Progress in Aerospace Sciences ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Progress in Aerospace Sciences

journal homepage: www.elsevier.com/locate/paerosci

A review of space robotics technologies for on-orbit servicing

Angel Flores-Abad [a,*], Ou Ma [a], Khanh Pham [b], Steve Ulrich [c]

[a] New Mexico State University, Mechanical and Aerospace Department, Las Cruces, NM 88003, USA
[b] U.S. Air Force Research Laboratory, Kirtland Air Force Base, NM 87117-5776, USA
[c] Carleton University, Spacecraft Robotics and Control Laboratory, Ottawa, Canada K1S 5B6

ARTICLE INFO

Article history:
Received 10 September 2013
Received in revised form
7 March 2014
Accepted 8 March 2014

Keywords:
Space robotics
On-orbit servicing
Spacecraft dynamics and control

ABSTRACT

Space robotics is considered one of the most promising approaches for on-orbit servicing (OOS) missions such as docking, berthing, refueling, repairing, upgrading, transporting, rescuing, and orbital debris removal. Many enabling techniques have been developed in the past two decades and several technology demonstration missions have been completed. A number of manned on-orbit servicing missions were successfully accomplished but unmanned, fully autonomous, servicing missions have not been done yet. Furthermore, all previous unmanned technology demonstration missions were designed to service cooperative targets only. Robotic servicing of a non-cooperative satellite is still an open research area facing many technical challenges. One of the greatest challenges is to ensure the servicing spacecraft safely and reliably docks with the target spacecraft or capture the target to stabilize it for subsequent servicing. This is especially important if the target has an unknown motion and kinematics/dynamics properties. Obviously, further research and development of the enabling technologies are needed. To motivate and facilitate such research and development, this paper provides a literature review of the recently developed technologies related to the kinematics, dynamics, control and verification of space robotic systems for manned and unmanned on-orbit servicing missions.

Contents

* Corresponding author.
E-mail address: af_abad@nmsu.edu (A. Flores-Abad).

http://dx.doi.org/10.1016/j.paerosci.2014.03.002
0376-0421/

1. Introduction

Statistical data reveal that, on average, 100 satellites (from 78 to 130) were launched every year in the past decade. Most of them performed their missions without any major problems. However, a small number of them experienced anomalies and even failures of various degrees of severity [1]. In the past, launcher failure was the most common cause of failure. However, on-orbit failures have exceeded launch failures in recent years for the first time [2] and cumulatively account for losses of billions of dollars [3]. Besides, every launched satellite eventually runs out of fuel and thus, must be decommissioned even if the satellite may still be functional [4]. A number of studies [5–7] have demonstrated potential savings in terms of cost effectiveness of in-flight repair of damaged spacecraft, and a model that also includes risk and uncertainties analysis was presented by Sale et al. [8,9]. For these reasons, the National Aeronautics and Space Administration (NASA) realized the importance of robotics on-orbit servicing operations to protect their assets in space as early as the 1980s [10,11]. The term *on-orbit servicing* (OOS) refers to the maintenance of space systems in orbit, including repair, assembly, refueling and/or upgrade of spacecraft, after their deployment. It is notable that such complex space missions have motivated the development of new space robotics technologies and several experimental demonstration missions including both manned and unmanned missions [12].

A space robotic system (also referred to as space manipulator or space robot) for an OOS mission typically consists of three major components: the base spacecraft or servicing satellite, an n-degree-of-freedom (n-DOF) robot manipulator attached to the servicing satellite, and the target spacecraft to be serviced. A spacecraft-manipulator servicing vehicle (illustrated in Fig. 1) is sometimes termed the servicing system.

The capturing process includes a series of operations. After having completed the far and close-range rendezvous maneuvers [13] with the target satellite, the servicing spacecraft remains at a safe, station-keeping, distance from the tumbling target satellite. Then, the capture operation mode starts, which may be divided into four phases. The first phase corresponds to the observing and planning phase for acquiring motion and physical properties information about the target satellite, to plan how the robot manipulator should grasp the target. The second phase is to control the robot to move toward the planned grasping location, such that the robotic arm is ready to capture the target. The third phase consists in the actual capture (physical interception) phase in which the manipulator physically grasps the capturing device of the target satellite. The fourth phase is the post-capture phase, where the captured target is stabilized along with the servicing system. Fig. 2 shows the four phases of the capturing maneuver.

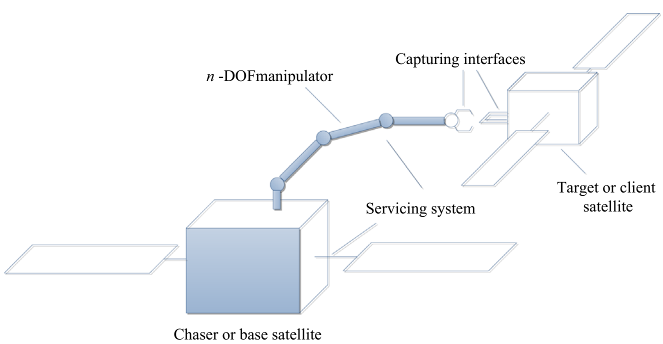

Fig. 1. Components of a spacecraft servicing system for on-orbit servicing.

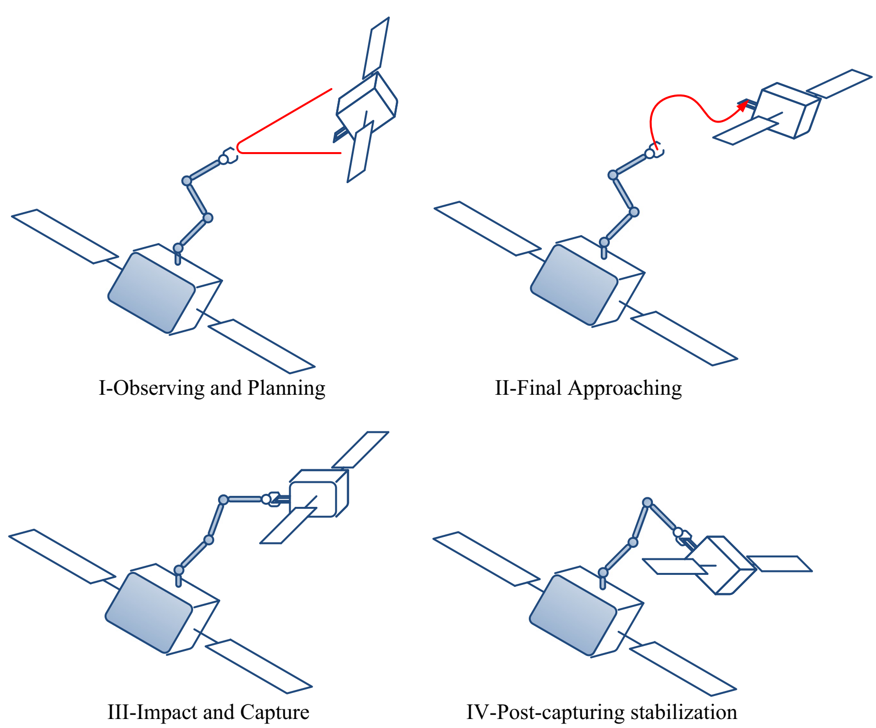

Fig. 2. The four phases of a satellite capturing operation.

Please cite this article as: Flores-Abad A, et al. A review of space robotics technologies for on-orbit servicing. Progress in Aerospace Sciences (2014), http://dx.doi.org/10.1016/j.paerosci.2014.03.002

This paper provides a survey of the literature on different topics related to space robotic systems for manned and unmanned on-orbit servicing missions. The remainder of this paper is organized as follows. Section 2 presents background information on the existing space robotics manipulators and demonstration OOS missions. Then, the basic approaches for the kinematics and dynamics modelling of space manipulators are presented in Section 3. It is followed with a description of the schemes for accomplishing an approaching maneuver in Section 4. In Section 5, path planning and control techniques for approaching a target satellite are discussed. Section 6 outlines the methods for capturing the target satellite with the less reaction on the base and the proposed stabilization approaches. Section 7 discusses the flexibility problem inherent to lightweight space robotic manipulators. In Section 8, the existing test facilities employed for ground-based verification of spacecraft servicing systems are described. Finally, a conclusion is provided in Section 9.

2. Background

Ever since the first deployment of the Shuttle Remote Manipulator System (SRMS) from the cargo bay of the Space Shuttle Colombia in 1981, robotic systems have been used on many space missions, and are also employed on the International Space Station (ISS). Developed by the Canadian Space Agency (CSA), SRMS is a 15.2 m long, 6-DOF robotic manipulator known as Canadarm which has conducted numerous on-orbit service missions [14]. Nowadays, with the advances in robotics technologies, some of the current space manipulators can move with high dexterity to support or even replace astronauts for some precise, complex or risky tasks. For example, with the addition of Dextre (also known as the Special Purpose Dexterous Manipulator or SPDM for short) to the Space Station Remote Manipulator System (SSRMS), many delicate assembly and maintenance tasks that were previously performed by astronauts during spacewalks can now be carried out by the robot [15]. The SSRMS, nicknamed Canadarm2, is a 7-DOF, 17-meter long robotic arm with a symmetric structure capable of walking around the ISS. The manipulator has a modular design for easy maintenance and force–moment sensors for advanced robotic control [16].

In addition to the SRMS and the ISS's Mobile Servicing System (the main ISS robotic system comprising the SSRMS, the SPDM and the Mobile Remote Servicer Base System which acts as a movable platform for the SSRMS and the SPDM), other ISS-servicing robotic systems have been designed by some international space agencies. The Japanese Experiment Module Remote Manipulator System (JEMRMS), built by the Japan Aerospace Exploration Agency (JAXA), is a robotic manipulator system intended for supporting experiments conducted on the Exposed Facility (EF) of the Japanese Experiment Module (JEM) [17]. This robot includes a 6-DOF, 10-meter long main arm, and a 6-DOF, 2-meter long small fine arm (SFA) designed to perform dexterous tasks [18]. The European Robotic Arm (ERA), developed by the European Space Agency (ESA), is a 11-meter manipulator with 7-DOF, two booms and a reallocable base to be attached to the Russian segment of the ISS [19].

