GO-GREAT: GLOBAL OPTIMISATION - GUIDANCE IN REAL TIME

ESR – Executive Summary Report

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1 INTRODUCTION

1.1 Purpose of the Document

This report provides an overview of the activities performed during the study GO-GREAT: Global Optimisation – Guidance in REAl Time. The study was performed by Airbus Defence and Space for ESA under **ESA/ESTEC Contract Number RFP/3-15943/19/NL/CRS/hh.**

The document will guide the reader through:

- §4: the objectives, requirements, modelling assumptions and the reference scenario considered during the study;
- §5: the description of the two main guidance functions developed under the study: the Non-convex and SCP GREAT algorithms, including their trade-offs, methods used and programme architecture;
- §6: the On-board suitability assessment;
- §7: the description of the Functional Engineering Simulator used to undertake the functional and performance tests of the implemented GREAT algorithm;
- §8: the overview, results and outcomes of the V&V campaign of the guidance function;
- §9 the benchmarking of the GREAT algorithm implementation on the CVX environment;

Finally, Section §10 will provide a summary of the results and considerations resulting from the whole study. Moreover, it provides an overview of potential way forward and recommendations for the continuation of the project with the required industrialisation steps in order to scale-up the TRL of an on-board guidance in real-time, improving autonomy for operations beyond Earth orbit of spacecraft employing electric propulsion.

2 APPLICABLE AND REFERENCE DOCUMENTS

2.1 Applicable Documents

The following documents are applicable and are referred to as [AD xx] in the text:

Number	Title	Document Number	Issue
[AD01]	Reference coordinate system	ECSS-E-ST-10-09C	-
[AD02]	Control engineering handbook	ECSS-E-HB-60A	-
[AD03]	Proposal AO/3-15943/19/NL/CRS/hh "Space Missions Global Optimisation for Spacecraft Guidance"	ESA RFP/3-15943/19/NL/CRS/hh	-

2.2 Reference Documents

The following documents are referenced for supporting information and are referred to as [RD xx] in the text, or are developed in parallel during the project study [TN xx] and [UM xx], or produced during the meetings [MN xx]:

Number	Title	Document Number	Date/ issue
[RD01]	The Global Exploration Roadmap, International Space Exploration Coordination Group (ISECG)	-	Jan 2018
[RD02]	ESA website, url: https://www.esa.int/Our_Activities/Operations/Angelic_halo_orbit_chosen_for_humankind_s_first_lunar_outpost	-	July 2019
[RD03]	NASA website, url: https://www.nasa.gov/what-is-artemis	-	July 2019
[RD04]	Whitley, R. J., Davis, D. C., Burke, L. M., McCarthy, B. P., Power, J., McGuire, M. L., and Howell, K. C. "Earth-Moon Near Rectilinear Halo and Butterfly Orbits for Lunar Surface Exploration." 2018 AAS/AIAA Astrodynamics Specialists Conference, Snowbird, Utah.	-	2018
[RD05]	Shirazi, Abolfazl & Ceberio, Josu & Lozano, Jose. Spacecraft trajectory optimization: A review of models, objectives, approaches and solutions. Progress in Aerospace Sciences. 10.1016/j.paerosci.2018.07.007.	-	2018
[RD06]	Wang, Z. and Grant, M. J. "Minimum-Fuel Low-Thrust Transfers for Spacecraft: A Convex Approach." IEEE Transactions on Aerospace and Electronic Systems, 54(5):2274–2290.	-	2018
[RD07]	IPOPT: Documentation, url: https://coin-or.github.io/Ipopt/index.html	-	2019
[RD08]	Davis, Diane, et al. "Orbit maintenance and navigation of human spacecraft at cislunar near rectilinear halo orbits."	-	2017
[UM1]	U.M.1 – FES User Manual	ADSS-TN-1000752359	Issue 3
[TN11]	T.N 1.1 – Summary of Literature Review	ADSS-TN-1000646806	Issue 1
[TN12]	T.N.1.2 – Reference mission definition	ADSS-TN-1000883588	Issue 1
[TN21]	T.N 2.1 – Requirement definition document	ADSS-TN-1000699615	Issue 1
[TN22]	T.N 2.2 – On-board guidance function preliminary definition and design	ADSS-TN-1000699679	Issue 3

[TN31]	TN 3.1 – On-board guidance algorithm prototype architecture, design description, and on-board execution suitability assessment.	ADSS-TN-1000751941	Issue 3
[TN32]	TN 3.2 – FES simulator design description.	ADSS-TN-1000752340	Issue2
[TN41]	TN4.1 - On board guidance V&V report	ADSS-TN-1000818496	Issue 3
[FR]	FR – Final Report	ADSS-TN-1000863583	Issue 2
[TAS]	Technology Achievement Summary	-	2020

3 ABBREVIATIONS AND DEFINITIONS

3.1 Acronyms

The following abbreviated terms are defined and used within this document:

Abbreviation	Meaning
AOCS	Attitude and Orbit Control Subsystem
BE	Backward Euler
FE	Forward Euler
FES	Functional Engineering Simulator
EP	Electric Propulsion
ESA	European Space Agency
GO-GREAT	Global Optimisation – Guidance REAl-Time
IPM	Interior Point Method
NLP	Non Linear Programming
NRHO	Near Rectilinear Halo Orbit
OBC	On-Board Computer
OD	Orbit Determination
RCS	Reaction Control System
SCP	Sequential Convex Programming
TC	TeleCommand
wrt	with respect to
V&V	Verification & Validation

4 BACKGROUND AND ASSUMPTIONS

The present international cooperation scenario for robotic and human space exploration, in which the European Space Agency (ESA) is an active stakeholder, is focusing on mission architectures that revolve around building and exploiting a crew-tended Cis-Lunar space station, known as Lunar Orbital Platform-Gateway (LOP-G). Candidate orbits for this vehicle are the Near-rectilinear Halo Orbit (NRHO). As a consequence, the capability to inject spacecraft in NRHO is key to many future exploration missions.

In addition, Electric Propulsion (EP) technology has reached a level of maturity that makes it the preferred option for several commercial, science and exploration missions due to superior efficiency (e.g. higher specific impulse) compared to chemical propulsion technology.

On this basis, it is conceivable that future missions aimed at reaching the LOP-G will make use of EP as main propulsion technology. Under such scenario, a transfer from Earth orbit (e.g. EP) to NRHO will last several months and typical operations are based on frequent contacts with a spacecraft operation centre that is in charge of generating and uploading attitude and/or orbit guidance profiles. This approach is driven by a purely radio-metric ranging and Doppler based navigation from ground.

Substantial savings in ground operation cost can be envisaged by moving the guidance function on-board. Under this new scenario, an on-board guidance algorithm could make use of advanced navigation capabilities (e.g. through vision-based relative navigation based on triangulation with Earth and the Moon, observation of the Moon limb, etc.) to reduce the frequency of radio-metric ranging and therefore opening the possibility of an on-board generation of the guidance profiles. These guidance profiles shall be generated to achieve optimal EP thrust direction while ensuring sufficient illumination of solar arrays, ensuring communication capability (when relevant) and complying with the applicable attitude constraints.

4.1 Objectives and Requirements of the project

The main goal of the GO-GREAT study is to assess the preliminary performance (both from a GNC and software execution load perspective) of on-board attitude guidance algorithms for the next commercial, science and exploration missions using low-thrust propulsion. The reference mission for this development is the optimisation of low-thrust transfers using EP to and from Cis-Lunar space (e.g. to/from NRHO). In order to enhance the autonomy of future challenging missions, the real-time/on-line convex optimisation will make use of a reference solution obtained preferably using global nonlinear optimisation techniques and enable adaptability to a realistic flight profile. The capabilities of the on-board algorithm will be demonstrated on a realistic benchmark of the reference mission.

4.2 Reference mission scenario

At the beginning of 2018 the last edition of the Global Exploration Roadmap reaffirmed the interest of 14 space agencies to expand human presence on the Moon and in particular the concept of a Lunar Orbital Platform-Gateway (LOP-G) as first human outpost around the Moon [RD01]. During Q2 and Q3 2019 several updates on the LOP-G mission have been provided, in particular the 18th of July 2019 ESA announced that the Gateway will follow a southern L_2 NRHO [RD02]. This pionieristic objective is shared with NASA (Artemis program), which announced the 25th of July 2019 that by 2024 it will send astronauts aboard the Orion spacecraft to the LOP-G, where they will live and work around the Moon. The crew will take expeditions from the Lunar oupost to the surface of the Moon in a new human landing system before returning to the orbital outpost; crew will ultimately return to Earth aboard Orion [RD03].
Currently the assembly of the Gateway is expected to occur on-orbit and the missions to/from the Moon will be performed exploiting orbital transfers between the LOP-G and parking orbits [RD04]. As a result, the operational environment of a LOP-G will be characterised by the 3-body problem, meaning that the interaction between Moon and Earth gravitational field affects consistently the spacecraft dynamics. The orbital motion is then perturbed by other natural perturbative accelerations such as the solar radiation pressure, caused by the Sun irradiating the spacecraft according to its surface-to-mass ratio and illumination condition, moon gravity harmonics, due to Lunar geopotential irregularities, and Sun gravity.

4.2.1 The reference trajectory: low-thrust Weak Stability Boundary transfers

The GO-GREAT reference trajectory is an EP transfer via SEL2, with a thrust-to-mass ratio of $0.09\ N/t$, as shown in Figure 4-1. It represents a ~6 months WSB transfer to the NRHO going towards the Sun-Earth Lagrange point L2 region.

The duration of the final insertion thrust arc is of nearly 22 days, spiralling down in the Earth-Moon rotating frame towards the target NRHO, and a Deep Space Manoeuvre is also required, of about 16 days.

