AITIVE-GNC

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Executive Summary

This document summarizes the activity and findings of the contract.

(**ESA Contract N°: 4000133980/21/NL/CRS**).

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1 Introduction

1.1 Purpose of the activity

The study proposed during the AITIVE-GNC project, see Figure 1, was aiming to make a formal link between the AI-based ML and the control theory-based reasoning and optimization within a challenging space GNC scenario (Mars EDL landing). The objective of the project is to identify mathematical approaches to support the design and the verification of the next-generation AI-based GNC architectures and functions. More specifically, the objective is to focus on explainability, robustness of the system while providing means to formally assess these properties.

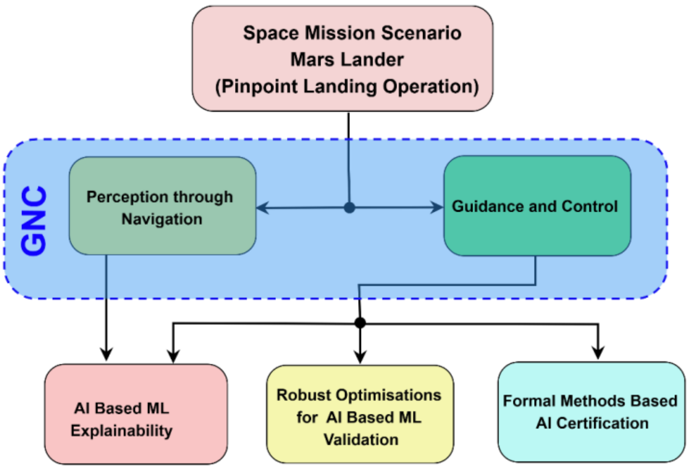

Figure 1:AITIVE-GNC Project Tasks

As the topic of AI for GNC is very broad, the consortium has focused in three (3) areas of the Deep-NN safety and verification problem: Explainability, Robustness and Formal verification.

Each partner of the consortium tackles the problem using different techniques:

- **Explainability for AI GNC systems**
  - ✓ City University of London Approach: via SHAP (Shapley-Based Value Algorithm)
  - ✓ NUMALIS Approach: via Abstract Gradients
- **Robustness for AI GNC systems**
  - ✓ City University of London Approach: via a novel “Keep-Close Approach” using reference model and IQCs.
  - ✓ ENAC approach: via LPV and reachable sets
- **Formal methods for verification for AI GNC systems**

- ✓ NUMALIS approach: via abstract boundaries
- ✓ ENAC approach: via Signal Temporal Logic (STL) and improvement of the CoCoSim library.

The proposed test bench for explainability and formal verification is based in the generation of a dataset of images with "craters". These have been generated by City University of London based in the SW "PANGU".

The proposed test bench for robust control with NN is based in a Mars EDL (Entry Descent and Landing Scenario). The data for the scenario is derived from a 6DOF simulator provided by SpinWorks.

1.2 Reference documents

Ref. ID	Title
D1	Review Document
D2	Mission Definition, Framework Definition, Benchmark Requirement, Study Cases, Test Plan
D3	Comparative & Trade-off Analyses: AI4Control Framework & AI4 GNC Systems
D4	AI techniques for Control – AI4GNC Framework & AI4 GNC Systems Justification Files, SW and Study Cases
D5	AI techniques for Control – AI4GNC Framework & AI4 GNC Systems Justification Files, SW and Study Cases for the Development
D6	Benchmark AI techniques for Control – AI4GNC Framework & AI4 GNC Benchmark Detailed Design
D7	Benchmark AI4GNC Systems & AI4GNC Framework Test Plan Execution Validation
D8	Study Synthesis and Way Forward, Maturation Plan
SW1	Trade-off analysis SW

SW2	AI4GNC Framework & AI4 GNC Systems SW Prototype
SW3	E2E Simulation, design and analysis framework
SW-UM	Software User Manual
TR	Artificial Intelligence Techniques for GNC Design, Implementation And Verification - Expro Plus (AITIVE-GNC), Technical Proposal.

1.3 Acronyms

EDL	Entry, Descent and Landing
GNC	Guidance, Navigation and Control
IQC	Integrated Quadratic Constraint
ML	Machine Learning
NN	Neural Network
LPV	Linear Parameter-Varying
ROA	Region of Attraction
SHAP	Shapley Based value algorithm
STL	Signal Temporal Logic

2 Activity Description

2.1 Generic Description of the Consortium

2.1.1 Companies Involved

The project in this proposal is to be performed by **the City University of London** as a Prime contractor, and with **ENAC, NUMALIS** and **Spin.Works** as subcontractors.

Figure 2: AITIVE Project Consortium.

