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1 INTRODUCTION



The landscape of space exploration and operations is undergoing a profound transformation. As missions become more ambitious, longer in duration, and increasingly reliant on autonomous systems, the traditional paradigms of spacecraft design and control are being challenged. Historically, spacecraft have operated under tightly scripted procedures, with most decision-making centralized on Earth. However, this model is no longer sustainable for the next generation of space missions, which will involve complex, multi-agent systems operating far from Earth, often with limited or delayed communication.

At the same time, the aerospace sector itself is experiencing a fundamental disruption. On one side, the SpaceTech industry is being reshaped by strong global competition, accelerated exploration efforts, and a booming NewSpace economy. On the other, we stand at the dawn of an emerging orbital space economy, marked by rapid growth in low Earth orbit (LEO) transportation, constellations deployment, and an upcoming revolution of in-orbit servicing.

In this context, the European Space Agency (ESA) has launched the In-Space Proof-of-Concept (InSPoC) initiative with the goal to de-risk technology development towards a future space transportation ecosystem involving a portfolio of interoperable In-Space Transportation Vehicles (ISTVs). A key enabler on this path is the transition from point-to-point missions to a modular, scalable “hub-and-spoke” space transportation network as this approach can provide the backbone for a cost-effective logistics architecture from now to 2050. This network will support not only constellation phasing and orbit raising, but also the growing needs of in-orbit servicing and exploration.

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The InSPoC-3 activity aims to explore and validate the integration of artificial intelligence (AI), autonomy, and cooperative capabilities into spacecraft systems. The goal is to lay the groundwork for a new class of intelligent, adaptable, and resilient space-based logistic infrastructure that can support a wide range of future missions – from satellite constellations and orbital servicing to deep-space logistics and planetary exploration.

InSPoC-3 draws inspiration from other high-tech sectors, particularly the automotive industry, which has successfully transitioned from hardware-centric to software-defined platforms. Companies like Tesla have demonstrated the power of agile development, over-the-air updates, and AI-driven decision-making in enabling vehicles to adapt to changing environments and user needs. These same principles are being investigated for space systems, where the ability to reconfigure, learn, and evolve in orbit is becoming a critical requirement.

The analysis in this activity is structured around four strategic domains, on-board autonomy and reconfigurability, on-board safety and longevity, shared intelligence for in-space cooperation, and spacecraft fleet management. Each domain is examined in detail, with attention given to both current capabilities and future needs.

In addition to domain-specific challenges, the study identifies several cross-cutting issues that affect all areas of spacecraft design and operation. These include the trade-off between system longevity and technological modernity, the reliability and explainability of AI systems, and the governance of data across distributed and autonomous platforms. Addressing these challenges requires not only technological innovation but also new approaches to system architecture, software engineering, and mission planning.

Ultimately, the InSPoC-3 initiative represents a strategic step toward redefining how spacecraft are conceived, built, and operated. By embracing AI, modularity, and autonomy, ESA and its partners are preparing for a future in which space systems are not just tools, but intelligent agents capable of adapting to the unknown, collaborating with one another, and supporting humanity’s expanding presence in space.

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2 STRATEGIC DOMAINS AND THEIR CHALLENGES

