Systems & Advanced Technologies Engineering S.r.l.

→ DISCOVERY

AI-BASED ON-BOARD RECONFIGURABLE FDIR AND LIFETIME PREDICTION FOR CONSTELLATIONS

Demonstrated feasibility and benefits of the use of mature AI-based diagnostics and prognostics solutions in a constellation scenario towards increased on-board intelligence and safety.

Definition of end-to-end workflow foreseeing hybrid on-board and on-ground deployment options, system reconfigurability, and the evolving role of the "human in the loop".

AI-BASED ON-BOARD RECONFIGURABLE FDIR AND LIFETIME PREDICTION FOR CONSTELLATIONS

Executive Summary

Early technology development

NEW CONCEPTS FOR ONBOARD SOFTWARE DEVELOPMENT

Affiliation(s): S.A.T.E. Systems and Advanced Technology Engineering s.r.l., OHB System AG

Activity summary:

Autonomous and enhanced on-board FDIR and prognostics is one of the most urgent developments to reduce operational costs and response time to unexpected events, especially in constellations scenarios. This project demonstrated the feasibility and benefits of the adoption of new approaches to this problem, leveraging solutions already implemented by SATE in other fields. The project defined both the flight and the ground systems, with focus on the former. The workflow defined includes hybrid on-board and on-ground deployment, system reconfigurability, and the evolving role of the "human in the loop". Relevant benefits have been measured through specific Key Performance Indicators.

→ THE EUROPEAN SPACE AGENCY

Publishing Date: 21/06/2024

Contract Number: 4000139974/22/NL/GLC/ov

Implemented as ESA Initial Support for Innovation

ESA Discovery & Preparation

From breakthrough ideas to mission feasibility. Discovery & Preparation is laying the groundwork for the future of space in Europe

Learn more on www.esa.int/discovery

Deliverables published on https://nebula.esa.int

Systems & Advanced Technologies Engineering S.r.l.

→ DISCOVERY

AI-BASED ON-BOARD RECONFIGURABLE FDIR AND LIFETIME PREDICTION FOR CONSTELLATIONS

Delivery 8.2

EXECUTIVE SUMMARY

ESA Technical Officer(s): Luis Mansilla, ESTEC, Noordwijk

S.A.T.E. Systems and Advanced Technologies Engineering S.r.l., Venice, Italy

EUROPEAN SPACE AGENCY

CONTRACT REPORT

The work described in this report was done under ESA contract. Responsibility for the contents resides in the author or organisation that prepared it.

Client: ESA

Document N°: 710024-REP-WP800-T002-Rev.2 Copy _1_ of _1_

Date: 25/06/2024 *Pages:* 20

Authors:	*Checked:*	*Authorised:*
C. Brighenti (SATE), J. Caudepon (OHB)	Chiara Brighenti	Attilio Brighenti
	Chiara Brighenti	Attilio Brighenti

Publishing Date: 21/06/2024

Contract Number: 4000139974/22/NL/GLC/ov

Implemented as ESA Initial Support for Innovation

→ THE EUROPEAN SPACE AGENCY

ESA Discovery & Preparation

From breakthrough ideas to mission feasibility. Discovery & Preparation is laying the groundwork for the future of space in Europe

Learn more on www.esa.int/discovery

Deliverables published on https://nebula.esa.int

CONFIDENTIALITY

This document is issued under Contract No. 4000139974/22/NL/GLC/ov between

ESA-ESTEC, Noordwijk

and

S.A.T.E. - Systems and Advanced Technologies Engineering, Venice

Reproduction, transmission, transcription, translation into any form or language, is subject to the Contract conditions.

REVISION SHEET

Sheet	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Rev.	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Sheet	16														
Rev.	2														
Sheet															
Rev.															
Sheet															
Rev.															
Annex															
Rev.															

DOCUMENT HISTORY

Rev.	Date of issue	Description
0	07/06/2024	Issued for Final Review
1	21/06/2024	Updated base on FR RIDs
2	25/06/2024	Footer updated based on project controller request

Changes other than typing/grammar proofing, brought with Rev. x, are marked by the following annotation on the right margin and shaded in yellow.