City, University of London (UCITY): is a global university. City currently has over 18,000 students (46% at postgraduate level) from more than 160 countries and staff from over 75 countries. More than 130,000 former students from over 180 countries are members of the City Alumni Network. City has been educating students in London since 1894. We joined the University of London federation in 2016. We develop world leading research which responds to issues of global concern, attract talented staff and students from around the world and are part of a global community of alumni, employers and partners. 7,505 of all students at City are from outside the UK, representing 39% of total enrolments. Of these, 12% were from within and 28% were from outside the EU. 43% of the City's academic staff are from outside the UK. In the 2014 UK Research Excellence Framework 75% of the City's submission was rated as either world-leading or internationally excellent. In the 2014 Research Excellence Framework, 23% of City's submitted research was considered world-leading (4*) and 52.5% was considered internationally excellent (3*); 1,470 research journal publications from the staff at City were with an international co-author. This accounts for 42.8% of all publications.

ENAC: is the French University of Civil Aviation. The research laboratory is specialised in Aeronautics, in several fields such as Optimisation, Computer Science and Human-Machine Interaction and Data Visualisation, with first-quality access to ATM experts and engineers, satellite operators and pilots. The mission of the "Interactive Informatics" team is to study interactions, in particular between humans and computer subsystems, with the objectives of better understanding the phenomenon of interaction and mastering the design of more efficient interactive systems, including embedded control systems.

Numalis: is a French SME employing a dozen engineers and PhD profiles. Numalis is a software editor since 2015 specialising in the formal analysis of critical systems. The company is the leading provider of formal tools to validate Artificial Intelligence. Its expertise is more specifically related to the robustness and explainability of deep neural networks. Numalis is already active in the French critical embedded ecosystem (aeronautics, space, defence) and in large R&D projects regarding AI use and validation in critical systems. Its customers are leading key accounts in the domain of aeronautics, transportation and defence. Numalis is one of the few companies capable of doing abstract interpretation on AI. Numalis also brings its expertise and leadership in the standardization committees dedicated to AI.

Spin.Works: is an aerospace company based in Portugal, founded in 2006 and dedicated to the development of unmanned systems for the aeronautics, space and defence markets. The company is focused on the fields of image processing, flight control systems, embedded systems and precision mechanisms, for which a highly specialized, multi-disciplinary engineering team of about 20 people has been assembled. Besides taking part in all major technical activities, the founders also own the company's stock (100%). The annual turnover in 2019 was about 1 MEur. The management structure of Spin.Works is defined along two main branches. The first is the executive branch, which includes the Chief Executive Officer at the top together with a Management Board and the Chief Financial Officer. The second branch of management contains other support areas such as Quality, Human Resources and Information Technology.

2.2 Performed Tasks

The following tasks have been performed.

- **Task 1:** review formal mathematical approaches for the development of a robust and explainable AI technology for Embedded Space GNC systems. This includes ML Assisted design and development process (requirements capture and management, physical modelling, analysis, design, verification, and optimisation tools).
- **Task 2:** Establish the functional and performance requirements applicable to an AI-assisted GNC design process and to an AI-augmented GNC system.
- **Task 3:** perform trade-off of suitable mathematical AI approaches compatible with the current GNC architectures and design processes (model-based approach), including complexity, effort and expected benefits assessment.
- **Task 4:** Preliminary design to establish the AI techniques suitable for modelling, control and verification needs in the view of robust and explainable AI- supported GNC architectures and functions.
- **Task 5:** develop a prototype set of benchmark problems for AI-assisted GNC design and AI-augmented GNC systems as well as for AI-supported autonomy (using either

the in-orbit assembly scenario or the precision landing scenario including handling of failures and degradations).

- **Task 6:** Detailed design and coding of the established AI techniques applied to AI-assisted GNC design and to AI-augment GNC system.
- **Task 7:** assess the performance and robustness of the AI-assisted GNC system.
- **Task 8:** Definition way forward AI4GNC Technology Deployment.

The documentation created is listed on the list of references.

