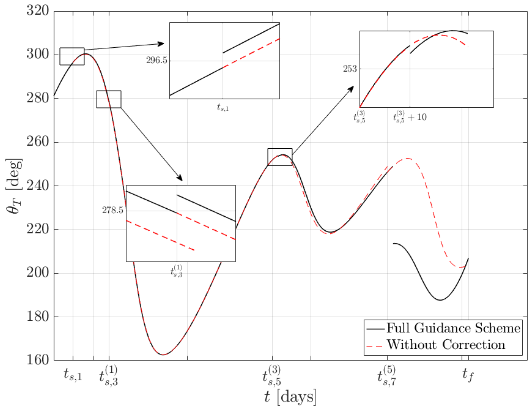

Fig. 9: In-plane angle corrected trend from Earth to asteroid 2014 YD.

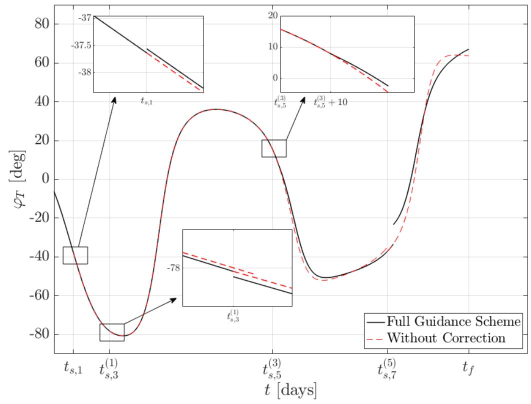

Fig. 10: Out-of-plane angle corrected trend from Earth to asteroid 2014 YD.

6 Spacecraft Compatibility

To be applicable to a real CubeSat mission scenario, firstly the indirect onboard guidance algorithm has to posses the capability of imposing operational constraints. This implies the imposition of **duty cycles**, an alternation of coasting and thrusting arcs forced at pre-defined time instants needed for navigation tasks. Being time-dependent and discontinuous constraints, they are not easy to be introduced in the indirect formulation. Their presence is indeed usually taken into account in the preliminary trajectory design phases optimizing a transfer with only a limited percentage - usually 80 to 90% - of the maximum thrust available. Homotopy techniques, a class of methods conceived to deal with discontinuous structures allowing the solution of the original discontinuous problem starting from an easier one, have been recently employed to imposed forced coasting arcs both in indirect [42, 43, 44] and in direct [14] methods.

We have developed an alternative indirect formulation based on the modeling of the duty cycles as interior-point constraints. The solution method relies on the

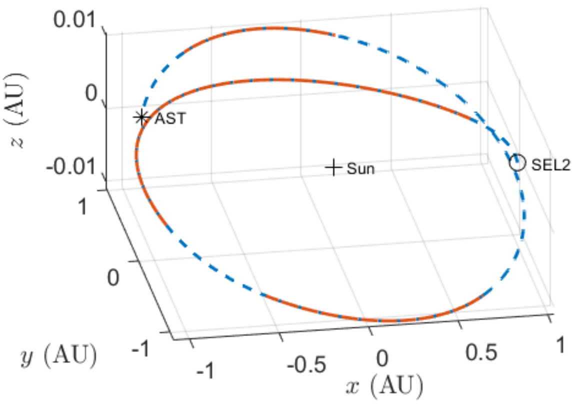

Fig. 11: Operational compliant trajectory representation.

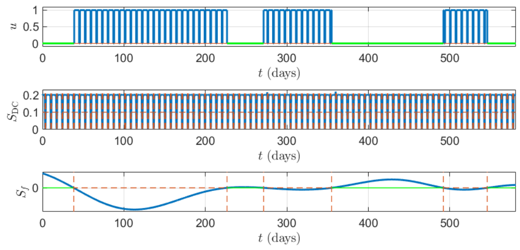

Fig. 12: Profiles of the thrust profile and of the switching functions for the operational compliant trajectory.

use of analytical derivatives, a switching times detection techniques, as well as a pre-computation of them, and a triple continuation scheme rapidly generating operational compliant low-thrust trajectories. The result is an algorithm capable of modeling duty cycles with duration of any kind, without any prior knowledge on the structure of the control law. The details of the scheme will be published on a dedicated work. Hereafter the application to a CubeSat interplanetary transfer towards an asteroid is shown as example (Figs. 11 and 12).

Apart from the duty cycles imposition, to use indirect methods on board they have to be compatible with spacecraft GNC boards, characterized by limited computational resources. To be run on a processor representative of onboard resources, the indirect algorithm has been re-thought from an on-ground configuration to an onboard-oriented one, starting from the memory allocation, the structure of the code itself, and the kinds of integration and solver used to iterate the solution in the root finding process. All of this has been applied to the aforementioned algorithm. It has been automatically coded from Matlab to C language, and deployed on LEON board (the microprocessor typically exploited by the European Space Agency for its missions[‖]) and on Zedboard (an innovative board containing the Xilinx Zynq-7000 SoC, more performing of the LEON board, and state-of-the-art for CubeSat[**], Fig. 13) in processor-in-the-loop (PIL) tests.

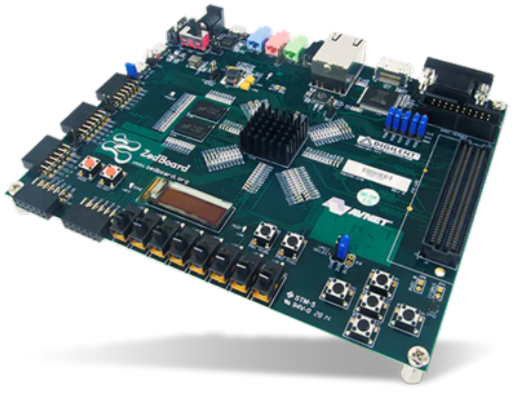

Fig. 13: Zedboard.

The results obtained are compatible with the nominal ones obtained on normal machines, requiring around 5 to 10 CPU times the nominal CPU time on the Zedboard, and 100 CPU times the nominal CPU time on the LEON board. Moreover, these time factors are proved to be almost constant. Their repeatability makes PIL tests feasible, and with estimable execution times.

7 Conclusions

An idea of an onboard guidance algorithm based on an indirect formulation is presented. The main requirements for an autonomous application of a trajectory optimization algorithm are discussed and individuated. These requirements are compared to the capability of indirect methods, with an enlightenment of strengths and drawbacks identified. The drawbacks are analysed, and compared to the peculiar application of these methods on board. The main solutions designed to address each drawbacks are presented.

As regard the characterization of the convergence region, a preliminary Monte Carlo analysis is presented. This clearly show that a convergence region, a state space where the convergence is ensured, exists, even having a complex nature. For the design of a mapping for a good initial guess to ensure reliability, the preliminary results of a DA map are presented. Finally, for as regard the

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[‖] www.esa.int/Enabling_Support/Space_Engineering_Technology/LEON_the_space_chip_that_Europe_built Last access on 7th September 2023

[**] www.xilinx.com/products/boards-and-kits/1-8dyf-11.html Last access on 7th September 2023

CubeSat compatibility, the preliminary results for an operational compliant indirect algorithm are shown, as well as the compatibility of the aforementioned algorithm on representative GNC boards.
All these elements together, allow the design of an optimal, reliable, and sustainable indirect-based autonomous guidance algorithm.

Acknowledgments

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