Rev. x

LIST OF CONTENTS

ANNEXES

none

1 SCOPE

This document is the Executive Summary of the project under contract no. 4000139974/22/NL/GLC/ov between ESA-ESTEC, Noordwijk and S.A.T.E., for the activity AI-BASED ON-BOARD RECONFIGURABLE FDIR AND LIFETIME PREDICTION FOR CONSTELLATIONS.

It represents Delivery 8.2 of the contract.

This document has the following the structure:

1. Project overview
2. Use cases and application scenario
3. System description
4. Performance test results
5. Project achievements
6. List of definitions and acronyms

2 PROJECT OVERVIEW

Constellations require complex operations and must grant high service availability. This makes autonomy and enhanced on-board FDIR one of the most urgent developments for the reduction of operational costs and of reaction times to events. Recent activities aim to use AI to improve FDIR. However, some key issues have to be faced:

1) the lack of suitable OPS data resolution for algorithms training on ground,
2) the need for a FDIR that is robust to the variability of the satellite operational contexts, which may not all be tested or simulated during the mission preparation.

The activity aimed at defining a complete workflow to deal with the above issues and assessing the feasibility and usefulness of the SATE CLUE library that implement advanced techniques exploiting Machine Learning to improve current FDIR systems in terms of: Early detection of incipient faults, Early identification of possible root causes, Time to failure prediction.

The project objectives included:

- Definition of requirements and application scenario
- Definition of the end-to-end workflow and design of the on-board an on-ground components foreseen in the workflow (with focus on the on-board Core Module)
- Customisation of the CLUE library for a selected on-board use case with flight representative simulated data
- Deployment and test of the CLUE library into a space representative processing unit
- Extraction of Key Performance Indicators to assess benefits over standard SoA FDIR approaches.

The proposed solution is innovative in that:

- It implements a reusable workflow for the exploitation of existing simulation models to generate data,
- It uses the CLUE libraries that were developed and validated in operations by SATE in the automotive and energy fields, which can be easily reconfigured for multiple use cases;
- It foresees a Training-over-the-air approach as part of the operational workflow to exploit OPS data labelling by operators, which can even be applied to multiple satellites:
    a. The CLUE modules are retrained on-ground with data downloaded upon occurrence of new conditions to be checked by experts and then updated on the flying constellation,
    b. Recovery plans are adjusted based on experience, i.e. based on recovery actions applied by operators to manage specific failure conditions, provided that these can be recognised automatically,
    c. The actual time to failure is evaluated based on events and prediction uncertainty automatically adjusted on the constellation.

The project was carried out by S.A.T.E. as Prime contractor, and OHB System as subcontractor, contributing respectively to the following tasks:

- Requirements definition, AI-FDIR Core Module design and implementation for selected use case, end-to-end workflow definition, testbed setup, verification tests, KPI measurement tests, discussion of achievements.
- Use case definition, requirements definition, simulated data generation, AI-FDIR Management Module design, review of end-to-end workflow, KPIs targets definition and results evaluation.

3 USE CASES AND APPLICATION SCENARIO

The project addressed the AOCS subsystem as a first use case to show the capabilities and performance of the proposed approach, with particular focus on RWs and electronics.

The Reaction Wheel performances can have significant impact on the S/C pointing accuracy. Early detection of Anomalies related to Reaction wheel assemblies (RWAs), being main actuators for the SC attitude control, can prevent the risk of having degraded performances.

In the case of an anomaly leading to a reconfiguration of the RWA, proper anticipation to the failure allows performing this reconfiguration in a controlled scenario, preventing unwanted reconfigurations during critical SC manoeuvres, which could ultimately impact the service availability.

The on-board execution of the monitoring allows accessing all sampled telemetries from all subsystems at maximum sampling rate, which may be necessary to properly characterise the behaviour of these components and detect early symptoms of malfunctions.

