

Chapter 20

Future Trusted Autonomous Space Scenarios

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20.1 Introduction

This chapter describes the nature of the space environment that makes autonomous space systems a desirable application; describes the various types of space activities in near-Earth and deep space missions, and examples of autonomous systems deployed in space to date; outlines the current state-of-the-art of the intersection between trusted autonomous systems and autonomous space systems; and then presents a variety of possible future trusted autonomous space scenarios.

20.2 The Space Environment

The space environment is harsh and remote - a natural domain for autonomous systems. Beyond the protection of the Earth's atmosphere, man-made objects operating in space do so surrounded by extremes of temperature, high energy radiation, and near-vacuum (but not complete vacuum - for example, in Low Earth Orbit, dissociating and ionising radiation results in rarefied monatomic atoms and ions, for example oxygen and hydrogen, that interact negatively with satellites).

Space weather - disturbances to the near-Earth space environment resulting from solar activity - adds significantly to the complexity of the space environment, and poses additional threats to space-based (and ground-based) activity [1]. Solar disturbances including Coronal Mass Ejections (CMEs) transfer energy and momentum into near-Earth space, triggering magnetic storms [2]. We know from experience that

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space weather can degrade or even destroy spacecraft - yet our understanding of and ability to predict the dynamic space environment is poor.

Furthermore, artificial space objects do not fly simple orbits. Manoeuvres of spacecraft in orbit around other bodies (such as Earth) are non-intuitive and complex. Near-Earth space is not a vacuum, and has a non-uniform gravitational field. The latter is well understood, but the interactions that occur between space objects and their local dynamic space environment, known as astrodynamics, are non-negligible, and integrate to produce significant orbital perturbations.

Space is also becoming increasingly congested. The risk of in-orbit collisions is growing and can ultimately limit our use of space [3]. Inactive satellites and collisions are both contributors to a vast artificial space population. The Space Object Catalogue, which contains over 20,000 satellites or debris objects greater than (currently) 10cm diameter, will expand by an order of magnitude as new sensors are deployed this decade. The catalogue seeks to maintain accurate knowledge (and its uncertainty), of the orbit of each object in space, so that close approaches of space objects can be predicted and the probability of collisions computed, for evasive action to be taken (if possible, and if deemed necessary) by satellite operators on a case-by-case basis.

Deep space planetary exploration missions traverse vast distances across the solar system. This in turn brings into play the time delay for radio transmissions between Earth (in particular, Earth-based control rooms) and the remote spacecraft. For example, signals from Earth to Mars take between 3 and 22 min, depending on the position of each planet in their orbits around the Sun.

The distance from Earth to assets in space, whether they be in deep space or GEO or even LEO, is such that latency of communications can be an important issue, particularly when timeliness is important - for example, when performing planetary orbit insertions, or avoiding collision events. Trusted Autonomy can be very important for handling such issues successfully.

One final characteristic of the space environment relevant to Trusted Autonomy is that by its very nature, space is hostile to human life and therefore the ability to have close human supervision, management and operation of space systems is inefficient, costly and dangerous. This dictates extensive use of unmanned technologies, with the need for built-in autonomy; ranging from simple fault detection and isolation functions for hardware protection through to full, goal driven autonomy, depending on the complexity and purpose of the mission.

20.3 Space Activity - Missions and Autonomy

Space activity can be considered in terms of either in-orbit activity near Earth or deep space missions including planetary exploration. Robotics and autonomy play a role in each.

The near-Earth region can be divided into the typical orbit regions occupied by satellites: Low Earth Orbit (LEO), extending from a few hundred km to two thousand km above the Earth's surface; Geosynchronous Orbit (GEO), approximately 36000 Km above Earth where satellites orbit the Earth at the same rate that the Earth rotates beneath them; and Medium Earth Orbit (MEO), the region between LEO and GEO. Satellites in LEO are typically those performing remote sensing missions such as environmental monitoring, maritime observations, forestry and crop surveying, and more. The largest and most famous LEO satellite is the International Space Station. Satellites in MEO are typically those performing Global Navigation Satellite System functions (GPS, Galileo, etc.). Satellites in GEO are typically providing communications capabilities, including telephone, television and internet or weather forecasting services. Space science spacecraft are flown in a range of Earth orbits depending on the particular science objectives and implementation of the experiments and instrumentation.