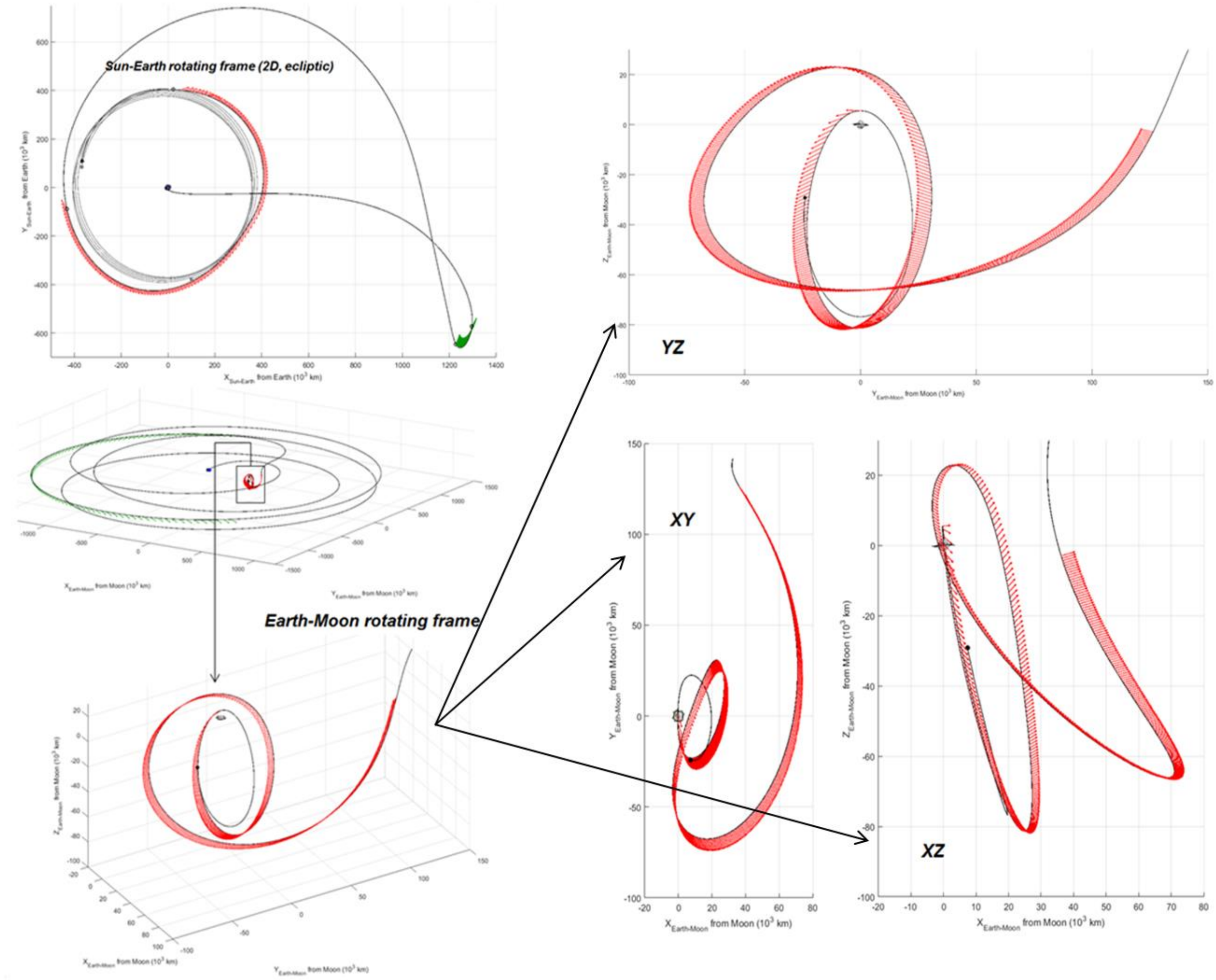

Figure 4-1: Reference transfer-SEL2 with $T/m{\sim}0.09\ N/t$, represented in the Sun-Earth rotating frame centred at the Earth (top-left) and in the Earth-Moon rotating frame centred at the Moon (bottom-left. On the right: Zoom on end game and NRHO orbit insertion.

4.2.2 The reference spacecraft

The reference spacecraft used to assess the performances of the autonomous on-board guidance function is representative of a service platform with steerable solar panels along the pitch axis and a MGA antenna. The spacecraft main engine is based on low-thrust EP, producing a net thrusting force along the roll axis and characterised by a gimbal range of 20°.

4.2.3 The reference navigation performance

During the algorithm performance assessment, the autonomous guidance function will rely on the position and velocity estimation from one or more sequential ground stations RF links, with source of errors and measurement frequency reported in [TN12].

4.2.4 The operational constraints

The GO-GREAT main operational constraint is the minimisation of the Ground intervention during the guidance operations, as per R-GUI-PER-04.
Moreover, the trajectory optimisation problem is in principle independent on the spacecraft attitude, but the presence of long firing arcs and of a propulsion system whose performances are strongly dependent on the on board power generation system make the enforcements of inequality constraints on the attitude necessary, in order to meet the solar panels and antennas pointing requirements [TN21].

Nevertheless, giving the possibility to rotate the solar arrays around the spacecraft pitch axis, the maximum Sun exposition can be always achieved with a combination of platform rotation around the roll axis and solar array rotation around the pith axis, making the SAA constraint not necessary. However, it is beneficial for the study to introduce a constraint on the solar panels orientation. The extreme case is the one of fixed solar arrays with normal parallel to the thrust direction: in this case the constraint can be enforced by bounding the SAA between $\pm 20°$. A trade-off solution is to consider a relaxed constrain, bounding the SAA between $\pm 50°$, which is relaxed to $\pm 70°$ with the addition of the EP gimbal range, as represented in Figure 4-2.

For a service mission, representing a strong candidate scenario for the study, the possibility to communicate during all the firing time is seldom requested, as well as the use of an high-gain antenna (narrow beam width and high data rate). As a result, a spacecraft embarking a steerable medium gain antenna can be the best solution to be able to communicate with ground with almost every attitude, without affecting the optimisation problem with additional constraints. For the sake of optimisation problem complete definition a communication constraint is proposed as function of the Earth line of sight (ELoS), between thrust vector and satellite-Earth direction, assuming a Medium Gain Antenna (MGA) with $35°$ half-cone angle, which has to be bounded between $55°$ and $125°$, which is relaxed to $35°$ and $145°$ with the addition of the EP gimbal range, as shown in Figure 4-1.

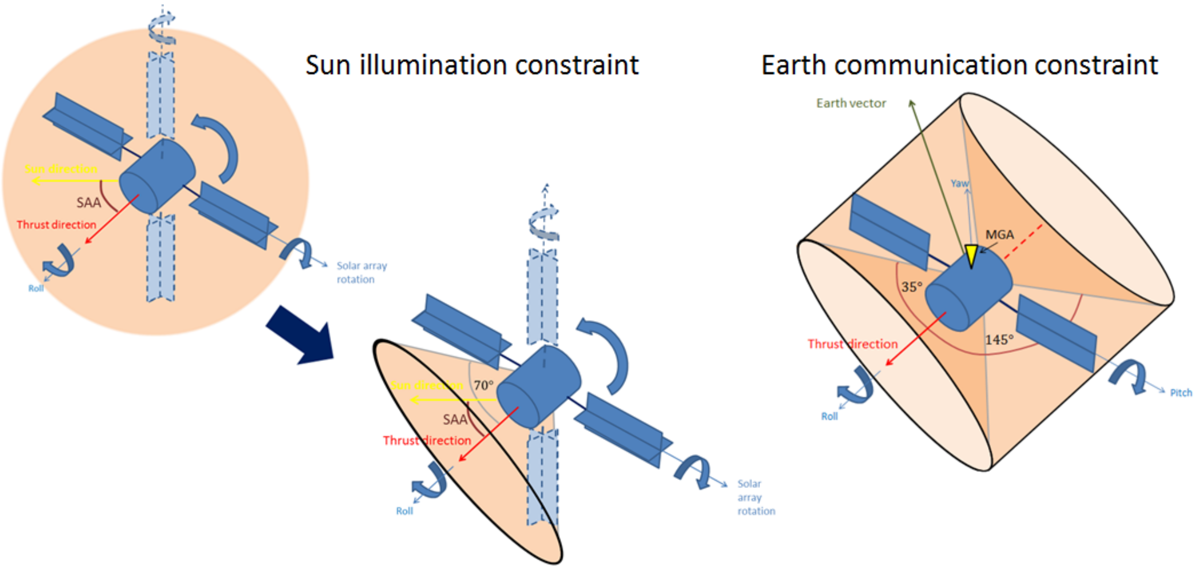

Figure 4-2: Top left: solar arrays can orientate their normal to every direction in the space maintaining fixed the thrust direction by combining a platform rotation around roll axis and an array rotation around pitch axis. Bottom left: Relaxed constrain assuming a confined Sun Aspect Angle. On the right: Earth communication constraint.