The use case implemented considered the following relevant failures modes of the AOCS component:

- Reaction wheel (RW) bearing degradation (abrupt or slow drift of the bearing friction)
- Reaction wheel bearing temperature sensor failure (open or short circuit)
- Electronics failure (wrong commanded torque)

The project implemented the first steps of the configuration of the AI-FDIR Core Modules, exploiting OHB System simulator of the AOCS system.

The RW model is a high-fidelity simulation block, which implements a mathematical model to represent the performance and functionality of a reaction wheel, while emulating its real interface.

The workflow envisaged for the application of AI-based FDIR systems for satellites constellations exploits the large amount of data that are generated throughout the system design, testing and operation phases.

The proposed workflow foresees the exploitation of existing simulation models to generate the required data for the initial training and configuration of the diagnostic modules, and for their initial test with realistic fault injection strategies.

Test data can be exploited to validate and update the models with real data, producing (when feasible) simulated faults applied during tests. In the end-to-end workflow, the use of Avionics Test Bench is included as part of the system development process, considering that it is more representative of the flying system in terms of configuration and generated data. Also, its use would make it possible to refine the models in subsequent steps, thereby providing feedback for the improved design of the platform from the models refinements based on AIT/AIV tests results and issues, as well as based on flight data.

When new satellites are launched, they can be monitored as soon as they are flying, with no need to collect months of data for models training.

The end-to-end workflow defined in the project encompasses the steps for the On-Board AI-FDIR system development and those for the system adjustment during operations, through the Training-over-the-air approach to obtain retraining requests directly from the on-board system and automate the validation and update of the new configuration. The workflow includes the possible hybrid (on-board and on-ground) deployment of the system and the evolving role of the human in the loop.

Publishing Date: 21/06/2024
Contract Number: 4000139974/22/NL/GLC/ov
Implemented as ESA Initial Support for Innovation

4 SYSTEM DESCRIPTION

The On-board system is composed of two main SW Modules: the AI-FDIR Core Module, implementing the FDIR and prognostic functionalities, and the AI-FDIR Management Module, in charge of the data exchange with the Core Module.

The AI-FDIR Core Module is based on SATE's CLUE Modules (**Figure 4-1**), that implement advanced techniques exploiting Machine Learning to improve current FDIR systems in terms of: Early detection of incipient faults, Early identification of possible root causes, Identification of multiple unrelated yet concurrent faults, Time to failure prediction.

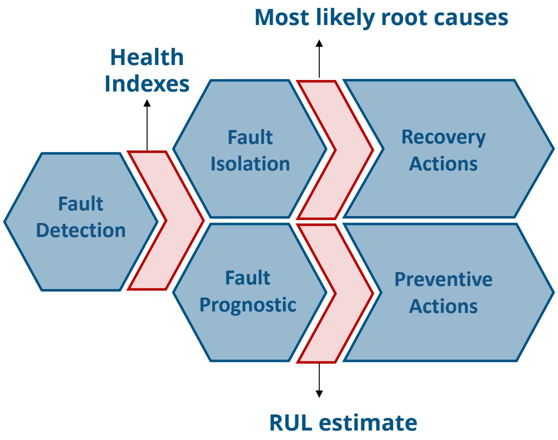

Figure 4-1 – CLUE library main modules and output

The CLUE Modules have successfully been applied in commercial applications to large fleets of industrial vehicles, where its modules were trained and configured using nominal data of 10 to 20 vehicles, and applied to continuously assess the health status of fleets of more than 20.000 vehicles with the same engine type, yet with different setups. The CLUE Kernel Modules trigger early alerts of incipient failures, providing predictions of the time to failure and indications on the most likely root cause. This allows vehicles stop before the failure occurs and perform the required workshop operations, speeding up troubleshooting and avoiding wrong components replacement.

In this project the CLUE modules were configured to diagnose the following **AOCS** components:

- Reaction wheels bearings
- Temperature sensors
- Electronics

with the objective to significantly improve the standard FDIR approach of these components.

