→ PREPARATION

LOOP: Preparing the foundations of circular on-orbit economy through a commercial refurbishment mission of a spacecraft in GEO

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Executive Summary Report

Study

OSIP Campaign: System Studies for the Circular Economy in Space

Affiliations: Growbotics Space Ltd (Prime)
Thales Alenia Space UK Ltd (Sub 1)
3Keel Group Ltd (Sub 2)

Activity summary:
We evaluated a mission concept to robotically refurbish a GEO satellite by replacing a component of the Electric Propulsion subsystem. We performed a case-study to evaluate the suitability of existing propulsion systems for refurbishment. We created a set of circular economy system maps to envisage what the future in-orbit circular economy would look like, and identified a business case that supports refurbishment based on purely commercial value. We conclude that for refurbishment to be feasible, new satellite platforms need to be designed that support robotic servicing, and that further work needs to understand the impact of design choices on the circular economy.

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1. Introduction

This document is a concise summary of the findings from the LOOP study, carried out between September 2024 and February 2025. The project team was led by Growbotics in partnership with Thales Alenia Space and 3Keel.

This summary report is intended for non-experts in the field. For further detail, please refer to this study's Final Report.

2. Project Background

The activity set out to outline a mission concept for a refurbishable GEO satellite platform that is realistic before 2040. We proposed this as the next logical step in the development of the circular in-orbit economy, a step that has a strong commercial justification as well as sustainability benefits.

Our initial objectives were:

1) Outline and trade-off mission concepts to define high level requirements for refurbishable missions and elaborate corresponding business and sustainability case
2) Investigate impacts of refurbishment at sub-system level through case study to understand relationship between lower-level design and high-level concepts
3) Inform technology development roadmaps with flowdown of requirements from the mission, providing validated use cases linked to market needs

In the frame of this challenge, run as a SYSNOVA competition on the ESA OSIP platform, the objective was to propose a mission that can be taken forward into upcoming ESA ministerials by the Clean Space team, that is realistic by 2040 and reflects a lower budgetary request (in the order of tens of millions of euros rather than hundreds). Reflecting this, our objectives changed through the course of the study to focus on more of the detailed mission design for an IOD to demonstrate refurbishment in GEO, instead of analysis of the refurbishment processes and future platform design.

Our key outputs of the project are

1) LOOP IOD Mission Design
2) Analysis of the serviceability of Electric Propulsion
3) Circular Economy System Map

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3. Methodology

This study adopted the work breakdown structure presented in Figure 1 below.

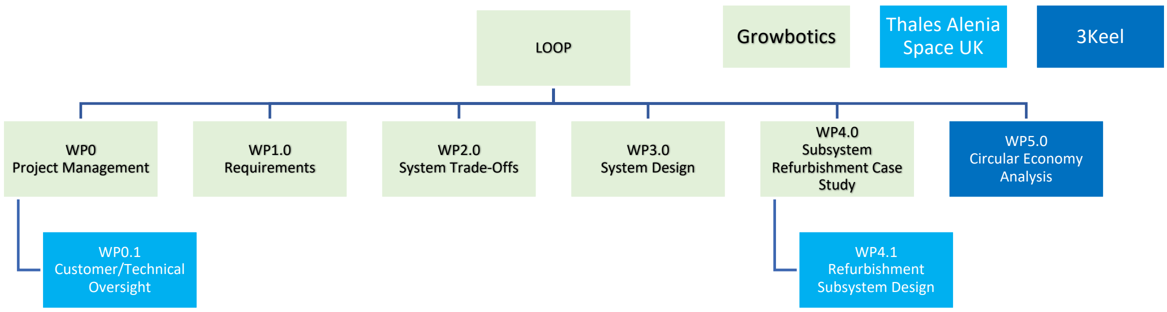

Figure 1: LOOP Project Work Breakdown Structure

Growbotics was responsible for the core Work Packages (WPs) regarding project management (WP0), requirements (WP1), and system design (WP2 & WP3). WP1 established high-level requirements for in-orbit refurbishment as a commercial service and an In-Orbit Demonstrator (IOD) by exploring potential use cases, given the emerging nature of the ISAM sector. A business case analysis compared cost of refurbishment vs replacement, and business models were refined through user engagement. WP2 then evaluated and traded-off refurbishment concepts against five weighted criteria, including contribution to the circular space economy, customer value, technical feasibility, client satellite modification requirements, and scalability potential. Finally, WP3 developed a system concept for the IOD mission, following a waterfall approach that defined operations concepts, mission phases, and system functions, leading to an architecture with system budgets while also identifying critical technologies and potential risks requiring mitigation.