4.3 Autonomous guidance architecture and scheduling

The GREAT guidance activation frequency during the mission is a design parameter that affects the optimisation algorithm convergence time: the longer the time horizon the higher the computational effort to obtain an optimum thrust profile. During nominal mode, the AOCS controller, whose state knowledge is affected by the *navigation error*, maintains the spacecraft in the *control deadband* as represented in Figure 4-3. The GREAT activation is triggered if the instantaneous *control error* exceeds a fixed threshold.
The sources of this error can be due to:

- The deviation of the actual trajectory with respect to the reference trajectory in real dynamics :
    - The orbits in the high nonlinear dynamics of the Earth-Moon-Sun system are characterised by unstable manifolds, where even a small initial perturbation with respect to the reference trajectory will produce a significant drift over relatively short propagation time. GO-GREAT reference transfer orbit is indeed based on the four body problem (4BP) dynamics, where for example the lagrangian orbits have practical instability after 2-3 revolutions.
    - Non-modelled dynamics and disturbances induce a propagation error, which significantly lead the spacecraft trajectory to deviate/drift from the nominal one. In particular the GREAT performance testing campaign will make use of additional disturbances, such as the one deriving from the SRP knowledge uncertainty.
    - Uncertainties in the EP model, providing an actual thrust that for long firing times can make the spacecraft diverge from reference trajectory. This makes more likely to have a significant drift from the nominal state during the firing arcs.
- Update of navigation inputs thanks to more precise (and more computationally or operationally demanding) navigation technologies that can be executed at relaxed frequency to improve real-time navigation (for example involving absolute estimation, visual-based, delta-DOR, ground processing). This will affect the initial navigation error, which will be varied in accordance to each technology performance to simulate the effects on the GREAT algorithm. The typical source of errors and measurement frequency characterising these technologies are reported in [TN21].
- Launcher injection error to the reference transfer trajectory (at the start of the simulation). In particular, launcher performance will be used to initialise the GO-GREAT GNC loop in the simulations to assess the effect of an initial error at the beginning of the reference mission.

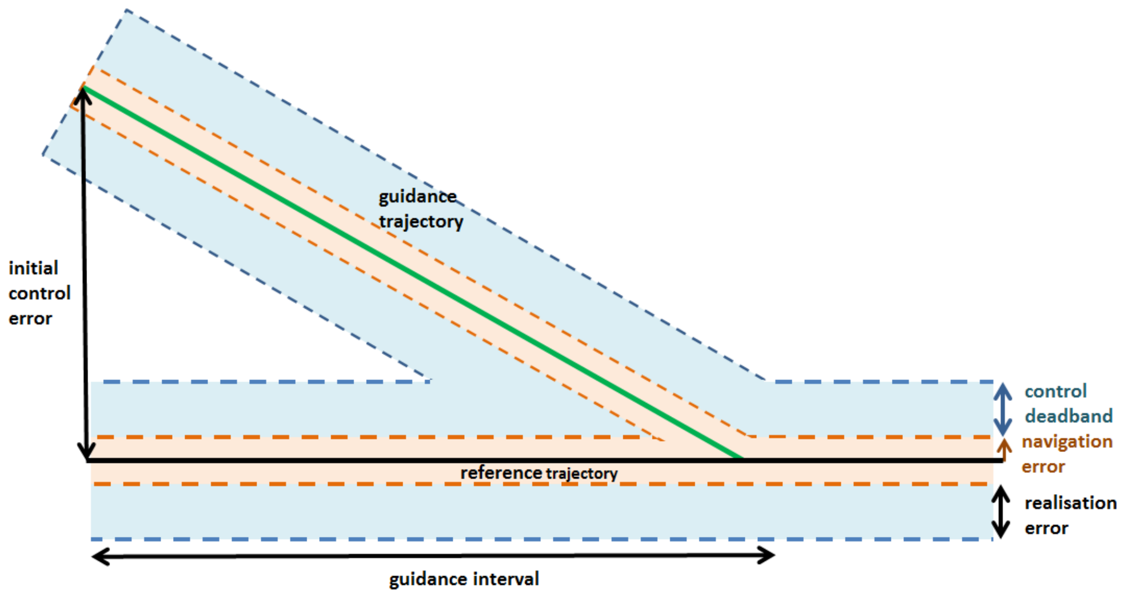

Figure 4-3: Navigation and realisation error schematics.

5 AUTONOMOUS GUIDANCE ALGORITHM TRADE-OFF AND SYNTHESIS

In order to be compliant with the GO-GREAT study requirements on the guidance profile's propellant-optimality and autonomy [TN21], the **optimal guidance approach** has been identified as preferable with respect to the classical ones [TN11].
The baselined algorithms to implement and test in the study are:

1. The **Non-convex implementation**: based on the Modified Thrust Model based guidance problem, exploiting the slack variable substitution reported in [TN22] to decouple state and control variables.

2. **The Sequential Convexified Program (SCP) implementation**: based on the iterative convexification of the Modified Thrust Model based guidance problem, exploiting the slack variable substitution reported in [TN22] to decouple state and control variables.

Both the code versions are formulated with a direct method and solved using either multiple-shooting or the collocation technique. In particular, the baselined algorithms are schematically represented in Figure 5-1.

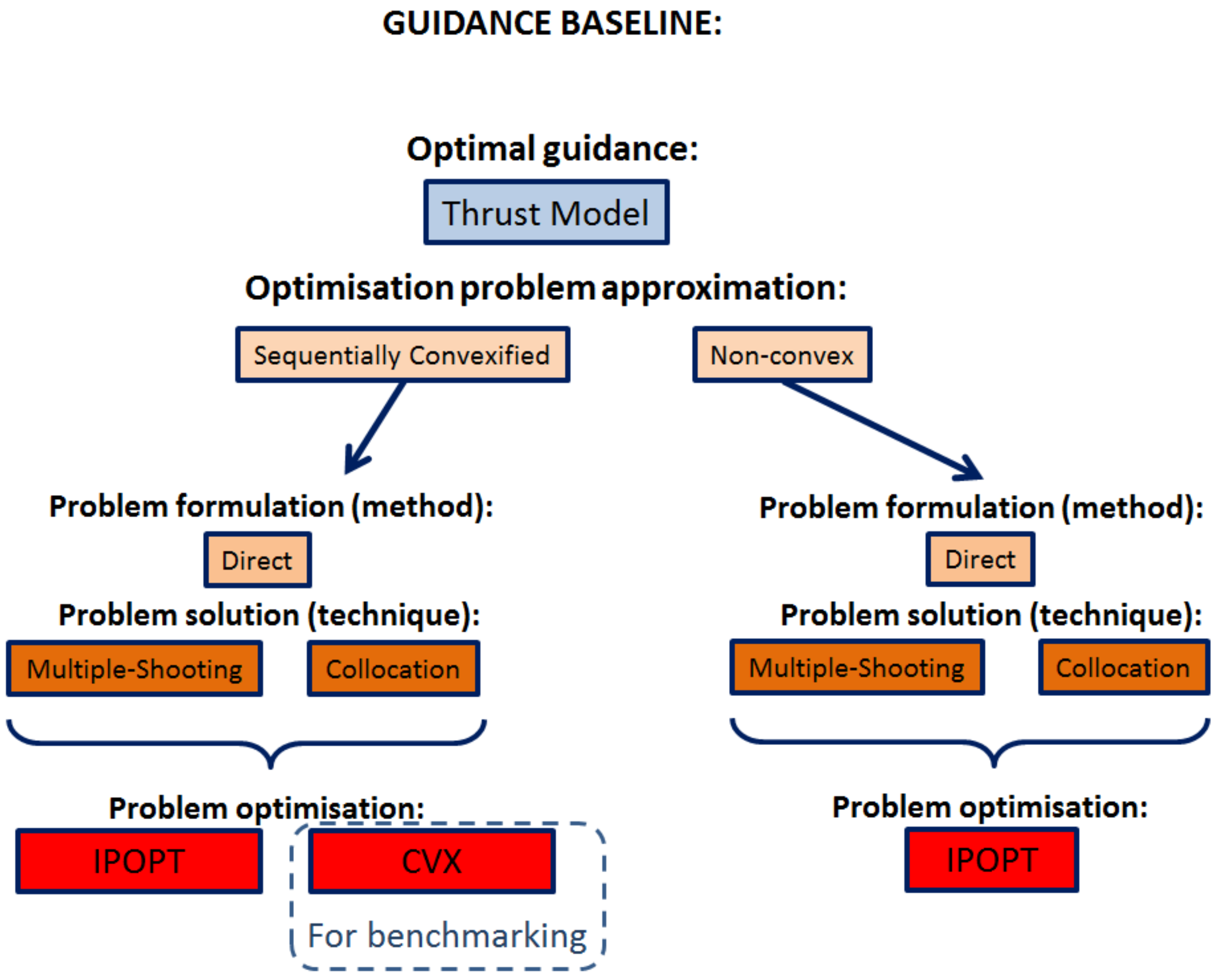

Figure 5-1: Guidance on-board autonomous algorithm baseline.

5.1 Thrust Model and its convexification

The Thrust Model (described in [TN22]) is based on the following assumptions:

- Attitude dynamics is neglected: GREAT will provide the thrust profile to the AOCS, which will drive the spacecraft dynamics to follow the GREAT reference. The attitude around the thrust direction is a design parameter.
- GREAT optimises the thrust profile, but not the attitude control torques, which are provided by the AOCS.
- GREAT can be activated during pre-planned time windows for trajectory correction or continuously, providing a complete trajectory re-planning (longer horizon, corresponding to higher computational cost).
- The reference frame adopted is the EME J2000 inertial frame.
- In accordance with REQ-G-F-05 in [TN21], the model relies on a full ephemeris orbital dynamics, since CR3BP does not describe properly the NRHO mid-long term evolution.

The Thrust Model is characterised by an high degree of autonomy being the Flight Control team in principle not involved in the guidance loop and provides the optimum thrust profile, resulting propellant efficient for the main engine. As a consequence, the attitude control effort is not optimal and could lead either to saturation of reaction wheels or not optimal usage of attitude RCS propellant. Finally the formulation presented in this subsection makes more challenging the enforcement of constraints directly on the spacecraft angular rates and accelerations.
The main characteristics of an optimisation based approach assuming the Thrust Model are summarised in Table 5-1.

	Thrust Model
Optimisation variables	7 states and 3 controls $(\boldsymbol{r}, \boldsymbol{v}, m)$ $(T, \alpha_x, \alpha_{zy})$
Applicable constraints	Attitude-constraints in function of thrust direction
PROs	• High degree of autonomy; • Nonstiff dynamics with respect to Complete Model.
CONs	• Main engine propellant efficient (control effort is bounded but not optimised).