The AI-FDIR system will be an independent agent, complementary with the classical PUS & Threshold-based FDIR.

The AI-FDIR Core Module SW will be generated as a precompiled static library based on C/C++ code to allow integration with the Central SW in the target HW Platform.

As such, the AI-FDIR system will interact with the Central OBSW: the input to be considered by the AI-FDIR includes satellite housekeeping parameters as well as parameters that are not part of the housekeeping telemetry, and derived parameters.

The processor running the AI-FDIR Core Module could be the Central CPU, a co-Processor module in the central OBC, as depicted in **Figure 4-2**, or as a distributed high performance processor that would communicate with the central OBC via SpW or SpF interfaces depending on the necessary data transfer needs.

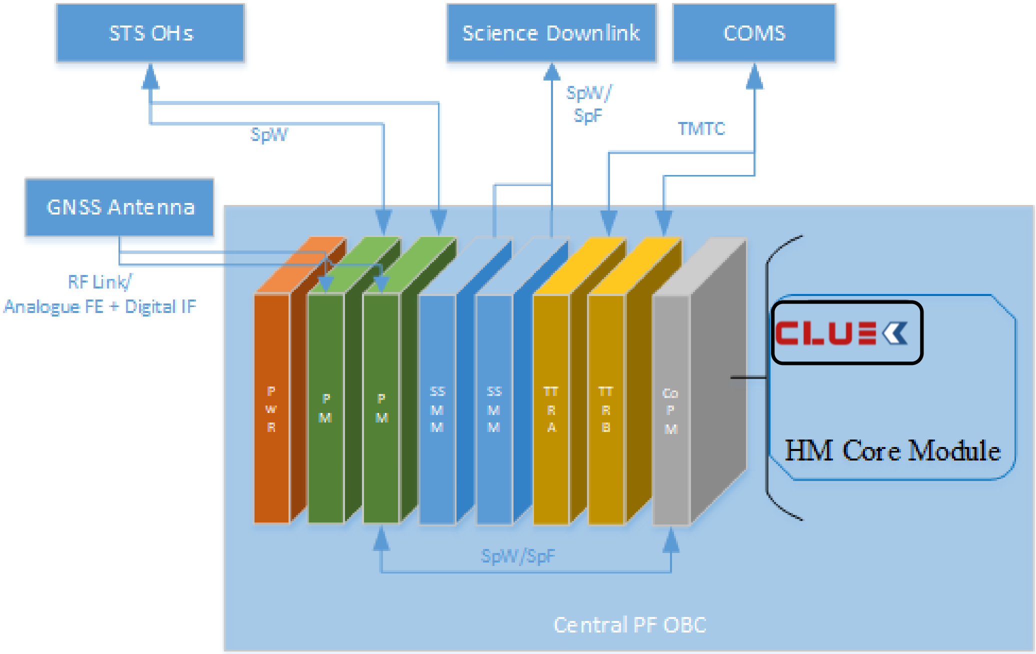

Figure 4-2 Potential implementation of HM Core Module as part of the SC avionics arachitecture.

Both Beyond Gravity Lynx single board computer or its GR740 variant Oryx SBC (depending on the Mission characteristics) are considered promising candidates for the targeted application, either as a standalone co-processor, as a coprocessor integrated via Mezzanine board in the Central OBC, or as part of the Core Processor of the OBC, integrating HM Management Module and HM Core Modules.

The testbed demonstration showed that processor performances in the range of >150 DMIPS would be required to meet the performances reported for the proposed solution.

Legacy OBC products such as the OBC NG, broadly used within the harmonized Avionics of OHB platforms, offers ~100 DMIPS, which could penalize the achievable performances of the proposed system.

Yet, centralized solutions with more performant processors broadly available in the market such as the GR740 (offering > 400 DMIPS per Core) could comfortably enable presented performances without the need to go for a de-centralized Avionics Architecture.