Deep space exploration missions began with the manned Apollo program, but to date have almost entirely consisted of unmanned spacecraft missions. These include space probes that have flown past all planets in the Solar System (and in the case of the Voyager 1 and New Horizons spacecraft, have flown beyond Pluto); space probes that have been placed into orbits around planets or moons of planets (for example, Mercury, Venus, Mars, Jupiter, Saturn, Titan); planetary landers on planets, moons, asteroids and comets (for example, landers on Mars, Jupiter, Titan, as well as the Japanese landing on the asteroid Itokawa and ESA's recent Rosetta comet landing); and the various robotic rovers currently active on the surface of Mars. Considerable effort is currently being expended by the US, Europe, China and India, towards renewed manned deep space flight, and in particular towards manned missions to Mars and eventual colonization of Mars. In the shorter term, planetary rovers planned for the moon (China, India, Japan) and Mars (NASA and ESA) will continue to be developed and deployed.

Most spacecraft operations are automated, in so far as control functions and routines are uploaded via telecommand for immediate execution or, more typically, at predefined times in strict ordered sequences. For example, almost all remote sensing satellites automatically acquire images at predefined geographic locations and downlink them to Earth, while maintaining correct attitude with on-board sensors and reactions wheels. In-orbit robotic capabilities such as the Canadarm remote manipulator arms are controlled by astronauts. Few autonomous space systems, where the system makes decisions in order to achieve high level goals without human intervention, exist.

As described by the UK Robotics and Autonomous Systems Network [4], space robotics and autonomous systems will play a critical role in mankind's ability to explore and operate in space, "by providing greater access beyond human space-flight limitations in the harsh environment of space and by providing greater operational handling that extends astronauts capabilities". Indeed, NASA's Technology Roadmap for Robotics and Autonomous Systems [5] has the goal to extend and enhance human reach into space, and our ability to manipulate assets and resources, to prepare planetary bodies for human arrival, support astronauts in space operations,

and enhance mission operation efficiencies. A component of that goal involves the issue of safety and trust - in particular, to develop proximity operation technologies that allow humans to work safely side-by-side with robots or to be safe on or around robotic vehicles. The emphasis here is on the human-machine interaction, and the safety of the human in that interaction.

Gao et al. [4] further comment that autonomous systems can improve human and system safety by reducing human cognitive loads in complex situations, and can enable the deployment and operation of multiple space assets without significant increase in the level of ground support. Autonomous systems can also reduce human workloads by managing routine activities requiring constant monitoring over long periods of time. Frost [6] adds to these roles of autonomy in space systems, the concept of “virtual presence”, in which scientific investigation, in particular data analysis and the discovery that stems from it, is aided when the scientist is far removed from the instrument. In other words, autonomous ability for the space asset in orbit or deep space (and for example, in extremely isolated situations such as inside the seas of Europa) to not just acquire data but determine the value of that data and make decisions accordingly. For example, the NASA Swift spacecraft is able to autonomously abandon a pre-defined observation plan if it detects a Gamma Ray Burst and swiftly re-point its high resolution telescopes at the source within 90 s to capture the temporal dynamics of these highly energetic and rare events.

Frost [6] summarises some of the few examples of autonomous space systems that have been deployed: in 1998, the Deep Space 1 mission, with Remote Agent architecture, provided the first operational use of artificial intelligence (as described by Frost, an architecture that integrated constraint-based planning and scheduling, robust multi-threaded execution, and model-based mode identification and reconfiguration) in space, including complete autonomous operation for 29 h during which it responded to both simulated and real failures; Earth Observing 1, a remote sensing spacecraft launched in 2000, was able to employ autonomous acquisition and processing of science data, including autonomous detection in 2007 of an anomalous heat signature, self-scheduling of a new observation, and thus observing volcanic eruption of Mt. Erebus; the Orbital Express program led by Defense Advanced Research Projects Agency for robotic, autonomous on-orbit re-fueling and re-configuration of satellites - in 2007 this program, employing four levels of supervised autonomy ranging from telecommanded approval, to automatic action if ground override has not been enacted in a certain time, to autonomous operation with occasional communication with ground for verification, to fully autonomous operations where ground analysis only happens when a problem occurs, successfully used two prototype servicing and serviceable satellites to demonstrate autonomous capture and re-servicing; and Mars Exploration Rovers which are able to autonomously plan paths to objectives while avoiding obstacles, and autonomously process captured images and make decisions about what should be down-linked to Earth and what new observations should be made.

An additional aspect of space activity is worth considering here. Traditionally, the common feature of these satellites is that almost all perform their missions as individual large, sophisticated and expensive spacecraft. Space is currently undergoing

transformation however, due to the miniaturisation of electronics and the increased ease and reduced cost of access to space, for both government, commercial and research/education players. This is leading to opportunities for developing and flying “game changing” payloads that either perform existing space-based tasks in disruptive ways, or enable entirely new applications. The opportunities include robust autonomous formations and swarms of miniature spacecraft with fractionated or disaggregated sensor capabilities. The implications however, include the increasingly pressing need for managing the congested space environment, for example through autonomous space traffic management systems and/or autonomous spacecraft collision avoidance capability.

