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Resiliency in Space Autonomy: a Review

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Abstract

Purpose of Review: The article provides an extensive overview on the resilient autonomy advances made across various missions, orbital or deep-space, that captures the current research approaches while investigating the possible future direction of resiliency in space autonomy.

Recent Findings: In recent years, the need for several automated operations in space applications has been rising, that ranges from the following: spacecraft proximity operations, navigation and some station keeping applications, entry, decent and landing, planetary surface exploration, etc. Also, with the rise of miniaturization concepts in spacecraft, advanced missions with multiple spacecraft platforms introduce more complex behaviours and interactions within the agents, which drives the need for higher levels of autonomy and accommodating collaborative behaviour coupled with robustness to counter unforeseen uncertainties. This collective behaviour is now referred to as resiliency in autonomy. As space missions are getting more and more complex, for example applications where a platform physically interacts with non-cooperative space objects (debris) or planetary bodies coupled with hostile, unpredictable, and extreme environments, there is a rising need for resilient autonomy solutions.

Summary Resilience with its key attributes of robustness, redundancy and resourcefulness will lead toward new and enhanced mission paradigms of space missions.

Keywords Space robotics · Robot manipulators · Sub-T exploration · Distributed spacecraft · Resiliency · Autonomy

Introduction

With the advancements in rocket science, space engineering, astrophysics and robotics, the theme of space movement, which was once the exclusive domain of science fiction, the space odyssey is rapidly approaching reality. In the history of space achievements, the human-crewed mission to the Moon was a global turning point. The exploratory nature supported by technological progress makes human beings place footprints beyond the Earth. The inquisitiveness toward the search for life on other planets and looking for the possibility of space colonization drives the current space missions directed toward planetary exploration [1••]. Analysing the soil environment on the extraterrestrial surface, mineral harvesting [2], and energy harvesting [3] are some of the futuristic objectives for planetary exploration. Apart from planetary exploration, there are increasing interest in the exploration of small celestial bodies like asteroid and comets. Knowledge on historical evidence of asteroids impact motivated research directed toward planetary defence systems to protect our mother Earth. In search of historical evidence regarding the formation and evolution of the universe, robotic space missions have been carried out as technology demonstration of sample returns from near-earth asteroids [4–9]. Moreover, deep space celestial bodies, where the radio signals originating from the Earth cannot reach, serves as a favourable location for installing radio observatories for cosmological studies and to explore extra-terrestrial life [10, 11]. With the aim of comprehensive space inquisitive and

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the purpose of scientific exploration, space agencies across the globe are collaborated and built International Space Station (ISS), which reaches a sustainable on-orbit human establishment.

With the advent of the twenty-first century, with the wake of miniaturization and the rise in commercially off-the-shelf components for building small spacecraft (mainly nanosats), the space industry is heading towards more innovative and cost-effective approaches to accomplish ongoing orbital and deep space missions. In addition, the space sector is evolving into a new era that is characterised by new dimension of cooperation and interaction between governments, private sector, and society, which is also defined as Space 4.0/New space. Specifically, there is a rise in the new aerospace community (mostly private aerospace companies) advocating for low-cost access to space and spacecraft technology. As a result, the next-generation space missions focus on the prospect of more complex orbital operations, which include active debris removal, on-orbit servicing through rendezvous and docking, cooperative missions with multiple satellites such as constellation and cluster formations, and so on [12••]. In addition, traversing the uncharted territories such as Halo orbits around the Lagrange points, probing multiple asteroids and comets across the solar system and beyond, autonomous soft-landing on planetary bodies, etc. are some of the very challenging missions that are becoming increasingly common.

In order to accomplish such a diverse range of complex and challenging mission objectives, both within and beyond the low-earth orbits, advanced robotic system is integral to any sustainable space exploration and exploitation program [13]. Space robotics is crucial since they operate tirelessly and cost-effectively in the hostile and partially known outer space environment without endangering human lives. Space manipulators [14], an integral part of conventional space robotics systems, provide predictable control over target behaviour. Robotic manipulator arms are mounted on spacecraft as part of space manipulator systems. Additionally, space/robotic systems are essential for maintaining the existing space infrastructure and serving as an essential technology for space missions.