In additional to the aforementioned ISS servicing robotic manipulators, a number of other experimental space manipulators have been developed and successfully flown in space. DLR developed the Robot Technology Experiment (ROTEX) to study and experimentally demonstrate robotics technologies aboard the Space Shuttle [20]. A variety of teleoperation modes were verified despite several seconds of delay, such as on-board teleoperation, teleoperation from the ground, and sensor-based offline programming. Later, DLR developed the Robotics Component Verification on the ISS (ROKVISS) robotics experiment [21]. Long term DLR's space robotics projects were presented in [22]. DLR is also developing Space Justin, a humanoid robot capable of performing complex repair tasks in orbit. This humanoid has a head, torso, and arms, but no wheels or legs, as it is expected to be mounted on a spacecraft. While the long-term objective is to have Justin operate autonomously, this robot is expected to be teleoperated from the ground [23]. Similarly, NASA developed Robonaut 1 (R1), a dexterous robot to assist astronauts during Extra Vehicular

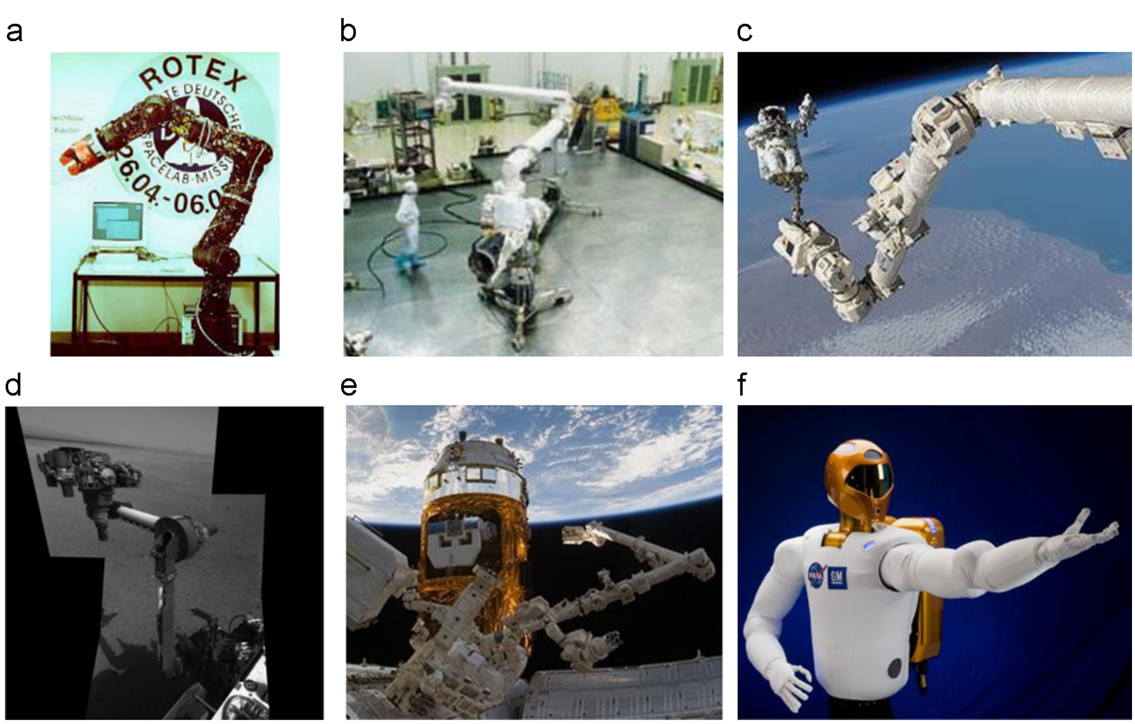

Fig. 3. Examples of robots which have served in current or past space missions: (a) ROTEX of DLR [20], (b) JEMRMS of JAXA [17], (c) Canadarm of CSA [14], (d) Curiosity robotic arm of JPL (http://www.jpl.nasa.gov/spaceimages/), (e) SSRMS and SPDM of MDA (http://www.mdacorporation.com) and (f) Robonaut 2 of NASA-GM [25].

Activities (EVA) tasks. R1 has the ability to work with existing EVA tools and interfaces in high-fidelity ground-based test facilities [24]. Further, NASA and General Motors jointly developed a second generation of R1, the Robonaut 2 or R2 for flight testing on ISS. This is a state-of-the-art, dexterous, anthropomorphic robot that has significant technical improvements over its predecessor making it a far more valuable tool for astronauts. Upgrades include increased force sensing, greater range of motion, higher bandwidth, and improved dexterity [25]. R2 arrived on the ISS in February 2011 [26] becoming the first humanoid robot in space and is currently undergoing testing. While working side-by-side with human astronauts, Robonaut 2 will actuate switches, use standard tools, and manipulate space station interfaces, soft objects and cables. Some of the space robots are shown in Fig. 3.

Robotic manipulators are well suited to execute highly repetitive tasks that would be too time-consuming, risky and expensive if performed by astronauts. Besides, space robots require much less infrastructure than humans (e.g. life support systems), which makes them preferable in space [27]. Exhaustive lists of possible applications of robotic on-orbit servicing are found in [28,29], which can summarized as follows:

Assembly, maintenance and repair. Highly advanced robotic systems are commonly used on the ISS and play a key role in station assembly and maintenance: moving equipment and supplies around the station and servicing instruments and other payloads attached to the space station (such as batteries and electronic components). Typically, those manipulators are self-relocatable and can move from one location to another on the ISS by translating along a special truss of the station or inchworm-like locomotion over a network of grapple fixtures on the station.

Spacecraft deployment, release and retrieve. For nearly three decades, robotic arms have also been used to deploy, release, and retrieve spacecraft of all sizes. Not only they can retrieve satellites, but they can also assist with berthing/de-berthing of a spacecraft to a station. This has been done for module redocking on the MIR orbital complex [30,31].

Extravehicular activity support. Robotic manipulators have proved to be useful in supporting astronauts during EVA tasks. One of the best examples of such an operation occurred in 1994, for the on-orbit fixing of the Hubble space telescope (HST) [32], which is widely known for advancing astronomy and scientific understanding of the universe. During long and meticulous repairs, a robotic arm was used to hold the telescope still while the astronauts were replacing the solar arrays and fixing the attitude control system and the main computer of the spacecraft. The complete operation lasted 35 h and 28 min and it was a success. Robotic arms assisted astronauts for several more repairs of the HST in 1997, 1999, 2002 and 2009. More frequently, during spacewalks on ISS, astronauts also anchor themselves to robotic arms in order to reach specified spots and stay anchored with respect to the ISS.

Inspection. CSA developed an extension to the Space Shuttle's robotic arm to perform on-orbit inspections of the Shuttle's thermal protection system, known as the Inspection Boom Assembly (IBA), whose main role was to inspect the thermo protection titles around the body areas of the Shuttle where the SRMS could not reach by itself [33]. Weighing 211 kg (excluding sensors), and nearly 15 m long, the IBA had roughly the same dimensions as SRMS. Once in orbit, the SRMS would pick up the IBA and move it around the necessary positions to permit a complete inspection of the shuttle tiles and other critical surfaces to ensure a safe return to the Earth [34].

Refueling. Extending a satellite's operational life might gain considerable economical savings [6]. Recently, NASA used the ISS's Canadarm2 and the Dextre robots to accomplish an experimental demo of robotic refueling mission. In this mission, Dextre used four unique tools to demonstrate a refueling tasks, including cutting and manipulating protective blankets and wires, unscrewing tiny caps and accessing valves, transferring fluid, and putting a new cap in place for future refueling activities [35] (see Fig. 4.)

Fig. 4. Candarm2 and Dextre performing a demo of a robotic refueling task [35].

Multi-arms cooperation. Two arms can also work together towards accomplishment of difficult tasks that would be otherwise impossible to achieve by just a single arm. This occurred on April 28, 2001 when SSRMS transferred a piece of equipment over to SRMS. This event is now referred to as a *handshake in space* of the two Canadian robotic arms. SSRMS and SPDM have also performed cooperative work on ISS, such as the SSRMS is often used as a mobile platform for the SPDM to perform some work (see Fig. 4). It is expected that future space robots such as Robonaut2 will perform more multi-arm cooperation tasks.

Several space agencies have developed robotic OSS missions. The Experimental Test Satellite VII (ETS-VII) of the JAXA is considered the first robotic OOS demonstration mission, which included a 2-meter long, 6-DOF robotic arm mounted on an unmanned spacecraft. The experimental system was launched in November 1997, with the objective to verify technologies for autonomous rendezvous and docking (AR&D), and robotic servicing in space [36]. The experiment included a variety of tasks such as teleoperation from the ground with a time-delay, robotic servicing tasks such as orbital replacement units (ORU) exchange, deployment of a space structure, and capture and berthing of a target satellite. To avoid flying away due to a possible failed capture, the robotic capture task was performed while the two satellites were still physically tied using a latching mechanism [37]. A study on the challenges introduced by teleoperation with time delays for ETS-VII was reported in [38].

Defense Advanced Research Projects Agency (DARPA) in conjunction with Boeing successfully launched and accomplished the Orbital Express mission in 2007. As an advanced OOS technology demonstration mission, it demonstrated the technologies of one spacecraft servicing another one such as autonomous rendezvous and docking, in-orbit refueling, and robotic ORU replacements. During the mission, a robotic arm autonomously transferred a supplemental battery and backup computer to a target spacecraft designed to be serviced [39,40]. Another DARPA OOS program was the Spacecraft for the Universal Modification of Orbits (SUMO), which was executed by the Naval Research Laboratory. Initiated in 2002, the program aimed at combining a detailed stereo photogrammetric imaging with robotic manipulators to grapple space objects of an existing spacecraft for servicing [41]. A laboratory demonstration provided realistic test and evaluation of critical technologies associated with unaided target approach and capture

Please cite this article as: Flores-Abad A, et al. A review of space robotics technologies for on-orbit servicing. Progress in Aerospace Sciences (2014), http://dx.doi.org/10.1016/j.paerosci.2014.03.002