Table 5-1: Characteristics of an optimisation based guidance assuming the Thrust Model.

The necessity to include a constraint on the thrust vector angular rate, drives the definition of the Modified Thrust model, exploiting the finite differences between integration time steps Δt, to obtain the rate of change of the angle between two successive thrust directions. The same approach can be used to obtain the constraint on the thrust vector angular acceleration, affecting the most the attitude control effort. With this technique the spacecraft rates and accelerations are indirectly bounded by constraining the thrust vector angular rate and acceleration.

In the case of the Modified Thrust Model, following the procedure demonstrated in [RD06], it is possible not only to convexify the optimisation problem, but to also decouple the control from the state, which is helpful in eliminating the high-frequency jitters and improving the convergence of the sequential convex method developed in Subsection §5.2. The steps to follow are reported [TN22].

5.2 Sequential Convex Programming

When the *non-convex* problem undergoes a convexification process, the resulting *convex* problem can be quickly solved with an Interior Point Method (IPM), which does not require initial guesses since it allows the algorithm to start from a self-generated feasible point.

One of the most common techniques to convexify the optimisation problem is to do it iteratively [RD06]: a procedure known as Sequential Convex Programming (SCP).

Of course the approximation stands only when the state is sufficiently close to the reference solution and a potential risk during linearisation is rendering the problem unbounded, because new states and control sequence can significantly deviate from the nominal ones: as a consequence it is possible to enforce a *trust-region*, function of a user-defined tolerance.

The resulting convex problem is then solved iteratively as reported graphically in Figure 5-2. The solution of the SCP algorithm cannot be proven to be a global optimum, since it relies on a discretised and simplified optimisation problem.

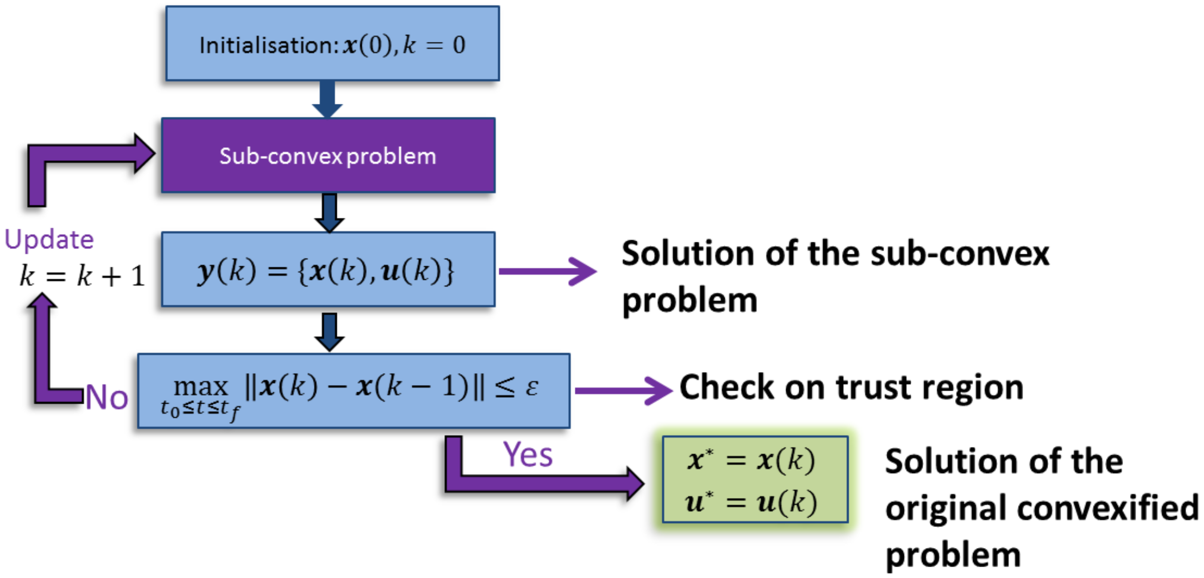

Figure 5-2: SCP method.

5.3 The GREAT algorithm architecture

The prototype autonomous guidance algorithm [SW1] has been developed in the study as a standalone executable program interacting with the user[1] by loading and writing text files in .dat format. This is intended to reflect the real-life implementation of the GREAT function, taking the inputs detailed in [TN31] directly from the OBC datapool. The main program and 5 subroutines are sequentially called by the main program at every iteration of the optimisation problem, as shown in Figure 5-3 and Figure 5-4 for the Non-convex and SCP implementations respectively.

The guidance software is designed to be interfaced with the spacecraft OBC and AOCS as described in [TN22] and autonomously activated during the mission in accordance to the scheduling presented in [TN22].

[1] **Or an automatic procedure through batch files, or any programme interface, like Matlab.**

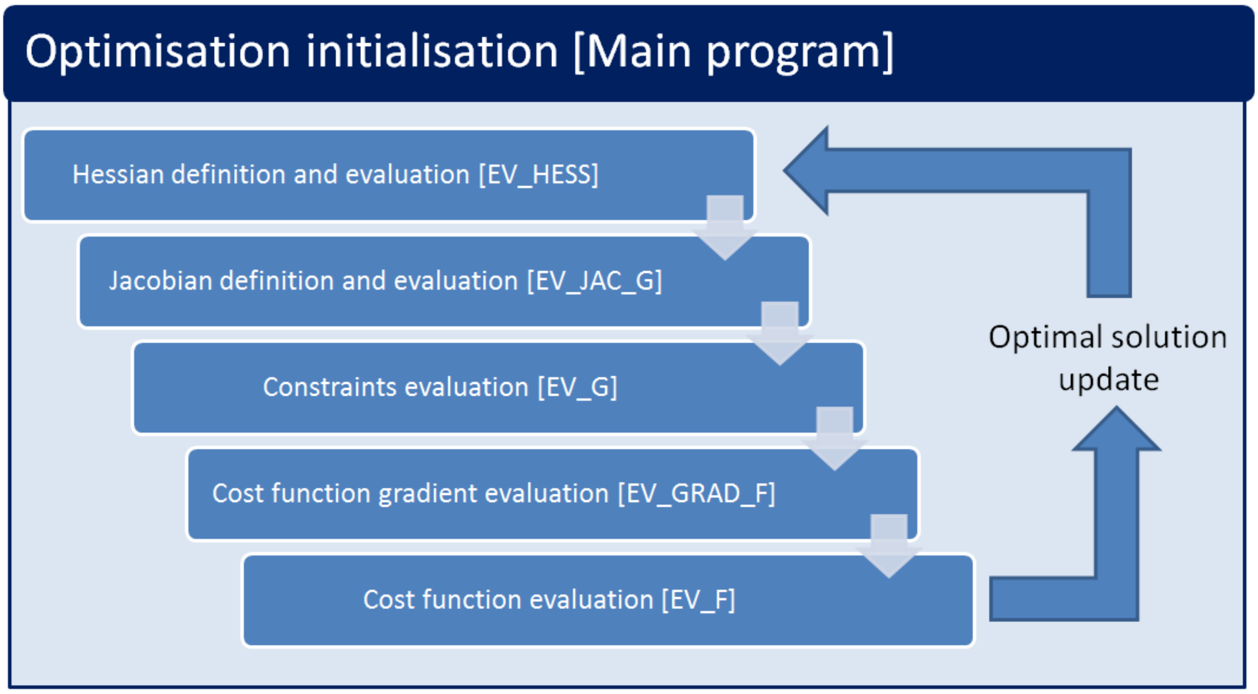

Figure 5-3: Autonomous Non-convex guidance algorithm prototype block diagram.