Space robotic system with autonomous operation will be the key enablers. Typically, spacecraft in conventional Earth-bound missions receive guidance commands from Earth for their orbital correction needs. However, for sensitive close-proximity operations such as a docking mission, as well as for missions with greater navigational uncertainties such as inter-planetary close proximity missions, establishing a telemetry connection to orbital and deep-space vehicles is a significant concern due to the inherent communication latency and navigation uncertainties. Consequently, autonomous robotic systems [15••] for space exploration and exploitation are attracting the frontier of current research. For deep-space missions, such as missions beyond the Moon and Mars, the need for autonomy arises from the long communication delays in relaying the two-way communication for making remote operations. An example could be the landing mission on a distant celestial body, where remote operations are nearly impossible considering the significant communication delays and, thus, demands for more advanced, robust, and reliable autonomy onboard. Thus, space robotics is currently evolving and pushing the space community towards a paradigm shift in terms of the use of new technology combined with autonomy concepts to accomplish many challenging and innovative mission scenarios which are impossible to achieve with the present state-of-the-art partial or complete human-in-loop mission execution practices.

However, in reality, such autonomous robotic systems may encounter adverse scenarios, such as exploration through extreme and unforeseen environments leading to structural degradation, subsystem failures like sensors and actuator malfunctioning, experiencing unexpected disturbances etc., which might limit the durability and scope of consistent operation. Thus, making space robotic systems resilient to failure is a significant challenge for practical deployments. In order to sustain operation in such a hostile situation, a sufficient degree of dexterous flexibility and redundancy in mission-level design and system-level design with onboard intelligent decision-making capability are crucial factors. Thus, space robotic systems demand a high degree of resiliency in strategic planning, designing and system-level autonomy, incorporating reliability in sensing, perception, localization and motion planning.

In general, a system is termed to be resilient if it demonstrates (i) robustness, i.e. the ability to maintain desirable performance irrespective of the disturbances or unseen or unpredictable situations, (ii) redundancy, i.e. the ability to overcome any sub-systems failures by either replacing the faulty part or by adapting this component with its reduced functionality, and lastly (iii) resourcefulness, i.e. the system adapts to the changes in the surroundings as well as to the changing mission needs to some extent. Across different fields of systems, resilience is defined differently. According to sociology and ecology [16], resilience is a quality of social and ecological systems that allows them to adapt to changes and persist. Recent years have seen the emergence of the resilience concept in engineering, which encompasses more broader aspects incorporating self-healing, fault tolerance, self-repair, sustainability, reliability, and survival capacity of systems in a complex engineering framework.

In the recent past, space missions involving multiple agents operating in collaboration have been explored with the aim of obtaining complex robotic behaviours that are difficult to achieve using single-agent systems. Years of robotics research have allowed the derivation of a multitude of multi-agent collaboration techniques applicable to several domains, including navigation, coverage, manipulation and more. Although not necessary, techniques involving multi-agent systems deal with the aspect of resilience against adverse and complex conditions in the process of agent-to-agent cooperation. For example, a team of CubeSats is tasked to autonomously and collaboratively rendezvous, inspect, dock, and manipulate a non-cooperative tumbling spacecraft, where it is highly likely that certain conditions can cause one or more agents to degrade partially or entirely. At this point, the teamed resilience should autonomously adjust the overall mission plan in order to complete the desired mission tasks in the best possible manner, irrespective of any faults. In general, robot resilience depends on the following factors: (1) the type of recovery strategy used and the number of recovery strategies used, (2) the performance of the function that can be recovered, (3) the number of resources required for the recovery of the function, (4) the time it takes to recover the function.