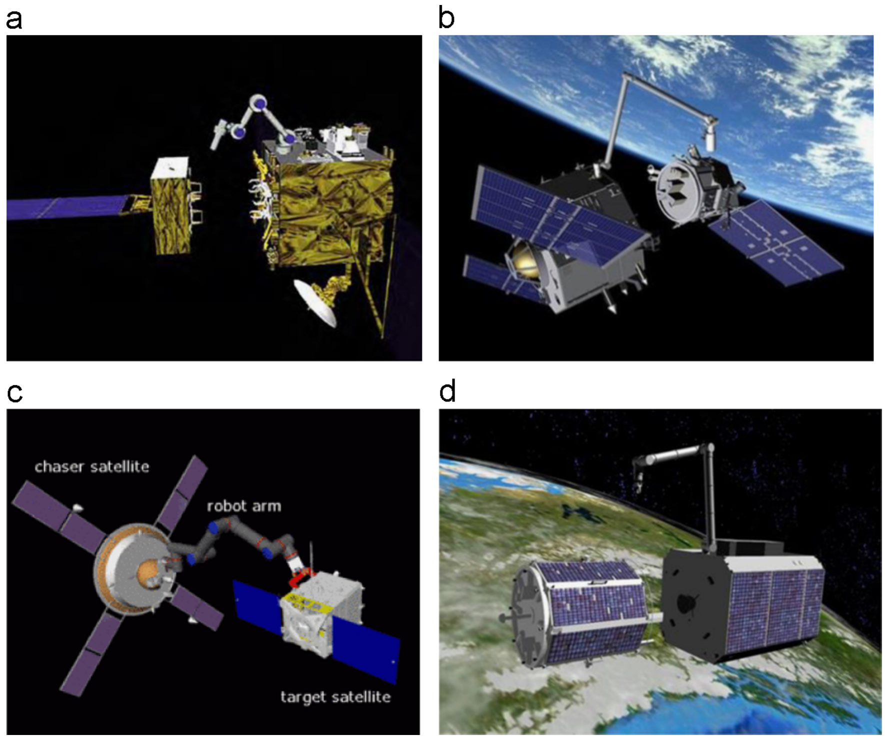

Fig. 5. Different concepts of on-orbit servicing missions: (a) ETS-VII of JAXA [36], (b) orbital express of DARPA [39], (c) TECSAS of DLR/CSA/RKA [52] and (d) DEOS of DLR [53].

[42]. The program was renamed to Front-end Robotics Enabling Near-term Demonstration (FREND) with the objective of performing AR&D with satellites that have not been built to enable robotic servicing [43]. The FREND program used a 7-DOF flight robotic arm system with its associated avionics to accomplish full-scale laboratory demonstration of autonomous rendezvous and grapple of a variety of spacecraft interfaces [44,45]. The FREND robotic arm is being currently utilized in a new DARPA OSS program, called PHOENIX, which is aimed at removal and reuse of some existing parts of decommissioned satellites in GEO orbit [46]. The program started in July 2012 and its first keystone mission in 2015 plans to demonstrate harvesting an existing, cooperative, retired satellite aperture, by physically separating it from the host non-working satellite using on-orbit grappling tools controlled remotely from the earth. The aperture will then be reconfigured into a new free-flying space system and operated independently to demonstrate the concept of re-using space asset [47,48].

In 2002, the United States Air Force Research Laboratory (US AFRL) demonstrated accurate detection, tracking and pose estimation of on-orbit targets to enable satellite rendezvous and docking operations with the Experimental Satellite System 11 (XSS-11) mission [49]. Similarly, NASA sponsored the Demonstration for Autonomous Rendezvous Technology (DART) project which was launched in 2005 [50]. The objective was to validate innovative hardware and software systems enabling autonomous rendezvous maneuvers. The integration of an advanced video guidance sensor and autonomous rendezvous and proximity operations algorithms was also intended. The proximity rendezvous operation was not completed before the fuel was used up during rendezvous maneuvering [51].

Another recently planned OOS mission known as Technology Satellites for Demonstration and Verification of Space Systems (TECSAS) was jointly developed by DLR, CSA, and RKA (Russian Space Agency). TECSAS consisted of a servicer satellite equipped with a robotic arm and a target microsatellite to be captured and serviced in orbit [52]. The mission comprised different phases in which numerous features were to be demonstrated, such as far rendezvous, close approach, flying-around inspection, formation flight, capture, stabilization and calibration of the coupled system, flight maneuvers with the coupled system, manipulation on the target satellite, active ground control via tele-presence, and passive ground control during autonomous operations. While the multi-nation effort of this mission was discontinued due to the priority shift of individual participating agencies, Germany nevertheless continued their development work under the Deutsche Orbital Servicing Mission (DEOS) mission. The main purpose of this revamped mission is to find and evaluate procedures and techniques for rendezvous, capture and deorbiting of a noncooperative spacecraft from its operational orbit [53,54]. The DEOS mission objectives are divided into primary and secondary mission goals. The primary mission goal comprises capturing of a slow-tumbling (4 degrees per second) and non-cooperative satellite by a manipulator and controlled re-entry of the rigidly coupled satellites within a given re-entry corridor [55]. Fig. 5 shows some of the above-mentioned mission concepts.

A few commercial OSS programs are also currently being developed. One is the ConeXpress Orbital Life Extension Vehicle (called CX-OLEV) which is being developed by Orbital Recovery Limited (ORL) to extend the operating life of large geostationary satellites [56]. The other is being developed by Space Exploration Technologies (SpaceX), the first private company to launch a servicing mission to the ISS. The goal is to demonstrate reliable crew and cargo transportation services for the ISS, thereby replacing the Space Shuttle's capability. In May 2012, as shown in Fig. 6, the SpaceX vehicle (Dragon) successfully accomplished its first docking with the ISS [57], delivered about 1200 lbs of water, food, and other supplies for the astronauts stationed in ISS. Thus far, the vehicles of both commercial programs have not yet been equipped with a robotic arm.

3. Kinematics and dynamics of space manipulators

The main differences between space robots and ground-based manipulators are that the base of a space manipulator is not fixed to the ground and the gravity forces exerted on them are reduced. The robot is instead flying or freely floating (including rotating) in an orbital environment. Also, the dynamics of the manipulator and its base are coupled, because movements of the manipulator disturb the attitude of the spacecraft, complicating the kinematics and dynamics analysis of the system [58–62].

Regarding the base spacecraft, three types of operation are considered. The first type corresponds to the free-flying case, where the base is actively controlled and hence, the entire servicing system is capable of being transferred and orientated arbitrarily in space. The utilization of such a system may be limited because the manipulator motion can both saturate the reaction jet system and consume large amounts of fuel [63]. In the second type, the base attitude is controlled by using reaction wheels, leaving the spacecraft only in free translation. These two categories are split because in some cases only the control of the attitude change is enough to reach the target position and to avoid loss of communication with ground stations and disorientation of solar panels. The third type is the free-floating case, where the attitude control of the base is inactive and thus, the base is completely free to translate and rotate in reaction to the manipulator motion. Similar to some other authors, for instance [64,65], we will merge the first two categories (fully actuated and partially actuated) into the free-flying case.

3.1. Kinemo-dynamics

Kinematics of a manipulator describes the relationship between the motion variables of the end-effector (EE) in a Cartesian space and those of the joints of the manipulator in the joint space. In a ground-fixed manipulator case, the position of the EE in an inertial frame depends only on the current joint positions (in joint space) and the geometrical parameters of the manipulator. However, for a free-floating manipulator, any EE position change in an inertial frame is a function of not only a change of the joint positions but also the change of the inertia distribution of the manipulator which is configuration dependent. Thus, in general, the inverse and forward kinematics problem for a space manipulator is also considered a dynamic problem because it involves the manipulator's inertia properties.

Fig. 6. The SpaceX Dragon capsule captured by the ISS's robotic arm. The commercial craft brought food and other supplies to the station [57].

3.1.1. Kinemo-dynamics of single-arm space manipulators

One of the seminal works analyzing the kinemo-dynamics of space manipulators was presented by Longman [61], where the author demonstrated that given the history of the robot joint angles as a function of time, the final joint angles can be used as in the standard fixed-base manipulators problem to obtain the robot's end-effector position relative to the base spacecraft. Then, by the principle of angular momentum conservation, it is possible to get the inertial position of the satellite as well as its orientation. Following such a method, the authors were able to find a feasible inverse kinematics solution that achieves not only the desired end-effector position but also the desired spacecraft attitude. The workspace was also analyzed and found to be a perfect sphere whose radius is a monotonically decreasing function of the manipulator's mass. Umetani and Yoshida [66] developed an inverse kinematics solution by defining the *Generalized Jacobian Matrix* (GJM), which is a function not only of the joint angles but also of the inertia parameters. They further showed that the GJM is very close to the conventional Jacobian matrix of the same manipulator as if it was fixed to the ground when the mass of the manipulator is much smaller than the mass of the base spacecraft. Nevertheless, it was demonstrated in [64] that the rank of the GJM is deficient at some configurations in the manipulator's joint space, which makes the manipulator unable to move its end-effector in some directions of the inertial space. These singular configurations cannot be determined solely by the kinematics of the system, instead, they also depend on the system's inertia properties. Hence, they are called *dynamic singularities*. The authors also showed that the end-effector's linear and angular velocities in inertial space can be expressed solely as a function of the manipulator joint angles and rates, and that they do not depend upon the uncontrolled linear and angular velocities of the base spacecraft. A Moore–Penrose pseudo-inverse version of the GJM was used to overcome the dynamic singularities problem by using the redundant DOFs of the space manipulator system [67]. However, this formulation is even more complex than the generalized Jacobian technique.

Another effort to provide tools that aid at understanding and solving the kinematics and dynamics problem of space manipulators was done by Vafa and Dubowsky. They introduced the *Virtual Manipulator* (VM) concept [59]. The VM is a massless kinematic

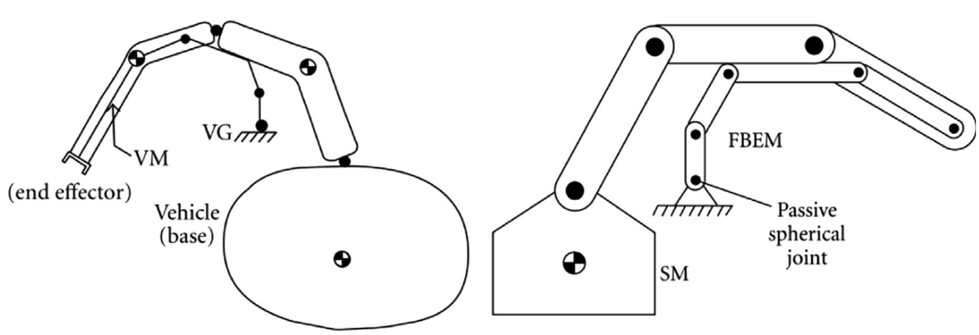

Fig. 7. Virtual manipulator and dynamically equivalent manipulator representation of a space servicing system: (a) a space manipulator and its corresponding VM [58] and (b) a space manipulator and its corresponding DEM with its first joint being spherical [68].

