EXECUTIVE SUMMARY REPORT

FTC-CRE

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1.0	11/12/2023	13	First issue
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1. INTRODUCTION

The work presented in this report was carried out under, and funded by, the European Space Agency's Technology Development Element (TDE) programme (ESA contract No. 4000136228/21/NL/CRS "Fault Tolerant Control Of Clustered Rocket Engines"). The views expressed herein can in no way be taken to reflect the official opinion of the European Space Agency.

1.1. PURPOSE AND SCOPE

This document is an output of the FTC-CRE project, under the responsibility of GMV and the FTC-CRE consortium. This document is identified as deliverable ESR, and presents the findings of the ESA funded TRP activity "Fault Tolerant Control Of Clustered Rocket Engines".

1.2. SCOPE

This report provides a concise summary of the findings of the work done during the contract.

1.3. DEFINITIONS AND ACRONYMS

1.3.1. DEFINITIONS

Concepts and terms used in this document and needing a definition are included in the following table:

Table 1-1 Definitions

Concept / Term	Definition

1.3.2. ACRONYMS

Acronyms used in this document and needing a definition are included in the following table:

Table 1-2 Acronyms

Acronym	Definition
ACT	Actuators
AoA	Angle of attack
ECI	Earth-centered inertial reference frame
EMA	Electromechanic actuator of TVAS system
Ex	Engine number x
FB	Body-frame reference frame
FDI	Fault Detection and Isolation
FDIR	Fault Detection and Isolation and Recovery
FES	Functional Engineering Simulator
FTC	Fault Tolerant Control
HIL	Hardware in the Loop
IB	Intermediate Burn
LB	Landing Burn
LP	Landing Pad
MC	Monte Carlo
MECO	Main Engine Cut-Off
MIL	Model in the Loop
OBSW	On Board software
OCP	Optimal Control Problem
PIL	Processor in the Loop
RSW	RSW reference system: radial (R), along-track (S) and cross-track (W)
SC	Spacecraft
SCvx	Successive Convexification
TRL	Technology Readiness Level
TVAS	Thrust Vector Actuated System
TVC	Thrust Vector Control

2. REFERENCES

2.1. APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.x]:

Table 2-1 Applicable Documents

Ref.	Title	Code	Version	Date
[AD.1]	Fault Tolerant Control of Clustered Rocket Engines, Statement of Work	ESA-TECSAGSOW-022725		

2.2. REFERENCE DOCUMENTS

The following documents, although not part of this document, amplify or clarify its contents. Reference documents are those not applicable and referenced within this document. They are referenced in this document in the form [RD.x]:

Table 2-2 Reference Documents

Ref.	Title
[RD.1]	Miramont P., "Ariane 5 on board software: redundancy management", in *Proceedings of the 2nd Embedded Real Time Software Congress*, 2004.
[RD.2]	Giannini M. and Cruciani I., "VEGA LV Qualification process: GNC aspects on HWIL testing and analysis", in *Proceedings of the 5th European Conference for Aeronautics and Space Sciences*, 2013.
[RD.3]	Orr J. S. and VanZwieten T. S., "Robust, practical adaptive control for launch vehicles", in *Proceedings of the AIAA Guidance, Navigation, and Control Conference. American Institute of Aeronautics and Astronautics*, 2012.
[RD.4]	Miao X., et al. "Successive Convexification for Ascent Trajectory Replanning of a Multistage Launch Vehicle Experiencing Nonfatal Dynamic Faults", *IEEE Transactions on Aerospace and Electronic Systems* 58.3, 2039-2052, 2021.
[RD.5]	Barrows T., and Orr J.S., *Dynamics and Simulation of Flexible Rockets*, Academic Press, 2020.
[RD.6]	Navarro-Tapia D., et al., "Structured H-infinity control design for the Vega launch vehicle: recovery of the legacy control behaviour", in *Proceedings of the 10th International ESA Conference on Guidance, Navigation and Control Systems (ESA-GNC)*, 2017.
[RD.7]	Simplicio P. et al., "New control functionalities for launcher load relief in ascent and descent flight", in *Proceedings of the 8th European Conference for Aeronautics and Aerospace Sciences*, vol. 10, 2019.
[RD.8]	Orr J. S. and Slegers N.J., "High-Efficiency Thrust Vector Control Allocation", *Journal of Guidance, Control, and Dynamics*, Vol. 37, No. 2, 2014.
[RD.9]	Navarro-Tapia D., et al, "Legacy Recovery and Robust Augmentation Structured Design for the VEGA Launcher", *International Journal of Robust Nonlinear Control*; 29:3363-3388, 2019.
[RD.10]	Navarro-Tapia D, "*Robust and Adaptive TVC Control Design Approaches for the VEGA Launcher*", PhD thesis, University of Bristol, 2019.
[RD.11]	Navarro-Tapia D., et al. "Performance and robustness trade-off capabilities for the VEGA Launcher TVC System", in *Proceedings of the 8th European Conference for Aeronautics and Aerospace Sciences*, 2019.
[RD.12]	Reynolds, T.P., et al. "Dual quaternion-based powered descent guidance with state-triggered constraints", *Journal of Guidance, Control, and Dynamics,* 2020.
[RD.13]	Szmuk M. and Acikmese B., "Successive convexification for 6-DOF Mars rocket powered landing with free-final-time", in *Proceedings of AIAA Guidance, Navigation, and Control Conference,* 2018.
[RD.14]	J. Doyle, A. Packard and K. Zhou, "Review of LFTs, LMIs, and mu," Proceedings of the 30th IEEE Conference on Decision and Control, Brighton, UK, 1991, pp. 1227-1232 vol.2, doi:10.1109/CDC.1991.261572
[RD.15]	A. Marcos, D. Mostaza and L.F. Peñín, "Achievable moments NDI-based fault tolerant thrust vector control of an atmospheric vehicle during ascent", in Proceedings of the 7th IFAC symposium on fault detection, supervision and safety of technical processes, 2009.
[RD.16]	Marcos, A., Navarro-Tapia, D., Simplício, P., Bennani, S., "**Robust Control for Launchers: VEGA study case**," Journal of the Society of Instrument and Control Engineers, March 2020, vol. 59, no. 3, pp. 192-202.

3. OBJECTIVES AND ORGANIZATION

The project entitled "Fault-Tolerant Control of Clusters of Rocket Engines (FTC-CRE)" is an activity supported by the European Space Agency aimed at the demonstration of guidance and control (G&C) laws for launch vehicles with cluster of engines, with focus on reconfiguration capabilities in case of propulsion and TVC failures.

Fault tolerant control for a cluster of engines in launchers has re-gained attention in recent times thanks to the development of capabilities of new reusable launchers. Most mission failures in the last quarter of the century were caused by loss of propulsion or failures in Thrust Vector Control (TVC). The use of fault tolerant control (FTC) functions for launch vehicles is nowadays mostly passive, based on hardware redundancy (e.g. Ariane 5 launcher [RD.1]), with the adoption of active FTC schemes very limited and mainly based on ad-hoc solutions (e.g. VEGA launcher [RD.2]), and advanced control techniques such as the adaptive augmentation control scheme used by the SLS [RD.3], which is shown to augment the envelope of the mission and avoid potential loss of vehicles. However, the redundancy provided by the cluster of engines can be intelligently exploited to mitigate failures that affect propulsion or thrust vectoring.

The main objective of the activity is the definition of the most suitable set of requirements, methodologies, diagnosis system and G&C architecture that are fault-tolerant, to ensure the vehicle's stability and performance boundaries remain satisfied. Other objectives include:

- To design, implement and verify fault tolerant control allocation techniques for launch vehicles with clustered engines
- To define the most suitable set of requirements, methodologies, diagnosis system and G&C architecture that enable to effectively detect a failure and put in place the measures to ensure that the vehicle's stability and performance boundaries remain satisfied.
- To focus on approaches that are promising in terms of numerical efficiency, convergence and scalability.
- To derive a G&C architecture with embedded fault tolerant capabilities shall be addressed in an end-to-end manner using modern control design techniques.
- To trade-off of candidate model and/or data-based FDIR techniques shall be performed as part of the activity
- Analysis of the impact and suitability of all FDIR functions, although the detailed design and implementation shall be focused on recovery techniques only
- To consider both the reconfiguration of the control structure/parameters and the re-computation of the mission trajectory/target,
- Analysis of the level of system degradation up to which control reconfiguration must be able to cope with, and from which a trajectory re-planning/re-targeting is necessary
- To reach TRL 3 for the designed fault tolerant G&C algorithms
- To develop a moderate-fidelity multi-physics model of a clustered engine launcher
- To developed algorithms and demonstrate them on representative scenarios during both launch/ascent and landing/descent flight phases