Scientists and researchers worldwide are attempting to develop the robust structural design of space robots supported by a resilient autonomy stack for both orbital as well as deep-space space exploration. In view of that, the present work provides an extensive overview and coordination of current research approaches while investigating the possible future direction of resilient space autonomy solutions. Space autonomy is included in several operational categories, which are covered in this article. In an overview, the organization of the article is presented as follows. The article primarily analyses the requirement for resiliency in space autonomy from the perspective of "Planetary Exploration" and "In-orbit Robotic Missions". In the first part of the article, resiliency aspects associated with autonomous planetary surface and sub-surface exploration, such as "Resiliency in Structural Design" in terms of autonomous reconfigurability of exploration robots, "Collaborative Sensing, Localization and Mapping" characterized by advanced cognition and perception, intelligent "Autonomous Path Planning", "Mission Planning and Resource Management" including "Autonomous Landing" for viable space transportation are discussed. The next part of the article considers resiliency in autonomy associated with the in-orbit operation, such as "On-Orbit Servicing/Actuation" for reusability of existing satellites, "Orbital Guidance and Motion Planning", "Attitude and Orbit Control System" and "Autonomous In-orbit Resilient Navigation" for collaborative planning and operation for future space missions. Finally, discussions and remarks are included in the "Conclusions" Section.

Planetary Exploration

Ever-lasting quest for the existence of life in the past or present, planetary exploration is gaining increased momentum with the aim of developing a long-term research base for scientific exploration [17, 18]. Space agencies across the globe agreed upon the associated standard space road map [19] on the realization that the upcoming exploration missions need to be empowered by a manifestation of self-sustainable resilient autonomy. Typically planetary surfaces are exposed to environmental perturbation due to dynamic cosmic events such as meteoroid showers and large temperature variations, which makes it challenging to reveal the trace of archival events in planetary history. On the contrary, deep subterranean voids are most suitable for planetary settlements and preserve consistent evidence of long-term origin, history, and structure, such as the presence of water remains, traces of life and other evaporative compounds. In view of that, next-generation planetary exploration aims to focus on explorations through Sub-Terranean voids. Space robotics has evolved in the past years towards deploying rovers and aerial robots in interplanetary missions. These technologies have been proven to be effective on Earth [20], as well as on Mars [21] with the most recent deployment of the Perseverance rover and Ingenuity UAV. Despite the immense breakthrough in planetary exploration, multiple challenges are still present when it comes to the resilient autonomy of the deployed space robotic systems, which introduces a risk for the future success of space robotic exploration missions. Such multi-agent robotic exploration typically requires resiliency in structural design, localization, mapping, local path planning and global mission planning sub-modules, which are discussed in the following subsections.

Resiliency in Structural Design

The current trend of mechanical designs of space robots such as wheeled rovers or robotic arms are configured based on classical mechanical fabrication supported by rigid joints [22]. Such structural systems designs without any provision for structural reconfiguration are not resilient for operation in coarse space environments, where it needs to withstand rough terrestrial and extraterrestrial conditions. The space environment consisting of ultraviolet radiation, charged particles, meteoroids, and debris exposes equipment to a multitude of diversity that differs from those on Earth. There are three significant sources of space radiation, which predominately appear from particles trapped in the magnetic field, solar energetic particles from the Sun, and galactic cosmic rays. It is difficult to shield against space radiation particles (especially galactic cosmic rays), which can cause severe effects on construction materials, thereby defeating the functionality and fundamental aspects of long-duration resilient space missions. Moreover, due to the lack of atmosphere in space, low pressure and wide variation of temperature range intensify the adverse effect [23].

The primary concerns for the construction of space robots need to account for the structural design aspects that enable lightweight framework [24] while making it durable [25, 26] for more extended operation. In view of that, metallic alloys or fibre-reinforced polymer composites are the most suitable materials that have been heavily investigated [27]. However, future space missions are coming with critical requirements where the space robots are supposed to be exposed to extreme scenarios such as high-impact collision, in situ mining and construction of extraterrestrial habitation, where the scope of the conventional design is limited. In order to conquer the barrier of the conventional design, researchers are looking forward to using specifically designed smart materials [28–30] for use in space construction [31]. Appropriate polymers, especially macro-porous polymers and foams, provide additional functionalities such as variable stiffness or tensegrity-inspired micro-structures.