Please cite this article as: Flores-Abad A, et al. A review of space robotics technologies for on-orbit servicing. Progress in Aerospace Sciences (2014), http://dx.doi.org/10.1016/j.paerosci.2014.03.002

chain whose base is fixed in the inertial space at a point called the virtual ground (VG) and whose tip is at an arbitrary point on the real manipulator tip. The VG is located at the center of mass of the manipulator-spacecraft system. This point does not move in the inertial space when there are no external forces applied on the system. Once the VM is constructed, it moves with the real manipulator. The endpoint of the VM is always coincident with the endpoint of the real manipulator. These properties enable both kinematics and dynamics of a space manipulator system to be modeled in the same way as its corresponding VM which is like a ground robot because its base is always fixed in the inertial frame.

In the above-mentioned approaches to find kinematics model, no generalized expression for the total momentum is obtained, which may lead to some numerical inefficiencies. Therefore, Saha [68] proposed to derive the total momentum of a space manipulator in terms of an arbitrary body, which is called *primary body*, and it was shown that when the end-effector is chosen as the primary body, it will lead to a kinematics model that results in the most efficient algorithms.

Note that a VM is an idealized massless kinematic chain and thus, it can only be simulated in a computer but cannot be physically built. This means that the concept of VM cannot be used as an experimental method for space manipulators. Liang et al. [69] first proposed the concept of *Dynamically Equivalent Manipulator* (DEM). The DEM goes beyond the VM concept because it represents a space manipulator both kinematically and dynamically and thus, it can be physically built for experimental study of the dynamic behavior of a space manipulator. The DEM is a fixed-base manipulator whose first joint is a passive spherical joint and whose kinematics and dynamics models are identical to those of the corresponding space manipulator system. The first joint is fixed in the same point where the VG of the VM is located. The lengths of the links are also the same as those of the VM. The dynamics of the DEM maps identically the dynamics of the space manipulator under the action of a control law. This equivalence is valid not only for the free-floating case where the base attitude is uncontrolled but also for the case where the base attitude is actively controlled. The DEM concept was employed to test some control methods which were originally developed for fixed-base manipulators but would be used for space manipulators. For example, different adaptive controllers have been verified using the DEM concept in [70–73], and recently, a singularity free formulation of the DEM was presented in [74]. The concepts of VM and DEM for a simple space manipulator are shown in Fig. 7.

Authors in [75] presented a solution of the inverse kinematics problem for space manipulators using optimization criteria rather than applying conventional schemes based on pseudo-inverse matrix methods. To handle the dynamic singularities, in [76] a method called *Singularity Separation Plus Damped Reciprocal* (SSPDR) was proposed. The approach separates the singularity parameters from the inverse Jacobian matrix, replaces their reciprocals using the damped reciprocals, and combines that information with the measured angular velocity of the base. Then, the dynamic singularity problem is transformed into a kinematic singularity problem which can be handled by many existing techniques.

3.1.2. Kinemo-dynamics of multiple-arm space manipulators

The use of multiple-arm systems instead of a single-arm manipulator offers some advantages from the OOS point of view. In this case one of the arms can be used to follow the planned trajectory while the other is used to compensate the reaction on the base satellite, as demonstrated by Yoshida et al. [78], where dynamics and kinematics analysis of multiple-arm space robots was discussed. The authors obtained the GJM for a dual-arm case, so that a proper motion control of the multiple manipulators can be implemented. Advantages in coordinated control between the manipulator and its base spacecraft were also discussed. Fig. 8 shows the artistic representation of ATLAS (Advanced Telerobotic Actuation System), which is a dual-arm space manipulator system proposed by Ellery [79] as a potential space robot dedicated to OSS. Kinematics and dynamics modelling of ATLAS can be found in [77].

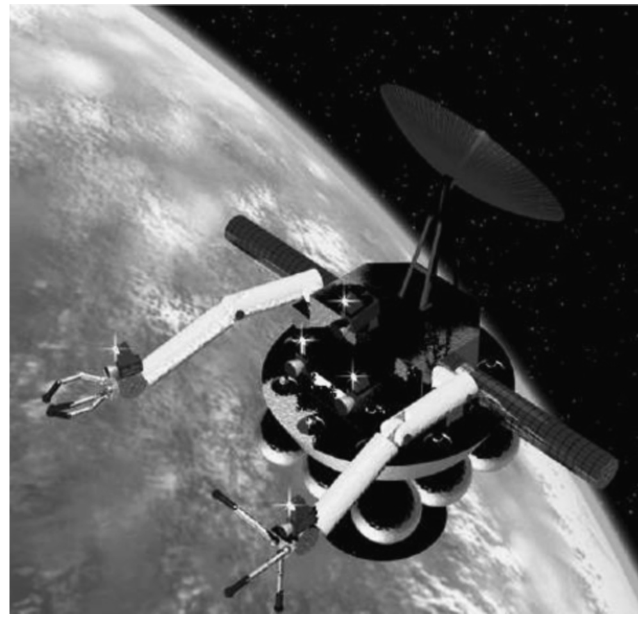

Fig. 8. ATLAS robotic servicer concept [77].

Moosavian and Papadopoulos [80] developed and compared two kinematics models of multiple-arm space manipulators, called the barycentric vector approach and the direct path method. It was found that the latter requires significantly less computations for position and velocity analysis, as it results in equations with simpler terms. Later, the same authors presented an explicit dynamics model of a multiple-arm manipulator system based on a direct path kinematics approach [81]. Derivation of the equations of motion resulted in an explicit formulation of the system's mass matrix and the generalized nonlinear inertia forces. The obtained explicit dynamics model of a multiple-arm manipulator can be implemented either numerically or symbolically. A method based on the treatment of structural changes which is suitable to analyze the dynamics of space manipulators with multiple arms was presented in [82,83]. The computational efficiency of the algorithm was studied to conclude that the method is simple to implement and can be easily parallelized.

3.2. Contact dynamics

A critical portion of the dynamics modeling for the OOS applications is contact dynamics (including low-speed impact dynamics). Contact dynamics is one of the most difficult areas in multibody dynamics and is still an active research subject. An early application of contact dynamics in space robots was reported in [84], where, assuming a point contact scenario, the contact force is modeled as an impulse function. However, the main modeling difficulties arise from the complicated geometries of the contact interfaces such as the ones shown in Fig. 9. Thus, Ma et al. [85,86] developed a generic contact dynamics modeling and simulation system to support the development and operations of the ISS robotic systems SSRMS and SPDM. They further developed a model reduction technique to improve the efficiency of high-fidelity but usually very time-consuming contact dynamics simulations [87]. Model reduction of contact dynamics is a very difficult problem and it is still an active research topic because of the highly nonlinear nature of the involved impact-contact mechanics.

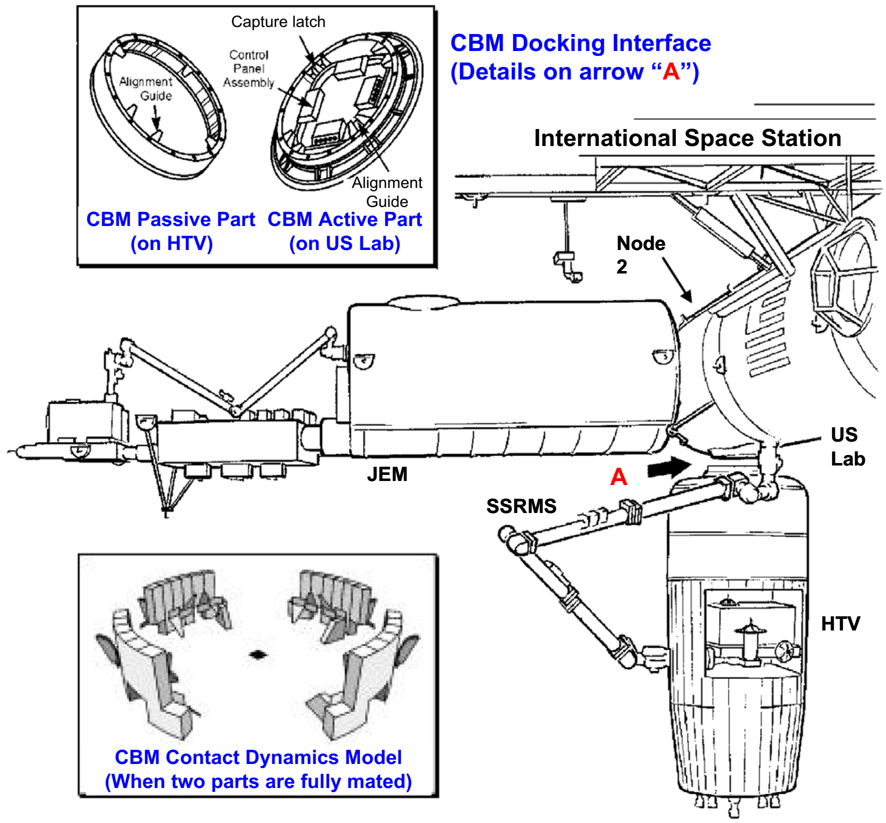

Fig. 9. Contact interfaces for robotic berthing the H-II Transfer Vehicle (HTV) to the ISS [85].

An approach that considers the generalized constraint forces between a space robot's end-effector and the target satellite as internal forces rather than as external forces was presented by Shibili et al. [88], where the initial conditions for the post-impact motion were obtained from the impact model. Nenchev and Yoshida [89] also addressed the contact dynamics modeling and control issues for space manipulators. Ma et al. [90] developed a control strategy for achieving high fidelity contact dynamics simulation of a new, robotics-based, hardware-in-the-loop (HIL) rendezvous and docking simulation. They used the EPOS (European Proximity Operations System) facility as a HIL simulation platform to test and validate OOS tasks developed by DLR and ESA. Abiko et al. [91] introduced a contact dynamics simulation for capturing a floating target by a long reach space manipulator with a snaring-wire type end-effector. The authors used this kind of end-effector because current space manipulators such as the SSRMS are equipped with a latching end-effector with three snare wires inside. An experimental evaluation of the contact/impact dynamics between a space robot and a tumbling object was introduced by Uyama et al. [92]. To study the contact phenomenon and avoid hard impact, the authors employed a stiff manipulator with compliant wrist. The coefficient of restitution and the contact duration were used as evaluating parameters. Sawada et al. [93] focused on the contact dynamics of the manipulator's end-effector and the grapple fixture of a target satellite. To validate the method, they set up a hybrid simulation using a numerical model and a 6-DOF robot with a 6-axis force–torque sensor. The authors also employed a three-wired end-effector mechanism. A survey of general contact dynamics modeling techniques can be found in [94].