The joint expertise of the proposed consortium, composed of GMV's Portuguese and Spanish subsidiaries, plus TASC and SABCA. For the team compositions, GMV has established a set of driving criteria they should match:

- GMV-P is identified as study manager since they will perform most of the activity work and they have the most advanced capabilities in simulation, robust control design and implementation and validation and verification of complex GNC design
- GMV-ES is appointed as subcontractor leading the responsibilities in Launcher System definition, Requirements derivation, Failure scenario definition and Nominal and reconfiguration guidance design and implementation
- TASC Ltd. was chosen due to their capacity to bridge the academic research with industrial development, but foremost for their expertise in launcher control and fault detection isolation (FDI) and fault tolerant control (FTC) –see section 1.4.4 "Background of the company(ies)" of the technical proposal.
- SABCA is the European leader in TVC actuator design. They have been responsible of the TVC for all the Ariane Launchers, VEGA and VEGA-C. SABCA also produces actuators used in aeronautic for moving parts as aileron, elevator, rudder and spoiler that may be interesting to be considered within the activity. Their experience in selecting the right products and possible realistic failures associated is invaluable.

4. APPLICATION, SYSTEM AND PROPELLED PHASES

The study case has been selected to be a representative launcher whose design has been iterated with ESA throughout several past projects to be representative of a wide scope of future potential clustered TVC launchers. The activity focused on the flight of the 1st stage, which includes the ascent phase of the full vehicle up to separation, and the descent and landing of the separated stage, where the first stage is propelled by a 5-engines cluster, with cross-shaped arrangement and each of the engines is actuated by 2 TVC actuators ,Figure 4-1.

The reference trajectory has been generated with an internal trajectory optimization tool developed by GMV, using a nominal mission with the following characteristics. The optimization tool generates an optimal trajectory from Kourou Launch Base to reach the objective orbit minimizing the consumed fuel. The main requirements for the ascent mission are that the Qalpha must be lower than 80 kPaº, to avoid severe aerodynamic forces affecting the launcher, and that the roll rate shall be lower than 5º/s, to approximate that the pitch and yaw attitude control channels are decoupled form the roll.

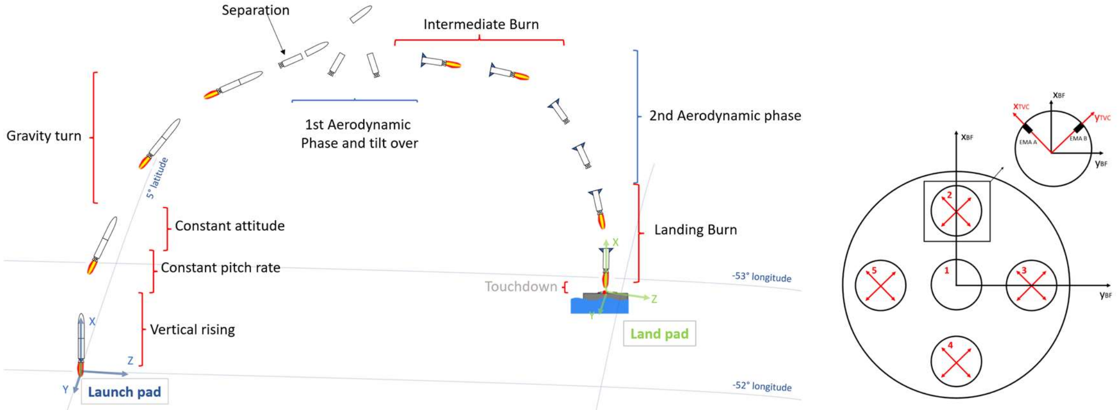

Figure 4-1: Mission phases (left) and flight trajectory (right), Configuration of the TVC actuators for the cluster of engines of the 1st stage with respect to the Body Frame (right)

As for the reference descent trajectory, a downrange scheme was used consisting in two propelled phases, intermediate and landing burn, joined through an aerodynamic phase, Figure 4-1. The reference trajectories for both burns are generated using SCvx and considering 6-DoF and the total available propellant mass.