With this alignment, soft robotics design [32] have taken considerable attention from advanced research. Such designs predominantly enable adjustable structural shape and allow flexibility of operation in cluttered space environments, making the structure resilient to impacts, falls and crashes. Soft material technologies not only provide structural resistance to the overall system but also it has the capability to absorb shocks, heal, and modify the structural properties from rigid to visco-elastic, thus making the robot squeezable. In order to resist structural deformation in harsh mission conditions and provide sufficient resiliency for unforeseen impact, self-healing materials [33] are being considered as the frontier of the current technological development. Self-healing materials change the mechanical properties through their stiffness-controlled principles [34, 35] and thereby indulge autonomously repair of inherent flaws that appear due to sudden impact or damage. In view of that, the next-generation space robotic designs are focusing on hybrid integral structures where the robotic joints would be made of soft materials in conjunction with the variable stiffness materials for the construction of the structural elements.

Collaborative Sensing, Localization and Mapping

In order to enable a higher degree of resiliency through Sub-T, exploration needs to involve multi-robot collaborative operation with multi-modal [36] operational capability. The multi-modal configuration [37], such as the collaborative functionality of aerial and ground robots, will establish an expandable outreach of the exploration domain and enhance the durability of operation. Moreover, the involvement of multiple robotic units will provide redundancy to the overall system without the risk of exposure to mission failure [38] in cases one or more subunits become operational.

When multiple aerials and on-ground robots are being deployed to explore, it is necessary to identify and localize each robot and perceive its ego-motion. Towards this direction, multi-sensor fusion-based resilient pose estimation is an essential prerequisite, which enables autonomous motion planning and decisions about future actions. In this direction, various multi-sensor fusion algorithms [39] improve perception and localization related to the surrounding environment. Mostly multi-sensor fusion relies on extended Kalman filter–based estimation [40] approaches that consider linearized dynamical motion, which embeds numerical errors induced by inaccurate linearization. Moreover, classical filtering approaches are sensitive to faulty measurements and sensor failure. In contrast, various Simultaneous localization and mapping (SLAM) frameworks are established for the structured environment. A few SLAM frameworks embark on the challenge of unstructured, uncontrolled and unknown natural environments [41]. However, in general, SLAM-based exploration methods are computationally expensive and require a high configuration onboard computers to localize and store the previous information on the map accurately.

While operating with multiple robotic units, efficient reconstruction of a local map with a low degree of information is essential to keep track of exploring areas more efficiently. The multi-robot dense mapping literature considers various approaches [42] that have been proposed as concepts, including sub-map matching, sharing and alignment, factor graphs integrating inter-robot observations, segmentation and descriptors map fusion formulated in a probabilistic framework [43, 44]. A map-based motion planning and autonomous navigation are presented in [45]. Perception modalities have also been reported in planetary rover navigation, terrain classification, and mapping [46].

Autonomous Path Planning

In order to realize the concept of hyper-modality robots [47], risk-aware path planning [48] is necessary to be considered. Autonomous path planning algorithms for ground-based robotic manoeuvres on planetary exploration are documented in [49, 50] and for ground and aerial robots in [51]. Autonomy for re-configurable robots is evolving as a revolutionary aspect of space robotics for a wide variety of locomotion [52, 53], while the geometry-morphing aerial platforms focus on the design of the platform and the low-level control scheme to maintain its stability when shape reformation occurs during the flight [54, 55]. In order to validate such planning algorithms, realistic simulation framework is an essential alternative before deploying the configuration in space. In view of that, numerical modelling for the design of aerial robots for interplanetary missions has evolved over the last decade with an increase in computational capacity and more efficient numerical codes. The aerodynamics has been of particular interest, especially for robots with rotor blades [56, 57], where the Ingenuity UAV is the latest vehicle operating on the Martian surface. The aerodynamics is also important in various instrument designs, such as sensors and hot-wire anemometers [58].

