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Grappling Spacecraft

Carl Glen Henshaw,[1] Samantha Glassner,[1] Bo Naasz,[2] and Brian Roberts[2]

[1]Naval Center for Space Technology, US Naval Research Laboratory, Washington, DC, USA; email: glen.henshaw@nrl.navy.mil

[2]Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, Maryland, USA

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Abstract

This article provides a survey overview of the techniques, mechanisms, algorithms, and test and validation strategies required for the design of robotic grappling vehicles intended to approach and grapple free-flying client satellites. We concentrate on using a robotic arm to grapple a free-floating spacecraft, as distinct from spacecraft docking and berthing, where two spacecraft directly mate with each other. Robotic grappling of client spacecraft is a deceptively complex problem: It entails designing a robotic system that functions robustly in the visually stark, thermally extreme orbital environment, operating near massive and extremely expensive yet fragile client hardware, using relatively slow flight computers with limited and laggy communications. Spaceflight robotic systems are challenging to test and validate prior to deployment and extremely expensive to launch, which significantly limits opportunities to experiment with new techniques. These factors make the design and operation of orbital robotic systems significantly different from those of their terrestrial counterparts, and as a result, only a relative handful of systems have been demonstrated on orbit. Nevertheless, there is increasing interest in on-orbit robotic servicing and assembly missions, and grappling is the core requirement for these systems. Although existing systems such as the Space Station Remote Manipulator System have demonstrated extremely reliable operation, upcoming missions will attempt to expand the types of spacecraft that can be safely and dependably grappled and berthed.

1. INTRODUCTION

Robotic spacecraft are among the most visible applications of robotic hardware and algorithms. NASA uses a large robotic arm system, the Space Station Remote Manipulator System (SSRMS), to assemble new modules for the International Space Station (ISS) and to berth incoming spacecraft delivering crew and supplies. Rovers with arms explore Mars, collecting and caching samples for future return to Earth. Movies and television shows depict humans and robots exploring space side by side (or, in *2001: A Space Odyssey* and *Battlestar Galactica*, as possible adversaries).

However, the world has yet to deploy a corps of robotic astronaut assistants. Robots are not regularly repairing broken satellites, topping off the tanks of satellites low on fuel, or upgrading instruments, computers, or batteries on aging space telescopes. Public perception seems to be running ahead of reality in this most obvious area of robotic applications.

This article provides a survey overview of the most basic operation to be performed by our new robotic astronaut overlords: that of approaching and grappling a free-flying satellite in need of service, fuel, or a simple tow to a different orbit. Specifically, we concentrate on using a robotic arm to grapple a free-floating spacecraft, as distinct from spacecraft docking and berthing, where two spacecraft directly mate with each other, a technique with a great deal of history and literature (1, 2). Readers should also note the excellent review articles on space robotics more generally by Flores-Abad et al. (3), Gao & Chien (4), and Yoshida (5); the compendium edited by Skaar & Ruoff (6); and the tutorial overview by Ellery (7).

2. OVERVIEW, TERMINOLOGY, AND CONCEPTS

The basic problem of grappling a client spacecraft can be neatly divided into two approaches depending on whether the client has been engineered to be robotically serviced. These two approaches are referred to as prepared (or sometimes cooperative) and unprepared servicing.

Prepared clients usually have a robotic grapple fixture along with perceptual aids such as optical fiducials to facilitate an autonomous or teleoperated robotic grapple. Relatively few spacecraft have such fixtures because they add mass and complexity, and consequently cost. However, spacecraft intended to provide service to the ISS have grapple fixtures and fiducials compatible with the SSRMS, and satellites that were launched on the Space Shuttle often had similar fixtures that allowed them to be deployed by the Shuttle arm. Likewise, the DARPA Orbital Express mission launched a demonstrator client spacecraft with a robotic grapple fixture and optical fiducials (8). These designs are discussed in detail below.

Most spacecraft, however, are designed with no considerations for robotic servicing. Because launch costs are high and correlated with payload mass—costs have historically ranged from \$2,500 to more than \$100,000 per kilogram, depending on launch vehicle and orbit (9; 10, p. 802)—spacecraft are designed to be as lightweight as possible. The nature of microgravity allows spacecraft designers considerable flexibility in designing lightweight structures, and the high cost of launch actively incentivizes them to do so. As a consequence, functional spacecraft elements such as solar panel arrays and large deployable antennas are often not designed to support their own weight because on orbit they have none. These structures are frequently supported with lightweight carbon fiber booms that are not intended to survive the loads imparted by a robotic grasp.

Spacecraft are also designed to survive both the extreme cold (−130°C) and the extreme heat (+100°C) experienced on orbit (10, pp. 428–34). Thermal control systems for spacecraft almost always include thermal blankets, typically either mylar or multilayer insulation, covering most of the spacecraft structure. Thermal blankets are easily torn, especially once they have spent years exposed to the high-free-oxygen environment of low Earth orbit or the high-ionizing-radiation environment of geosynchronous orbit (11). Because they are intended to either reject or absorb heat, depending on whether the component they are insulating generates heat, they tend to be black, white, or highly specular. This, combined with the fact that solar illumination is approximately 40% greater on orbit than on Earth's surface due to the lack of atmospheric attenuation (12; 13, p. 21), means that thermal blankets pose a high-dynamic-range (HDR) imaging challenge as well as a manipulation challenge.

Finally, although in most cases spacecraft are designed with three-axis attitude control systems, some older spacecraft stabilized their pointing axis using gyroscopic stabilization; this required them to rotate about their principal axis of rotation at rates of 30–60 rpm (10, pp. 359–64). Derelict spacecraft generally do not have functioning attitude control systems and can be expected to be slowly tumbling, although the tumble rates depend greatly on the rotational inertia of the spacecraft, its surface area, and its orbit.

Thus, not only do they lack robotic fixturing, but most spacecraft also are relatively fragile, lack obvious hard points suitable for a robotic grapple, and are difficult to image with visible-light sensors. If they are derelict, they may have significant tumble rates.

For such unprepared clients, a handful of approaches for successful robotic grappling have been developed. One approach involves using the liquid apogee engine (LAE) nozzle as a grapple fixture (2). Many, although not all, satellites have rocket engines that are used to finalize the orbit of the satellite after it has been released by the launch vehicle. The paraboloid shape of the nozzle provides a natural robot-friendly grapple feature that can mechanically align an end effector as it is inserted. LAE nozzles are also typically of uniform shape and color across different satellites and therefore provide a relatively uniform optical feature for visual servoing or other relative pose estimation and alignment techniques.