The algorithms are analyzed and validated within a Functional Engineering Simulator (FES), including gravity gradient torque, the gravitational acceleration with J2 perturbation, the wind and atmospheric models, and the aerodynamic loads. For the Actuators we have the propulsion system, responsible for computing the thrust force and mass consumption, the thrust vector control actuator; and eight cold gas thrusters to control the roll rate.

In particular, the TVC simulator consists of a Multiphysics Simscape model of an actuation system composed of two electromechanical actuators (EMAs), its control and power electronics and the power supply (battery). The model includes among others the permanent magnet synchronous motor, the gearbox and the ball screw, the power switches, sensors and the software controller and the nozzle dynamics. The healthy TVC behaviour has been validated against real test data of SABCA's EMAs. The failures considered in the test scenarios of this project are also implemented in the actuator's module. The TVC model can trigger and simulate faults of electrical or mechanical components in the system which lead to the loss of power or the stuck of an actuator.

The Failure Detection Isolation and Recovery (FDIR) function receives the telemetry from the TVC and the engines and triggers the recovery actions of the Guidance, TVC Control and TVC Dynamic Allocation. The Guidance function is responsible for providing the launcher reference attitude (pitch and yaw angles) and reference velocity to the flight control, depending on the phase of the flight, as decided by the LVM. The Control function computes the TVC deflections and thrust levels necessary for attitude and trajectory tracking.

5. BASELINE GUIDANCE AND CONTROL

Algorithms for guidance and control under *nominal* conditions (without failures) was designed and validated to provide a baseline to which we can compare the impact of the modelled failures, and the recovery strategies in terms of control authority, control performance, and dispersions at the end of the first stage flight. The baseline guidance for ascent uses an open-loop scheme scheduled with non-gravitational velocity, being the most used approach for endo-atmospheric on-board guidance consequence of its simplicity compared with closed-loop schemes.

The baseline descent guidance refers to the problem of transferring the first stage of the launcher from the separation point to the target landing pad. Unlike the ascent trajectory, Power Descent (PDG) trajectories exhibit a wider range of angles of attack and the rocket engines do not perform at maximum thrust continuously, instead, they actuate in a throttleable way. Reusable descent trajectories require also very precise final states with few deviations and model uncertainties to be able to land at the preestablished landing pad location. Therefore, position and velocity are optimal variables that the guidance need to output besides attitude when defining the guidance algorithm for a reusable descent scenario. For the same reason, the baseline guidance for descent is required to be a closed-loop implementation instead of the open-loop ascent guidance to be able to compensate for the deviations.

The descent flight trajectory has been designed to account for a first aerodynamic phase, the intermediate burn, a second aerodynamic phase, in which the launcher is subjected to aerodynamic forces and reaches the maximum dynamic pressure, and lastly, the landing burn. However, the guidance commands solely during the propelled phases, i.e., LB and IB, where the reconfiguration under propelled failures is to be studied. A python formulation for SCvx was developed, analyzed, and integrated in the FES for Intermediate and Landing Burn scenarios. Landing point estimation and IB initial conditions can be easily extracted in the FES to initialize the algorithm and adapt to new conditions triggered by the ascent phase. Landing point and propellant mass have been refined for the case of the nominal descent scenario.

Regarding the control design, the synthesis uses specific operational points along the nominal trajectory, to obtain a linear structured $\mathcal{H}_\infty$ controller with parameters which can be scheduled throughout the flight. The Linear Time Invariant (LTI) and Linear Fractional Transformation (LFT) mathematical models for design and robust analysis [RD.14] are defined for the linearized dynamics of the rocket launcher along points of the trajectory, under the usual assumptions of small angles and a gravity turn trajectory [RD.5]. This control design approach has been widely used throughout the years for the purpose of rocket launchers robust control [RD.6] due to the advantages offered by the $\mathcal{H}_\infty$ framework, in terms of capabilities for robust control design and analysis for linear systems.

The LTIs and augmented plants are defined for each lateral channel to address attitude and drift control. For the simplification of the synthesis model, the following assumptions are taken for the nominal operation on the control. The synthesis of the controller is performed by fine tuning the weighting functions of the augmented plant for a suitable tradeoff between control of attitude, drift and aerodynamic loads (weight on Qalpha for the load relief of the vehicle [RD.7]), while ensuring stability. After the synthesis, the LFTs are used with μ analysis to check robust stability and performance against requirements under uncertainty.

