INVITED PAPER

Robotics and AI-Enabled On-Orbit Operations With Future Generation of Small Satellites

This paper provides an overview of the robotics and autonomous systems (RAS) technologies that enable robotic on-orbit operations on SmallSat platforms.

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ABSTRACT | The low-cost and short-lead time of small satellites has led to their use in science-based missions, earth observation, and interplanetary missions. Today, they are also key instruments in orchestrating technological demonstrations for on-orbit operations (O^3) such as inspection and spacecraft servicing with planned roles in active debris removal and on-orbit assembly. This paper provides an overview of the robotics and autonomous systems (RASs) technologies that enable robotic O^3 on smallsat platforms. Major RAS topics such as sensing & perception, guidance, navigation & control (GN&C) microgravity mobility and mobile manipulation, and autonomy are discussed from the perspective of relevant past and planned missions.

KEYWORDS | Autonomous systems; robotics; small satellites

I. INTRODUCTION

Small satellites have revolutionized access to space by drastically reducing the cost of launching and operating a satellite in space. This has opened new opportunities for universities, the commercial sector, and the national space agencies. The low-cost and short-lead time for small satellites (or smallsats), identified in this paper as sub-1000-kg systems [1], [2], has led to their adoption in numerous science-focused missions [3], [4], e.g., Earth imaging using the Michigan Multipurpose Minisatellite (M-Cubed) carrying the CubeSat On-board processing Validation Experiment (COVE) [5], weather monitoring using the GEO-CAPE ROIC In-Flight Performance Experiment (GRIFEX) [6], and CubeSat Infrared Atmospheric Sounder (CIRAS) [7] satellites. Small spacecraft are also valuable testbeds for maturation of space technology, e.g., validating high-data rate Earth–satellite communication using the Intelligent Payload Experiment (IPEX) CubeSat [8], and formation flying demonstration using CanX-4 and CanX-5 nanosatellites [9]. Commercial companies like Planet Labs have launched over 200 CubeSats and are delivering great benefit to mankind by freely publishing their Earth imaging data [10]. Moreover, CubeSats and nanosatellites are also being considered for interplanetary exploration missions, e.g., Mars CubeSat One (MarCO) for relaying communications between a Martian lander and Earth-based ground stations [11], Near-Earth Asteroid Scout (NEA Scout) [12] and Arkyd series [13] for studying asteroids, and Lunar Flashlight to investigate lunar craters [14]. Thus, there is significant potential for scientific and commercial returns from small satellite missions in Earth orbit and beyond.

Today, smallsat platforms are also key instruments in orchestrating technological demonstrations relevant for on-orbit operations (O^3). O^3 (read O-cubed) comprises the following broad operations: on-orbit servicing (OOS) [15] of spacecraft involving tasks such as inspection, repair,

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and assisting astronauts with extravehicular activities (EVAs) [16]; on-orbit assembly (OOA) of modular systems such as large aperture telescopes [17], [18]; and active debris removal (ADR) [19]. These are discussed in more detail in the subsequent sections.

A key enabler for O^3 are the different technology capabilities broadly defined by the term robotics and autonomous systems (RASs) for small satellites [20], [21], which is the focus of this paper. Space robots and small satellites allow us to overcome limitations in exploring and operating in harsh environments where it is too risky for human astronauts. Autonomy enables difficult and risky robotics operations by exploiting advances in sensing and perception, computational capabilities, and reduces human cognitive load. Modern RAS for O^3 is a multidisciplinary field that builds on our knowledge of space engineering, terrestrial robotics, computer science, electrical and mechanical engineering, systems engineering, etc.