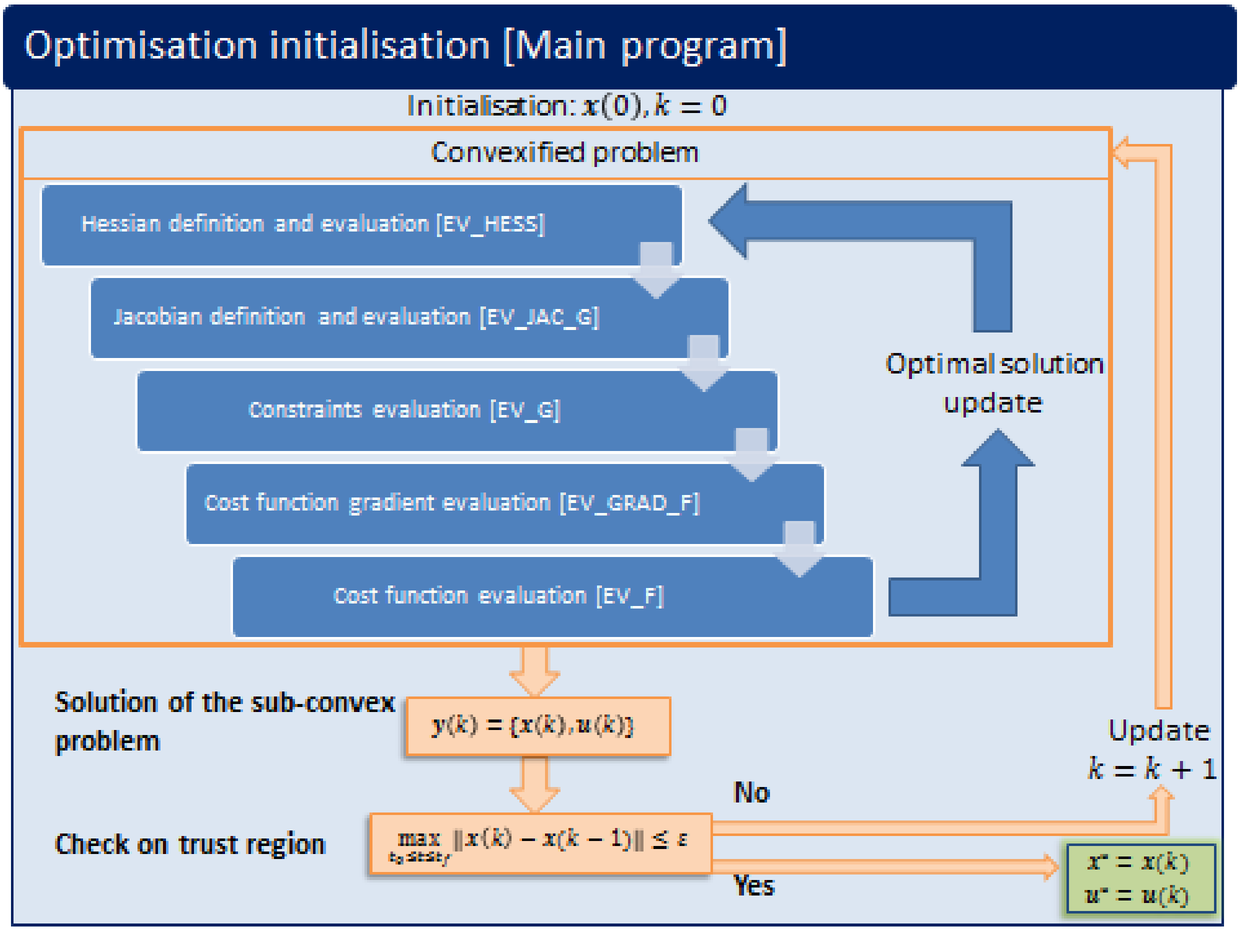

Figure 5-4: Autonomous SCP guidance algorithm prototype block diagram.

6 ON-BOARD EXECUTION SUITABILITY ASSESSMENT

The proposed guidance computation is cyclical with a requested activation frequency in the order of once every one week, which potentially can be realised outside the software real-time domain. The first step is to evaluate how the preliminary measurements presented before translate into a few common hardware architectures used on previous space embedded projects.

The functional development by the AOCS team of the guidance software in the GO-GREAT study uses a commercial Intel-i5 laptop clocked at 2.4 Ghz pinning the computation on one core. Assuming that this platform provides roughly 7 DMIPS/MHz/core, this equates to approximately 17000 DMIPS at 2.4 Ghz. For the realisation on-board, a first comparison is from the well qualified platform in space using LEON3 OBC with a single core at 32Mhz, providing 1.4 DMIPS/MHz (i.e. 45 DMIPS). Assuming a single OBC in cold redundancy, because the computing platform is running also the other processes ("standard" AOCS SW, TCS SW, payload SW for example), it is necessary to allocate a fixed amount of CPU time to the long duration computation: 1% is a conservative figure reflecting the low priority aspect of the guidance activation demand.

With these assumptions a computing factor ratio of 40,000 between the test platform based on the Intel-i5 and the LEON3 is a conservative allocation. This means that the mean computation performance of 3s of the guidance software on commercial computer would translate in an on-board profiling of 3s x40,000 = 120,000s = 33 h.

The table below provide the on-board guidance algorithm profiling, expressing the CPU usage for this computation across several known processors with respect to the reference PC simulation.

Platform		RAM (Mb)	DMIPS/Mhz/Core	Duration(s)
PC reference	Intel i5 2.4Ghz	8000	6	3
On-board space processors	LEON3 32Mhz	256	1.4	120000
	LEON4 250Mhz	256	1.6	108
	ARM A53 1Ghz	1000	2	22

Table 6-1: On-board guidance algorithm profiling considering 1% of CPU allocation.

In all cases, the computation on a flight platform will take several seconds to complete, which confirms it does not fit in typical space software architecture based on real-time operating system where a real-time cycle is in the order of 100ms. An implementation for the algorithm will need to spread the computation across several minor cycles. Three realisation strategies could be developed.

- The first realisation option is to use the available hardware with real-time operating systems, exploiting their existing scheduling functionality of allocating low priority activities for long-term processing: this is the usage of the background task ATERF. When programming the threads of the OBC, this task executes when all other tasks have been executed until the end of each real-time minor cycle. Currently it is commonly used for iterative memory scrubbing but could be re-purposed for long duration computation relatively easily. The management of the execution of the threads of the guidance software is automatically done by the background task creating breakpoints through the guidance algorithm. From reference missions, the spare time of the CPU is about 1%-5%, hence the above profiling in Table 6-1 represents a conservative scenario.

- One drawback of the first option is that the completion time of the realised guidance software on-board would be non-deterministic (note the completion is already non deterministic on-ground, because uses an iterative optimisation process until convergence is reached). To provide full observability under a planned execution schedule, the second realisation option is to not rely on the automatic management of the spare CPU time by the background task, but anticipate it by SW code design, which requires to split the guidance algorithm in many smaller computation sub-codes which fit in the real-time minor cycle (for example 1ms out of 100ms) and are therefore sequenced during the computation slots. The management of the sequencing is done by providing a set of counters "state" that identifies the part of the guidance software sub-code, which gives observability of the execution status in the telemetry, hence tracking the execution until completion. This option hence requires additional burden to the designer and programmers of the guidance software, by defining a processing budget of the SW code, since it could prove complex to undertake from an algorithm point of view. The implementation of this second strategy brings the benefit to take trace of the GREAT progressive execution in the background task ATERF, but it does not come with an improvement in execution time.

- The third possible approach would be to use more complex CPU, able to take advantage of the Linux Operating System where the real-time constraints could be relaxed. However if the algorithm implementation is simpler in this context, the rest of the applications running on the platform would need a significant new design (using hypervisor for example). Moreover, implementing the autonomous guidance algorithm on a more modern architecture (i.e. AEM A53), makes the execution time decrease thanks to the higher clocking frequency.

In terms of memory usage, the number of software database parameters is significant, but their required allocation is not dynamical and its total size is not a concern. In particular, this is well within the RAM capability of a LEON3 processor.

It is worth highlighting that the guidance software developed in this GO-GREAT study requires the use of optimisation libraries which would need to be ported to the target platform. This could prove easier on modern computing platforms running Linux rather than a traditional operating system (using C and C++) although nothing prevents it.

This analysis shows that even if hardware space-qualified computation platforms exist today, other choices for implementation of the guidance software designed in the GO-GREAT project are available, each carrying non-negligible consequences. The following follow-up studies would be useful to consolidate assumptions made in this preliminary assessment to raise the TRL of the proposed software:

- Investigating the use of Fortran to C compiler to generate C code from the algorithm.
- Investigating the optimisation libraries and their possible portability to space platform.
- Prototype long duration computation capacity on existing LEON3 development platforms.

7 FUNCTIONAL ENGINEERING SIMULATOR

The FES [SW2] has been developed in the study as a standalone executable program interacting with the user[2] by loading and writing text files in .dat format and iteratively calling autonomously the GREAT.exe program execution to evaluate the optimal guidance profiles when requested during the simulated mission scenario's timespan, as represented in Figure 7-1.

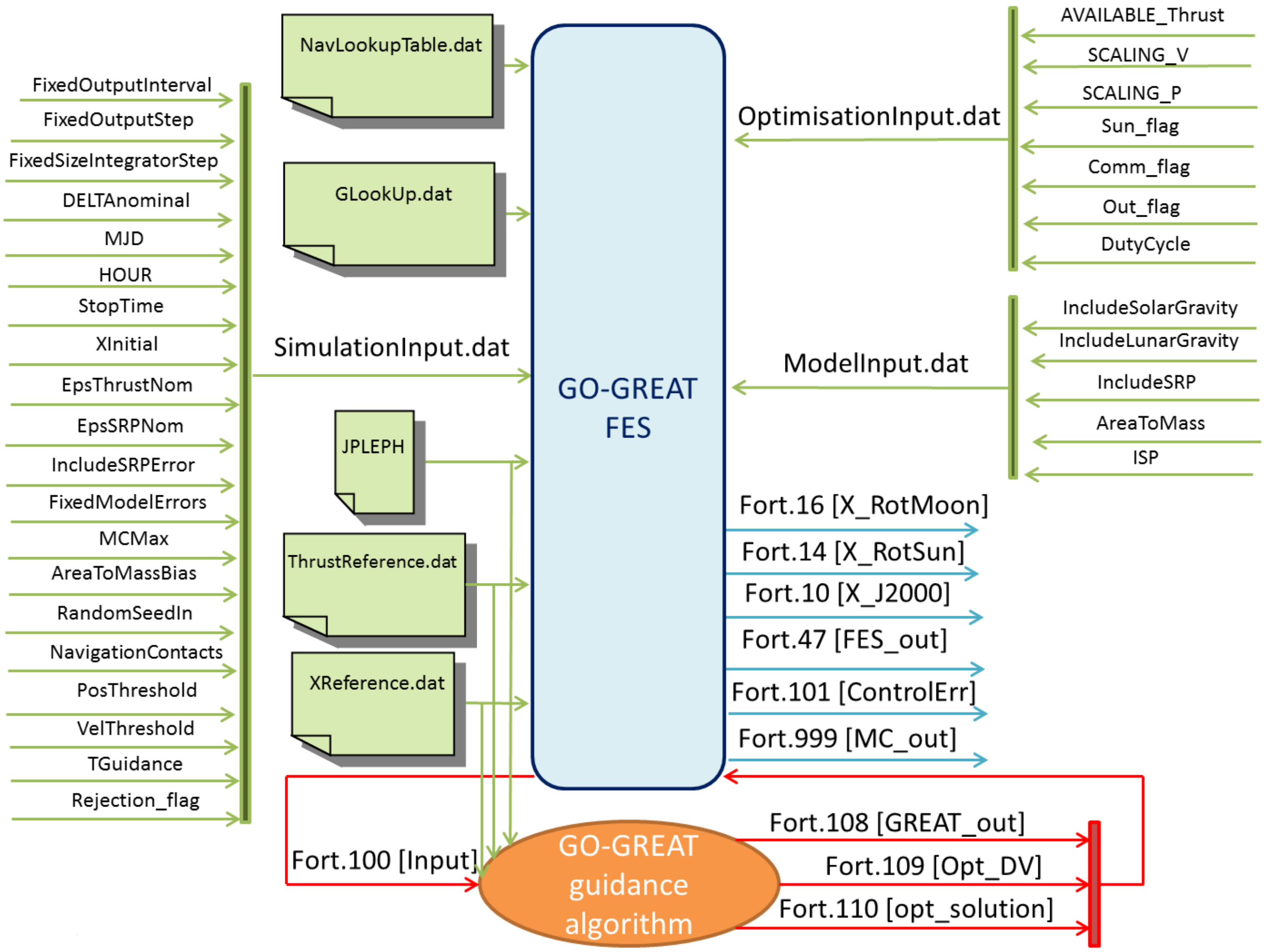

Figure 7-1: FES inputs and outputs.