20.4 Current State-of-the-Art of Trusted Autonomous Space Systems

The development of autonomous space systems should include, as described in NASA [4, 5], the consideration of verification, validation, safety and trust. NASA Langley now have an Autonomy Incubator that is performing R&D towards autonomy that they occasionally describe as trusted autonomy. The use of the word “trust” in relation to autonomous space systems makes excellent intuitive sense, given the high stakes associated with space activity and especially when humans are involved. However, it would appear from the literature that when developing autonomous space systems, the need to be able to trust them before deploying them is a given. While the body of research recorded in the literature for trusted autonomous systems is growing, and likewise the amount of autonomy being developed and built into space systems is also growing, little has been reported to date on the intersection of these two fields. The only rigorous treatment of trusted autonomy for space systems in the literature to date is that of Freed et al. [7].

Freed et al. describe some of the above examples (Deep Space 1, Earth Observing 1), and point out that the autonomy built into them was less than originally intended, or only allowed in a post-mission phase, and that in general, their deployment has been limited due to a lack of trust. The lack of trust is ascribed to the difficulty in evaluating the behaviour of software designed to make complex decisions, and to the inherent research focus or custom nature of the software.

To build confidence in the reliability of complex software for autonomous space systems, Freed et al. describe verification and validation approaches (V&V), that employ runtime analysis and model checking; software design architectures that enable tractable modular verification tasks; and automated code generation combined with V&V technology to yield automatic formal V&V. Another critical aspect of building trust in autonomous software (called intelligent automation software by Freed) is ensuring that the domain experts - the engineers and scientists for the space activity - are involved in the design, development and verification of the software. This can include developing strategies that enable the domain expert to directly

participate in the coding of the models built into the software, while the software engineers take full responsibility for the more general purpose engine at the heart of the software.

Key to building trust however, according to Freed, is the incorporation of variable autonomy - the ability of the intelligent control software to support dynamic changes in the degree of autonomy. Variable autonomy advances the concept of selecting desired levels of autonomy when designing a space system, such as described by Proud et al. [8] and de Novaes Kucinskis and Ferreira [9]. It allows the human user or the autonomous system to adjust the system's level of autonomy as required by the current situation. It minimizes the necessity for human interaction, but maximizes the capability for that interaction - hence increasing the level of trust in the system. Freed outlines several principles for building effective variable autonomy systems.

Finally, Freed elaborates on the importance of building trust through long deployments - the test of time - and identify factors relating to building trust in the process. These include interfaces for humans to manually adjust autonomy; accounting for equipment degradation and the need for the ability of the system to perform safety shutdowns; logging system states to assist restarts; and supporting intermittent monitoring.

Freed concludes that by focusing efforts on V&V, variable autonomy and long deployments, highly capable and reliable autonomous space systems can be developed that can help extend our presence in space.

20.5 Some Future Trusted Autonomous Space Scenarios

As discussed above, autonomous space systems make good sense and indeed are essential if human usage and exploration of space is to expand, both in reach and in complexity. Trusted autonomous space systems will allow such activity to be pursued with confidence. There are various scenarios that can be envisaged in which space systems will be critical. Some of these are already in various stages of development and demonstration - for example the obvious scenarios of on-orbit satellite servicing/repair; autonomous on-board data processing, analysis and decision making - for example, for remote sensing for both Defence and civilian applications; and for future human habitation in space, which could include both deep space colonisation and space tourism. These are not elaborated upon here. Instead, three future trusted autonomous space scenarios are offered - a near-term scenario that pulls together some current applications of autonomy to space; and medium- and long-term scenarios based on the urgent need to manage the complex near-earth space environment without creating havoc and on the current transformation of space technologies towards miniaturisation.