Robotic O^3 involves a robotic agent (or chaser) operating on a client spacecraft (also called a target), which can be further classified as cooperative or noncooperative targets. A variety of technological challenges exist in robotic O^3 such as pose estimation of chaser and target, relative station keeping for proximity operations, autonomous rendezvous and docking maneuvers, and manipulation. Over the last two decades, important in-space demonstrations using smallsats have been performed to evaluate the maturity of these underpinning technologies. As the first smallsat inspector, the Autonomous Extravehicular Activity Robotic Camera Sprint (AERCam Sprint) [16] played a pivotal role in the development of other small platforms such as the Synchronized Position Hold Engage Reorient Experimental Satellites (SPHERES) [22] and Astrobee [23], [24]. In 1997, the Japanese Engineering Test Satellite VII (ETS-VII) was used to conduct autonomous and teleoperated robotics research into rendezvous and docking, and in-space manipulation with a cooperative target microsatellite [25]. The general trend of miniaturization can be evidenced in DARPA's Orbital Express [26] which utilized a 1100-kg chaser to demonstrate Autonomous Rendezvous and Docking (ARvD) to refuel and transfer a battery unit and flight computer to a 224-kg target satellite. More recently, NASA's Robotic Refueling Mission (RRM) [27] utilized a mini-satellite target in its operations. The mission heralds a new age for working with satellites not designed for servicing, dispelling one of the many myths against OOS. These missions and other relevant systems are discussed in subsequent sections. It should be noted that both small and large platforms have their place in the greater space robotics scheme; small free-flyers like the AERCam Sprint can operate in proximity scenarios where larger systems cannot. Equivalently, refueling may be an operation that is best left to larger agents. Thus, robotic smallsats are not necessarily replacements for larger platforms but will complement them.

At this moment, O^3 are in the demonstration phase and smallsats have been prominent in them. Our position is that their role as critical mission elements is inevitable as the space robotics community moves toward the realization of O^3 missions. This paper discusses significant recent developments in RAS on smallsat platforms for a variety of orbital operations and associated demonstrations. The layout of the paper is as follows. Section II provides a background in the area of small orbital robots. Section III discusses some of the key enabling technologies in the current platforms and indicates future directions for development based on the current state of the art in both small and large platforms. Section IV concludes the paper. This work is not intended to be a comprehensive review on orbital robotics (identified as space robotics for orbital applications such as space telescope assembly, satellite repair, etc. [28]) but presents a bird's eye view of this vast field. For interested readers, we recommend the exhaustive surveys on space robotics [29], on-orbit robotic servicing [30], and active debris removal [31].

II. ROBOTIC ON-ORBIT OPERATIONS: BACKGROUND

A typical O^3 involves a free-flying chaser performing an action on a target. The baseline for the chaser is performing passive tasks without directly affecting the state of a target, e.g., inspection. If it is desired to alter the state of a target, the operation will involve docking or capture with an appendage on the chaser such as a robotic arm with end effectors. This creates obvious parallels between debris removal and servicing activities like refueling, repair, and maintenance. Finally, the free-flying manipulator system may also be used to perform assembly. Thus, based on the nature of the task performed by the chaser, we discuss O^3 in three categories:

- passive OOS for tasks such as inspection;
- ADR and active OOS for operations involving an extant client;
- OOA which involves the assembly or creation of a new client (which may subsequently require active or passive OOS).

The remainder of this section discusses recent developments in each of these areas involving robotic smallsat platforms.

A. Passive On-Orbit Servicing

The last 20 years has seen important progress in realizing small free-flying robotic systems for inspection and assisting astronauts on the ISS. Vision-based inspection systems are especially important due to the many risks posed to spacecraft and astronauts from the growing threat of space debris [32], [33]. Such systems allow monitoring spacecraft health and also increasing space situational awareness (SSA). Further, the principles underpinning inspection are integral toward performing other proximity operations in ADR and active OOS, such as docking and capture.

To date, AERCam Sprint [16] is the only inspection robot to be used outside a spacecraft for EVA assistance. It was teleoperated for 75 min, by astronaut Steve Lindsey, alongside EVA astronaut Winston Scott on STS-87 in 1997. This nanosat-class robotic assistant's success informed the development of a smaller platform with increased autonomy called the Mini AERCam [34]. It has yet to be flown but has been ground-tested on air-bearing tables.

Another nanosat-class platform that has been flown in the pressurized microgravity environment within the ISS, and is still active, is SPHERES [22] developed at the Massachusetts Institute of Technology (MIT, Cambridge, MA, USA). The SPHERES facility comprises three identical satellites that are equipped with onboard navigation systems. Their modular design extends their capabilities to perform a wide range of experiments. So far, they have been used to demonstrate formation flying [35], magnetic propulsion [36], and vision-based navigation through the addition of the VERTIGO Googles [37], [38] developed through the Low-design Impact Inspection Vehicle (LIIVe) program [39]. The goal of LIIVe is to develop vision systems to inspect legacy spacecraft at single-meter ranges.