Mission Planning and Resource Management

The SubT voids consist of unknown extreme terrain features like rocky, granular, and sandy terrains, flat, high-slop areas etc. Thus, a mission planner is associated to provide high-level tools that enable resource allocation by assigning individual agents of the multi-modal platform to transverse through such extreme terrains while considering the kinematic constraints of each individual sub-component. Mission planners for exploration missions have moved from remotely planned to semi-autonomous ground-in-loop approaches in the quest of achieving consistent high levels of productivity [59]. Several approaches with autonomous onboard identification and selection of science target to cover in the surrounding based on the ground-expert defined criteria [60], whereas in [61] additional onboard scheduling is introduced to improve the resource utilization of the rover. Perception modalities have also been studied in planetary rover navigation, terrain classification, and mapping [42, 43].

Autonomous Landing

In order to explore and set up an extraterrestrial base as a habitat environment, space transportation plays a significant role. A planetary exploration mission's success is viable only on the successful execution of landing on the planetary surface at a carefully selected landing site. Landing missions require fragile and rather expensive payloads to be delivered to the targeted planet using space vehicles; due to this fact, an autonomous safe landing is critical for the success of the mission [62]. Such autonomous missions require a fuel-optimal guidance scheme that assures the soft landing with near zero touchdown velocity [63] for protecting the rover and other instruments while maintaining vertical orientation. Moreover, unmanned autonomous missions are usually preferred for long-duration space exploration for good reasons such as lower risk, elimination of a life-support system, and so on. Due to these advantages, autonomous missions are gaining increased attention globally. However, the guidance of a spacecraft for soft-landing is quite challenging due to complex requirements along the trajectory and the limited capability of the associated hardware. In the recent past, advancements of technology and improved reliability on hardware have enabled unmanned autonomous missions for long duration space exploration.

A brief review of the performance assessment of various descent guidance algorithms that have been previously used for practical missions is summarized in [64]. Typically exploit guidance algorithms [65, 66] are preferred. Even though numerical guidance algorithms have the capability to incorporate realistic motion planning by associating various levels of constraints, the iterative solution approaches demand an intensive computational burden. However, with the remarkable advancement in computational efficiency of next-generation space-grade processors [67], the numerical optimal control algorithms [68–74] have taken considerable attention of researchers as the next best alternatives for near future missions. In view of that, various progressive approaches such as second-order cone programming–based convex optimization [75] and other numerical guidance law [76] are proposed for the powered descent phase of Mars soft landing. The need for dexterous autonomy promotes the concept of visual perception-enabled [77] provably safe relative guidance strategies with a high degree of resiliency incorporating constrained sensor field-of-view [19], ground collision avoidance and uncertainty handling as the research frontier.

In-orbit Robotic Missions

With the enormously increasing space activity across the globe, satellite populations have dramatically increased in the Geosynchronous Equatorial Orbital regime. The numerous discarded objects like spent rocket stages, inoperative satellites, and fragments from disintegration, erosion and collisions are continuously gathered in space orbits. The possibility of potential collisions with the existing space debris causes potential threats to upcoming space missions. The situation might pose cascading collision, leading to catastrophic effects [78], [79], which would cause a significant impact on industry, individuals, and nations worldwide.

In order to get rid of such a situation, space debris mitigation [80–83] has taken considerable attention of research. Small celestial bodies such as asteroids or comets also pose another source of threats to life on Earth. [9] and [84] require autonomous solutions for in-orbit manipulation or deflection of potentially destructive asteroids which has become another significant concern for space robotics researchers. To execute such a highly complex mission accurately, the overall space autonomy stack must be resilient enough to ensure fail-safe operations.