4. Observation and planning phase

The tasks of the observation and planning phase may include to acquire the 6-DOF motion information including the position, attitude, linear and angular velocities of the target body; identify physical properties such as the inertia parameters; determine when and where to grasp the target, and plan the motion trajectory for a final approaching and capturing. A malfunctioning satellite or an orbital object may have a tumbling motion and poses unknown kinematics and dynamics properties. Therefore, it becomes essential to predict its motion pattern and identify its kinematics and dynamics properties. Another necessary task for a robotics-based OOS mission may consist on guiding a space manipulator to perform proximity rendezvous to a target satellite. The term "proximity" means that the servicing spacecraft has completed its orbit transferring and it has been in a very short distance to the target satellite [13].

4.1. Target motion prediction and parameter identification

In order to estimate the position and attitude of a target satellite, Nagamatsu et al. [95] proposed a 12th order extended Kalman filter method. To verify the validity and applicability of the method, experiments were performed to capture a free-flying object by using a 3D hardware simulator with a 5-DOF manipulator. Huang et al. [96] used the estimation scheme introduced in [95] to develop an algorithm for tracking trajectory planning. The authors assumed that the target has a symmetric geometric shape and the target's size, shape and mass were all known. Besides, the handling location was determined by human inspection. It was also assumed that the target is equipped with visual markers, signal reflector, and GPS device for simplification. Thienel et al. [97] took advantage of the fact that the HST is equipped with vision-based sensors to develop a method for estimating the angular rates of the HST. The method was used in the estimation part of a tracking control scheme in [98]. Assuming that an object is not acted upon by any external force and moment, the motion of the target satellite was predicted in [99]. Litcher and Dubowsky,

Please cite this article as: Flores-Abad A, et al. A review of space robotics technologies for on-orbit servicing. Progress in Aerospace Sciences (2014), http://dx.doi.org/10.1016/j.paerosci.2014.03.002

using 3D vision sensors, proposed an architecture for estimation of dynamic state, geometric shape, and model parameters of an object in orbit, with potential application to satellite capturing [100]. To allow a faster prediction, range data as measured by stereo vision or a laser range sensor was used to estimate the motion and the parameters of the target in [101]. Inaba et al. [102] introduced the design concept of a visual servoing system for a space robot and presented the experimental results using the Japanese ETS-VII test bed. They analyzed the system requirements such as computing power, frequency and range of measurements as well as accuracy. Assistance from the ground was considered to choose a time line to maintain acceptable light conditions. From the visual information of a stereo-vision system, reference [103] proposed an iterative recursive least-square pose refinement to perform the relative pose estimation of a floating object. Xu et al. also introduced an autonomous path planning method for target capturing in [104,105]. The target features were extracted based on the visually measured information via the hand-eye camera and the target pose (position and orientation) and velocities were estimated using a Kalman filter scheme. Disturbance on the base due to manipulator's motion was also estimated and reduced. The authors validated the method using both computer simulations and experiments. Along the same line, from noisy measurements of a vision system, a Kalman filter was used to estimate the motion state and some dynamics parameters for the capture of a tumbling satellite in [106]. A 3D-image generated by a PMD (photonic mixer device) camera was used for determination of the relative distance and orientation, as well as the motion identification of a satellite [107]. A markerless visual 3D model-based servoing using a monocular camera mounted on the chaser was presented in [108]. The system also included a robotic arm, and a chaser satellite mockup as shown in Fig. 10.

An extension of this work was presented in [109], where the authors used a GPU (Graphic Process Units) acceleration and 3D rendering to track targets of complex geometrical shapes. A fault tolerant pose estimation algorithm for a free-floating space object using large range sensor was presented in [110], where the 3D vision data was integrated using a Kalman filter. To perform the experiments, a Neptec's Laser Camera System was used for real time scanning of a satellite model attached to the manipulator arm, which was driven by a simulator according to orbital and attitude dynamics, as depicted in Fig. 11. English et al. presented analysis and lessons learned from the real-time vision systems for dynamic pose estimation used by NASA in the assembly of the ISS and for AR&D operations [111]. Visual servoing using CCD cameras for simulation of space robot capturing was presented in [112,113].

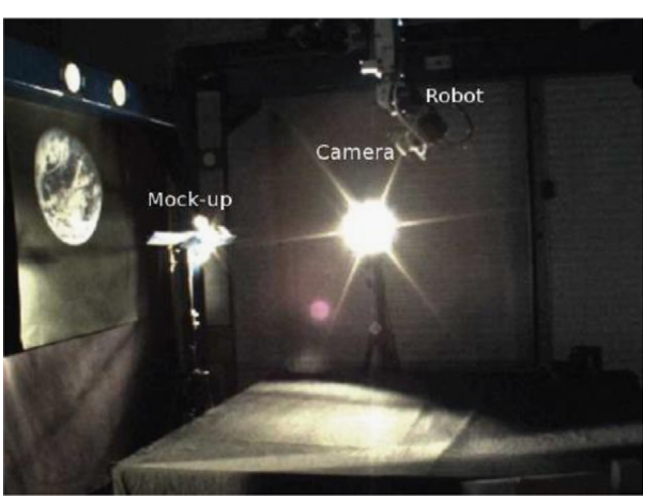

Fig. 10. Experimental setup for pose estimation with a monocular camera [108].

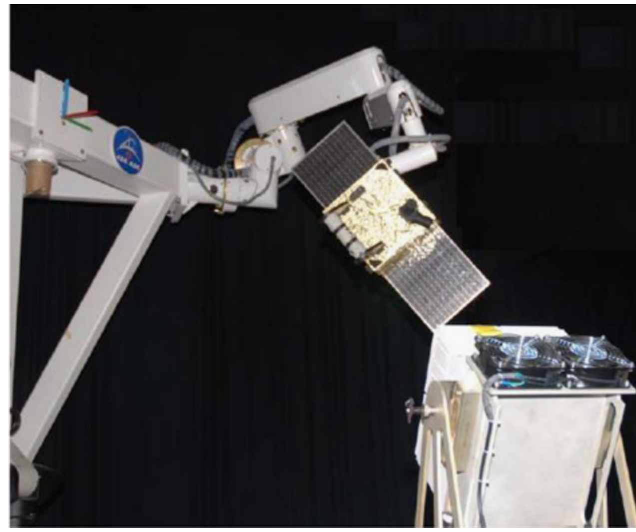

Fig. 11. Experimental setup for satellite's position/attitude estimation using Neptec's laser rangefinder scanner [110].

Issues such as lighting, computer power and time delays were taken into account.

Based on stereo camera hardware, the Massachusetts Institute of Technology (MIT) Space Systems Laboratory is currently developing relative vision-based navigation and control techniques for autonomous inspection and 3D mapping of an unknown, uncooperative spacecraft that is spinning and tumbling at different rates [114–116]. The vision-based system has been successfully demonstrated onboard the ISS and several tests have been conducted to analyze its performance. An image-based visual servoing considering the vibration induced by the manipulator's links motion was presented by Sabatini et al. [117,118]. In order to increase the system robustness and to reduce the possibility of failure, an extended Kalman filter for the estimation of the feature motions was developed.

The inertia parameters of a target satellite may not be the only unknowns. Due to fuel consumption, hardware reconfiguration, payload deployment, or capturing of a flyer, the inertia properties of the servicing satellite may also change. Therefore, dynamics parameters identification methods have been proposed to handle this problem [119]. The first work in this sense was proposed by Murotsu et al. [120,121], where two parameter identification methods for the captured payload were introduced. One method was based on the linear and angular momentum conservation law, and the other on Newton–Euler equations of Motion. The latter required measuring velocities and angular accelerations. The ETS-VII robot was used to test a number of inertia parameter identification methods, such as the case of an algorithm developed by Yoshida and Abiko [122] to identify the masses, moments of inertia and products of inertia, of a free-flying space robot, without requiring torque or acceleration measurements. The method made use of measurements of the joint velocities, reaction wheels and the base attitude, and was complemented with the use of the gravity gradient effect. A method for identification of the base spacecraft's inertia parameters of a free-flying robot was introduced in [123,124]. This work was part of the GETEX Dynamic Motion experiments carried out by DLR in collaboration with NASDA (now JAXA) on the ETS-VII satellite. Using measuring data, the parameters identification method refined the inertia parameters as an optimization problem where the cost function is the sum of the differences between the simulated and the measured velocity. Inclusion of noise was also considered. Ma et al. [125] proposed an on-orbit inertia identification method which uses an onboard robotic arm to excite the angular velocity changes of the base spacecraft and then using the measured angular velocity changes to identify the unknown inertia parameters of the base spacecraft. Since the robotic arm is powered by solar energy, the approach does not require the use of fuel. Further, as the method was derived from the momentum equation of the system, it requires the measurement of velocities only, and does not need any information of the acceleration and energy-dissipating internal forces. The latter is very difficult to accurately measure.

4.2. Proximity rendezvous for autonomous capturing and docking

Most of the actual rendezvous studies deal with cooperative targets. However, a space robot for OOS may demand the proximity or close-range rendezvous with a noncooperative target spacecraft. Therefore, this section focuses on research studies applicable to proximity rendezvous operations with noncooperative target objects. A two-phase navigation solution for rendezvous with a tumbling satellite in a 2D space was studied by Fitz-Coy and Liu [126]. The target vehicle was assumed uncontrolled but having constant linear and angular velocities. It was shown that this kind of maneuvers requires two phases. In the first phase, the LOS (line-of-sight) rotation is driven to zero while aligning the capturing mechanisms of the two vehicles. During the second phase, the chase vehicle maintains the angular velocity of the target and simultaneously reduces the range-to-go rate to zero. In both phases, the berthing mechanism is aligned with the LOS and the angular velocity of the vehicle relative to the LEO is kept in a small value. In [127] a method for matching angular velocities between the servicer and the target by changing the target's moments of inertia was presented. Similarly, Tsuda and Nakasuka [128] proposed a strategy that assumes that the chaser spacecraft is equipped with long adjustable booms. After estimating the moments of inertia of the target, the chaser spacecraft adjusts the length and orientation of its booms, to synchronize its motion with that of the target. Once the motion is synchronized, the same rotation pattern as the target can be maintained, with no control torque required.