While the initial motivation of SPHERES was on developing systems for EVAs, the benefit of free-flying systems in assisting astronauts for intravehicular activities (IVAs) has also recently been explored in the Smart SPHERES program [40]. One of the limitations of the SPHERES platform is its reliance on consumables; primary batteries are used for electrical power along with canisters of compressed CO_2 for the propulsion system. This is being addressed in the Astrobee [24], [41], [42], a dedicated IVA robotic assistant for routine tasks such as tool inventory maintenance. Its development team envisions that swarms of Astrobees will eventually perform more complex tasks such as on-orbit telescope assembly. A very recent addition to the ISS is JAXA's Internal Ball Camera (Int-Ball) for reducing time spent by astronauts in photographing; according to JAXA, the crew on the Kibo module spend about 10% of their current working hours in photography operations. The Int-Ball free flyer is capable of autonomous navigation [43]. Fig. 1 presents images of some of these free flyers.

B. Active Debris Removal and Active On-Orbit Servicing

Rapid growth of space debris poses risks not only to current missions, but also future ones as access to certain orbits may be cut off in the future [32], [33]. Though an ADR mission is a high priority for all space agencies, one is yet to take flight. A variety of mission concepts to tackle this issue have been proposed [31] and most planned demonstrations envisage the use of smallsats. Apart from the launch and rendezvous phases, an ADR operation has the additional challenge of debris capture and disposal operations. Both robotic and nonrobotic options for performing these tasks have been proposed. However, Table 2 in [31] shows that the robotic options using single and dual robotic manipulators [44], and tentacles [45] are at the highest technology readiness level (TRL) relative to systems such as nets and harpoons. Thus, the robotic options are the more likely candidates for these missions. A study on ESA's e.Deorbit mission [46] examined the use of tentacles with and without robotic arms; through simulations, it is shown that robotic arms improve

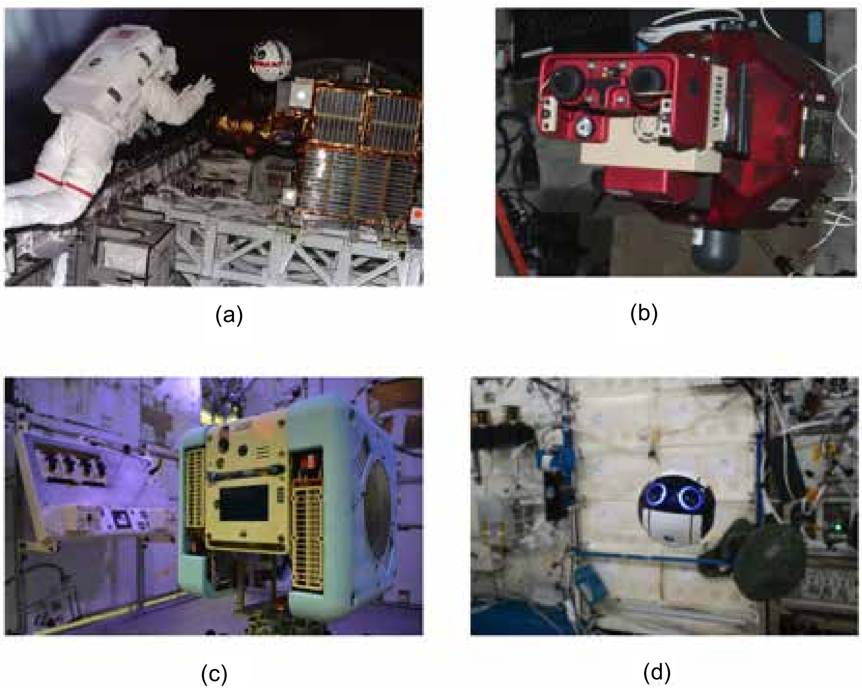

Fig. 1. ***(a) AERCam Sprint (image credit: NASA). (b) SPHERES with Vertigo Goggles (image credit: MIT [38]). (c) Astrobee (image credit: NASA Ames Research Center and IEEE Spectrum [23]). (d) Int-Ball (image credit: JAXA/NASA [42]).***

system performance. However, they increase the overall cost. Aviospace's CApture and DEorbiting Technologies (CADET) [47] project has also proposed the use of tentacles for ADR.