The roll control is not a focus of the study, and a logic-based RCS is put in place to limit the roll rate using 8 cold gas thrusters placed symmetrically around the cross section. Due to the cluster configuration of the engines, the application of the control torque is over-defined with redundant configurations of the deflections of the 4 outer nozzles. A baseline engine allocation unit decides the contribution of each of the engines to the total moment torque required for attitude and drift control. The allocation algorithm uses a high-efficiency quasi-linear algorithm based on a weighted Least Squares generalized inverse and augmented with a null-space method [RD.8].

For the descent phases, the lateral control synthesis the same methodology as for the ascent phases, but now focused limiting drift and position control. Additionally, a longitudinal controller has been also included for control and tracking of the guidance descent velocity profile. During the Landing Burn it is necessary to ensure a feasible vertical velocity before landing, but it has been also observed that including a longitudinal control also for the Intermediate Burn phase of the descent enhances the capabilities of the rocket to autonomously adjust its longitudinal velocity for braking horizontally as intended from guidance.

6. FAILURE SCENARIOS AND RECOVERY ACTIONS

This work considers realistic, failures in one of the cluster's engines as well as thrust vectoring failures. Since the goal of is to develop fault-tolerant G&C algorithms, the considered failures are those that decrease the performance of the launcher but that are not catastrophic. In general terms and ignoring catastrophic failures (e.g. an engine chamber breach), propulsion failures involve a partially or totally off-nominal thrust delivery by the propulsion system (engine failures F1-F4), Table 6-1.

Table 6-1 Failure and recovery actions considered for the different propelled phases

Failures considered and modelled				**Recovery actions studied**		
Description			**Id**	**Ascent burn**	**Descent phase**	
Type	**Outer vs central**				**Intermediate burn**	**Landing burn**
Loss of thrust	in central engine	< 40%	F1	R1		
		> 40%	F2	R1, R3	R1	
	in outer engine	< 40%	F3	R1		
		∈ [40-70] %	F4a	R1, R2, R3, R4		
		>70%	F4b	R1, R4	R1, R3	R1*
Jamming of TVC	in outer engine	at non-zero deflection	F5	R1, R3	R1	
Loss of power of TVC	in outer engine	Static disturbance load	F6a	R1	R1, R3	
		Dynamic vibration	F6b	R1		

The faults in the central and outer engines are split as they have different effects. The former results only in force (i.e., thrust) deviations, while the latter leads to force and torque deviations (due to the geometrical off-center configuration, Figure 4-1). Regarding the levels of thrust loss for the outer engine, a preliminary analysis on the fault level effect was performed using heuristically 60%, at which it was observed already fault effects. It was decided to use 40% as a lower bound on the fault level where the effects are less strong and 70% as an upper level where they are known to be strong, Table 6-1.

In addition, two severe failures have been considered for the TVC actuator (F5-F6), Table 6-1. A TVC jamming-like behavior, modelled as one EMA stuck at a fixed non-zero position, leading to a non-zero deflection of one degree of freedom of one engine (one direction of its thrust). The loss of power behavior is modelled as having one EMA free to move, leading to one degree of freedom of one engine uncontrolled. Besides the case of force eccentricity and quasi-static acceleration, pushing the engine to one of its ends of stroke, it was also investigated the impact of dynamic vibration on the free TVC.

At the control and guidance level, the investigated recovery strategies rely on control reconfiguration and trajectory re-planning based on the detected failure, and were defined as:

- R1: use an allocation algorithm to optimize thrust levels and deflections within the cluster to compensate for the loss of thrust, TVC failures and any induced parasitic torque [RD.15].
- R1*: reassignment to healthy engines in case of loss of thrust to provide the best thrust and torque authority recovery, taking also into account the undesired induced lateral forces.
- R2: switch to a controller designed to be robust to the failure up to a certain tolerance level, replacing the baseline TVC controller by an FTC-based controller designed to be robust against propulsion failures. The FTC control design problem is formulated in the structured $\mathcal{H}_\infty$ control framework using the closed-loop interconnection that includes the key features for TVC launcher control design proposed in [RD.9] and [RD.10].
- R3: Action that changes the TVC inner-loop control gains (*R3*) to reflect a temporary-stressed, but higher-performance TVC.
- R4: Onboard guidance trajectory re-computation considering the detected failure.