However, there are several technological challenges that remain to be solved to make this approach feasible in practice. A more recent work by Matsumoto et al. [129] proposed the use of the natural dynamics to complete a passive fly-by approach and an optimal trajectory for close-range rendezvous with a rotating satellite, considering issues such as collision avoidance between the manipulator and the target satellite. Ma et al. [130] designed an optimal trajectory for a spacecraft to approach a tumbling satellite by minimizing time and fuel. They obtained the required thrust force profiles that would guide the chasing spacecraft to approach a tumbling object such that the two vehicles would eventually have no relative rotation and thus, a subsequent capture operation can be safely performed with a normal docking or capture mechanism. A guidance methodology to generate fuel-optimal trajectories using a mixed-integer linear programming (MILP) solver was developed by Breger and How [131]. The work by Boyarko et al. [132] expanded the scope of Ma et al. [130] by taking into account the proximity motion dynamics, and considering the full 6-DOF model, and by determining both the minimum-time and the minimum-control (energy) solution to the rendezvous problem. Another paper by the same authors [133] considered three different performance indexes adding further constraints to match terminal attitude and angular rate, along with position and velocity. In both studies, the optimal trajectory planning was analytically formulated through the use of the Pontryagin minimum principle and solved numerically with a Gauss pseudospectral approach. A simpler algorithm for trajectory planning in real time that can be handled more easily by an onboard computer is the widely used glideslope algorithm [134,135]. A glideslope is defined as a straight path from the current location of the chaser spacecraft to its intended destination, which may be a target spacecraft's center of mass, a docking port, or a location of interest near the target. The guidance equations are based on the closed-form solution of the linear Clohessy–Wiltshire equations. To mitigate the fuel-optimality problem inherent to the glideslope approach, cubic spline-based analytical guidance laws can be employed. Recently, building upon the work of Sultan et al. [136] for spacecraft formation flying, Fejzic [137] developed a collision-avoidance cubic spline-based planning algorithm for spacecraft docking by defining way-points to avoid an obstacle. Once the position and the attitude were measured based on stereo vision, autonomous rendezvous and robotic capturing of a non-cooperative target was proposed by Xu et al. [138]. 3D simulation results were performed to verify the algorithm. Xin and Pan [139] developed an optimal control of spacecraft approaching a tumbling target. They minimized the flexible motion induced by large angular maneuvers using a nonlinear optimal control technique.

5. Final approaching phase

In order to perform on-orbit servicing, the servicing satellite, which is assumed to carry a manipulator, has to first approach following a desired trajectory to the target satellite. Here, approach implies the approaching motion of a manipulator or manipulators to the target satellite.

5.1. Path planning and control of a single-arm free-floating system

In the absence of external forces, the system's linear and angular momentums should be conserved. Although both of them are represented by velocities, the linear momentum is exhibited by the motion of the center of mass of the whole system and can therefore be integrated into the equations of positions instead of velocities. This implies that the linear momentum equations are integrable. On the other hand, the angular momentum equations cannot be represented by their integrated form, which means that they are nonholonomic [140]. Some researchers have used these nonholonomic and redundant characteristics to develop interesting solutions for robot path planning and control algorithms [77].

5.1.1. Nonholonomic path planning

Inspired by the astronauts' motion allowing them to reorient their body by just moving the limbs, Vafa and Dubowsky [62] proposed a special cyclic motion trajectory of a manipulator's joints to change the base spacecraft's orientation. They called the method *Self-Correcting Motions*. In the method, a nominal trajectory was selected for the end-effector and base orientations. Then, the selected joint motions are executed assuming that the base remains stationary. If at any point the base orientation deviates from its desired path by more than a specific amount, then a selected series of small cyclic motions were added to the joint motions to correct the vehicle orientation. The same authors introduced a technique called *Disturbance Map* (DM) [141], which can aid at selecting paths that reduce the disturbances of the spacecraft by identifying the direction of the joint movements, which results in minimum or maximum disturbances. The method ignores the effort of the attitude control system and assumes that the system has zero initial angular momentum. The DM can be constructed by dividing the space manipulator's joint space into a grid of points. At every point the directions of minimum and maximum spacecraft movements are plotted. Later, Dubowsky and Torres [142] presented an improved version of the DM called

Please cite this article as: Flores-Abad A, et al. A review of space robotics technologies for on-orbit servicing. Progress in Aerospace Sciences (2014), http://dx.doi.org/10.1016/j.paerosci.2014.03.002

Enhanced DM (EDM) and showed how it could be effectively used to plan the manipulator motion for reducing the disturbances to the base spacecraft. An optimal approaching motion was obtained in [143] which assumed unknown target's inertial property. The EDM was used in manipulators with more than two degrees of freedom while the original DM was used only for a 2-link planar case. The same authors showed in [144] that the EDM can be used with the objective of minimizing the fuel usage for attitude control. Another extension of the DM concept to the case of planar polar manipulators was presented in [145]. The method of self-correction motion assumes small cyclic movements to neglect the nonlinearities of orders greater than two and it requires many cycles to make even a small change in the vehicle orientation. To solve this problem, Nakamura and Mukherjee [146] proposed a path planning scheme that deals with the total nonlinearity of the satellite/manipulator system. The method is based on a Lyapunov function to control both the base orientation and the manipulator's joints by actuating the manipulator's joints only. The scheme was called *Bi-Directional Approach*. Two desired paths were planned, one starting from the initial configuration and going forward, and the other starting from the initial configuration and going backward. A drawback of this technique is that it is affected by singularities. Papadopoulos [147] proposed a path planning technique in the Cartesian space that not only reduces the disturbance but also avoids the dynamical singularities. The author found that a workspace point may or may not induce a dynamic singularity, depending on the joint space path. To solve this ambiguity, he defined the *Path Dependent Workspace* (PDW) to contain all workspace locations that may induce a dynamic singularity. If the PDW is subtracted from the reachable workspace, the *Path Independent Workspace* (PIW) is obtained. All the points in the PIW are guaranteed not to have dynamic singularities.

Control strategies using an underactuated space manipulator to reduce the load and power-usage have also been proposed [148]. This study revealed that it is possible to make all the manipulator's joints converge to desired values by controlling only the actuated joints. DeSilva utilized a local optimization approach to generate trajectories that minimize the reaction torques and forces transferred to the base spacecraft [149].

Pandey and Agrawal [150] proposed a method called *Mode Summation* for planning a Cartesian path of a free-floating system with prismatic joints. Their method avoids inversion of the Jacobian matrix and it also results in a singularity-free path for the end-effector. However, the requirement for the desired final attitude was not taken into account. Lampariello and Deutrich [151] applied a similar method, but to a system with rotational joints only.

Nechev et al. introduced the *Reaction Null Space* (RNS) to find the manipulator's motion that yields no spacecraft attitude disturbance when following a predefined path [152,153]. A reactionless trajectory generation strategy based on the RNS to find manipulator's paths without affecting the attitude of the base was also proposed by Piersigilli et al. [154]. Similarly, using the RNS idea, a model and control law for the JEMRMS with the SFA attached on it was proposed by Fukazu et al. [155].

To overcome the dynamic singularity problem in the Cartesian space path planning, Xu et al. [156] used the direct kinematic equations instead. In their method, the joint trajectories were parameterized by polynomial or sinusoidal functions first. Then, the joint functions were normalized and the system of equations about the parameters was established by integrating the differential kinematics equations. Finally, the parameters were solved by an iterative Newtonian method. The drawback of this technique is that the convergence time may be long because of the required numerical iterations. Furthermore, there exist different paths to reach the desired pose because of the nonholonomic nature of the free-floating system.

Fernandes et al. [157] showed that the falling cat problem is equivalent to the nonholonomic motion problem of a free-floating space robot and they used this analogy to develop a near-optimal motion planning method. The authors applied the method directly to a space manipulator platform in [158], using a 3-DOF Puma robot as a manipulator attached to a space platform. One drawback of the approach is that it needs symbolic manipulation software to obtain the Jacobian matrices which are required by the algorithm.

The path planning problem of a free-floating target with a manipulator having angular momentum was addressed by Yamada et al. in [159,160]. To find a closed-loop path, the authors proposed a variational optimization approach in joint space for trajectory planning. In that way, the required change of the satellite orientation can be obtained using joint control only. Suzuki and Nakamura [161] demonstrated that a free-floating space robot having 6-DOF cannot follow an arbitrarily desired trajectory in the 9-D generalized coordinate space (three coordinates for the base spacecraft and six for the manipulator) with only the joint controls. Then, they proposed a method to approximate the desired 9-D path by introducing a perturbation around the path, resulting in a *Spiral Motion* trajectory. With the objective of reducing the disturbances on the base, Yoshida et al. proposed the *Zero Reaction Maneuver* (ZRM) in [162]. The ZRM is obtained by making the angular velocity of the base zero in the angular momentum equation. The existence of the ZRM is limited to 6-DOF manipulators. Most of the above-mentioned methods are time consuming. A computationally inexpensive method developed for terrestrial mobile manipulator systems was extended for potential use in space robotics [163], but it has not been validated for a space application.

The bi-directional approach requires that the joints stop at the switching point and the self-correcting method is based on small cyclical motions. These techniques yield non-smooth trajectories. Papadopoulos et al. [164] proposed a smooth planning methodology in joint space for planar free-floating space manipulators that allow an endpoint Cartesian location control and a simultaneous control of the base attitude. In this method, smooth and continuous functions such as polynomials were employed. Further work showed that the final configuration accessibility is improved drastically when high order polynomials were used for the joint angle solution. The planning problem was reduced to solving a set of nonlinear equations representing the integral of motion. Based on the same idea, the authors of [165] developed a numerical path planning approach for the general case of an n-DOF manipulator. Taking into account of the dynamics of large space manipulators, Belousov et al. [166] proposed a two-stage iterative algorithm that can generate collision-free robot motion paths.

Recently, Franch et al. [167] have employed flatness theory to plan trajectories for free-floating systems. Their method requires the selection of robot parameters so that the system is made controllable and linearizable by prolongations. Agrawal et al. extended this method to a three-link spatial space robot in [168]. Using genetic algorithms, a nonholonomic path planning approach was introduced by Xu et al. [169]. The method's advantages are the motion of the manipulator and the disturbance to the base are practically constrained; the planned motion path is smooth; and the convergence of the algorithm is not affected by the singularities. A nonholonomic path planning technique was proposed based on a particle swarm optimization in [170]. The method was applied to the target berthing and base re-orientation after the capture of a target. Assuming that the path was predefined, Nanos and Papadopoulous [171] developed a Cartesian space path planning method that provides the initial configuration of the system and avoids dynamic singularities. Therefore, it allows effective use of the entire workspace. Two recent algorithms aiming at minimizing the reaction torque transferred to the spacecraft during manipulator maneuvers were presented by Cocuzza et al. [172]. One of the solutions is based on a weight Jacobian pseudoinverse and the other is formulated using constrained least squares [173].