JAXA is actively pursuing ADR and OOS utilizing smallsats. Their initial proposal of a robotic ADR mission using electro dynamic tethers (EDTs) [48] informed the development and ground testing of a robotic arm of the space debris microremover (SDMR) [19]. The SDMR is a small satellite equipped with a robotic arm and EDT for debris capture and propellant-less orbital transfer of the target. JAXA have also proposed an orbital maintenance system concept [49] to inspect, repair, and remove satellites. The relevant imaging technologies for this mission were successfully tested on a microsatellite in space [50].

Given the overlapping nature of activities in ADR and active OOS, DLR has developed a single-arm mission concept called DEutsche Orbital Servicing (DEOS) [51]. Ground-based demonstrations of crosscutting technologies in ARvD [52], [53] are being performed at the EPOS test facility [54] with a flight experiment planned using two smallsats as chaser and target.

The DARPA initiatives, Phoenix [55] and Robotic Servicing of Geostationary Satellites (RSGS) [21] along with NASA's Restore-L [56] build on the success of Orbital Express [26] to demonstrate servicing capabilities with the Front-End Robotics Enabling Near-Term Demonstration (FREND) robotic arm [57]. The goals of these missions are to demonstrate the servicing of satellites that were not originally built for in-space servicing. The current state-of-the-art OOS demonstration is NASA's RRM [27] wherein the Dextre robotic arm serviced a small spacecraft. DARPA's Orbital Express exploited the use of small platforms in its experiment on autonomous rendezvous and docking. As the definitions of the other missions get clearer, the role of smallsats in them will become more apparent.

The involvement of robotic smallsats in ADR and OOS is thus evident. Images from relevant missions are presented in Fig. 2.

C. On-Orbit Assembly

The case for OOA of large space structures was cemented by the construction of Mir and the ISS [58]. Apart from space habitats, there is a scientific need for larger telescopes. However, limits in contemporary launch vehicle fairing are a constraint to getting these systems to space as a monolithic structure. The consensus in the broader space community is that the only feasible option for building and operating such large space structures is autonomous OOA from modular elements [59]. Recently, there has been activity in the smallsat community in implementing some of these ideas. The most notable planned mission is the Autonomous Assembly of a Reconfigurable Space Telescope (AAReST) project [17] developed by the California Institute of Technology and Surrey Space Centre to demonstrate the docking of multiple smallsats to form a larger synthetic aperture using a magnetic latching system, and Light Detection and Ranging (LiDAR) systems for Guidance, Navigation, and Control (GN&C). Apart from this, strategies involving robotic arms for in-space assembly has been discussed by commercial smallsat companies [60]. Telescope assembly using the SPHERES satellites was proposed in [18] and, more recently, tested for a generic OOA in a ground-based testbed [61]. The previously discussed satlets in DARPA's Phoenix program exploit a cellular architecture which does not require specific docking

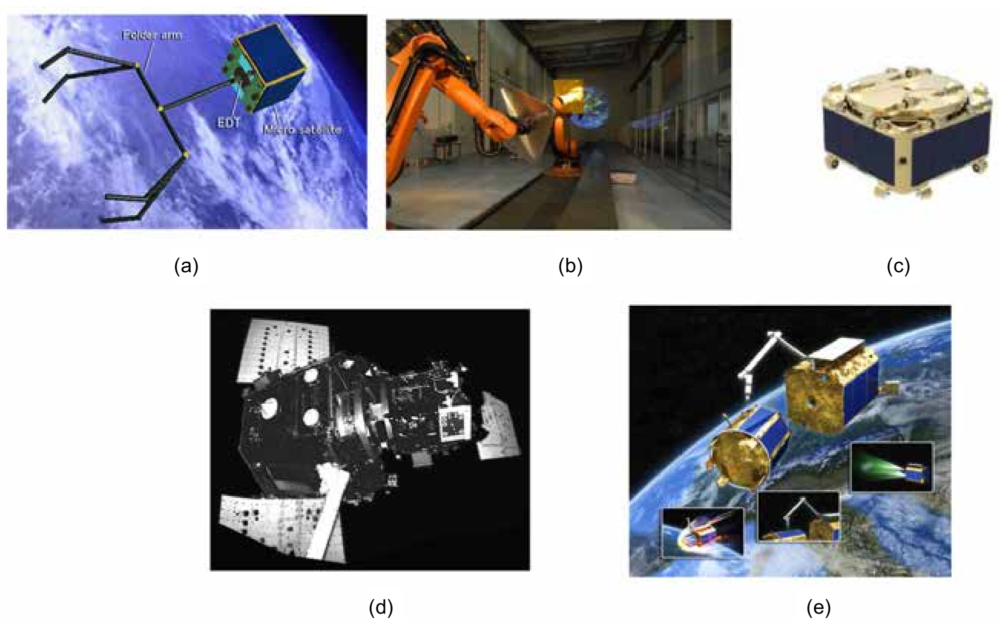

Fig. 2. ***(a) SDMR [19]. (b) EPOS facility [54]. (c) DARPA satlet [121]. (d) Orbital Express [26]. (e) DLR's DEOS [51].***

orientations and positions [62] which could offer greater flexibility in assembling large structures.