The primary disadvantage of LAEs as grapple fixtures is that they are not present on all satellites. Exact percentages are difficult to find, but in general, geosynchronous satellites are more likely to have LAEs due to the fairly complex orbital maneuvers and large fuel requirements needed to maneuver a geosynchronous satellite into its intended position in orbit, whereas low and medium Earth orbit satellites often do not require such complex maneuvers. In addition, LAE nozzles are constructed of highly specific materials with specialized surface coatings to survive the heating inherent in rocket engine burns and have very precise nozzle and throat geometries in order to deliver thrust symmetrically along the desired thrust vector, and it is not clear how manipulation by a robot affects these properties. Therefore, there is some risk inherent in firing a rocket engine whose nozzle has been previously used as a grapple fixture.

A second approach is to grapple using the launch vehicle adapter interface. All satellites arrive in space via a launch vehicle and must be securely fastened to the launch vehicle during launch. There are two primary interface types: Marman rings and separation bolts (also referred to as sep bolts) (10, p. 336). Marman rings are more popular, with an estimated 75% of all satellites using one. There are three primary types of Marman rings: types 937, 1194, and 1666 (14, 15). An example Marman ring is shown in **Figure 1**.

Launch vehicle adapter interfaces are appealing as robotic grapple features because every satellite has one and because they are designed to survive the loads imparted during launch, which can be momentarily as high as 5–6 Gs (10, p. 740). In addition, launch vehicle adapter interfaces play no role in the subsequent operation of the satellite, and therefore manipulating one robotically does not pose any direct risk to its functioning. Like LAE nozzles, they are also relatively uniform in shape and therefore provide an obvious target for visual servoing algorithms.

A major disadvantage of launch vehicle adapter interfaces is that they have a relatively low profile, in some cases protruding only a few centimeters above the surrounding spacecraft structure. And in at least one common satellite design, the Boeing 601, the Marman ring is typically covered

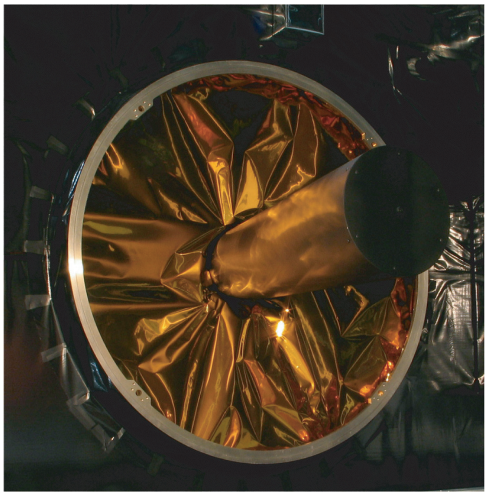

Figure 1

A Marman ring with thermal blanketing. The gold blanketing inside the ring is mylar; the black blanketing outside the ring is black multilayer insulation. Multilayer insulation can also be white, depending on whether the portion of the spacecraft being blanketed must absorb or radiate heat. The black protruding element in the center is a low-fidelity mockup of a liquid apogee engine. Photo courtesy of the US Naval Research Laboratory.

by a deployable thermal blanket after launch, making it inaccessible. In addition, Marman rings have surface treatments that make them somewhat specular.

Finally, some proposed robotic spacecraft programs have investigated grappling other common structural elements, such as the carbon fiber booms used to support solar panel arrays or deployable antennas (16) or astronaut handholds such as those on the Hubble Space Telescope (17).

The disadvantages of these approaches include that there is little similarity in the location, the size, or even the presence of such structures among disparate satellite families; that such structures are typically not designed to take any external loads, unlike both LAE nozzles and launch vehicle adapter interfaces; and that it is difficult to make any reliable assumptions about the surface reflectivity properties of such components, which makes it challenging to design machine vision algorithms to detect them. This approach may be more suited for orbital debris disposal missions where the client is not a satellite per se but rather a derelict upper-stage rocket body or a section of spacecraft that has experienced an orbital collision, or for specific missions, such as a hypothetical space telescope robotic servicing mission where there is one or a limited number of clients whose geometry is well known.

3. HISTORICAL MISSIONS

The first rendezvous and docking maneuver of two spacecraft in orbit was performed by astronauts Neil Armstrong and David Scott during the Gemini VIII mission in 1966 (18). During the Apollo, Salyut, Skylab, and Apollo–Soyuz programs, many additional rendezvous and proximity operations (RPO), captures, and docking operations were performed using similar methods. These missions all used direct-dock systems (e.g., none used robotic arms); instead, there were relatively large docking adapters attached to each spacecraft, which were flown together by the astronauts and/or cosmonauts.

The first robotic arms in space were the five Canadarms, also known as the Shuttle Remote Manipulator Systems (SRMSs), which were used from 1981 to 2011 on the Space Shuttle to deploy, maneuver, and capture payloads (19). Notably, the SRMS was used to capture the Hubble Space Telescope for each of the five servicing missions between 1993 and 2009 (20). The SRMS was a 6-degree-of-freedom (6-DOF), 15.2-m arm teleoperated by an astronaut at a console in the back of the Space Shuttle flight deck. The control station had two 3-DOF hand controllers, one for translation and one for rotation; two windows allowing direct observation of payload bay operations; and video feeds from cameras, including cameras located at the elbow and on the end effector. Typically, optical alignment aids were also present on target satellites to aid in alignment (21). The SRMS used a wire-snare capture end effector described in Section 4.1.2.

A second iteration, Canadarm2, also known as the Space Station Remote Manipulator System (SSRMS), has been in operation on the ISS since 2001 (22). This 7-DOF, ∼17-m arm has a variety of uses, one of which is grappling ISS resupply vehicles. The SSRMS may be operated from one of two workstations on the ISS, each of which is equipped with hand controllers similar to those used for the SRMS, video displays, and windows. The SSRMS may also be controlled via scripts by operators on the ground (23). For a detailed examination of the design of both the SRMS and SSRMS systems, including mechanical design, controller design, and operation, see the comprehensive overview by Nguyen & Hughes (24).