20.5.1 Autonomous Space Operations

One scenario which could be realised in the near future, involving expansion and integration of existing methodologies and technologies such as have been described above, is in an increase in the level of autonomy embedded into the full scope of operation of a space mission once it has reached orbit. The space mission cost, often neglected or underestimated in early planning and system design phases is the ongoing cost of performing space operations. The cost drivers for this segment of the mission include, (1) the cost of acquiring access to the physical infrastructure to downlink telemetry from the spacecraft, i.e. the ground station, (2) the cost of planning routine mission operations based on the needs and priorities of the customer and the physical constraints of the spacecraft and payload (for example, thermal, power, fuel, propulsion, ΔV , on-board data storage constraints and ground sun illumination angle conditions), (3) the cost of processing telemetry through a pipeline to generate the corrected and calibrated data products, and then interpreting them to provide actionable knowledge to end-users, and (4) the cost of employing highly skilled, experienced staff to assess the probable impacts of unforeseen contingencies on the ability of the space system to deliver its service reliably and effectively and to then make the correct operational decisions based on limited information. A common feature of these cost drivers is that they tie up expensive resources (for example; ground stations, experienced engineers) for extended periods of time performing relatively routine activities, interspersed with bursts of activity with high levels of criticality (for example; downlinking imagery indicating the threat of flooding in a highly populated area, or planning the recovery of a spacecraft which has lost attitude due to a temporary fault in a single subsystem before the entire spacecraft is lost). If Trusted Autonomy of both the space segment and the ground segment can be incorporated into space operations in an efficient and cost effective manner, then the ongoing cost of operating space missions can be significantly reduced. By increasing the amount of processing and interpretation of data within the space segment, fewer human and physical resources are required to downlink and process redundant data on the ground. By automating the analysis and interpretation of operational information from disparate sources, the engineering costs of operating the spacecraft and responding to anomalies are reduced. The key challenges to increasing the level of Trusted Autonomy in spacecraft operations and gaining these benefits lie in the difficulty of gaining sufficient confidence to entrusting an asset costing typically several hundred million dollars to such a system, the heuristic and probabilistic nature of some spacecraft operational decisions and the difficulty of algorithmically encoding features like experienced, engineering judgement into such systems.

20.5.2 Autonomous Space Traffic Management Systems

At present, global networks of space surveillance and tracking sensors feed data to centralized space operations centres - the primary one being the Joint Space Operations Center operated by Air Force Space Command. Effort is made to maintain orbit information for the entire Space Object Catalog, propagate orbits, predict the probability (and associated uncertainty) of conjunctions and collisions, and provide satellite operators as much time as possible to decide whether to take evasive action.

As the number of space actors, including non-government actors, increases, and as the number of miniature spacecraft in orbit grows from hundreds to many thousands, the current sensor network and conjunction warning approach will be insufficient. By combining autonomous sensor networks on the ground (including non-traditional sensors such as Square Kilometre Array) and in orbit, for both space object location and behaviour and for space environment dynamics; and by using high fidelity physics-based simulations of the dynamics space environment and the behaviour of space objects in that environment to train neural-network based surrogate models for real-time high accuracy orbit predictions for each tracked space object; and by constructing suitable communications networks to communicate to all live satellites that have manoeuvre capability; a global trusted autonomous space traffic management system can be envisaged that safely assists the large future spacecraft population to manoeuvre through complex debris fields without collisions, and safely queues and guides future rapid launch/responsive space access satellite launches to safely reach orbit at very short notice. The autonomous sensor and orbit prediction aspect of this scenario is currently under development in Project Ananke, led by the University of Arizona and including Air Force Research Laboratory and industry. Ananke is designed to provide autonomous rapid information for human decision makers to trigger appropriate action. A fully autonomous space traffic management system would extend this to include the decision-making and action into the system itself.

20.5.3 Autonomous Disaggregated Space Systems

Disaggregated systems of spacecraft are often discussed, particularly for military applications in which formations or swarms of small spacecraft fly in orbit, with the payload distributed across the formation such that information can be determined or capability achieved that would not be possible with a single or small number of spacecraft, and that robustness/resilience of the system is achieved. For example, consider some of the work of the Australian Centre for Field Robotics on cooperative UAV systems and UAV-based decentralized air surveillance systems, in which Decentralised Data Fusion and Control capability is combined with a variety of sensors, on-board processing and complex communication networks between platforms to build up surface terrain maps by the system in real time [10]. Such a system could be extended to include the space domain, with multiple sensors deployed across not

only large numbers of networked miniature spacecraft, but also across high and low altitude UAVs. The system would be robust against failure of or damage to individual members of the swarm. It would need to have a level of at least partial autonomy, such that it can acquire, process and fuse data and make decisions for further acquisitions without the need for consulting with ground stations (which may be out of range), and such that it has the autonomous ability to disperse sufficiently to avoid congestion and collisions (with each other and with other spacecraft and debris) and then reform. It would need to be autonomous because of the complexity of the system and the complexity of the GNC problem. It would need to be trusted, partly for the autonomy needed to achieve its mission, and partly so that it achieves its mission without adding to the space debris field.

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