OOA is clearly in a nascent stage and the activity in the smallsat community is among the most promising of an early demonstration.

III. ENABLING TECHNOLOGIES AND CHALLENGES

O^3 tasks utilize a number of overlapping core robotics technologies which are broadly categorized as:

- sensing and perception;
- GN&C;
- microgravity mobility and mobile manipulation;
- onboard autonomy and intelligence.

Sections III-A–III-D will delve deeper into these topics, current trends, and needs in these different areas.

A. Sensing and Perception

Sensing and perception is the first essential system component required for the successful performance of proximity operations by a chaser. In theory, various sensing modalities (e.g., monocular or stereo cameras, GPS, LiDAR, and RADAR) can be used to localize a chaser relative to a target. Simultaneously, it is also necessary to estimate the pose of the target; also, in the case of unfamiliar targets like debris, a 3-D model must be reconstructed. The nature of the target is one of the several factors that influence sensing choices on the chaser. A cooperative target can be classified as active or passive. An active one communicates its pose (location and attitude) to a chaser via radio; a passive one might use fiducial markers or retrorefelectors to assist the chaser in estimating this information. On the other hand, if the target is uncooperative then it can be further classified into targets with known and unknown geometry, with the former being especially relevant to O^3. This grander pose estimation problem for both cooperative and noncooperative spacecraft is widely studied and exhaustively surveyed in [63].

Generally, electro-optical sensors (e.g., monocular and stereo cameras, LiDAR) are "the best option for pose estimation in close proximity" [63] operations. Monocular and stereo cameras are passive sensors that require additional image processing to extract depth information, making their use computationally expensive. Additionally, the images often have a wide dynamic range due to the harsh illumination in space which leads to both overexposed and underexposed regions that may not be solved by adding artificial light sources [64]. Alternatively, LiDAR systems may be used for relative navigation as they are more robust to ambient lighting variations and provide direct depth information with the caveat that they are heavier, more expensive, and consume more power. Their performance also degrades if surfaces on the target produce specular reflections. Thus, mass, volume, and power requirements also strongly dictate sensor choice. Finally, the range from a target also impacts choice; thermal infra-red cameras have been used for the farthest relative bearing measurements, operating at tens of kilometers, while visible light cameras can be used at closer range. Scanning LiDAR can be used to determine position and orientations at ranges up to ~3 km [65], while conventional monocular cameras have the capability to precisely identify fiducial markers during close approach. Sensor choice for relative navigation is also discussed in [66].

Based on the open literature, the current state of the art for an IVA-type nanosat class robotic system is the SPHERES satellites which utilize ultrasound receivers and computer vision for localization [67] and navigation [68] using simultaneous localization and mapping (SLAM) algorithms for target pose estimation. Its intended replacement, the Astrobee, will utilize a monocular camera with augmented reality tags, WiFi, and 3-D depth sensors [69] to do the same. The 360-kg Demonstration for Autonomous Rendezvous Technology (DART) spacecraft had similar technical goals as EXperimental Small Satellite 11 (XSS-11) [70] but utilized a laser-based system known as the advance video guidance sensor (AVGS) [71]. As chasers get bigger, they offer the luxury of a sensor suite such as that seen on the Orbital Express which combines the AVGS with three imaging cameras for its relative navigation system called the Autonomous Rendezvous and Capture Sensor System (ARCSS) [72], [73].