Thales Alenia Space UK contribution to the project was twofold. First, leveraging their expertise in Electric Propulsion (EP), TAS-UK analysed the key life-limiting equipment used in EP subsystems (WP4.1), identifying opportunities for in-orbit refurbishment of commercial missions TAS-UK went on to analyse the constraints that current EP equipment would impose on a robotic servicer, and the modifications required to a potential client in order to facilitate the replacement of such equipment at the end of its operational lifetime. Second, TAS-UK acted in the role of customer/prime contractor (WP0.1), validating technical and commercial assumptions, providing recommendations and reviewing project outputs.

3Keel were focussed on identifying and defining the challenges currently complicating the development of detailed circular design guidelines for the mission (WP5.0). Through systems mapping, 3Keel worked to identify the complexities, trade-offs, risks, and options that need to be considered to avoid shifting problems unintentionally and ensure that solutions meant to improve sustainability through circularity achieve that goal. Drawing on their findings from several means, three system maps were developed, which depict lifecycle flows, environmental impacts, risks, and considerations for the continued development of the LOOP mission in three scenarios: (1) the current state, (2) a short-term refurbishment scenario, and (3) a long-term circular space ecosystem scenario.

4. Key Findings

The key findings of this study are divided into 5 parts, in summary:

1. **Analysis of the business case** determined that there are strong indications of opportunity for refurbishment in GEO if the satellites are designed to be refurbishable (i.e, not on existing infrastructure alone). Therefore, many changes need to be realised before satellite refurbishment services will be viable and the return on investment will take well over a decade to be realised at the current point. We propose 2 shorter-term business models to exploit in the short term that will create demand for refurbishment services in the longer term and allow a shorter-time horizon for investment returns to be realised.

2. **Definition of a mission concept** resulted in a novel architecture for an In-Orbit Demonstration (IOD) in which a satellite refurbishes its own Electric Propulsion, before dividing into two independent modules to demonstrate Proximity Operations & Docking (PO-D) manoeuvres.