The first autonomous robotic RPO maneuver and the first autonomous robotic grapple were carried out during the Japan Aerospace Exploration Agency's Engineering Test Satellite VII (ETS-VII) mission, also known as KIKU-7, in 1997. ETS-VII involved two satellites: Hikoboshi, the chaser, and Orihime, the target (25). It used both a direct-dock system (26) and a true robotic arm grapple system (27) that utilized a 6-DOF, 2-m robotic arm (28). It also demonstrated the operation of a robotic arm performing taskboard operations in space (29, 30). ETS-VII was functional for nearly two years and was made available to a number of researchers after its primary experimental goals had been met.

In 2007, the DARPA Orbital Express mission demonstrated on-orbit autonomous refueling and reconfiguration of satellites, performing RPO, capture, docking, and robotic grappling maneuvers (31, 32). Orbital Express consisted of two spacecraft, ASTRO and NEXTSat. ASTRO was a robotic servicing vehicle that had a single 6-DOF, 3-m robotic arm, a direct-dock berthing mechanism, and a specialized sensor suite that allowed it to autonomously rendezvous and capture another satellite. The sensor suite consisted of a set of visible and infrared long-range telescopes and a laser rangefinder for use in closing with the target vehicle up to distances of 1 km, a primary close-range cooperative laser-based system called the NASA Advanced Video Guidance Sensor (33, 34) that relied on laser retroreflectors on the target vehicle, and a backup Boeing close-range optical system called Vis-STAR. Vis-STAR relied on visible and infrared cameras and floodlights. At distances greater than 10 m, it relied on matching the outline of the target vehicle with a database of outline shapes, and as such did not rely on any special features of the target spacecraft. At distances closer than 10 m, however, Vis-STAR relied on optical fiducials mounted on the target vehicle (35, 36). NEXTSat was a demonstration vehicle designed to be serviced by ASTRO. It had a docking adapter, laser retroreflectors, and optical fiducials matching ASTRO's interface requirements (37).

The Orbital Express mission was carried out over several months in early 2007. The mission experienced two separate near-mission-ending failures, one due to a sign error in the attitude control system that caused the mated spacecraft stack to point away from the sun soon after orbital insertion, and another involving a flight computer experiencing an intermittent failure and reboot during RPO. However, both failures were recoverable. A paper by Friend (31) provides a fascinating account of real-time spacecraft fault management. Orbital Express ultimately demonstrated autonomous rendezvous and capture of a prepared satellite, both via direct dock and using a robotic arm (38). It successfully changed orbital replacement units and refueled

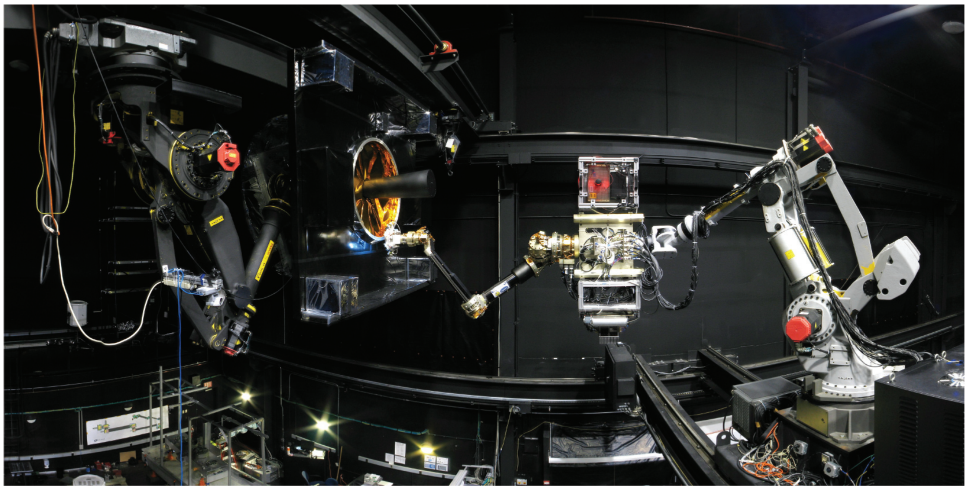

Figure 2

Laboratory testing of a Front-End Robotics Enabling Near-Term Demonstration (FREND) arm in the US Naval Research Laboratory's Proximity Operations Testbed, circa 2008. Photo courtesy of the US Naval Research Laboratory.

NEXTSat. It also demonstrated supervised autonomy (e.g., the robotic arm was not directly controlled by an operator). Instead, operators prepared motion scripts on the ground, verified them via simulation, and then uploaded them to the spacecraft for execution. Robotic grappling and berthing were performed autonomously and utilized visual servoing (39).

Several upcoming missions are intended to demonstrate grappling of unprepared spacecraft. DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS) (**Figure 2**) program will launch a robotic servicing vehicle equipped with two robotic arms tasked with high-resolution inspection, RPO, anomaly correction, cooperative relocation, and upgrade installation of geosynchronous satellites (40). Similarly, NASA's On-Orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1, previously known as Restore-L) mission is focused on performing RPO, grasping, refueling, and relocation of satellites using two of its arms (41) and conducting in-space assembly and manufacturing with its third arm as part of the Space Infrastructure Dexterous Robot (SPIDER) demonstration.

4. CORE TECHNOLOGIES

Free-flyer grappling involves two spacecraft and three key distributed control systems: (*a*) guidance, navigation, and control (GNC) systems that control orientation (of one or both vehicles) and translation (usually of only one of the vehicles, which we refer to as the active GNC vehicle), (*b*) a robotic control system that performs the final robotic capture and manipulation, and (*c*) a berthing system (not discussed here) to establish a rigidly mated stack if required to react to the loads of the servicing operations. In most servicing scenarios, the active GNC vehicle also hosts the robot system and the active half of the berthing system.[1] In the following sections, we discuss the core technologies associated with the GNC and robot systems.

[1]However, this is not the case for the most used free-flyer capturer, the SSRMS. ISS visiting vehicles are tasked with the active GNC role, while the ISS maintains its attitude and uses the SSRMS to perform free-flyer grappling of any visiting vehicle not designed to perform direct docking.

4.1. Mechanisms

Space systems in general are mass and power constrained and must operate reliably across the extreme temperature range experienced in orbit. Designing appropriate robotic arms, end effectors, and sensors that meet mission requirements for mass and power is a challenging design problem. Techniques for reducing the power or mass required by space-rated mechanisms are consequently a leading area of research in aerospace engineering.