The use of LiDARs is prominent in the transition to the larger mini-satellite platform. The 125-kg XSS-11 utilized a sensor suite comprising an active scanning LiDAR and a passive camera to demonstrate autonomous rendezvous in space. More recently, flash LiDARs, a type of scannerless LiDAR, are of interest to the space community for relative navigation [74] as it is both lighter and consumes less power with a tradeoff in image resolution [75]. The SpaceX dragon vehicle also uses this type of sensor to navigate during proximity operations with the ISS [75]. DLR is investigating the use of a photonic mixer device (PMD) camera as an alternative to scanning LiDARs [76]. These systems are also known as time-of-flight cameras. The use of plenoptic cameras for close-range robotic arm operations is currently being investigated as it offers the benefits of decoupling the effects of aperture size from the depth of field [77].

More generally, sensor development for relative navigation is an active field of research with NASA developing the Raven module consisting of an infrared camera, a flash LiDAR, and a visible camera with a variable field-of-view lens [78]; the visible camera's field of view is controlled using a zoom lens and the entire sensor package is maneuvered on a pan-tilt platform. Neptec's Tridar system is the current state of the art for in-space relative navigation around uncooperative objects [65], superseding the vision systems in the ETS-VII [79] and Orbital Express [72] for navigating around cooperative targets.

Thus, sensing and perception systems are an active field of research and technology demonstration.

B. Guidance, Navigation, and Control

The sensing and perception subsystem, described above, is strongly coupled with the guidance and control (G&C) subsystem. As discussed in Section III-A, perception involves pose estimation of the chaser and target using sensor data. In the spacecraft controls community, the acronym GN&C (guidance, navigation, and control) is often used; here, the term "navigation" implies that the pose estimation process is separated from the operation of the sensors. The GN&C system also includes Attitude Determination and Control System (ADCS) hardware, flight software, and algorithms. The ADCS hardware itself consists of sensors to determine the orientation and angular velocity, and the actuators for changing orientation of chaser as needed. Miniaturization of GN&C hardware is the main trend on smallsat platforms [80]. Except for integrated units, all other hardware are at high TRL. Further, innovative and safe propulsion technologies continue to be developed in the nanosat class. AERCam Sprint and SPHERES utilized high TRL cold gas thruster units for six-degrees-of-freedom (6-DOF) maneuvering which need replacement. The Astrobee and Int-Ball circumvent the need for thrusters with fan-based propulsion units.

In the context of O^3, the primary concern is in target-relative GN&C (also referred to as rendezvous GN&C [53]) which is reliant on relative sensing elements. However, GN&C systems for inertial navigation are equally important and can be used to improve target pose estimates [53]. In GN&C algorithms, the "guidance" function is responsible for planning the trajectory (both position and orientation) and the "control" function ensures that these trajectories are followed. In order to achieve autonomy, the onboard G&C system must be capable of computing robust, real-time solutions to an optimization problem that are verified [81] through simulations, ground testing, and flight technology demonstrations.

As almost all O^3 involve rendezvous and docking or capture, the current emphasis in relative GN&C focuses on maturing ARvD with cooperative [26], [82] and uncooperative targets [27], [53], [83]. A detailed historical perspective of manned and unmanned space rendezvous missions until 2005 is provided in [70]. Flight demonstrations such as DART and XSS-11 have focused on autonomous rendezvous but more recently docking has also been demonstrated by missions such as ETS-VII [84], Orbital Express [26], and RRM [27]. XSS-11 achieved its mission objectives and is the only smallsat to autonomously plan and rendezvous with a passive or cooperative resident space object (i.e., not one launched as part of the demonstration) in low Earth orbit. A number of low TRL validation of ARvD algorithms have been carried out on air-bearing testbeds [61], [82], [85]–[90]. In order to reduce collision risk due to relative state estimation errors during ARvD, the satellite can enter a safety ellipse trajectory around the target object. A safety ellipse trajectory is an out-of-plane elliptical periodic relative motion trajectory around the target such that the trajectory never crosses the velocity vector of the target [91], [92].

Though autonomous formation flying (AFF) flight demonstrations also validate similar GN&C technologies as ARvD, "the scientific literature makes a clear distinction between the two" [93]. Thus, AFF missions [94] are not covered in this paper; for this, we direct readers to the detailed surveys of Scharf *et al.* on formation flying guidance [95] and control [96], respectively, along with [3] for a survey of recent missions.

In summary, it is evident that GN&C systems of smallsats is a thriving research area with a wide spectrum of TRLs.