On-Orbit Servicing/Actuation

Once a servicing spacecraft is within the operating range of debris, the docking phase of the mission begins. Suppose the service spacecraft is using a robotic arm to capture the debris spacecraft. In that case, the robotic arm needs to be initially deployed in order to use it for grasping operations. Robotic space missions deployed for technological demonstrations involve robotic manipulators mounted on a space vehicle, requiring accurate navigation [85]. Such manipulators allow extreme dexterity to perform complex tasks such as capturing, docking, berthing, repairing, upgrading, assembling, refuelling, and any money more applications [86, 87] as the universal solution to conduct robotic space missions in an orbital environment.

Unlike on-ground operations, where the base of the robotic arm is fixed, in a space environment for on-orbit applications, the robotic arm is connected to the service spacecraft, which is floating, and as a result, the motion of the arm influences the translational and rotation dynamics of the base platform. Such dynamic coupling of the robotic arm and the spacecraft dynamics complicates the reconfiguration of the arm in the desired orientation [88, 89]. The deployment of the robotic arm follows the pre-grasping phase of the mission, where the relative translational and angular velocities between the service and the debris spacecraft is reduced as close to zero as possible so that the end effector of the robotic arm can maintain stable contact with the debris. Next is to plan the motion of the robotic arm in order to grasp and dock the desired debris [90]. During the post-grasping phase, manoeuvres are implemented in order to bring the debris very close to the servicing spacecraft to rigidly couple both spacecraft, which is then followed by either a deorbit manoeuvre or moving towards new debris that is to be removed. This on-orbit manipulation is equivalent to the aerial manipulation based on manipulators attached to drones, where lately there has been significant attention from the robotics research community [91].

Orbital Guidance and Motion Planning

In general, guidance law provides a real-time sequence of action in terms of force/acceleration to enable onboard planning of spacecraft trajectories. Whereas the spacecraft control is responsible for following the guidance-generated trajectories based on real-time feed from sensors in the presence of disturbances, measurement noise, and model uncertainties [19]. Traditional approaches on GNC strategies [92] to rendezvous and docking, found in the literature and used historically on-orbit, follow a glideslope trajectory [93] popularly known as R-bar (chaser approaches along the radial direction) and V-bar (chaser approaching along the forward velocity direction). Apart from these classical approaches, various progressive methods such as Genetic algorithm [94] and Search tree–based path planning [95] have also been studied to mitigate the guidance requirement of proximity operation. In addition to the above, several other optimization methods such as second-order cone programming (SOCP) [96], sequential quadratic programming (SQP) [97], and particle swarm optimization [98] have been studied in the literature for rendezvous and docking purposes. Since debris is a tumbling space object, it demands more intensive study when considering coupled nonlinear dynamics consisting of both attitudes as well as relative translational motion. This results in a different class of problems when compared to the traditional rendezvous and docking mechanism. Nonetheless, some study has been performed in this direction, dealing with docking with [99], a non-cooperative tumbling target using a real-time nonlinear MPC solution.