It is however noted that compared processor architectures are based on different instruction sets and therefore a one to one comparison, as outlined above, based on number of instructions per Time Unit may not be accurate and other Computational Performance Benchmarks like the OBPMark could be more suitable.

5 PERFORMANCE TEST RESULTS

This section presents the results of the performance tests carried out with the customized CLUE library for the AOCS use case, using the simulation dataset generated by OHB.

The performance of the AI-based FDIR solution is assessed based on Key Performance Indicators.

Performance tests carried out with representative simulated datasets with **more than 200 orbits** for each scenario:

- Variety of **nominal** conditions (including different **ageing** conditions of the bearing)
- **Mechanical** failure – **bearing friction abrupt increase**
- **Mechanical** failure – **bearing friction drift**
- **Electronics** failure
- **Temperature sensor** failure

Table 1 - **Overall Performance** (including mechanical failure, electronics failure and sensors failure detection)

KPI	Name	Definition	Evaluated over	Result	Target
1	Precision positive condition	Among all AI-FDIR alerts, how many are correct	all nominal orbits all orbits with failures	98.5%	> 99%
2	Precision false condition	Among all AI-FDIR alerts how many are incorrect	all nominal orbits all orbits with failures	1.5%	< 1%
3	Recall positive condition	Among all cases with off-nominal conditions how many are correctly identified by AI-FDIR alert	all orbits with failures	98.2%	> 90%
4	Recall negative condition	Among all nominal cases how many are correctly identified by AI-FDIR	all nominal orbits	90.5%	-
5	Missed standard FDIR alerts wrt AI-FDIR correct alerts	Among all correct AI-FDIR alerts how many are not detected by standard FDIR	all orbits with mechanical and electronics failures	82.1%	-

KPI	Name	Definition	Evaluated over	Result	Target
6	Early detection	Time interval between an alert by the AI-FDIR system and a real component failure (excluding crash breaking events) or standard FDIR alert	6 different simulated scenarios covering 90 days each with slow friction drift	15 to 50 days	>10 hours
7	Fault Isolation accuracy	Among all alerts generated by DKM models, how many are correctly classified into the specific type of fault	all nominal orbits all orbits with failures	99.6 %	> 99%
8	RUL estimate accuracy	Average accuracy of the prediction of a critical condition at alert set (excluding crash breaking events)	6 different simulated scenarios covering 90 days each with slow friction drift	77%	> 80%

Here follows an example of the result of the CLUE modules in one of the simulated conditions characterised by a simulated mechanical failure of the bearing (with slowly increasing bearing friction). The figure shows the Health Index evolution along time, which shows the decrease in the HI value from 100 (fully nominal) to 0 (critical condition). The HI starts decreasing after the failure is injected in the simulation. The CLUE alert is triggered about 53 days before the standard FDIR alert (i.e. upon exceedance of the estimated friction torque alert threshold).

Upon CLUE alert, the module also provides the type of failure identified and the RUL estimate. In this case the system detects the bearing mechanical failure (increased friction) and estimates about 22 days to reach a critical condition.

The RUL estimate is updated continuously: for example, when the HI is 50, the updated RUL estimate is of 25 days.