C. Microgravity Mobility and Mobile Manipulation

Microgravity mobility refers to the motion of free-flying robotic systems around other spacecraft such as the ISS. The SPHERES platform have only operated within the confines of the ISS. The AstroBee and Int-Ball, as IVA assistants, will be similarly confined within the ISS. Thus, as the AerCAM Sprint remains the only free flyer to be deployed outside a space vehicle to date, there is a growing need to increase efforts on developing more such systems for inspection. The development of such free-flying mobile units is strongly coupled with the realization of free-flying manipulator systems to tackle debris, assemble space systems, and repair in space. The literature on these systems is vast and has been covered in several space robotics surveys [29], [30].

The Astrobee's perching capabilities will push the development of miniaturized manipulator systems. Such perching capabilities are also being developed for DARPA's satlets by Honeybee Robotics [97] while Tethers Unlimited has developed the Kraken manipulator [98] for nanosatellites. While none of these systems have been space verified as yet, there is also a rich history of operational manipulator systems that can guide this work. The Canadarm, formally known as the Shuttle Remote Manipulator System (SRMS), is the cornerstone on which all space-based manipulators have been built so far. Apart from demonstrating the need for and versatility of in-space manipulation, it has inspired similar efforts from other space agencies. In 1993, DLR introduced the ROTEX [99] to the ISS making it the first remotely operated space robot and the Japanese ETS-VII was the first teleoperated free-flying robot arm. In the same year as ETS-VII, the Manipulator Flight Demonstration (MFD) [100] demonstrated the dexterous manipulation that would eventually be performed by the Small Fine Arm (SFA) on the ISS. Both agencies have continued to contribute to manipulator systems attached to the ISS; JAXA's SFA and Japanese Experiment Module-Remote Manipulator System (JEM-RMS) [101], and DLR's ROKVISS [102], [103] assist the ISS's Space Station Remote Manipulator System

(SSRMS) and Dextre in performing a variety of tasks such as payload module positioning.

Most of the manipulator systems aboard the ISS are capable of performing large-scale assembly while only Dextre has dexterous manipulation capabilities demonstrated by the RRM [27]. NASA's Robonaut [104] currently operates within the ISS with the vision of reducing astronaut risk during EVAs such as the Hubble Space Telescope servicing [105]. It is considered the state of the art in dexterous manipulation [106]. DLR's Dexhand is another noteworthy effort in the development of a space qualified robotic hand [107], [108]. The testing of gecko-inspired grippers to grasp and manipulate large tumbling objects in microgravity represents another compelling innovation to tackle the large debris problem [109]. Fig. 3 shows some of the relevant systems discussed in this section.

Thus, it is evident that much work continues to be done in the areas of manipulation and microgravity mobility. However, a parallel effort in the area of microgravity mobile manipulation is equally necessary in developing mission-defined free flying manipulators such as JAXA's proposed SDMR [19].

D. Onboard Autonomy and Intelligence

Autonomy is the ability of an agent to accomplish goals through rational decision making based on its knowledge and understanding of the world, itself, and the situation [110]. The need for onboard autonomous behavior in spacecraft is strongly influenced by communication latency between spacecraft and ground stations; even with continuous view of ground stations, satellites in geosynchronous Earth orbit (GEO) are subject to a communication latency of 240 ms while satellites in low Earth orbit (LEO) can go several hours without contact to ground stations. Thus, increased autonomous capability is imperative for continuous spacecraft operations and performing critical tasks which takes into consideration communication delays and lack of ground station visibility. Furthermore, autonomy is also necessary when dealing with environmental uncertainty that cannot be sufficiently or accurately captured in deterministic models, e.g., a lack of complete space situational awareness.

In general, autonomy is distributed across a system in three ways:

- no autonomy, i.e., human in the loop for all operations;
- full autonomy, i.e., the system performs all activities without a human in the loop;
- partial autonomy where humans are in the loop for some critical tasks.

Full autonomy is desirable in O^3 to increase mission reliability which becomes considerably more complex when dealing with uncooperative targets. Most spacecraft proximity operation demonstrations, apart from the RRM and SPHERES, have worked with cooperative agents. Even missions involving cooperative targets have proven difficult