5.1.2. Nonholonomic control

Depending on the control objectives, different schemes for controlling a free-floating system have been introduced. By using the GJM, Umetani and Yoshida [174] proposed a resolved motion rate control for a space manipulator. Later, a similar control approach was applied to redundant [175] systems. Nenchev et al. [67,176] developed a specific joint decomposition technique, called *Fixed-Attitude-Restricted* (FAR) motion, which allows a manipulator arm to move without inducing any reaction moments to the base spacecraft. Along with the solution of a conventional end-effector trajectory tracking, a solution of base motion control was also obtained. The *Coupling Factor* as a measurement of the degrees of dynamic coupling between the manipulator and its base was defined in [177,178]. This measurement can be considered as a performance index in the planning of the robot motion control. A differentially flat open-chain-based controller for a space robot equipped with two momentum wheels at the base was presented by Agrawal et al. [168]. The main advantage of the method is that it avoids the use of nonlinear programming (NLP) to solve the nonintegrable rate equations, which can provide only approximate solutions. During operation, small amounts of angular momentum tend to accumulate. Therefore, the ability to work on orbit under this condition was studied in [179–182].

Adaptive controllers have been widely proposed as a feasible solution to overcome the problem of uncertainties and parameters variation. Nevertheless, since the dynamics of a free-floating space manipulator cannot be expressed linearly with respect to a group of physical parameters, the design of the adaptive control law is quite complicated. An early adaptive control for space manipulators was developed by Walker and Wee [183], where uncertainties in the inertia parameters were considered. Since dynamics of space robots cannot be linearly parameterized, i.e., cannot be linearly expressed in terms of parameters, such as the mass and the inertia of the robot, adaptive control schemes based on a linear parametrization model cannot be applied. In order to overcome this problem, Gu and Xu [184] proposed an extended manipulator model, which is composed of a pseudo-arm representing the base motion and a real arm. The extended model can be linearly parameterized, thus the authors were able to design an adaptive control scheme for a space manipulator in the Cartesian space. The method was termed *the normal form augmentation approach*. A drawback of this approach is that it requires measuring the base spacecraft acceleration. Parlaktuna and Ozkan [185] also used an augmentation method but with a prediction-error-based adaptation approach, so that base acceleration is not needed. Wee et al. [186] proposed an adaptive control method with parameter identification, based on the principle of conservation of momentum. However, their method did not solve explicitly the nonlinear parametrization problem associated with the computed torque control. Neural network-based methods that do not require either the acceleration measurement or the linear parametrization of dynamic uncertainties were presented in [187,188]. On the other hand, McCourt and de Silva used a model predictive control in the space manipulator to deal with the problem of the unknown dynamics of a target satellite [189]. Abiko and Hirzinger [190] proposed an adaptive controller using the inverted chain approach. They focused on the uncertainty of kinematic mapping, which included the dynamic parameters of the system. Later, the same authors in [191] developed an adaptive controller considering kinematics and dynamics uncertainties. One advantage of the approach is that it has no need of measuring the angular acceleration, which was otherwise difficult. Wang [192] proposed an adaptive scheme using the adaptive inverse dynamics and the generalized dynamic regressor of a space manipulator. An adaptive controller based on a robust fuzzy compensator, capable of dealing with joint friction, disturbance and variation of payload, was presented in [193]. Wang and Xie [194] developed a passivity-based adaptive Jacobian tracking controller, where, by defining a new reference velocity termed *spacecraft reference velocity*, the proposed method does not involve the acceleration measurement. An adaptive controller that considers the presence of external forces was developed in [195]. Pazelli et al. used the DEM concept to perform theoretical research on adaptive robust controllers for free-floating systems [71,72] and later they performed an experimental investigation of adaptive procedures based on linear parametrization, neural networks and fuzzy systems [73]. On the other hand, Wang [192] introduced the *Generalized Dynamic Regressor* (GDR) to overcome the nonlinear parametric problem of the inertia matrix. Then, using the GDR, the authors developed an adaptive inverse dynamics control law. A recent progress in the development of adaptation schemes was presented in [196], where the authors extended the prediction error based adaptive Jacobian control of fixed-base robots to space manipulators. The introduced method is capable of dealing with uncertainties in kinematics as well as in dynamics.

Robust controllers represent another applicable solution to deal with parameters variations and unknown dynamics. Based on the second method of Lyapunov, Xu et al. [197] proposed a robust control to overcome the difficulty in controlling the internal dynamics subject to parameter uncertainties. Li [198] proposed a robust and adaptive composite control of coordinated motion for a space robot with prismatic joints. Later, the method was applied to a dual-arm robot [199]. A robust control for a dual-arm space manipulator with uncertain inertial parameters was introduced in [200] where the authors demonstrated that the dynamic equations of the system can be linearly dependent on a group of inertial parameters with augmented inputs and outputs. Huang et al. [201] proposed to transform a robust control problem into an optimal control problem by including the uncertainties in the objective function. The above-mentioned robust controllers do not compensate external disturbances such as sensor noise. Thus, authors in [202] developed a robust controller that addressed this need. Another advantage of the method is that it does not require measurement of the position, linear velocity and acceleration of the base with respect to the orbit. Pathak et al. [203] presented a method for robust trajectory tracking. The idea is based on the overwhelming robust trajectory control of a ground robot. A backstepping robust control for a dual-arm space robot was presented in [204]. And a robust controller, which can cope with model uncertainties and disturbances, was presented in [205].

Optimal controllers have been demonstrated to be a suitable option to reduce or nullify the undesirable attitude disturbance of the base satellite generated by the manipulator's motion during the final approaching phase. Oki et al. [206] extended the time-optimal control with specified paths from fixed-ground robots to free-floating robots. However, instead of assigning joint torque constraints, the authors constrained the reaction torque generated by the manipulator's motion. Later, Flores-Abad and Ma [207] developed an optimal controller based on Pontryagin's maximum principle to not only constrain but also minimize the reaction torque on the base. Besides, this approach features some other advantages such as it does not require zero relative velocity between the end-effector and the grasping handle of the target

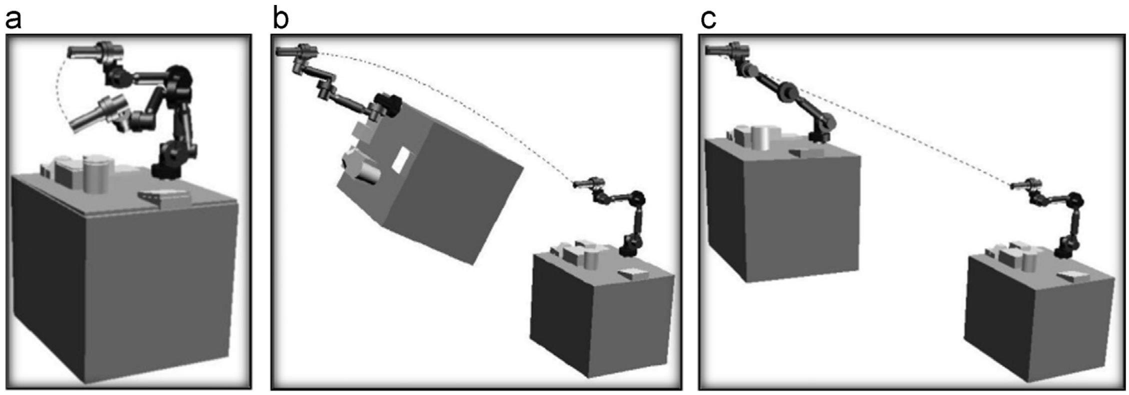

Fig. 12. Paths generated by the optimal motion planning algorithm [65]: (a) maneuver in the local workspace – free floating solution, (b) maneuver in the global workspace – free flying case and (c) maneuver in a global workspace – attitude fixed case.

satellite at the capturing moment, uncertainties were introduced in the manipulator's motion control scheme, minimization of servicing satellite's attitude disturbances was considered in the final robot approaching phase and at the capturing moment as well.

Some of the efforts being performed in nonholonomic path planning and control were discussed in [208,209]. Major advances in the kinematics and dynamics modeling and path planning as well as control of free floating space robots in the early nineties were reported in [210]. Those seminal works have laid a good theoretical foundation for some of the newer developments.

5.2. Path planning and control of single-arm free-flying systems

To increase the mobility and perform larger tip displacements, free-flying space robotic systems in which the associated manipulator is mounted on a thruster-equipped spacecraft have been proposed by some robotics scientist [211,212]. Furthermore, as described in [213], the use of a dedicated attitude controller will enhance the computational efficiency of the path planning and control algorithms. However, these types of robotic systems require a coordinated controller of the base spacecraft and the manipulator. Based on augmenting the control requirements to include the location and attitude of the spacecraft, Papadopoulos and Dubowsky [214] presented a coordinated control of both the base spacecraft and the manipulator. They used a transpose Jacobian-type controller. Xu et al. [215] proposed an adaptive control with an attitude control on the base. Such a method avoids the use of joint acceleration measurements, inversion of inertial matrix, and high gain feedback. Oda [216,217] also addressed the problem of coordinated control, where the robot control system estimates the angular momentum that the robotic arm produces and then the satellite attitude control system compensates the arm's reaction. Instead of performing a single inverse kinematics calculation at the beginning of a movement, multiple inverse kinematics updates based on an optimal algorithm were performed in [218]. Coordinated attitude control experiments using the ETS-VII were reported in [219], where the attitude of the spacecraft was stabilized. Taking the kinematic and dynamic constraints into account, an optimal motion for a free-flying system was formulated in [65]. The solutions were found for local and global motions. For the latter, the unnecessary spacecraft actuation was shown to be efficiently avoided. However, the final attained spacecraft attitude is known beforehand, and it is obtained only after an optimal solution is implemented. Fig. 12 shows the paths generated when using this optimal algorithm in a 6-DOF space manipulator. Based on the Pontryagin maximum principle, an optimal controller for a free-flying system was developed in [106,220]. A multivariable cost function was proposed to minimize the operation time and the relative velocity between the robot tip and the target.