Attitude and Orbit Control System

A space mission cannot be completed without an Attitude and Orbit Control System (AOCS). A satellite’s trajectory is set by the launcher that hauls it into orbit. It is selected by orbital dynamics experts years before the satellite is built, then manoeuvred into its operational orbit by smaller thrusters [100]. Thus, the onboard closed-loop control takes part in the spacecraft’s pointing direction. It is known as spacecraft attitude, and it proceeds along its orbital path. A two-layered hierarchical closed-loop control is implemented for space robotic orbit operations. A wide range of control schemes can be considered for those functions as it considers different kinds of information transfers from the outer to the inner controllers. Thus, a few robust and adaptive techniques are mentioned below; this paper [101] represents a growing number of spacecraft that are adopting new and more efficient forms of propulsion in space. Their limited thrust capabilities are characteristic of these high-efficiency propulsion techniques. Consequently, they must thrust continuously for long periods, making the spacecraft susceptible to missed thrust events. As a result of this study, neural networks were shown to be capable of autonomously correcting missed thrust events during a long-duration low-thrust transfer trajectory. In this article [102], the relative position tracking and attitude synchronization of non-cooperative spacecraft rendezvous with model uncertainty and external disturbances is proposed. Nowadays, the space industry relies heavily on free-flying robotic spacecraft. Space robot manipulators cause unwanted disturbances to the spacecraft platform, causing its attitude to change and potentially disrupting communication and solar energy collection processes as opposed to ground-based robots. Coordinated control of the spacecraft's attitude and the manipulator's motion is essential for successful space operations. In this [103], a novel adaptive variable structure control method is applied to implement a robust coordination controller for the space robot subjected to system uncertainties. This paper [104] tackles the problem of integrated translation and rotation finite-time control of a rigid spacecraft with actuator misalignment and unknown mass property. As a result of the natural couplings in the system, coupled translational and rotational dynamics of the spacecraft are developed, taking into account a thruster configuration with a misaligned installation and unknown mass. Similarly, [105], [106], and [107] represent resiliency operation for the spacecraft rendezvous and docking, controlling the uninhabited surface vehicle, berthing, repair and re-installation, and mitigation of different satellite operations in space missions.

Similar to the problem of designing trajectories for the on-orbit inspection of the debris spacecraft, exploring small celestial objects like asteroids and comets is recently emerging as a challenging trend amongst space agencies across the globe [108]. In search of the history of solar system evolution and trace of life, the scientific interest in celestial sample-return from Near-Earth Object and global attentiveness growing towards the rising demand for planetary protection drives high demand for asteroid exploration missions. In order to achieve such a diverse class of ambitious objectives, precise autonomous space navigation has critical importance [109]. Significant asteroid missions that have been successfully executed include NEAR-Shoemaker [110] that performed the first soft landing on an asteroid, Hayabusa returned a small sample [111] of the Itokawa asteroid, and most recent ROSETTA [112] mission that made the first landing on a comet's surface [113]. Asteroid missions have been conducted so far and require significant human intervention on the ground for supervision of the navigation process. In order to operate precisely around small bodies, the spacecraft must possess good knowledge of its pose (includes position, orientation, linear and angular velocity) as well as the asteroid's pose estimates along with the dynamic model to predict future states. In the absence of an accurate positing system, locomotion around unexplored space objects is difficult. In view of that, a comprehensive review of the orbital navigation framework is presented next.

Autonomous In-orbit Resilient Navigation

The evolution of modern sensor technology [39] enables unprecedented provision for autonomous perception and cognitive understanding for advancing the self-sustainability and resiliency of future embodied autonomous systems [114]. Obtaining relative pose with respect to the small celestial bodies, inoperative satellites, or space debris based on onboard sensors for proximity operations [85] is in the frontier of research in space navigation [115, 116]. With the immense advancement of image processing technologies [117], the vision-enabled pose estimation system is recently emerging with onboard camera-based navigation mechanisms for autonomous missions. Space imagery is characterized by dynamic illumination conditions, low features, high contrast, background noise, and low signal-to-noise ratio [116, 118]. This could compromise image processing algorithms and negatively impact estimation accuracy and robustness. Moreover, the non-cooperative space objects are, in principle, irregular in shape and size, while there do not exist any distinguishable marked features such as QR-code. In [119], a satellite onboard vision-based pose and angular velocity estimation is presented for a non-cooperative object without using artificial markers or targets for its operation. Monocular systems are examined for their robustness and applicability for estimating an uncooperative spacecraft's pose [120]. This study examines state-of-the-art techniques and provides insights into their limitations under adverse illumination and orbit scenarios. A visual servo system proposed in [121] is an approach to provide robust pose estimation of the target model and the calibration parameters (configuration parameters of the camera) in the presence of uncertainties. It works well in dealing with unknown targets and low illumination conditions. [122] describes an algorithm that uses stereo vision measurements to estimate the target geometry and states during rendezvouses with the target using a camera mounted on the arm of the chaser spacecraft. A sequential state estimation using monocular cameras is presented in [123]. A featured-based identification method is presented in [124], which estimates the target's motion even though lacking sufficient features by incorporating a point-wise motion model on all visible parts. Additionally, it can remove the complications associated with the sunlight reflection on cameras or use heavy sensors such as Lidar. This article [116] presents a fault-tolerant method combining Kalman filter (KF) and iterative closest point (ICP) algorithms in a closed-loop configuration for pose estimation of space objects. A novel adaptive unscented Kalman filter (AUKF) was introduced to estimate an arbitrary space target's dynamic state vector (position, orientation, linear and angular velocities). Using an adaptive Kalman filter in [125], a vision system can estimate the motion of a tumbling target satellite with greater robustness and accuracy. In addition, adaptive Kalman filters are capable of estimating model parameters, including the moment of inertia and centre-of-mass of the target satellite. For real-time pose and motion estimation of non-cooperative targets, a hybrid approach of adaptive extended Kalman filter and photogrammetry is developed in [126]. Unscented KF [127–129] combines images and measurement data collected from a coordinated network of distributed satellites and explores the concept of identifying targets with multiple spacecraft [12••, 130].