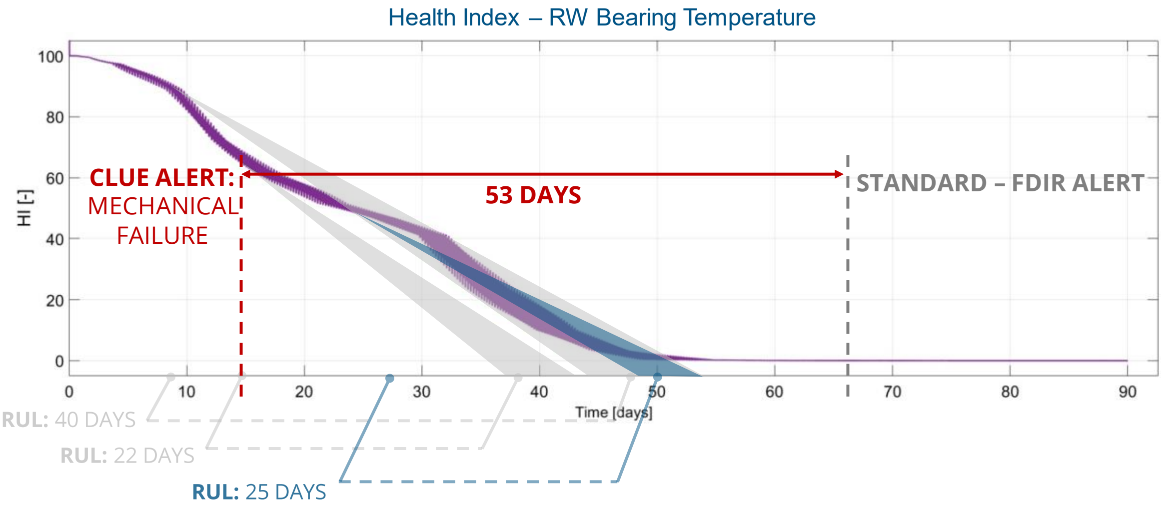

Figure 5-1 – Example CLUE result for simulated long friction drift (over 3 months run): 1) time evolving health index, 2) alert trigger upon detection of low health status, 3) estimate of the most likely component fault (mechanical failure in this case) at alert set, 4) time evolving estimate of the RUL (time to reach critical health status condition).

This shows that the CLUE HI information provides good insights into the health status of the AOCS components, ranging from 100 (fully nominal) to 0 (critical condition), in addition to the possibility to identify in advance the incipient failure type and have an evolving estimate of the RUL.

6 PROJECT ACHIEVEMENTS AND LESSONS LEARNT

The project demonstrated the following outcomes, which are relevant for the future adoption of the proposed solution for enhanced on-board FDIR:

1. **Possibility to exploit existing simulation assets for data generation and CLUE training**
2. **CLUE approach suitability and measure of benefits with respect to standard FDIR**
   - Early detection of incipient faults (from 2 weeks to almost 2 months in advance compared to standard FDIR)
   - Less than 1.5% False alerts and Missed alerts
   - More than 80% new events detected, not detected by standard FDIR
   - Early identification of possible root causes (more than 99% accuracy in the discrimination of the different types of failures),
   - About 77% average accuracy in RUL estimate.

   In addition, the tests carried out also verified that the output generated on-board satisfied the following additional key features:

     - The system is robust to ageing, i.e. it is not triggering alerts when an aged condition of the RW is observed (nominal aged conditions were included in the nominal test dataset, modelled by an increased baseplate temperature).
     - The system triggers a notification of need for retraining when monitoring a different operative condition compared to those used for the training and configuration of the system.
3. **CLUE approach generality**

   The CLUE modules were simply configured in this project starting from existing implementations running in other applications and domains, such as automotive. Therefore, this project demonstrated the approach generality and its suitability to cover other use cases in addition to the one addressed in the present activity, i.e. the RWs components.

   In order to include new subsystems and components, the CLUE Modules can be easily updated to include the required additional health status models and update the configuration of the Fault Isolation Module and RUL estimate to include these components.

   The same CLUE modules configuration can be used to monitor the AOCS system for all satellites of the constellation sharing the same components and working in similar operative conditions.
4. **Execution onto flight representative HW platform & resources requirements**

   A test bed was implemented to run on the CLUE modules on a representative HW platform, to measure required computational resources and assess feasibility in on-board applications. The board selected for the implementation of the testbed is the LS1046A-RDB by NXP, which shares the same processor as Beyond Gravity Lynx board. In the tests execution, a same core hosted the execution of the Linux OS, running with pre-emption, and the CLUE static library. Although this scenario is not representative of the flight one, it is deemed sufficient to assess the resource requirements, considering that the CLUE software has no dependencies on the OS or other external libraries, as it is self-contained C code.