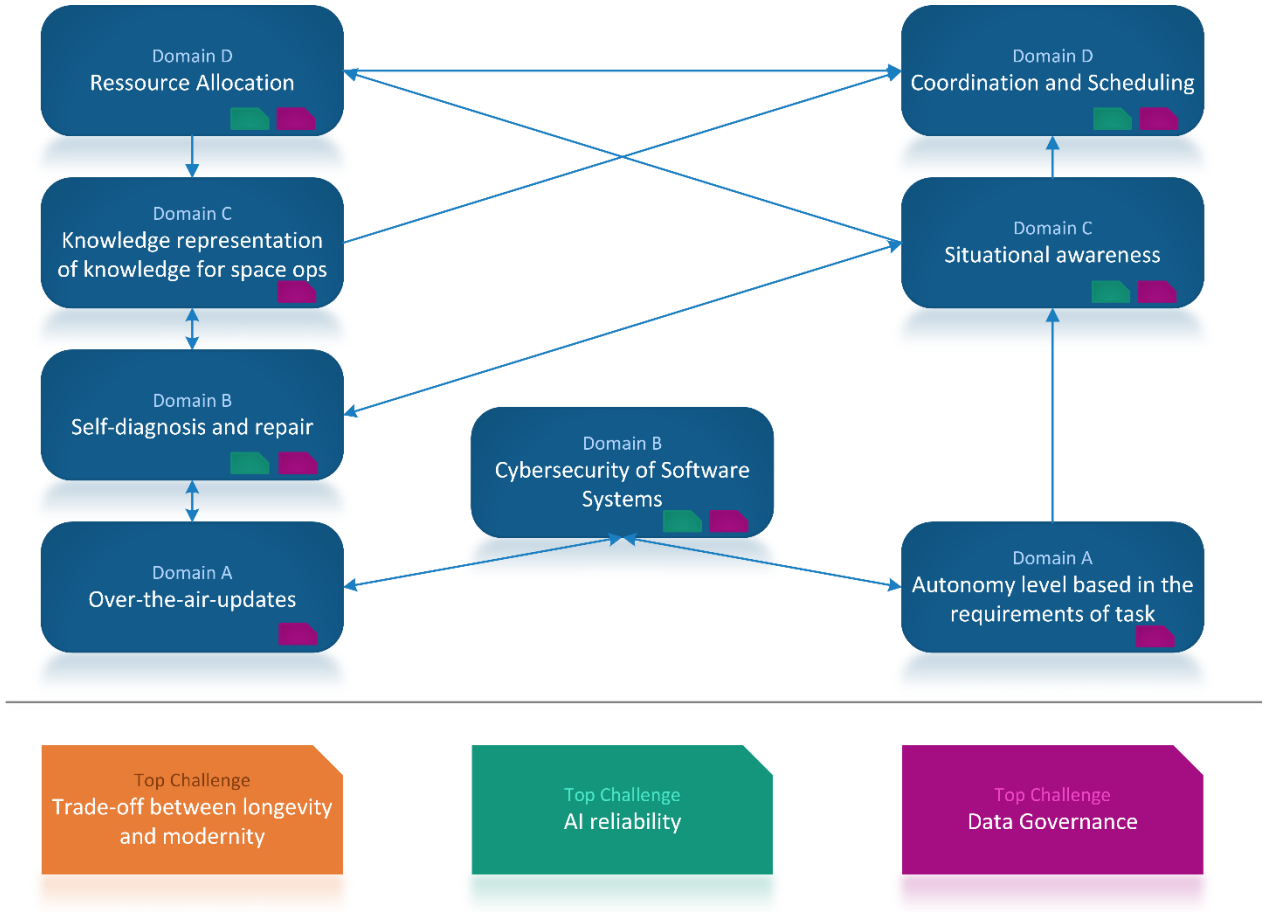

Figure 1: Dependencies of challenges across domains with top challenges highlighted.

To structure the complex landscape of future space operations, the InSPoC-3 project defines four strategic domains that reflect the most critical areas of technological development and operational transformation:

- On-board autonomy and reconfigurability
- On-board safety and longevity
- Shared intelligence for in-space cooperation
- Spacecraft fleet management

These domains serve as a framework for identifying the key challenges that must be addressed to enable intelligent, autonomous, and cooperative spacecraft systems. Each domain represents a distinct functional focus, ranging from how spacecraft make decisions independently, to how they ensure long-term reliability, collaborate with other systems, and operate as part of coordinated fleets. While the domains are conceptually separate, they are deeply interconnected as illustrated in Figure 1. Progress in one area often depends on advancements in another, and many of the enabling technologies span multiple domains.

The challenges within each domain are not hypothetical, they are grounded in the realities of current and emerging mission scenarios. They reflect the growing complexity of space operations, the increasing reliance on software and AI, and the need for systems that can adapt, learn, and recover in dynamic and often unpredictable environments.

The different challenges associated to each domain are illustrated in Figure 1 and are described in more detail in Table 1 below. The Identified transversal top challenges are presented in Chapter 3.

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Table 1: Overview over InSPoC-3 domains and challenges.