The complete list of inputs, outputs and libraries required to run the FES is reported in [UM1].
The description of the architecture of the GO-GREAT guidance algorithm is reported in [TN31].

7.1 The FES architecture

The simulator consists of one FES main program [SW2], several subroutines and the GO-GREAT guidance standalone executable [SW1], which perform the tasks broken down in the block diagram shown in Figure 7-3. In particular, the simulator architecture is intended to reflect the high level guidance operations during the mission, as shown in Figure 7-2.

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[2] **Or an automatic procedure through batch files, or any programme interface, like Matlab.**

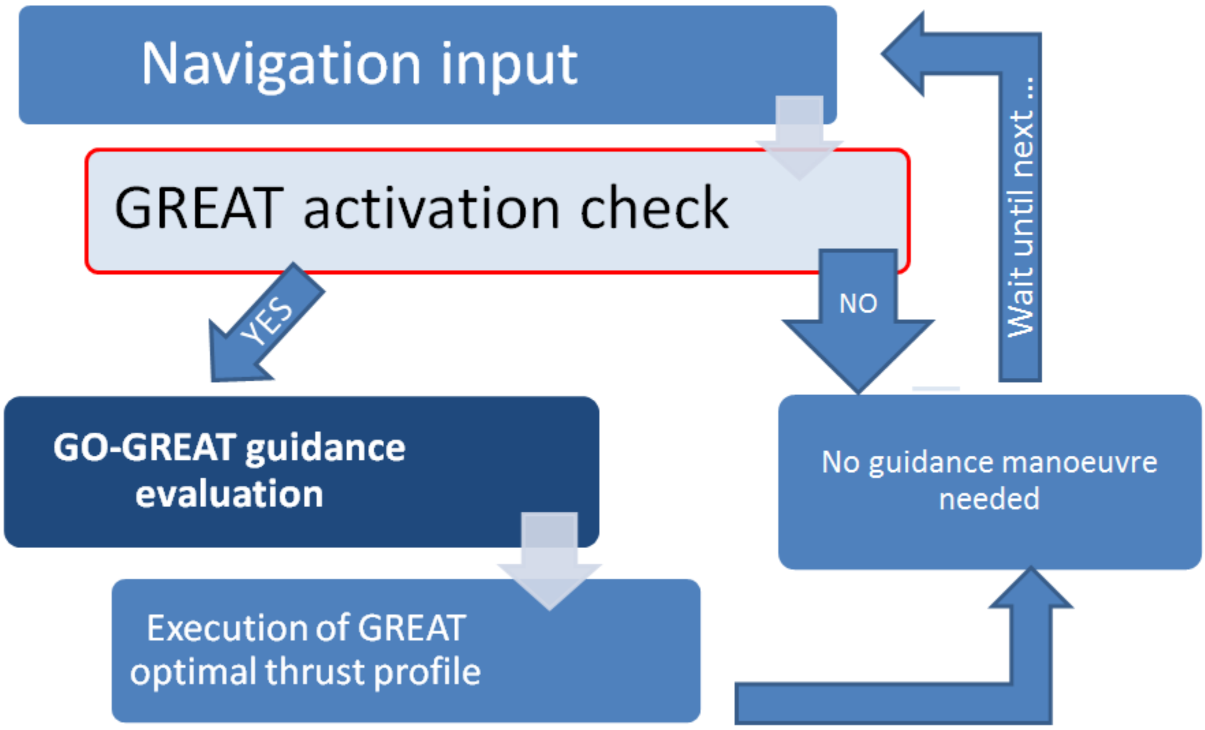

Figure 7-2: High level GNC operation tasking.

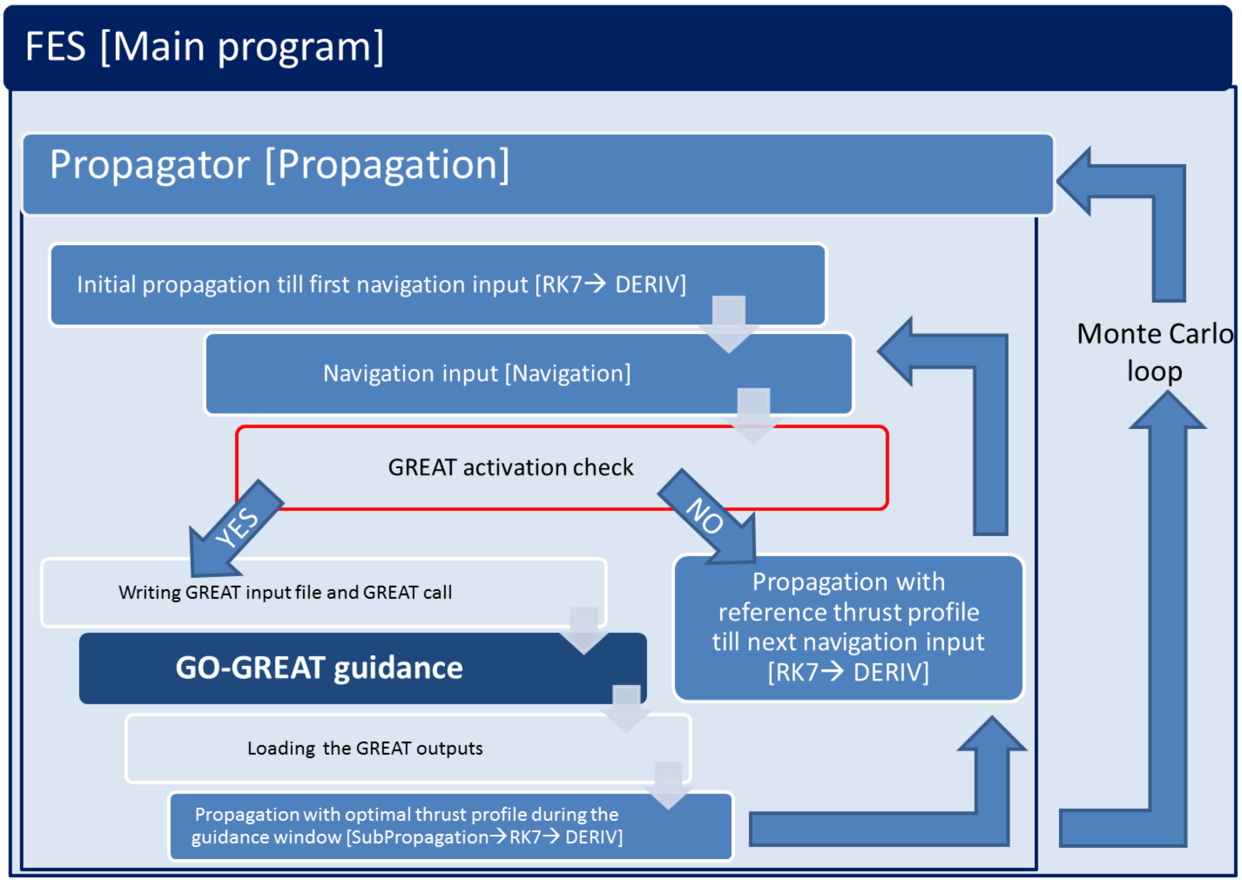

Figure 7-3: FES internal architecture.

8 VERIFICATION AND VALIDATION CAMPAIGN

The V&V campaign performed during Task 4 of the guidance algorithm designed in [TN31] in the FES and mission scenario documented respectively in [TN32] and [TN12], is documented in [TN41].

8.1 Functional verification matrix

The functional verification campaign success criteria and results are reported in [TN41]. Similar test cases to the one exploited to perform the GREAT functional verification were selected in the context of the benchmarking activity with CVX, documented in §9.

8.2 Performance validation matrix

The success criteria considered to assess the performance campaign results documented in [TN41] are based on the following performance metrics:

- The GREAT average and worst case running time on the simulation bench (seconds), assessed per reference mission simulation.
- The time between successive navigation/guidance operations (days), assessed considering all the GREAT activations and required ground-based OD performed during the simulation campaign;
- The navigation/guidance accrued time from the cumulated number of manoeuvers/OD (hours), assessed per reference mission simulation (considering 8h for each ground-based OD operation);
- The cumulated guidance Delta-V (m/s), assessed per reference mission simulation;
- The magnitude of the terminal position and velocity errors at the end of optimal thrust profile propagation (in km and m/s), assessed considering all the GREAT activations performed during the simulation campaign;
- The NRHO insertion error (in km and m/s), assessed per reference mission simulation.

8.3 Performance validation test scenarios

Three navigation strategies have been identified to define three different test scenarios, reported in Table 8-1.