4.1.1. Robotic arms. Robotic arms large enough to be useful for grappling or servicing tend to be fairly large, although there is a wide range in the size of such arms. The SSRMS is approximately 17 m long with a mass of 1,497 kg (42), while the Front-End Robotics Enabling Near-Term Demonstration (FREND) arm[2] used by RSGS and OSAM-1 is 2.3 m with a mass of approximately 80 kg (43). Robotic arms usually require a motor and gear train for each joint, with the gear train typically providing a gear ratio of at least several hundred to one. Such large gear ratios allow designers to use smaller motors and to operate them at much higher speeds, which in turn makes them more power efficient. Large gear ratios also assist in designing control laws because they have the effect of isolating the motor from environmental forces and the coupling forces from the motion of the arm joints themselves. However, gear trains with high gear ratios are themselves somewhat massive. Research into building smaller, lighter gear trains and more efficient electric motors is an area of significant interest in space robotics. Improved gear designs that reduce friction or backlash are also of interest, as are improved lubricants for such gears. Current state-of-the-art designs typically utilize brushless DC motors that operate at tens of thousands of revolutions per minute and harmonic gears, or in a few cases hybrid harmonic and planetary gear systems.

Two common methodologies are used for the design of robotic arms and their associated tool drives, end effectors, tools, and adapters. One design paradigm for robotic arms whose only function is grappling is to include the grapple mechanism (typically called an end effector) as part of the arm, as is done with the SRMS (44, 45), ETS-VII space robot (46), SSRMS (42), and Orbital Express Demonstration Manipulator System (39, 47). Another paradigm includes a tool drive and/or a tool changer at the end of the arm that can grasp a gripper tool, which can then be used to grapple an interface. These robots can also grasp other tools to enable them to perform other servicing and maintenance tasks. This mechanism is part of the RSGS (48) and OSAM-1 robotic arm designs.

One unique challenge in designing space arms is the trade-off between designing an arm with the lowest possible weight while still meeting mission goals and designing an arm that can be adequately tested on the ground prior to flight. To reduce mass, most space arms to date are not capable of supporting their own weight in gravity; of those listed in this section, only the RSGS and OSAM-1 arms are known to be able to function correctly in 1 G. Testing these arms and training teleoperators to operate them are consequently quite challenging.

4.1.2. Grapple mechanisms. The majority of the robotic static grapples (i.e., where the robotic arm and the object being grasped are mounted to the same spacecraft) and free-flying grapples (i.e., where the object being grappled is floating in space) performed in space have been performed

[2]FREND was a DARPA program intended to, among other goals, establish industrial suppliers for spaceflight robotic arms. The base FREND arm designed under the program was adopted by the DARPA RSGS and NASA OSAM-1 programs, although both programs have evolved the basic design in somewhat different directions.

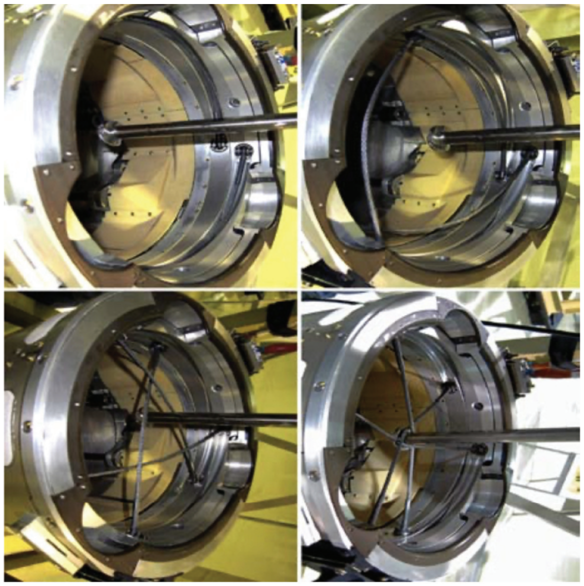

Figure 3

Shuttle Remote Manipulator System end effector snaring a grapple pin (44). Photos courtesy of NASA.

either by the SRMS during Space Shuttle missions or by the SSRMS on the ISS. Both of these robotic arms use an end effector that provides a large capture envelope [a cylinder 20.3 cm in diameter by 10 cm deep (49)]. Three snare cables close around a probe on a grapple fixture (**Figure 3**), providing for a soft capture and enabling capture before contact, after which the probe is drawn in and the grapple is rigidized. All of these grapples have used cooperative grapple features and have been performed with a human commanding the robot.

Another demonstration of grappling in space was performed by Orbital Express (47). NEXTSat was designed to be serviced and had a robot-friendly grapple fixture consisting of a compliant probe and a vision target plate that enabled autonomous grappling (50). During the mission, the manipulator system mounted on ASTRO performed four static grapples and two free-flying grapples of NEXTSat, all of which were performed autonomously.

4.1.3. Marman ring grippers. For objects that do not have grapple fixtures, a custom-designed tool is used to grapple a portion of the structure of the satellite. The most common structure to use is the Marman ring that attaches the satellite to its launch vehicle. A gripper tool is attached to the end of the robotic arm, which can then grapple the Marman ring.

4.2. Techniques, Sensors, and Systems for Rendezvous and Proximity Operations

Maneuvering two spacecraft into proximity of each other is known as orbital rendezvous, and subsequent maneuvering while in proximity is known proximity operations; together, these are referred to as RPO. Designing trajectories for orbital RPO is nontrivial due to the underlying nonlinear orbital dynamics. For an overview of designing orbital trajectories for rendezvous and grappling, see Reference 51; for the specific approach taken by the OSAM-1 mission, see

Reference 52. For a review of techniques used by the Space Shuttle program, see Reference 53, and for a historical overview of the development of these techniques, see Reference 54.

4.2.1. Orbital rendezvous and proximity operations. Free-flyer grappling of one spacecraft by another starts with one spacecraft performing a series of maneuvers to rendezvous and conduct close-proximity operations with the other (usually passing through a series of control volumes and/or ground authority-to-proceed points, as discussed in References 52 and 55). That spacecraft then holds its position and attitude within a relative translation and orientation control envelope while the robotic system completes the grapple.

4.2.2. Guidance, navigation, and control systems for rendezvous and proximity operations. The hardware systems required for active GNC spacecraft to accomplish RPO include inertial and relative navigation sensors, propulsive translation actuators, and propulsive or momentum-based attitude actuators. Of this hardware, only the sensors are unique to RPO operations. The GNC actuators, while driven in count and placement by the need for simultaneous and independent 6-DOF translation and orientation control, are standard spaceflight equipment. We discuss RPO sensors in more detail below.