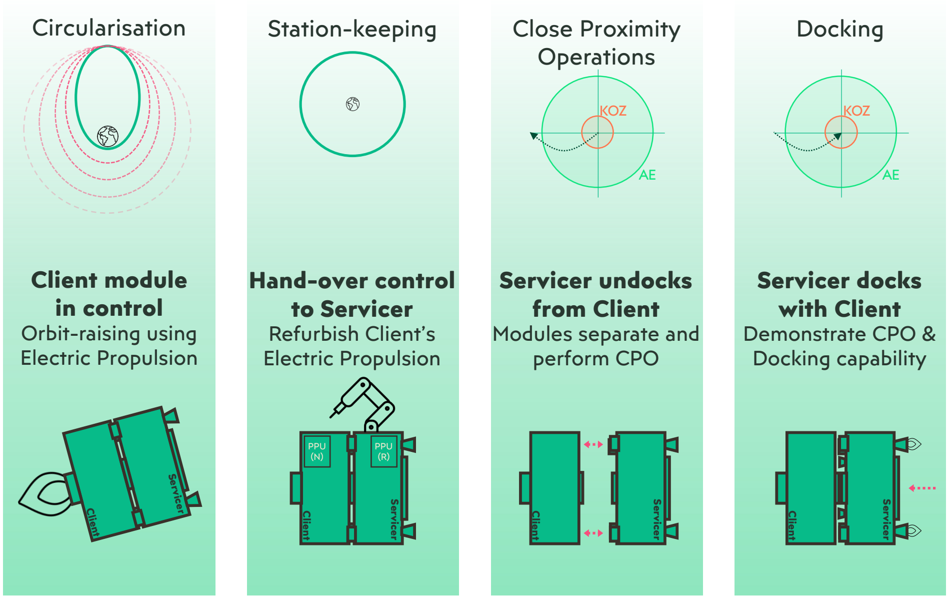

Figure 2: Baseline IOD operational phases

Figure 2 illustrates the baseline scenario after injection of the satellite into GTO, with the Client module performing the orbit-raising manoeuvre to the operational Geostationary Orbit (GEO). The orbit selection was driven by a desire to identify the driving requirements and quantify the difference between a demonstration in GEO and LEO. Although LEO would offer a lower-cost alternative, GEO was chosen as the most representative of the commercial service, but the impact of changing to LEO was quantified wherever possible.

An early use case analysis identified several potential targets for refurbishment. Power Processing Units (PPUs) within the EP subsystem power and control thrust through high-voltage solid-state electronics, and primarily fail through two key mechanisms: thermal stress from repeated on/off cycling which causes component degradation over time, and cumulative damage from radiation exposure. Given their representative interfaces and form factor, the PPU was thus selected as the equipment to be replaced on the IOD.

The satellite is divided into two modules, the Servicer and the Client, to allow the refurbishment demo to be performed *before* the PO-D demo mitigating the impact of a failed docking. The Servicer's payload consists of a robotic manipulator (RM), end effectors, replacement components and component storage. The refurbishment procedure involves a complex sequence of removing, storing, and re-integrating the PPU between modules, and finally verifying that the EP subsystem continues to operate nominally.

System budgets were established for mass, delta-v, power and volume to inform derivation of key requirements at subsystem-level compliance. A compliant system architecture was described, and an initial satellite configuration is presented in Figure 3 below.

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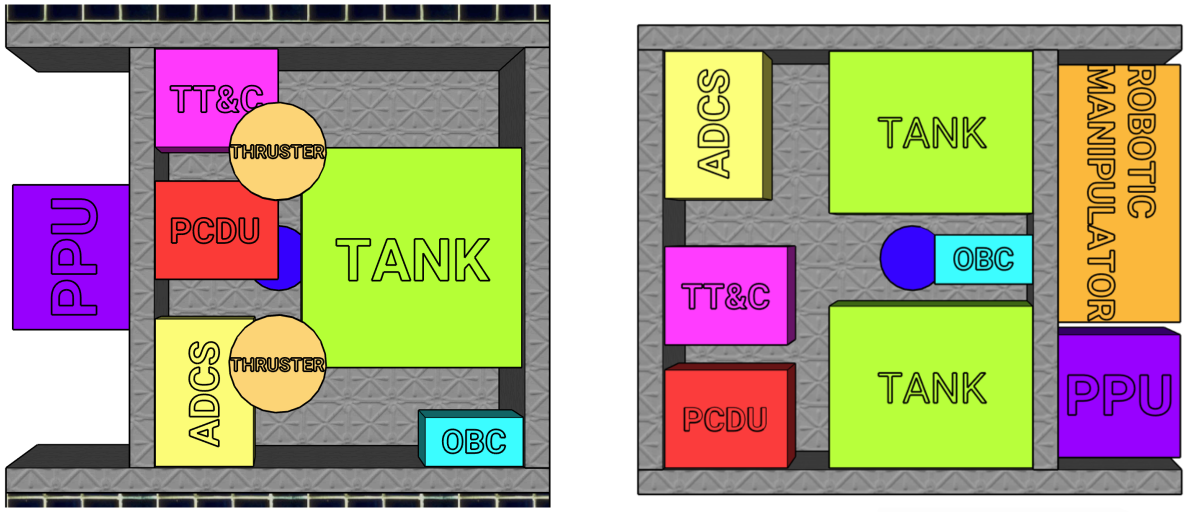