Navigation strategy	Nominal	Autonomous	Robust
Configuration	Nominal ground-based RF-only navigation profile	On-board navigation propagation within critical OD	Enhanced ground-based navigation for critical OD
Purpose	Demonstrate feasible scheduling of correction manoeuvres & navigation Delta-V	Demonstrate relaxation of ground interventions trades with more frequent on-board guidance re-planning remains feasible with on-board optimisation processing time	Demonstrate performance improvement (correction manoeuvers frequency & cost)

Table 8-1: Non convex attitude constrained algorithm performances comparison between multiple-shooting and collocation techniques.

The baseline estimation error profile used to feed the input of the on-board guidance software is derived with the assumptions of the mission reference scenario of the navigation performance presented in [TN21]. Figure 8-1 shows the profiles of diagonal components of the covariance matrix along the reference trajectory timeline.

In particular, the autonomous navigation profile exploits on-board visual based navigation during the final approach to the Moon with ground OD updates performed every 7 days, while the Robust scenario provides enhanced navigation performances with respect to the nominal scenario based on RF contacts with ground exploiting additional ground stations and 4 Delta-DOR (one during the first thrusting arc and three along the last thrusting arc). A duration of 8 hours for the OD was considered for each RF navigation update, and 24 h for each Delta-DOR.

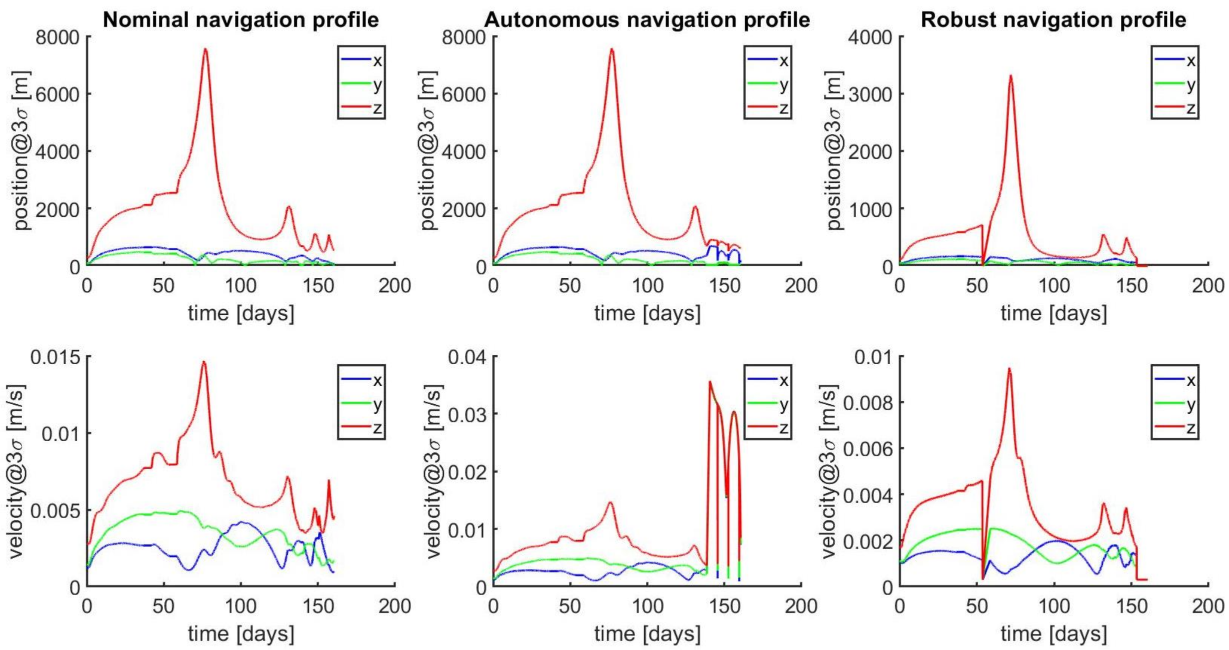

Figure 8-1: Nominal, Autonomous and Robust navigation profiles. Diagonal components of the covariance matrix error, reported as 3 times their square-root.

8.4 Performance validation plan

In particular 4 versions of the GO-GREAT algorithm where designed and implemented during the study [TN22]:

- The Non convex implementation:
  - with Forward Euler (as integrator for the multiple-shooting technique);
  - with Backward Euler (as collocation scheme for the collocation technique);

- The SCP implementation:
  - with Forward Euler (as integrator for the multiple-shooting technique);
  - with Backward Euler (as collocation scheme for the collocation technique);

The objectives of the performance validation campaign are:

- to assess the GREAT guidance algorithm performances;

- to identify which solution technique between multiple-shooting and collocation is more suitable for the GO-GREAT study;

- To compare the performances of the Non convex and SCP implementations.

As a consequence the following comparative analyses have been performed:

- The free-attitude alogirithm (without Sun illumination and Communication constraints) with respect to the constrained one (with all the constraints enforced). This is based on the Non convex version of the code implementing Forward Euler (multiple-shooting). Nevertheless, the same outcomes result between the comparison of the unconstrained and constrained versions of the other GREAT algorithm implementations.

- The Non convex algorithm implementing Forward Euler (multiple-shooting) with respect to the Backward Euler (collocation) based version.
- The SCP algorithm implementing Forward Euler (multiple-shooting) with respect to the Backward Euler (collocation) based version.
- The Non convex with respect to the SCP formulation.
- The Non convex and SCP algorithms performances before the last reference thrusting arc and during the last 10 days before NRHO insertion.

The results of the GREAT performance validation campaign are reported in [TN41], while in the next Subsection only the results referred to the baselined Non-convex guidance function implementing Backward Euler are reported with respect to the test scenarios reported in §8.3.

8.5 V&V campaign results

From the performance validation campaign presented it results that the GREAT algorithm embedding the Non convex formulation and the collocation solution technique is the most performing solution. As a consequence, a Monte Carlo campaign has been executed with 1000 simulations for each of the test scenarios defined in §8.3 and providing the results collected in Table 8-2.

Performance metric at 95% confidence level	Nominal Scenario	Autonomous Scenario	Robust Scenario
Cumulative Delta-V wrt MA [%]	13.1	13.1	13.0
Guidance + OD operations cumulative duration wrt the reference mission time-span [%]	11.2	8.5	13.9
Guidance operations cumulative duration wrt the reference mission time-span [%]	3.9	3.9	4.0
Worst case GREAT running time [s]	47.9	46.7	46.6
Average GREAT running time [s]	15.6	16	14.9
Days between successive guidance operations [days]	≥ 1	≥ 1	≥ 1
GREAT final error in position [km]	8.9	8.92	8.9
GREAT final error in velocity [m/s]	0.062	0.062	0.062
NRHO insertion error in position [km]	19.9	19.9	19.9
NRHO insertion error in velocity [m/s]	1.68	1.68	1.68

Table 8-2: Non convex collocation based attitude constrained algorithm performances comparison. The results consider complete simulations till NRHO insertion.

The previously reported results relative to the Nominal, Autonomous and Robust navigation strategies highlight that:

- The **autonomous scenario**, exploiting autonomous on-board navigation techniques (i.e. visual-based) during the approach to the Moon, provides the same performances of the Nominal scenario, proving the **feasibility of an even more autonomous system for the GO-GREAT reference transfer**. In particular, **the cumulative time spent performing guidance + OD is reduced**, because, when exploiting visual-based techniques, the navigation is performed on-board;

- The possibility to exploit a **more autonomous guidance + navigation strategy is beneficial especially during the thrusting arcs**, when the GREAT activation frequency arrives to 1 operation every 24h, lowering the ground operation effort.

- The **robust scenario** provides the same results with respect to the Nominal and autonomous strategies, indicating that **the driver parameter to increase the GREAT performances is the GREAT accuracy rather than the navigation errors**. Nevertheless, the analysis presented shadows the fact that increasing the navigation accuracy, makes **the number of GREAT activations drop during the first ¾ of the transfer**, while **during the last thrusting arc the frequency rises again till 1 activation per day**.

8.6 V&V campaign conclusions

In this Subsection the outcomes of the Verification and Validation campaign documented in [TN41] are reported:

- The results of the Verification campaign described in the aforementioned Section satisfy the functional verification matrix criteria.

- **The Non-Convex algorithm resulted compliant to all the requirements and the validation campaign success criteria, hence, demonstrating feasibility.**

- In the framework of the GO-GREAT study, the collocation solution technique is more performant with respect to the multiple-shooting especially in terms of GREAT activation frequency during the reference mission. In particular, only the version of the code implementing the Non convex formulation with collocation as solution technique satisfies all the performance campaign success criteria.

- The minimum time interval between successive guidance activations resulting from the validation performance campaign is 1 day for 39% of the occurrences. Indeed, during the thrusting arcs, the guidance operations are requested to be executed almost every day. This is mainly due to the length of the thrusting arcs and the kind of reference transfer considered (WSB), which is far less stable with respect to keplerian trajectories.

- Through the comparison between the results provided by the SCP and Non convex algorithms it is possible to assess that the latter outstands the performances of the convexified version: the GREAT activation frequency is half with respect to the SCP and the running time is approximately 33% lower on the average. Furthermore, the SCP algorithm accuracy, with the selected number of discretisation nodes per guidance activation (50), required to lower the computational time, is not enough to guarantee convergence during the last 10 days before NRHO insertion, during which the Non convex formulation results necessary.

- The application of the attitude constraints where applicable, following the logic implemented in [TN31], does not alter the algorithm performances both in case of SCP and Non convex versions.

- From the on-board suitability profiling documented in [TN31] it was possible to retrieve a posteriori the GREAT running time on three different on-board space processors both in case of the Non convex and SCP implementations, as reported in [TN41]. The outcome of this activity is that the current GREAT design is suitable for the development on the LEON4 and ARM A53 advanced space processors, but the running time characterising the implementation on the LEON3 results higher with respect to the minimum time in between guidance operations, making it unfeasible on a standard space processor.