Software for active GNC spacecraft includes sensor processing (e.g., computer vision or pose), inertial and relative state estimators [e.g., extended Kalman filters (56, 57)], translation guidance algorithms (to determine the desired path of the active vehicle relative to the passive one), control algorithms (to achieve that path) (58), autonomy management (usually a finite state machine or other task sequencer) (59; however, for more advanced spacecraft autonomy management, see 60), and fault detection, isolation, and recovery systems (e.g., to monitor for faults and ensure the relative motion is safe by executing a collision avoidance maneuver if necessary) (61, 62).

Key hardware and software on the passive GNC spacecraft (which is usually only passive in a translation sense—it usually controls its attitude as well) include radio frequency (RF) systems to determine and share its orbital state (either onboard or with the ground in the loop), fiducials to support relative navigation, and attitude control systems to optimally orient the spacecraft for RPO and capture.

4.2.3. Relative navigation sensors and fiducials for rendezvous and proximity operations. Sensors required for RPO include inertial sensors (e.g., GPS receivers, inertial measurement units, and accelerometers) and relative navigation sensors. As relative navigation sensors are more specific to RPO, we focus on those their corresponding fiducials. For a more detailed discussion of inertial navigation systems, see Reference 63.

RPO sensors are often described as active or passive, where active sensors emit energy to illuminate or irradiate the target, and passive sensors do not (e.g., visible and thermal imagers rely on sunlight or other lights external to the sensor assembly). Active sensors include RF systems like radars and communications system–based ranging as well as laser-based systems like laser range finders, velocimeters and altimeters (more commonly used for landing applications), illuminators [e.g., the Advanced Video Guidance Sensor (34)], and scanning and flash lidars.

4.2.4. Sensing challenges for rendezvous and proximity operations. The primary challenge for visible cameras is from the challenging space lighting environment. Issues regularly arise for these sensors from glare, shadows, and rapid changes in lighting (e.g., when the client vehicle passes into and out of eclipse). The ambient lighting environment is much more dramatic on space than it is on Earth—there is no atmosphere to spread the light (shadows are common and can be completely dark), and most human-made objects in space are covered in blankets or radiators

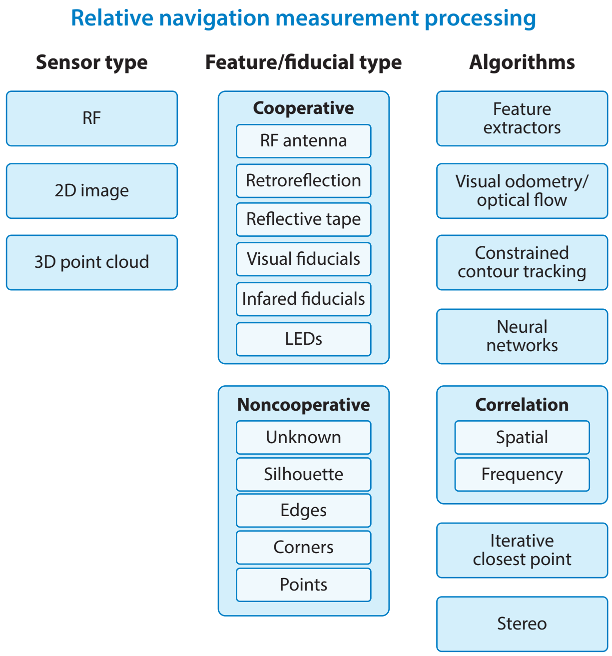

Figure 4

Relative navigation algorithm types. Abbreviation: RF, radio frequency.

that tend to be highly specular. The result is that most images from space contain both very dark regions and saturated regions and are very challenging to capture information from (64).

Potential near-term solutions include advance automatic gain control algorithms specifically tailored for spaceflight and HDR and event cameras, which partially address the glare/shadows aspect of this issue by promoting the development of detectors (and space qualification of existing systems) capable of increasing the range of luminosity, or the brightness range within an image. The dynamic range of camera detectors has been increasing dramatically in recent years.

4.2.5. Sensor processing and estimation for rendezvous and proximity operations. Two of the most challenging software aspects of GNC for RPO are pose estimation and navigation filtering. **Figure 4** shows some algorithms in use for pose estimation for a variety of sensor and feature types.

The NASA Raven program demonstrated online relative pose estimation of spacecraft in the vicinity of the ISS without the use of optical fiducials or other aids (65). For a case study in the design of an RPO sensor system, see the excellent overview of the Orbital Express system by Leinz et al. (35). For a comprehensive review of RPO sensors and algorithms, see the review by Opromolla et al. (66).

4.3. Robotic Control Algorithms

Most historical robotic satellite servicing missions have been designed around well-understood and well-constrained manipulation problems. Notably, the SRMS and SSRMS robotic arms, which between them have more operational hours on orbit than all other orbital robotics missions combined, interact solely with specialized grapple fixtures with optical fiducial alignment markers; the Orbital Express program similarly used grapple fixtures and fiducials, albeit at a different scale and for a wider variety of manipulation tasks. Missions that have not yet flown but are significantly along the path to flight, including RSGS and OSAM-1, envision grapple operations without dedicated fixturing but still with a limited number of grapple features that have well-understood geometries. In addition, flight computers, especially those used for mission-critical operations such as operating a robotic arm, tend to be multiple generations behind those available on the desktop. For instance, as of 2021, the BAE Maxwell, a widely used ARM-based flight computer, has a single CPU core that operates at up to 750 MHz. As a consequence, although there has been considerable progress in advanced perception, state estimation, and controls for terrestrial robotic systems, much of this capability is not required for spacecraft servicing missions, and the relatively constrained computing power available for such missions tends to favor simpler, more specialized algorithms.

4.3.1. Control algorithms. Most robotic arms used in spaceflight, including the arms used by the RSGS and OSAM-1 programs, use decoupled joint-level proportional–integral–derivative (PID) servo control laws. PID control laws are straightforward to design and relatively easy to tune and provide performance sufficient to meet most operating requirements. They require very little processing power and can be implemented using simple integrated circuits; because the control laws are decoupled, no communication between joints is required.