The resources required for the execution of the CLUE modules were collected and characterised, resulting into resource requirements that are highly compatible with existing space grade HW (processor performances in the range of >150 DMIPS would be required to meet the performances reported for the proposed solution).

The tests carried out included the verification of the reconfigurability of the Core Module without need for update of the software programme.

5. End-to-end workflow for operations and interactions with ground

The end-to-end operational workflow for the use and maintenance of the on-board CLUE modules through interactions with ground was defined in detail. This is a relevant output of the project, which was not limited to the implementation and demonstration of the diagnostic technologies but also to the definition of the operational approach to its use and maintenance, including the role of the human in the loop during operations.

Table 2 summarises the main lessons learnt from the activity.

Table 2 – Lessons learnt

No.	Title	Discussion
1	Benefits over current FDIR	The use case selected in this project, targeting the main AOCS components, demonstrated how more advanced techniques can significantly improve the on-board assessment of the health status of the satellite and its components, enabling the possibility to trigger alerts much earlier than the standard FDIR approach and generating new types of information that can be used onboard and sent to ground for an improved management of the platform.
2	Need for proper definition of nominal conditions	In order to properly configure the Core Module, it was necessary to clearly define with experts what is considered nominal and which are the conditions that should be triggering some warnings or alerts. The iterations on these aspects are crucial as well as the early definition of KPIs for performance and benefits evaluation.
3	Feasibility of use of existing simulation models	This study selected an existing simulation model of the RWs for the generation of training and test data. Originally developed as part of the AOCS simulator, this provided the advantage of combining sufficient fidelity for the simulation of representative failure cases with the ability to generate a high number of data sets with a long enough duration. Other simulators can also be re-used and adapted for this purpose. The operational satellite simulators/SatSims are natural candidates, as they simulate the entire satellite and the connection to the ground system. However, this often requires additional efforts and was left for future development in this study.
4	Need for representative EoL data for future validation	The Remaining Useful Life estimate module has been proved and tested on a limited dataset, achieving preliminary performances. It is necessary to expand the RUL estimate validation, including real End Of Life data that can allow better configuring the module to predict the lifetime.
5	Deployment and computational resources	The SW demonstration on the target representative board proved that the proposed solution is highly competitive with respect to other AI-based techniques in the literature, not only from the point of view of measured KPIs but also from the amount of computational resource required on-board. In addition, it has no dependencies from external libraries, which facilitate the deployment on a variety of target systems.
6	Exploitation for constellations scenarios	The proposed solution defines a training-over-the-air approach as part of the operational workflow to exploit OPS

No.	Title	Discussion
		data labelling by operators, which shows a large potential when applied to a constellation of satellites. Proposed solution allowing early failure detection can significantly reduce service downtime, maintenance costs and manual operator work; offering a value which increases proportionally with the scale of the Constellation.

7 TERMS, DEFINITION AND ABBREVIATE TERMS

Symbol	**Description**
AI	Artificial Intelligence
AOCS	Attitude and Orbit Control System
DBTP	Distributed Binary Tree Protocol
FDIR	Fault Detection Isolation and Recovery
FIM	Fault Isolation Module
HDSW	Hardware Driver Software
HI	Health Index
ISR	Interrupts and Service Routines
KPI	Key Performance Indicator
OBT	On Board Time
OBSW	On Board Software
OS	Operating System
PM	Processor Module
PSLIB	Packet Store Library
RTOS	Real Time Operating System
RUL	Remaining Useful Life
SpW	Space Wire
SpF	Space Fiber
SW	Software
TC	Telecommands
TM	Telemetry

PAGE PURPOSELY BLANK

Publishing Date: 21/06/2024

Contract Number: 4000139974/22/NL/GLC/ov

Implemented as ESA Initial Support for Innovation

→ THE EUROPEAN SPACE AGENCY

ESA Discovery & Preparation

From breakthrough ideas to mission feasibility. Discovery & Preparation is laying the groundwork for the future of space in Europe

Learn more on www.esa.int/discovery

Deliverables published on https://nebula.esa.int