The capacity to accurately estimate the pose of a satellite despite external disturbances and sensor failure is addressed in [131]; in the proposed method, a bank of observers is combined through median operations, showing that the method is resilient. Despite attacks on sensors, estimated states asymptotically converge to the actual states of the systems. The integration of multiple sensors with self-resiliency using a unique optimal isolation algorithm is proposed in [132]. The proposed method in [132] involves several stages to overcome the fault from the measurement signals. The concept of nodes is introduced to extract information from multiple asynchronous sensors in a sequential manner. Each node fuses position and orientation information from independent sensors separately. Essentially, the nodal architecture introduces the possibility of distinguishing partially defective measurements and broadens the possibility of fusing all the acceptable data. It would be beneficial to utilize the position measurement instead of discarding all sensor information if a sensor provides an accurate position and defective orientation measurement for a short period. In such a way, the information from each node is integrated into a weighted combination by employing a maximum likelihood estimator to obtain the most accurate pose collectively. A weighted combination of the information obtained from each node is used to obtain the most accurate pose using the maximum likelihood estimator. Moreover, it is challenging for robotic applications to operate in constantly changing landscapes. Sensor accuracy, failures, and noise in the operating environment can all affect the systems' ability to provide accurate pose information. Realistically, such corrupted sensor measurements often occur temporarily, for instance, in areas with inadequate illumination. Further fusion with other onboard sensors like lasers or infrared sensors is necessary to improve pose estimation accuracy and ensure resilience [133, 134].

Conclusions

In this article, we have presented a broad overview of the current research trends in the field of autonomous space robotic systems, specifically focusing on the various aspects that enable resiliency toward the sustainability of long-duration space missions. Space activities in current practices are comprehensively classified into two sub-categories: planetary exploration and on-orbit autonomy. For the case of planetary missions, exploration of the subterranean areas and voids, which are characterised by hostile, fully unknown and unstructured, extreme environments with zero possibility of ground contact (Earth-based communication), are considered to be the next frontiers for maximum science returns. Whereas in the case of on-orbit mission cases, future missions are moving towards the physical interaction and manipulation with both cooperative as well as non-cooperative tumbling objects. In view of these ambitious mission capabilities, various aspects of resiliency in the structural design of robotics systems, exploration strategies, and advanced autonomy approaches are identified and highlighted in the manuscript. Distinctly, the review brings out the fact that space activities across the globe are looking forward to pioneering solutions that will empower the future of space exploration missions by advancing the self-sustainability and resiliency of the embodied autonomous system.

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Declarations

Conflict of Interest The authors declare no competing interests.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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Papers of particular interest, published recently, have been highlighted as:

- • Of importance
- ••Of major importance

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