Domain and Challenges	Description
Domain A: On-Board Autonomy and Reconfigurability	This domain focuses on enabling spacecraft to operate independently and adapt to changing mission needs. As communication delays increase with distance from Earth, spacecraft must make decisions autonomously. Key technologies like modular software, over-the-air updates, and containerization support real-time reconfiguration, making systems more flexible and resilient.
Domain B: On-Board Safety and Longevity	Long-duration missions demand systems that can detect, diagnose, and recover from faults without human input. This domain addresses the need for predictive maintenance, cybersecurity, and self-healing capabilities. AI-driven diagnostics and redundant architectures help spacecraft withstand harsh space environments and extend operational life.
Domain C: Shared Intelligence for Advanced Cooperation In-Space	Future missions will rely on fleets of spacecraft working together. This domain explores how systems can share data, coordinate actions, and make joint decisions. Technologies like semantic knowledge representation, distributed computing, and AI teaming enable collaborative behaviour across autonomous agents.
Domain D: Spacecraft Fleet Management	Managing multiple autonomous spacecraft requires scalable coordination and resource allocation. This domain focuses on distributed planning, real-time scheduling, and predictive maintenance across fleets. The goal is to ensure efficient, synchronized operations while supporting growth and adaptability in complex mission architectures.

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3 CROSS-DOMAIN TOP CHALLENGES

While the InSPoC-3 project organizes its analysis around four strategic domains, it also identifies a set of overarching challenges that cut across all of them (c.f Table 2). These cross-domain challenges are not confined to any single area of spacecraft design or operation; rather, they represent systemic issues that must be addressed holistically to enable the successful deployment of intelligent, autonomous, and cooperative space systems. Three such challenges stand out as particularly critical:

- Trade-off between longevity and modernity
- Reliability of AI systems
- Governance of data

These cross-domain challenges form the connective tissue of the InSPoC-3 framework. They underscore the need for a systems-level perspective that integrates technological innovation with architectural foresight, operational discipline, and ethical responsibility. Addressing these challenges is essential to unlocking the full potential of autonomous, cooperative, and intelligent space systems.

Table 2: Overview over InSPoC-3 top challenges as identified in the study.

Challenge	Description and Technologies
Top Challenge Trade-off between longevity and modernity	Spacecraft must operate reliably over long mission durations yet remain adaptable to fast-evolving technologies. This creates a fundamental conflict between using proven, long-lasting systems and integrating modern, innovative capabilities. To resolve this, spacecraft architectures must shift toward modular, software-defined platforms that allow for in-orbit upgrades and decoupled hardware-software development cycles, enabling both stability and innovation.
Top Challenge AI reliability	As AI becomes central to autonomous operations, its reliability, transparency, and safety are critical. AI systems must not only perform accurately under uncertainty but also be explainable and trustworthy. This requires robust validation, formal verification, and hybrid approaches that combine data-driven learning with symbolic reasoning. Without dependable AI, autonomous decision-making in space cannot be safely realized.
Top Challenge Data Governance	Intelligent space systems depend on high-quality, secure, and accessible data. However, space environments pose challenges such as limited access to relevant data, fragmented legacy datasets, limited bandwidth, and the need for real-time availability. Effective data governance must ensure integrity, confidentiality, and interoperability across mission phases. Techniques like federated learning, synthetic data generation, and standardized metadata frameworks are essential to support AI training, mission planning, and operational resilience.

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4 TECHNOLOGICAL FOUNDATIONS

The InSPoC-3 project identifies a suite of enabling technologies that form the backbone of future intelligent and autonomous space systems. These technologies are presented in Table 3 and are deeply interconnected, supporting each other across the four strategic domains and addressing the cross-domain challenges of longevity, AI reliability, and data governance. Together, they represent a paradigm shift in how spacecraft are designed, operated, and evolved over time.

Table 3: Enabling technologies addressing the cross-domain challenges.