There are, however, several dynamics and control challenges that are relatively unique to the orbital spaceflight regime, including dynamic coupling between the robotic arm and the base to which it is mounted. Coupled dynamics may be nonnegligible when the spacecraft bus is not much more massive than the arm or where the arm is expected to move at high speed. In the first case, different arm poses result in significantly different mass and inertia characteristics for the bus attitude control system. In both cases, the motion of the arm induces motion in the bus, and the motion of the bus may also significantly perturb the arm. Typical spacecraft attitude control actuators, such as reaction wheels or rate moment gyros, may be treated as pure continuous torque actuators, and hence the coupled control of arm motion and spacecraft attitude encompasses fairly complicated nonlinear dynamics. These dynamics are Hamiltonian in nature (67) and can be treated with classic, if complex, techniques in nonlinear control (68–70) or adaptive control (71, 72). However, six-axis control of such systems is complicated by the fact that spacecraft bus translational control is usually effected using chemical thrusters. Thrusters are on/off devices with minimum on times and thus cannot be treated like ideal continuous force actuators. Spacecraft bus translational control systems are usually designed as bang-bang or bang-coast-bang laws for this reason (73).

Control of robotic arms attached to a spacecraft bus may be divided into free-flying (when the bus control is active during arm motion) (74, 75) and free-floating (when the bus control is inhibited) (76, 77) cases (69, 78). There has been considerable research on the design of both free-flying and free-floating arm–base control laws. Control of these systems can be complicated by the fact that the bus mass and rotational inertia parameters may be unknown or subject to nonlinear effects, such as solar panel flexibility and fuel slosh. In such cases, adaptive control may be used to estimate the unknown dynamics terms (71, 79). To date, however, few of these techniques have been demonstrated on orbit, with the exception being the control of coupled arm–base dynamics through resolved-motion rate control with a generalized Jacobian matrix (28).

When flight arms have significant joint and link flexibility due to being lightweighted, techniques for the control of flexible dynamics systems may be used (80–83). For robotic arms with significant flexible modes, such as the SRMS and SSRMS, strategies have included very slow commanded velocities and significant quiescent periods to allow the flexible modes to naturally damp out. The uncommanded motion of the SRMS when commanded rates were low during the deployment of heavy telescopes necessitated the development of a new software mode that reduced the crew's workload while commanding the arm (44). In the event that any of the arm dynamic effects are nonnegligible—for instance, if friction is expected to be a significant factor or if the arm has significant flexibility—more complex nonlinear or adaptive control laws may be used (71, 84).

Frequently, the control of the arm–base system is treated as a coupled problem with trajectory planning for the arm (85). Papadopolous & Dubowsky (86) showed that free-floating systems can have dynamic singularities, directions in which the arm is unable to move due to the coupled dynamics of the base. As a consequence, trajectory planning and control cannot be entirely decoupled for these systems because they are essentially nonholonomic (87–89).

For a comprehensive overview of dynamics, controls, and trajectory planning strategies for spacecraft with robotic arms, see Reference 3.

4.3.2. Force and compliance control. The control algorithms described above attempt to make a robotic arm accurately track a prescribed trajectory regardless of disturbance forces (90, 91). Force control, by contrast, attempts to make the arm exert prescribed force levels on objects in the environment. Compliance control algorithms trade off position and force in a controllable fashion (92, pp. 317–38).

For spacecraft grappling operations, compliance control is typically used to limit the forces exerted on the client spacecraft to prevent it from tipping off [e.g., being either inadvertently translationally pushed or rotationally spun away from the robot (93)], to limit the forces exerted on the robotic arm or client structure (94), or both. The Special Purpose Dexterous Manipulator, a dexterous servicing robot used on the ISS, uses a force/moment accommodation system that includes a 6-DOF force/torque sensor (95, 96). Orbital Express also had a force/torque sensor and an active force/moment accommodation system, but this system was not used on orbit; Ogilvie et al. (39) indicated that the force/torque sensor was instead used to monitor arm forces as an offline safety check. ETS-VII also used Cartesian compliance control to perform robotic pegboard tasks (27, 97), but it is not clear whether the system was used during grapple operations.

Both RSGS and OSAM-1 use different forms of impedance control (98, 99). RSGS, in particular, uses two forms of impedance control, one formulated in joint space for use when grappling (43) and one formulated in Cartesian space for tool change and other operations. Joint space impedance control allows the arm to limit its joint rates when using compliance control in the vicinity of kinematic singularities but inherently provides different Cartesian-equivalent compliance depending on the pose of the arm.

4.3.3. Machine vision. Machine vision refers to the development of techniques and algorithms to allow a computer to understand its environment by using imaging sensors (100). Space robotic systems typically utilize machine vision for two primary purposes: relative pose estimation between the robotic system and its environment, and the location of features of interest within the environment. In the first case, machine vision algorithms may be used in conjunction with cameras to form the basis of a proximity operations sensor suite that determines the position and orientation of a nearby spacecraft that is to be grappled. This function is required of any spacecraft that is to perform proximity operations and is not limited to robotic servicers. Frequently, machine vision systems designed for cooperative robotic grappling rely primarily on optical fiducials (101). The use of fiducials designed to be compatible with orbital lighting conditions improves robustness to lighting and alleviates the computational burden (102).

Orbital Express demonstrated a machine vision system, Vis-STAR, that was capable of determining the position and orientation of the NEXTSat spacecraft (36). At distances greater than 10 m, Vis-STAR worked by comparing the outline of the NEXTSat vehicle with a database of outlines that were precomputed from a geometric model of NEXTSat at a range of orientations, calculating the distance from the apparent size of NEXTSat. Thus, it did not rely on any special features of NEXTSat and would presumably work for a variety of target spacecraft. However, it appeared to have difficulties with rotationally symmetric spacecraft, such as some spin-stabilized or spun–despun satellites. When the Orbital Express robotic servicer, ASTRO, was closer than 10 m, the field of view of its cameras did not allow it to see the entire outline of NEXTSat, so it switched modes and relied instead on a set of optical fiducials on NEXTSat (35, 39).

RSGS and OSAM-1 will use machine vision to align the Marman ring gripper of the servicer spacecraft with the Marman ring of the client (103). RSGS uses a dedicated algorithm designed to robustly identify a section of a Marman ring within the field of view of one of the end-effector cameras of the arm and uses the resulting position estimate of the Marman ring as an input to a visual servoing system to drive the arm to alignment (104).