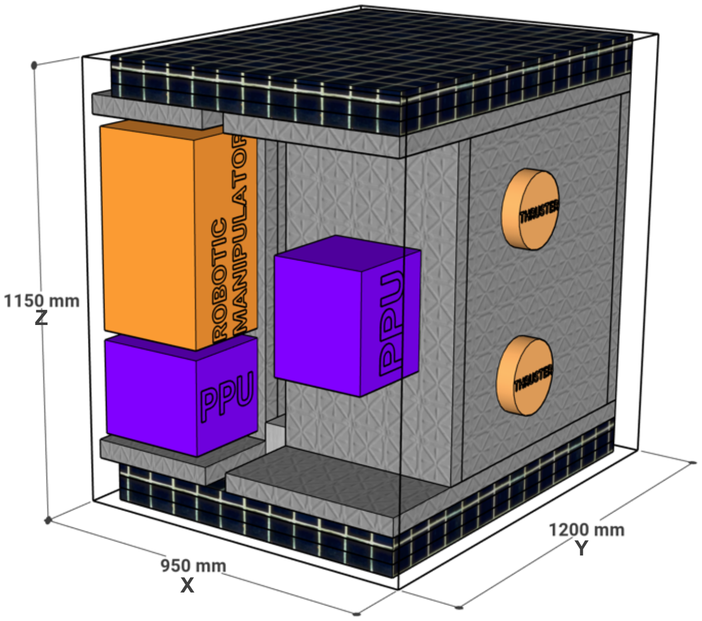

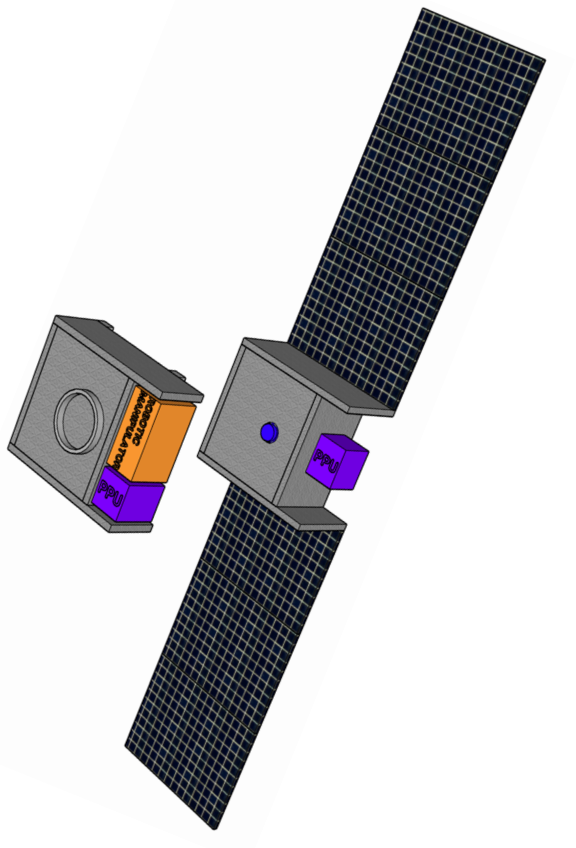

Figure 3: Configuration and layout of the LOOP IOD satellite

The EP, RM and Guidance, Navigation & Control (GNC) subsystems were identified as critical technologies for which fully-compliant OTS could not be identified, for which a technology roadmap was developed in line with the Challenge's timeframe (after 2028 but before 2040). Several risks were identified, including a challenging radiation environment and strict mass constraints, as well as achieving sufficient thrust from a low-cost EP subsystem. However, the architecture is compatible with a reduction in scope, either in orbit to LEO, or removal of ambitious PO-D goal objectives.

3. Investigation into the serviceability of electric propulsion

A survey of equipment used in the design of EP systems included tanks, pyro valves, gas filters, latch valves, pressure / flow control, EP thruster mechanisms, electric thrusters and PPUs. Life limiting factors were evaluated and the PPU and electric thrusters were elaborated in further detail. Refurbishment considerations were analysed with respect to equipment location and interfaces. The analysis identified specific challenges for post-launch refurbishment in accessing the PPU from outside the satellite and in de-integrating the thruster fluidic interfaces. Both equipment items are expected to require redevelopment to implement alternative interface connectors that minimise the complexity of the robotic servicing tools and processes.