Technological Foundations	Description
Software-Defined Architectures	Spacecraft are shifting from rigid hardware-based systems to flexible, software-defined platforms. Technologies like hypervisors and containerization allow modular, updatable systems that can adapt in orbit, enabling faster innovation and longer mission lifespans.
Explainable and Trustworthy AI	AI is central to autonomy, but it must be reliable and transparent. Appropriate Verification & Validation strategies in combination with Explainable AI (XAI) and hybrid models combining learning and reasoning help ensure safe, interpretable decisions in mission-critical contexts.
Sensor Fusion and Situational Awareness	To operate autonomously, spacecraft must accurately perceive their environment. Sensor fusion techniques integrate data from multiple sources, improving navigation, hazard detection, and coordination in multi-agent systems.
Secure and Resilient Data Operations	Data integrity and availability are vital for autonomy. Secure communication, encryption, and federated learning help manage fragmented datasets and ensure reliable AI performance, even in disconnected environments.
Readiness Metrics & Evaluation Frameworks	InSPoC-3 proposes a broader readiness framework beyond TRLs, including data, software, integration, service, and cybersecurity readiness levels. This helps to assess how technologies can be safely and effectively deployed in space missions.

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5 LOOKING AHEAD: A VISION FOR 2030 AND BEYOND

The InSPoC initiative is not only a response to current technological and operational challenges in space systems, but also a forward-looking framework that anticipates the evolution of space infrastructure over the coming decades. As we approach 2030 and look further toward 2050, the vision outlined in this document becomes increasingly ambitious, aiming to redefine the very nature of spacecraft, missions, and interplanetary logistics.

By 2030, the foundational technologies explored in this study, such as software-defined architectures, explainable AI, and distributed autonomy are expected to reach operational maturity. Spacecraft will no longer be static, single-purpose machines but dynamic, reconfigurable platforms capable of adapting to new tasks, environments, and mission phases. Over-the-air software updates, containerized applications, and modular avionics will enable spacecraft to evolve in orbit, extending their lifespans and expanding their capabilities without the need for physical intervention.

Artificial intelligence will play a central role in this transformation. By the end of this decade, onboard AI systems will be capable of real-time decision-making, anomaly detection, and adaptive mission planning. These systems will not only support autonomy but also enhance safety, efficiency, and responsiveness. Explainable AI techniques will ensure that human operators can understand and trust the decisions made by autonomous agents, while hybrid AI models will combine the strengths of data-driven learning and symbolic reasoning to deliver robust and interpretable behaviour.

Fleet operations will also undergo a significant shift. Rather than managing individual spacecraft, mission planners will oversee constellations and swarms of autonomous agents that coordinate their actions, share resources, and collaborate to achieve complex objectives. These fleets will be governed by distributed planning algorithms, service-level agreements, and predictive maintenance frameworks that ensure resilience and scalability. Interoperability standards and secure communication protocols will enable seamless integration across generations of spacecraft and across agencies and commercial partners.

Looking further ahead to 2050, the vision expands to include truly cognitive space systems – agents capable of reasoning, learning from experience, and adapting to novel situations without human oversight. These systems will operate in deep space, far beyond the reach of real-time communication, and will be entrusted with critical tasks such as in-orbit servicing, planetary exploration, and infrastructure assembly. Technologies such as neuromorphic computing, quantum-enhanced navigation, and self-repairing hardware will support these missions, enabling spacecraft to function autonomously for years or even decades.

The concept of the digital twin will also evolve. By mid-century, spacecraft will be accompanied by continuously updated digital replicas that mirror their physical state, operational context, and mission history. These twins will support predictive analytics, autonomous decision-making, and real-time coordination across fleets. They will serve as the foundation for a digital engineering continuum that spans the entire mission lifecycle from design and testing to operations and decommissioning.

In this future, space systems will no longer be isolated assets but intelligent, networked participants in a broader ecosystem of exploration, commerce, and science. They will collaborate with one another, adapt to changing conditions, and contribute to a sustainable and scalable presence in space. The InSPoC-3 project lays the groundwork for this transformation, offering a roadmap that bridges today's capabilities with tomorrow's possibilities.

The InSPoC-3 report presents a comprehensive and forward-thinking analysis of the challenges and technologies shaping the future of space operations. By embracing AI, software-centric design, and cooperative autonomy, ESA and its partners are laying the groundwork for a new era of intelligent, resilient, and scalable space systems. The outcomes serve not only as a technical reference but also as a strategic guide for navigating the complexities of next-generation in-space logistics and mission planning.

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