4.3.4. Trajectory planning. An automated robotic spacecraft must have the ability to plan the movements of its robotic arm or arms, and possibly to plan the motion of its bus as well. A trajectory planner performs this task by being given a starting position and one or more goal points (105, 106).

The most used satellite grappling systems, the SRMS and SSRMS, were and are primarily teleoperated, with gross trajectory planning typically done manually prior to complex operations being performed. For Orbital Express, trajectories were also designed on the ground prior to operations but were executed autonomously. This basic design choice is also used by RSGS and OSAM-1 (43). However, there is a deep body of research for trajectory planning for spaceflight robotic arms in the presence of moving obstacles, uncertain relative poses, noisy sensor feedback, and so on (107), or to optimize redundant degrees of freedom to avoid singularities (87, 108, 109) or minimize the disturbance torques exerted on the bus by the arm (110), with the latter approach being demonstrated on ETS-VII (111).

4.3.5. Inverse kinematics. Typically, for a 6-DOF robotic arm, there are a finite number of joint positions corresponding to a desired end-effector pose. For arms with more than 6 DOFs, there are typically an infinite number of arm poses that correspond to a given end-effector pose. In either case, the flexibility allowed by the arm kinematics can be used to optimize other criteria, such as obstacle avoidance, singularity avoidance, or joint velocity, with extra degrees of freedom allowing for considerably more complex schemes. For good overviews of inverse kinematics, see References 92 (pp. 113–44), 112, and 113.

Both RSGS and OSAM-1 use modified forms of resolved motion rate control (114, 115). RSGS enhances the standard damped–least squares resolved motion rate control algorithm with constraints to enforce collision avoidance, joint limits, and joint rate limits, while OSAM-1 explicitly modifies the end-effector trajectory to enforce singularity avoidance (116).

4.3.6. Planning, scheduling, and other decision-making. To achieve the very highest level of automation, a spacecraft must be able to operate without the intervention of mission controllers for extended periods of time. Such a spacecraft requires the ability to make decisions based on the outcomes of actions it has taken, various system failures, and events over which it does not have control. Because these are not completely predictable, the spacecraft must have considerable flexibility in choosing its future actions, and therefore the mission cannot be completely scripted. This general problem is of great interest to a wide community of researchers and is one of the foundational problems of the field of artificial intelligence. As a consequence, it has been an active area of research since at least the early 1960s (117).

For spacecraft, the most common approach taken to this problem is called a three-tiered architecture (often shortened to 3-T) (118). We are aware of two spacecraft that have used three-tiered architectures: NASA's Deep Space 1 mission, which demonstrated an onboard planner/scheduler capable of controlling an interplanetary science spacecraft for several days at a time, and EO-1, an Earth-observing spacecraft that autonomously monitors volcanic activity, recognizes unique phenomena, and schedules scientific observations using an onboard planner. Both spacecraft implemented planners written by NASA's Jet Propulsion Laboratory [Remote Agent (119) and Casper (120), respectively]. For robotic spacecraft, the approach to planning tends to be more limited. RSGS, for instance, utilizes an augmented state machine (121, 122); however, a three-tiered architecture was designed to assist SRMS ground operators (123).

4.3.7. Fault detection, isolation, and recovery. Standard fault detection on spacecraft consists of establishing expected operating conditions (expected temperatures of specific components, expected fuel use rates, etc.) and notifying mission controllers if these limits are exceeded. This technique tends to be conservative, signaling faults even when they do not exist. It may not be optimal for use on robotic spacecraft because of the difficulty in developing simple operating limits for very complicated robotic systems.

Orbital Express utilized a simple condition limit fault detection scheme; for an in-depth report on the fault conditions experienced during the Orbital Express mission, see Reference 31. More advanced fault detection schemes that use models of the systems and attempt to match sensor data with different hypothesized component failures have been proposed. NASA demonstrated such a system, called Livingstone, on Deep Space 1, EO-1 (124), and the ISS (125).

4.4. Teleoperation

Teleoperation can be used as an alternative to or in conjunction with the technologies described above. Virtually all of the robotic systems on NASA's crewed vehicles are teleoperated (24). The main arm of the Japan Aerospace Exploration Agency's Japanese Experiment Module is also teleoperated (126). Many laboratory demonstration systems have also baselined advanced forms of teleoperation or supervised autonomy (127–132). State-of-the-art robot servicing concepts typically require teleoperation to perform complicated repairs or upgrades. The exception to this was Orbital Express, which used supervised autonomy; Orbital Express was designed to service a target spacecraft that had carefully designed interfaces, so it could use scripted sequences of actions.

4.5. Situational Awareness

Teleperators are normally provided with situational awareness using cameras. However, in spaceflight operations it is often impossible to place cameras in useful places; for instance, it is often useful to have cameras pointed at the end effector in orthogonal locations, but this would require floating the cameras in space. Lack of situational awareness limits the ability of a teleoperator to reliably carry out manipulation tasks (133).

One technique for improving situational awareness entails using haptic feedback (134). Haptic feedback requires a specialized controller that is capable of exerting force against the operator. When used in conjunction with a force/torque sensor on the robotic arm, this allows the operator to feel the contact. Use of haptics in space is very challenging due to the relatively long communication time delay; this time delay, which is dominated by ground processing delays, can be as long as 7 s in low Earth orbit. ETS-VII demonstrated model-based haptic feedback through 7 s of time delay, an extremely challenging problem (135, 136).

5. TESTING AND TRAINING STRATEGIES

5.1. Engineering Requirement Flowdown

Spacecraft engineers have developed standardized techniques for generating subsystem specifications from system requirements and testing subsystems to verify they meet specifications. As a consequence of the extensive experience in the spacecraft engineering community, engineers can design subsystems according to flowdown requirements with some confidence that the spacecraft will function as a whole when the subsystems are assembled (10). Consequently, full system testing is often limited to thermal vacuum testing to verify the thermal properties of the spacecraft, vibration testing to verify the flexible modes, and acoustic testing to ensure that the acoustic energy from the launch vehicle will not damage the spacecraft. Specialized payloads are generally verified using specially designed test procedures, but the spacecraft is rarely tested as a full operating system. Indeed, such testing is often difficult or impossible, since spacecraft are not designed to operate in a gravity field or with an atmosphere present.

Unfortunately, the established techniques for subsystem requirement flowdown and subsystem testing may be insufficient for robotic spacecraft. Robotic systems, especially autonomous robotic systems, are extremely complex, and the various subsystems of an autonomous spacecraft interact with each other in ways that are unpredictable. This is a known difficulty with very complicated software systems and has led to the failure of several such systems, and it creates considerable additional system testing requirements for robotic spacecraft designers.