For both equipment items development paths was developed to identify areas for identifying and evaluating and trading off potential design modifications with servicing capabilities. The development paths considered mechanical, thermal and electrical MAIT procedures and interfaces to identify development considerations, propose development strategies and perform an initial evaluation of the impact on the subsystem or equipment.

Feasible design modifications by the 2030 timeframe for the IOD mission were analysed. For the PPU these identified the mechanical interface to the bus, the reuse of GSE jig mounting locations and standardisation of electrical connectors. If the standardised connector is a new component, redevelopment of the PPU around this as a driving requirement would be necessary, potentially making qualification timescales challenging to meet. Further analysis is also required with respect to external access to the PPU and thermal interfaces to the bus.

For the thruster module, existing manual handling jigs were also identified that could be developed into permanent flight features. Thruster thermal isolation would need revision to ensure permanent bonding, facilitating the in-space assembly process. Standardised electrical connectors and screwed fluidic connectors also present lower levels of redevelopment to implement.

4. Design rules for refurbishment

A survey of robotic equipment identified a wide range of products are under development for ISAM applications such as refurbishment, including robotic manipulators and multi-function interfaces supporting thermal, mechanical, electrical and data connections. Two interface strategies were identified for, use of multi-function devices and use of traditional connectors better suited to robotic handling. In all cases, products were found to be low maturity, typically around TRL 6, or requiring delta qualification before use in flight. This included the robotic manipulators in addition to interface products.

To further guide the development of refurbishable equipment, general design rules and preliminary high level interface requirements have been identified to provide a basis for systematic guidance when making design decisions for serviceability of a satellite at equipment, subsystem and system levels.

5. Systems Mapping of the Circular Space Economy

We created a set of three system maps depicting lifecycle flows, environmental impacts and other considerations in current, short-term and long-term scenarios. A central finding, is that an improved understanding and quantification of environmental impacts will be important for evaluating the trade-offs and impacts of solutions for improving sustainability and circularity. Such assessments should build on recent LCA work to cover both ecospheric and orbital impacts from space debris and we identified several instances where they must be intentionally set up to be sensitive to system-level effects. This will be important both to minimise the short-term ecospheric impacts from the development of circular solutions, such as in-orbit servicing, and to identify at what point these might be offset by potential ecospheric and orbital impact savings, i.e reduction of launches through refurbishment instead of replacement. These assessments will be key to ensuring that the LOOP mission and similar initiatives deliver on their sustainability objectives.

5. Conclusion

In light of the key findings of the work, we conclude that, in the pursuit of a circular space economy, the space industry should prioritise developing satellites which are refurbishable by design. “Servicer” satellites will become a critical part of ISAM infrastructure, but until client platforms are *serviceable*, the cost of servicing remains difficult to justify. In addition, the lag between initial demand for refurbishable satellites, and the eventual need for servicing, is likely to exceed 10 years, due to the long development cycles and extended lifetimes of GEO platforms.

Safely performing In-Orbit Servicing operations is, of course, a significant technical problem to solve, and the time required to develop such a capability within Europe should not be underestimated. However, even the most performant of robotic servicers could not reliably refurbish satellites as they are currently integrated. The case study into refurbishment of Electric Propulsion (EP) subsystems performed by TAS-UK has identified multiple specific issues posed by traditional assembly processes. Alternatives to tried-and-tested methods will need to be developed and qualified on a case-by-case basis.