- The accuracy of all the algorithm versions degrades during the last thrusting arc and the integration scheme used is identified as a potential cause: Forward Euler was selected because of its lighter computational demand and implementation complexity with respect to higher order schemes such as RK4 or RK7. Nevertheless, it introduces an integration error which is not negligible and that, once decreased, could also decrease the guidance activation frequency during the whole reference mission. On the other hand, the implementation of a more complex integrator could lead to a less computationally efficient algorithm. A mitigation of this effect may be the increment of nodes to provide a finer discretisation of the dynamics.

9 CVX BENCHMARKING

The CVX benchmarking activity performed as part of the Task 5 activities has the following main objectives:

- Provide a further functional verification of the SCP algorithm;
- Compare the algorithm running time performances with a different solver for convex problems optimisation (i.e. ECOS);

9.1 Preliminary remarks on running time profiling

It is understood that CVX and the GREAT IPOPT-implementation makes the profiling benchmark difficult, as the former is a modelling environment written in Matlab, while the latter is an optimisation problem written in Fortran and solved by IPOPT (Fortran version). However, it was tried to obtain the most accurate comparison possible by comparing the solver running time in CVX and the time required to execute the IPSOLVE command in IPOPT [RD07]. This should exclude the time required to allocate and re-shape the input arrays to be fed to the solver, but still present some limitation for the benchmarking.

9.2 CVX benchmarking results

Following the structure of the functional verification campaign documented in [TN41], five different benchmark simulations have been performed with the solver ECOS, detailed in [FR]. In particular, the solutions are almost identical <u>during the guidance firings.</u> These results confirm the cross-verification of the results obtained with the IPOPT-based SCP algorithm using ECOS. Nevertheless, is during the coast phase in between the two burns that the attitude profiles of the two implementations differ the most. In particular, this is considered to be caused by:

- The relaxation of the CVX problem;
- The impossibility to specify an educated initial guess in the CVX version as done instead in the IPOPT-based algorithm.
- The absence of any optimisation variable contribution in the problem objective in both the implementations. This is partially mitigated by the addition of eq.(1), but there is not a corresponding formulation in the IPOPT-based SCP algorithm.

Moreover, even respecting all the guidance problem constraints, the CVX formulation results more discontinuous. However, this is envisaged to be mitigated with a deeper tuning of the problem, which is considered out of the scope of Task 5.

The last 10 days on the last thrusting arc before NRHO insertion are critical for the SCP implementation, as documented in [TN41]. Indeed, while the GREAT Non-convex algorithm with 150 nodes discretisation manages to converge to an optimal solution which guarantees the insertion in the NRHO, the SCP version fails to prevent the spacecraft from diverging from the reference trajectory. This is due to the approximated dynamics, but especially by the reduced number of discretisation nodes used (50), to guarantee running time performances comparable with the Non-convex implementation, as reported in [TN41].
Indeed, maintaining 50 discretisation nodes, results in the same result obtained during the validation campaign for the GREAT SCP version: impossibility to converge during the last guidance operations before NRHO insertion, due to lack in solution accuracy.
Thanks to the use of CVX and solvers dedicated to convex problems optimisation (i.e. ECOS), it is possible to raise the number of discretisation nodes to 150 (to match the Non-convex implementation and as a consequence guaranteeing convergence even during the last 10 days before NRHO insertion) and beyond, without affecting too much the solver running time.
From the results presented in [FR], it is possible to conclude that 150 nodes are sufficient to match the IPOPT-based Non-convex algorithm accuracy (similar terminal errors), while resulting faster in terms of running time. It is important to mention that this profiling doesn't consider the solver inputs arrays memory allocation and re-shape, as presented in [TN41]. In order to have a more accurate profiling comparison between the CVX and the IPOPT-based implementation, the usage of CVX should be bypassed and substituted by a user-implementation, similar to what it has been performed for GREAT in [TN22] (at design level) and [TN31] (at implementation level).

10 CONCLUSIONS

In the context of the GO-GREAT study an autonomous guidance algorithm to perform reference trajectory tracking during WSB transfer to the Moon was designed [TN22] and developed [TN31]. A FES was implemented as well [TN32] to perform an extensive Verification and Validation campaign documented in [TN41].

10.1 Study results

The most remarkable trade-off and achievement are here reported in chronological order, reflecting the technical notes delivery and correspondent milestones:

- Both the Non-convex and SCP version of the GREAT guidance algorithm were implemented in the course of Task 3. In [TN31] are reported the details regarding both the implementations of the software, considering also its higher and lower level architecture and interfaces with the FES, whose description is instead contained in [TN32]. The FES and guidance algorithms have been delivered to ESA and approved at CDR.

- An extensive V&V campaign was performed during Task 4 leading to the verification of both algorithm functionalities and to the validation of their performances. In particular, from the outcomes of this activity, it resulted that **the Non-Convex algorithm implementing Backward Euler is compliant to all the requirements and the validation campaign success criteria, hence, demonstrating feasibility.** Moreover the on-board performance assessment reported in [TN41] proves the suitability of the GREAT on-board implementation on the LEON4 or ARM A53 processors, while the development on the LEON3 remains unfeasible due to the guidance activation frequency resulting from the performance validation campaign.

- A further functional verification was performed comparing the results obtained during the V&V campaign with a CVX implementation in Matlab using ECOS as disciplined convex program solver. The main conclusions are the following:

  - The comparison between the CVX and IPOPT-based version of the SCP is limited by the different nature of the two software: the former is a Matlab-based modelling environment, while the latter is a Fortran-based optimisation problem solved with a Non-convex programs solver.
  - Within the limitations reported above, it was possible to assess that the CVX (ECOS) version of the SCP is approximately one order of magnitude faster with respect to the IPOPT-based algorithm.
  - Increasing the number of discretisation nodes affects less the CVX implementation with respect to the IPOPT-based version and allows to match the Non-convex algorithm accuracy. This makes possible to find optimal guidance trajectories also during the last 10 days on the reference trajectory before NRHO insertion.
  - The functionalities of the IPOPT-based SCP algorithm were cross-verified by the comparison with the CVX results, which are almost identical to the ones obtained during Task 4 and reported both in this technical note and in [TN41].

- Finally a follow-up Monte Carlo campaign was performed to check the behaviour and the performances of the GREAT guidance algorithms if the maximum number of iteration (and indirectly constraining the available time to converge to an optimal solution) is limited to 100, as in the case of the CVX benchmarking reported in the point above. The conclusion of this last analysis is that 100 iterations are not enough to guarantee the required accuracy to prevent the spacecraft from diverging from its reference trajectory. Moreover, this effect makes the number of GREAT activations grow during the whole mission and resulting in an increase of the time spent performing Orbit Determination and guidance operations.

During the study the GREAT algorithms limitations have been identified:

- The algorithms profiling results reported in [TN41] revealed that both the Non-convex and SCP versions can ported on future on-board processors such as LEON 4 or ARM A53 boards, but cannot be executed on LEON 3 or older boards.

- The attitude constraints defined in [TN22] can be successfully enforced only if the initial and final guidance firing are approximately in the constrained zones. This was mitigated by including a dedicated logic, disabling the constraints in case the aforementioned condition is not met.

- The SCP algorithm running time is penalised with respect to the Non-convex version, as it requires more than one iteration to converge (i.e. solution of a convexified problem per iteration). This is effect grows as the number of discretisation nodes increases. Thanks to the benchmarking presented in §9.2 there are strong indications that the use of a disciplined convex program solver like ECOS can significantly speed up the code execution and decrease the effect a growing number of discretisation nodes has on the running time.

- The characteristics of the reference transfer (WSB) makes the dynamics of the spacecraft less stable more complex with respect to a classic keplerian transfer. For this reason the accuracy of the guidance algorithm in the final stage of the reference trajectory, during the last thrusting arc, decreases, making the SCP version fail in preventing the spacecraft divergence before NRHO insertion. This effect can be mitigated either by including a more complex integrator in the guidance algorithm (which would increase the complexity and potentially the running time as well) or by increasing the number of discretisation nodes, with a price to be paid in terms of execution time.

10.2 Technology assessment

The technological achievements and TRL reached in the context of this study are addressed in [TAS].

10.3 Development roadmap

This leads to the following recommendations for the continuation of the project with the required industrialisation activities in order to scale-up the TRL of an on-board guidance in real-time, improving autonomy for operations beyond Earth orbit of spacecraft employing electric propulsion, aiming to rise the TRL and potentially target a European mission within the upcoming Artemis programme (e.g. CLTV or EL3), leveraging the use optimization techniques in on-board platforms in Europe:

- The recommendation resulting from the on-board performance assessment could be investigated. In particular:
    - The porting from Fortran to C compiler to generate C code from the algorithm.
    - The portability of the optimisation libraries to space platforms.

- The Non-convex algorithm could be tested in a different reference scenario, such as a more stable keplerian transfer in Cis-lunar environment or between the Gateway NRHO and a LLO, to prove its generality and robustness.

- The Non-convex algorithm could be further optimised and embedded in a representative hardware providing also the porting of a dedicated solver.

- Further convex programming possibilities can be investigated. A similar industrialisation procedure to the one described above for the Non-convex algorithm can be performed with the SCP implementation. This can be done bypassing the CVX environment by "manually" pre-allocating and re-shaping the input to be fed to the disciplined convex program solver.

- Further tuning can be performed on the CVX implementation, comparing the performances of different disciplined convex programs solver, such as SDPT3 and SeDuMi.

- A roadmap could be drafted for future activities and recommendations with the ultimate goal of including the proposed optimized algorithms on-board an upcoming European space mission (e.g. CLTV or EL3).

DOCUMENT CHANGE DETAILS

ISSUE	CHANGE AUTHORITY	CLASS	RELEVANT INFORMATION/INSTRUCTIONS
1	-	-	Initial Issue for FR SVN simulator software revision 53
2	-	-	Minor layout corrections for Final Delivery SVN simulator software revision 53

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