5.2. System Testing

There are several methods used to test robotic hardware, which are summarized below. For a more in-depth review of microgravity simulation techniques, see Reference 137.

5.2.1. Air-bearing tables. Air-bearing tables work by using pressurized air to float a mass on a flat surface. Because they provide an inexpensive way to simulate frictionless dynamics, they are very useful for testing contact dynamics. They are also useful for testing proximity operations and formation-flying systems. The primary advantages of air-bearing tables are their very low friction characteristics and their low cost; their primary disadvantage is that they are typically planar and consequently simplify the dynamics of the systems they are simulating. Air-bearing tables are commonly used to validate the performance of robotic arms that cannot support their own weight in a 1-G gravitational field; such robots include the SRMS, SSRMS, Japanese Experiment Module Remote Manipulator System, European Robotic Arm, and Orbital Express arms. For an in-depth mathematical analysis of contact dynamics validation on an air-bearing table for the RSGS program, see Reference 138; for an exhaustive review of the use of air-bearing simulators for spacecraft testing, see Reference 139.

5.2.2. Six-degree-of-freedom motion platforms. In a 6-DOF motion platform, the spacecraft to be tested is mounted at the end of a large positioning device, which moves it as though it were on orbit. Larger 6-DOF motion platforms have the robotic arm mounted on a computer-controlled bridge or gantry crane. They provide the highest-fidelity proximity operations simulation of any simulation technique and can be used to validate the operation of proximity operations sensors, algorithms, and concepts of operations.

The disadvantages of 6-DOF motion platforms are their relatively high expense and their inability, due to their relatively low bandwidth, to accurately simulate contact dynamics. In addition, the motion platform structure can limit their range of motion. A specialized type of 6-DOF motion platform uses a Stewart platform, which has much higher bandwidth than more typical robots,

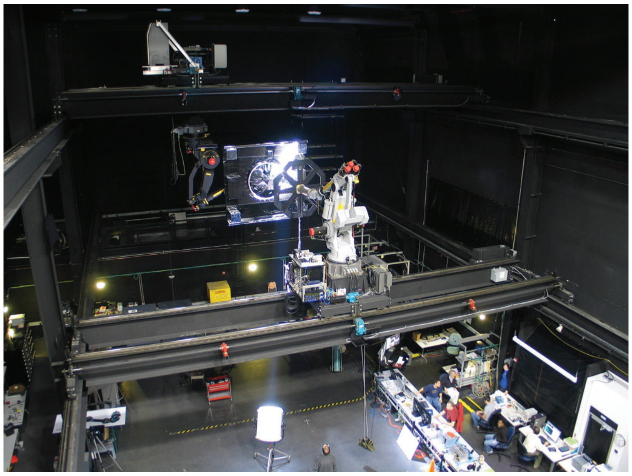

Figure 5

The US Naval Research Laboratory's Proximity Operations Testbed, a motion simulator with six degrees of freedom. Photo courtesy of the US Naval Research Laboratory.

to simulate contact dynamics. However, Stewart platforms typically have smaller ranges of motion and consequently simulate operations in a smaller volume. RSGS hardware and algorithms were validated in the US Naval Research Laboratory's Proximity Operations Testbed (43) (**Figure 5**). OSAM-1 visual servoing and compliance control algorithms are being validated using a Goddard Space Flight System 6-DOF motion platform based on a Stewart platform.

5.2.3. Neutral buoyancy. Neutral buoyancy—the use of water to simulate weightlessness—is commonly used to train astronauts to perform extravehicular activity. Some organizations also use neutral buoyancy tanks to test robotic vehicles. The primary advantages of neutral buoyancy are that it allows multiple cooperating vehicles to be tested and that it has no workspace kinematic limitations. It also allows robots and humans to work in the same workspace, facilitating training of joint human–robot servicing.

There are several significant disadvantages to neutral buoyancy as a robotics microgravity test facility. The facilities are expensive to build and operate. Spacecraft are not typically waterproof, so the system to be tested must be reengineered with waterproof features, which almost always requires an extra set of all the hardware to be used. Many sensors do not work the same way underwater as they do in space, and because the lighting conditions underwater are very different from those on orbit, machine vision algorithms for use in space cannot be tested underwater. Some sensors, such as lidars and radars, do not work at all underwater. The dynamics of systems tested underwater are significantly changed by the water, which adds significant amounts of damping. Contact dynamics are also significantly different, because of the added damping and because the boundary layer formed by the water effectively adds mass to the object being contacted.

5.2.4. Zero-G aircraft. Zero-G aircraft work by flying a parabolic trajectory. During the top portion of the trajectory, the aircraft experiences weightlessness. This period typically lasts 20–30 s and is followed by a period at approximately 2 Gs as the aircraft flies the bottom of the parabola. The short weightless period limits the testing that can be performed, and the 2-G period poses not insignificant safety hazards when using heavy, free-floating test articles. However, the Orbital

Express direct-dock mechanism (140) and contact dynamics validations for OSAM-1 (141) were tested in NASA's zero-G aircraft.

6. CONCLUSION

Robotic grappling of client spacecraft is a deceptively complex problem. It entails designing a robotic system that functions robustly in the visually stark, thermally extreme orbital environment, operating near massive and extremely expensive yet fragile client hardware, using relatively slow flight computers with limited and laggy communications. Spaceflight robotic systems are challenging to test and validate prior to deployment and extremely expensive to launch, which significantly limits opportunities to experiment with new techniques. These factors make the design and operation of orbital robotic systems significantly different from those of their terrestrial counterparts, and as a result, only a relative handful of systems have been demonstrated on orbit. Nevertheless, there is increasing interest in on-orbit robotic servicing and assembly missions, and grappling is the core requirement for these systems. Although existing systems such as the SSRMS have demonstrated extremely reliable operation, upcoming missions will attempt to expand the types of spacecraft that can be safely and dependably grappled and berthed. Future research directions for these systems include the development of lower-cost HDR sensors, improved control techniques for flexible manipulators, the design and (hopefully) adoption of standards for prepared grapple fixtures and fiducials, and the development of autonomous grasping algorithms, sensors, and hardware to enable the robust grappling of a wider range of client spacecraft and orbital debris.

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