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Since satellites remain in graveyard orbits for thousands of years, there is an opportunity to implement circular design in satellites launched today, to be managed by the servicing infrastructure of the future. Satellite manufacturers should then be incentivised to build a new generation of platforms urgently, before the market has fully emerged. Through analysis of the business case we find that refurbishment has a strong commercial justification and can enable significant cost savings and increased operational flexibility to satellite operators, and does not need to rely on sustainability to justify its value. However, the timeframes in which this can be realised are longer than typical private investment horizons. Thus a typical public-private partnership model is expected to be followed, but must be kick-started and coordinated at circular ecosystem level to ensure all elements of the economy are matured at the appropriate rate. It is also safe to assume that representative and robust demonstrations of refurbishment must be performed, in-orbit, before stakeholders can be expected to make such a significant investment.

The LOOP IOD mission elaborated in this study has two such demonstration objectives: 1) Replace the Power Processing Unit of its own EP subsystem; and 2) Perform close proximity manoeuvres and docking between a servicer and a client. GEO was chosen as the baseline orbit, with the aim to establish realistic requirements for the eventual commercial service, and identify the design drivers, in comparison with a more conservative demonstration in LEO. Several risks were identified, including radiation and mass constraints, as well as achieving sufficient thrust for orbit-raising from a low-cost EP subsystem. Several opportunities still exist for further refinement of the concept, however, including the possible exploitation of emerging OTV-to-GEO launch opportunities. Executing the corresponding technology roadmap would, in turn, yield a prototype “Satellite Repair Kit” of robotic end effectors and interfaces, by ESA CMin28.

The space sector is entering a new phase, marked by an acceleration in launches and the materials injected into orbit. A systemic shift is needed to transition from the current linear model, and the innovation required is expected to be several times higher than for other industries. ESA’s vision for a Space Circular Economy by 2050 and 2023 White Paper represent important stepping stones towards establishing a shared vision for this circular future, but as of yet, there is no universal agreement on what it should include or how it should be implemented. 3Keel’s work in this study has begun a circular economy systems map that can be used as a basis for future quantitative assessments to compare the environmental impacts of different solutions and scenarios, and to make it easier to spot risks of rebound effects and unintended consequences.

6. Future Work

Technology

- **Refurbishable GEO platform & equipment development**: Definition of a refurbishable GEO satellite architecture and the corresponding robotics processes. At equipment level, such as for the EP subsystem as proposed in this study, detailed concept trade-offs and designs for refurbishable solutions need to be

proposed, ideally via a breadboard model to demonstrate critical steps, reaching TRL 4/5 by 2028.
- **Robotic assembly design framework**: A structured design-for-refurbishment framework need to be developed, supported by simulation and physical testbeds.
- **Satellite repair kit**: Design, development and testing of the robotic system, including part handling of the replacement process, to reach TRL 4/5 by 2026 and 8/9 by 2028.
- **IOD mission and bus definition**. Further elaboration of the IOD mission concept and trade-off of platform options.

Business case

The business case must be continuously updated to align with evolving technologies and market dynamics. As designs mature, detailed cost analysis of servicing will be crucial to ensure viability of the business cases. Ongoing market validation with key stakeholders, including satellite operators, defence, and international customers, will further refine the commercial model. The main objective is to provide early validation for continued investment.

Circular economy

For a Circular Economy mission, we recommend:

- **Systematic implementation of circular economy principles:** Use the outputs and conclusions from the systems mapping to guide the continued definition of the mission, with different scenarios for the IOD (short-term) and end goal solutions.
- **Quantitative assessment methods:** Develop concepts for quantitative assessments of ecospheric and orbital impacts in the different scenarios, sensitive to the system-level effects identified through this work.
- **Elaborate ecosystem impact models for space environment:** Initiate collaborative efforts with others to ensure that designs are co-developed and approached with systems thinking and expectations of future technologies in mind. Analyse of the relative maturity and high-level potential environmental savings of different technologies envisaged for the long-term circular ecosystem to shortlist partners for engagement and design collaboration.

More broadly, we recommend a wider systems thinking approach is taken to defining and envisaging a circular space ecosystem, beyond singular mission proposals, and that ESA takes a leading role in defining, convening and coordinating. Given the strong lock-in effects and long development times in the industry, it is important that servicers and satellites are designed for expected future advancements in circular processes to avoid early obsolescence.

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