2.3 Schedule and Reviews

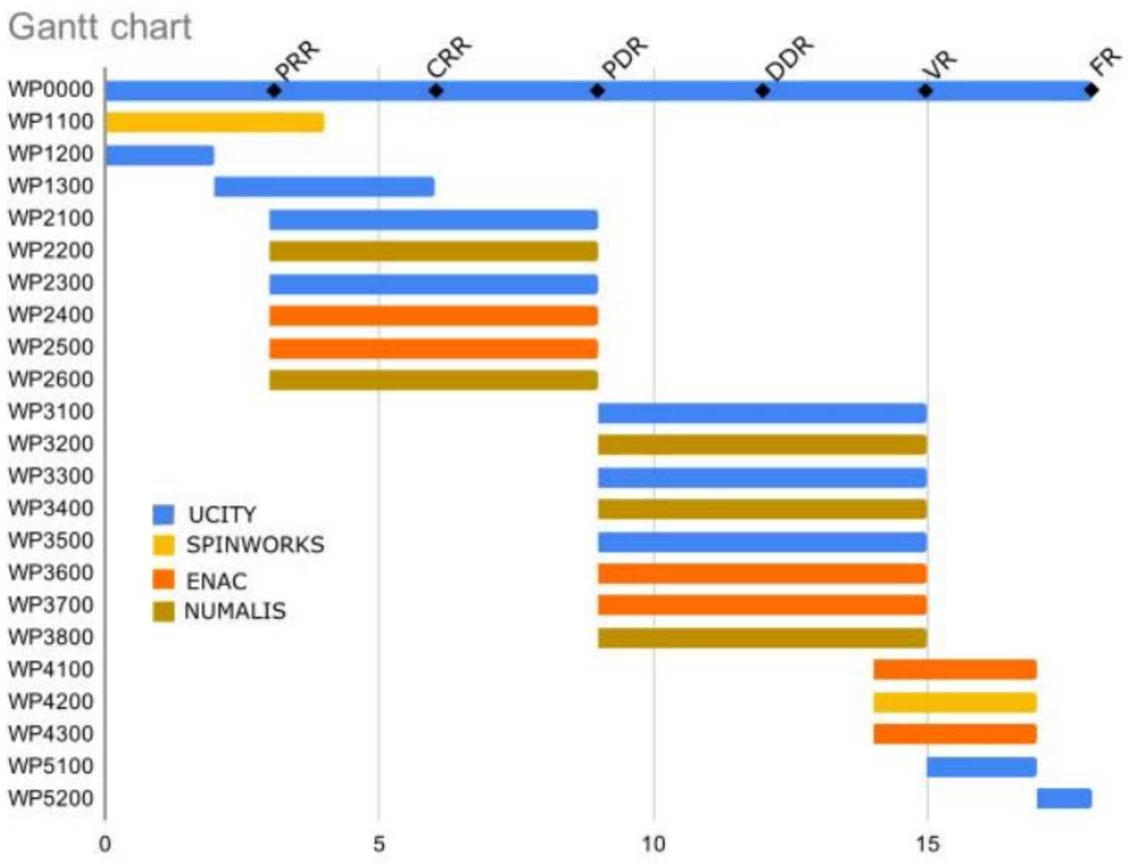

Figure 3: Bar Chart

The following table presents the schedule and reviews:

Review	Date	Result	Deliverables
KO	4th April 2021	Successful	
PRR /T0+3	07th July 2021	Successful	D1, D2, Early D3
CRR/T0+7	02nd November 2021	Successful	D3
PDR /T0+9	18th February 2022	Partially Successful Closeout needed	D4, D5
PDR closeout	18th March 2022	Successful	D4 and D5
DDR/T0+14	16th June 2022	Successful	D6
VR/T0+19	31st November 2022	Successful	D7
FR/T0+22	24th February 2023	Successful	D8, Final Report SW deliverables

3 Conclusions

The AITIVE-GNC project made a formal link between the AI-based ML and the control theory-based reasoning and optimization within a challenging space GNC scenario as introduced in this document. Also, it proposes novel solutions and techniques inspired from robust control theory and other formal methods to provide some levels of validation to the AI-based ML techniques and develops creative explainability mechanisms to open those AI-based ML black box schemes for GNC-based perception to increase the level of trust for space engineers to adopt those schemes. Moreover, through the AITIVE-GNC project, the consortium has identified mathematical approaches to support the design and verification of the next-generation AI-based GNC architectures and functions.

More specifically, the City University of London proposes a novel method called the keep-close approach to validate the Robustness of the neural controller with reference to a classical controller and uses the Shap value to assess the explainability of Deep neural network architectures. Formal methods are used by Numalis to explore the validation of both the robustness and explainability of neural networks performing various tasks (classification of images including robustness to different types of noises and interpolation on time series for an EDL scenario). Also, in the field of formal methods, ENAC has investigated STL (Signal Temporal Logic) as a way of automatizing the creation of specification and test oracles. It would be extremely interesting to be able to formally and exhaustively prove the validity of STL-based requirements for AI-based systems. Also, ENAC has developed a method to compute the outer approximations of the reachable sets for an NN-controlled nonlinear system. Leveraging this method and using the trained NN-based GNC and exploiting the LPV model for the ML, we then compute the outer approximations of the reachable sets. The method has been applied to an EDL scenario. All the EDL scenarios take as input the EDL Simulator and simulation data provided by SpinWorks. Finally, SpinWorks has provided test field data (terrain simulating craters). This data will be available in further studies.