The last (R4) is a guidance trajectory generation problem encompassing nonlinear dynamics and several nonconvex state and control constraints. One approach that has been explored in recent literature for handling both baseline and reconfiguration launcher guidance is Successive Convexification (SCvx)[RD.4]. This approach can address the nonconvex and nonlinear nature of the problem while making it amenable for closed-loop online implementation. The SCvx logic and problem formulation are based on [RD.12] together with great contributions from [RD.4] and [RD.13]. The solution here presented is an efficient and tailored collection of different pieces of strategies selected in an optimal way for our problem plus self-developed contributions.

7. CONCLUSIONS

The different recovery strategies were compared with the nominal dispersions and performance, to understand the capacity to recover control authority, control performance and dispersions at main engine cut off. The verification and validation campaigns were carried out using the nonlinear functional engineering simulator integrating the developed GNC and FTC functions. The different recovery actions were designed for different purposes: recover of control authority, control performance, or dispersions at MECO with respect to nominal.

It was shown for the ascent phase that dynamic TVC allocation approaches can provide recovery from propulsion failures up to 40% in a single engine. It can also cope with actuator failures. Above 40%, the combination of *R1* and *R2* gathers the benefits of *R1* to alleviate the loss of thrust by increasing the throttling of the healthy engines at their maximum capacity and of *R2* that can provide robustness against the failure by design.

In this activity, *R2* was designed to minimize the lateral deviations of the launch vehicle throughout the atmospheric ascent flight, but it is important to remark here the control design formulation proposed for *R2* can be tailored towards any of the other competing trade-off objectives during the ascent flight (e.g. attitude, drift, aerodynamic loads) or used to achieve a trade-off balance for the best global performance. The addition of *R3* to the recovery strategy (i.e. *R123*) provides approximately the same responses as the *R12* recovery function, indicating that the increase of TVC inner-loop bandwidth does not have much impact on the system.

The use of a guidance reconfiguration in combination with *R1* and *R2* (i.e. *R124*) maintains the advantages of *R12*, that is, re-throttling of the healthy engines and significant lateral deviation reduction. The latter aspect is not trivial since changes in the guidance profile might conflict with the control function and alter the controller performance. In addition, it is also shown that *R4* also further improves some performance metrics such as attitude and aerodynamic loads presenting lower peaks at maximum $Q\alpha$ region. Finally, the impact of the failure depends on the timing of the failure: an earlier time of failure degrades MECO performance, while a later time of failure degrades the control performance.

For the descent re-entry burn, the guidance trajectory and thrust profile is well under the maximum available, which plenty of redundancy to recover loss of thrust in a single engine. For propulsion failure scenarios, R1 (re-allocation) together with R3 (more aggressive TVC) can recover control authority, resulting in recovery of performance and stabilization. For these types of single engine thrust loss, the recovery of authority is enough to recover performance and stability. Failures in TVC actuation are more severe, especially loss of power, resulting in instability for some of the tested cases. Keeping the engine on with a failed EMA, results in higher lateral forces and roll, and induces commands closer to saturation. To mitigate the TVC actuator failure, the simplest solution would be to shut off the failed engine. This would reduce the problem to a total loss of thrust in a single engine, which can be tacked by R1 and R3.

Regarding the Landing Burn, the modelled failure was an engine which does not re-ignite at the start of the LB phase and seconds before touchdown. It was found that thrust authority recovery is critical for a safe landing, and a recovery action is strictly necessary to avoid a catastrophic touchdown. Using R1* the scenario with failure degrades and fails in the same manner as the baseline G&C, particularly in the presence of wind, suggesting that the recovered authority brings the control close to the limitations of the baseline G&C.
The guidance algorithm used Successive Convexification (SCvx) for trajectory generation of the reconfiguration ascent flight under loss of thrust scenarios and for nominal descent flight. This technique was selected due to its capabilities for on-board optimization that is very crucial for reconfiguration guidance and descent flight in general.

The analysis of the results provided the level of system degradation up to which control reconfiguration can be applied, and from which a trajectory re-planning/re-targeting needs to be performed. The SCvx guidance model under thrust failures has been proved to replicate the FES simulator close loop dynamics and have a sufficient representativity to make it suitable. The outcomes of the activity provide insight on the capacity of clusters of engines for recovery, methodologies for guidance and control architectures with embedded fault tolerant capabilities, and their demonstration to increase of the readiness level for recovery strategies of stability and performance in the presence of failures.

END OF DOCUMENT