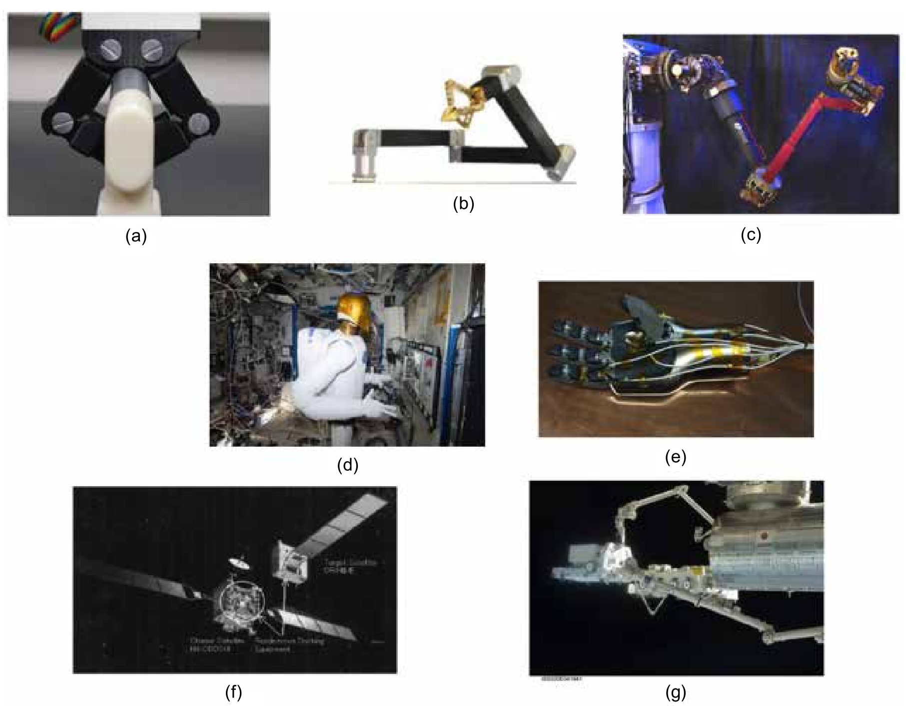

Fig. 3. ***(a) Astrobee Perching System (image credit: NASA Ames Research Center [42]). (b) KRAKEN arm (image credit: Tethers Unlimited [98]). (c) FREND arm [57]. (d) Robonaut 2 (image credit: NASA [120]). (e) DexHand (image credit: DLR [108]). (f) ETS-VII (image credit: JAXA[84]). (g) JEMRMS and Canadarm (image source: NASA [119]).***

as seen in the loss of the DART spacecraft upon collision with its target [111]. Thus, achieving full autonomy is still an open field of research. The challenges span the areas of algorithm and software development [103].

Development of onboard motion-planning algorithms is an exciting field with applications that transcend spacecraft relative GN&C. A critical requirement is robustness of algorithms capable of running in real time on a robotic smallsat. This has led to much work into real-time motion planning [112], [113]. Similar developments can be found in the literature on free-flying space manipulators [114]–[116], which are pertinent to O^3. See [30] for a survey of recent developments in this area involving free flyers.

Space robots for O^3 needing high levels of autonomy and extreme fault tolerance are also good candidates for self-reconfiguration software. For example, suboptimal performance of a navigation camera would result in poor performance of the GN&C system. However, this could be circumvented if a system could autonomously solve errors and reconfigure itself. One such approach has recently been proposed and successfully tested on autonomous planetary rover mockups [117], [118]. Here, the onboard software can reconfigure itself by tracking data from sensors and actuators. The software also contains an ontology describing the environment in which it operates to accurately self-reconfigure the system based on fuzzy reasoning. The utility of a similar approach to developing self-reconfigurable software for robotic smallsats during OOA of large telescopes has recently been discussed [60].

Given the comparatively low TRL of autonomy technologies, significant attention is focused on overcoming these challenges which will set the platform for the first full O^3 smallsat mission.

IV. CONCLUSION

The smallsat platform has opened space to participants from universities and the commercial sector who have complemented the work of national space agencies. Their wide adoption in a variety of missions clearly demonstrates the significant potential for scientific and commercial value. Another consequence of this democratization of space has been in raising the TRL of many of the underlying RAS technologies, which in turn have enhanced the role of smallsats as key instruments in demonstrations for O^3. In this paper, we have discussed the recent progress and possible future directions in the core RAS technology areas of sensor development, GN&C, mobility, manipulation, and autonomy that are enabling these demonstrations. Though important progress has been made in each of these fields, several challenges still remain, especially in the area of mobile manipulation and autonomy. Overcoming the hurdles in these areas will lead to the realization of the first full O^3 mission in which smallsats are sure to play a central role. ■

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