5.3. Path planning and control of multiple-arm systems

The use of multiple arms to capture a tumbling object offers some advantages in the control of a space robot because one of the arms can be used to follow the trajectory and the other or others to compensate for the reactions, such as the case of the method presented in [221]. Yoshida et al. [78] designed a coordination controller for a dual-arm space robot and showed that the torque required to follow a determined path is smaller when using two arms, thus saving total energy. Agrawal and Shirumalla [221] presented a planning motion strategy using a dual-arm manipulator where one arm was commanded to perform desired tasks while the other provided compensating motions to keep the base inertially fixed. To ensure stability in the control of a dual-arm system, Yale and Agrawal [222] presented a Lyapunov-based controller, where the disturbance torque transmitted to the spacecraft by the motion of the manipulator was reduced by altering the order of the reference trajectory polynomial and coefficients. Another motion control was developed based on the general three-dimensional equations of motion. An efficient algorithm for computing the GJM and the resolved acceleration control for multi-arm space robots was presented in [223]. Dynamics modeling of multiple-arm systems and motion control of the end-effectors coordinated with the base spacecraft to chase a moving object was proposed in [224,225]. The authors improved their control algorithm by using the *Modified Transpose Jacobian* (MTJ), which allowed storing data from control command at the previous time step [226]. Based on the dynamics coupling and measuring method, Huang et al. [227,228] proposed the *Dynamic Balance Control* concept to justify the use of one arm to compensate for the disturbance caused by the other arm. Chen and Guo [229] introduced an adaptive coordinated control of the base satellite and a dual-arm manipulator. The asymptotic stability of the system was proven by Lyapunov's method. The proposed control method has the advantage that it can eliminate the effect of uncertain parameters of the robot. A numerically more efficient on-line coordinate control of a dual-arm space robot was presented by Xu et al. [230]. The key point of the method is the separate analysis of the linear and angular momentums. However, the method requires the two arms to be fully identical and mounted centrosymmetrically with respect to the centroid of the base. Thus, the authors extended their work to a more general case by introducing the concept of *system centroid equivalent manipulator* and avoided singularities because such an approach does not need to resolve the differential kinematics.

Please cite this article as: Flores-Abad A, et al. A review of space robotics technologies for on-orbit servicing. Progress in Aerospace Sciences (2014), http://dx.doi.org/10.1016/j.paerosci.2014.03.002

6. Capturing and post-capturing phases

The capturing phase involves physical interception and thus is highly risky. The main goal is to capture the moving and possibly tumbling target without destabilizing the attitude of the base spacecraft. Once the target is successfully captured, the combined system must be stabilized as soon as possible to avoid damaging and to start the corresponding service of the captured target.

6.1. Free-floating case

An early effort to study the effect of physical contact between a space manipulator and a tumbling object was reported in [231]. Their system aimed at simulating the catching and handling of a free-flying target with the manipulator installed on a light structure emulating a space satellite (see Fig. 13). The relative motion between the space robot and the target was simulated by servo mechanisms. While the manipulator was in contact with the target, the momentum was derived by integrating the force measured by force/torque sensors.

The effect of impacts upon a flexible-link free-floating space robot was discussed by Cyril et al. [232]. The method also determines the initial conditions for post-impact simulation. Since it is difficult to sense the impact force precisely because impact is a short-time phenomenon and force sensor signal is very noisy, Yoshida et al. [233] modeled the collision dynamics, using the *Extended Generalized Inertia Tensor* (Ex-GIT) without sensing the impact force. Ex-GIT is an extension of the conventional GIT for ground-based chains. They formulated the collision problem focusing on the velocity relationship just before and after the impact considering the momentum conservation law. The authors also proposed the concepts of *Impulse Ellipsoid* and *Impulse Index* to conveniently express impulse characteristics. In addition, in order to count for the joint behavior with resistance during the impact, the theory was improved by introducing the concept of *Virtual Rotor Inertia* [234]. However, the analysis mainly focused on the moments just before and after the collision. Yoshikawa and Yamada [235] followed this concept and provided mathematical proof in the frequency domain and the method was experimentally verified [236]. Wee and Walker [84] studied the dynamics of contact between space robots and developed an algorithm to achieve both trajectory tracking and impulse minimization. Their study revealed that the impulse at contact moment could be minimized by the optimization of a scalar cost function based on the gradient projection technique. Impact experiments for estimating the impact effect were reported in [237,238], the experimental platform consisted of a rigid manipulator supported by a flexible deployable structure. In [239], Yoshida and Nenchev [89] utilized the concept of RNS (Reaction-Null Space), which corresponds to the null-space of the coupling inertia matrix to find out proper manipulator configurations, to achieve a safe capture and minimize the impact. The authors extended the study to investigate the joint reaction and the base reaction due to the impulsive force. They used the RNS and the FAR (Fixed-Attitude-Restricted) technique to analyze the pre-impact phase and develop a post-impact control law keeping the base reaction in a minimum value. One drawback of this method is that since it is based on the angular momentum conservation, after the impact, the momentum is exchanged between the base and the manipulator, thus action of additional base actuators to stop the system is required. However, this approach allows having the momentum with the lowest velocity in the manipulator and effectively stops the angular momentum of the base in a relatively short period of time.

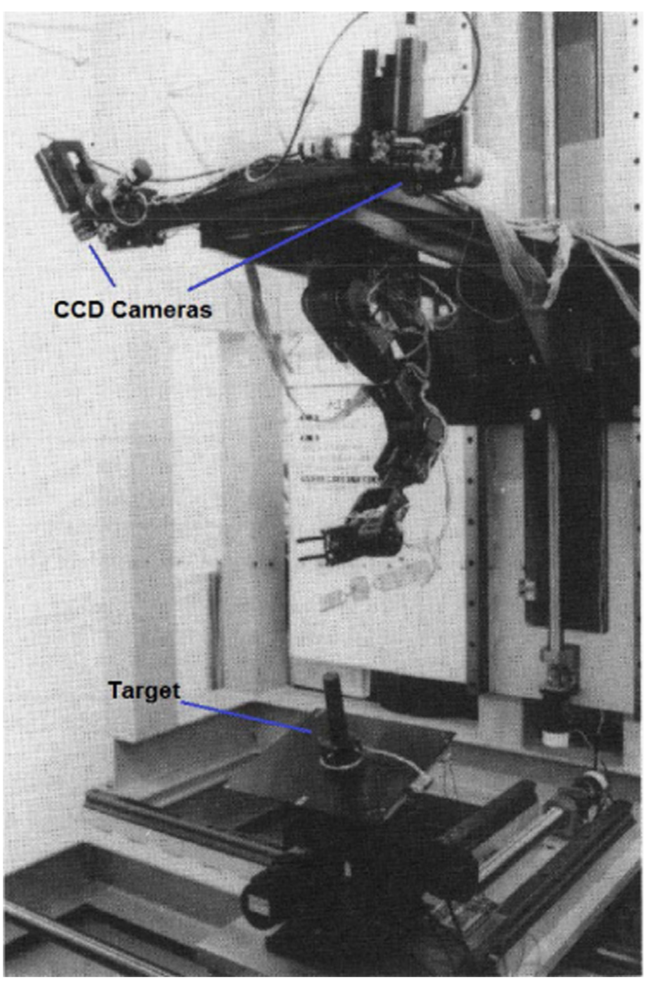

Fig. 13. Photograph of the system to perform catching and handling of a free-flying target. It consists of an up-down table with a manipulator and two CCD cameras (the space robot), and a 2-axis translational and 3-axis rotational table (the target) [231].

Cyril et al. [240] studied the dynamics associated with the capture of a spinning satellite. Nevertheless, it was assumed that at the time of capture there is zero relative velocity between the payload and the end-effector of the manipulator, which is very unlikely the case in reality as it requires that the robot tip must move as fast as the grasping point of the tumbling object. This is very difficult or even impossible if the target object has a fast tumbling motion because the tip speed of a manipulator is always limited not only by the joint rate and torque limits, but also by the attitude tolerance of the servicing satellite. Cyril and Jaar [241] analyzed the behavior of a space manipulator capturing a flexible payload during the impact and the post-capture phase. Papadopoulos and Paraskevas [242] proposed a methodology based on the well-known *Percussion Point of Bodies* to minimize the forces instead of the momentum transmitted to the base of the manipulator when grasping an object. The authors proposed some guidelines for the best configuration of mechanism at time of impact. Huang et al. [243] also found that the configuration of the space manipulator at the contact moment is an important factor to consider in order to reduce the impact effect. Then, authors in [244] proposed an optimal approach trajectory planning method for minimizing the impact. In the same direction, a genetic algorithm to search optimal configuration of a space manipulator at the capturing instant to reduce or eliminate the impact effect was proposed in [245]. To control the system after grasping the object, an adaptive approach was employed considering the flexibility of the transported object [246].

During the impact phase, the interaction with the environment should be considered. Hybrid position/force control has been a basic strategy adopted. However, control mode switching is required at many points during the task [247]. To handle that problem, in [248] an impedance-based scheme has been proposed for controlling the dynamic interaction of a manipulator with the environment. Yoshida and Nakanishi [249,250] used impedance matching to model the contact motion between a space manipulator and a non-cooperative satellite. Based on this model, the authors proposed a criteria to decide if the contact is maintained with the target or if the target is pushed away. Experiments were carried out using two manipulators as a motion simulator of the servicer and the target. Later, Nakanishi et al. [251] introduced the *virtual mass* concept to represent the influence of the hand impedance on the target motion, so that it is possible to prevent the pushing of the target after contact.

Most of the previous works modeled the contact dynamics only as an impulse force acting on the tip of the manipulator. Nevertheless, in reality, the contact model is more complicated. Thus, a more realistic contact model should be included for a more truthful study. To this end, a generic contact dynamics modeling and simulation software package called Contact Dynamics Toolkit (CDT) was developed to support the development and operations of the SRMS, SSRMS and SPDM robots [252]. The software is capable of modeling multi-point frictional contact between objects with complex geometries. It has been experimentally validated for simulating various contact behaviors such as impact, bouncing, sliding, rolling spinning, sticking and jamming. The CDT software was later integrated into a satellite docking simulator to support the development of satellite docking systems [253]. A robotics based simulator for verifying microgravity contact dynamics was developed in [254]. Liu et al. [255] studied the effect of payload collision on the dynamics and control of a flexible dual-arm space robot when capturing an object. An impact model to study the contact during a grasping operation was studied in [256,257] and an active damping controller was designed to reduce the impact effect. The contact forces were calculated using the Hertz model. Impact dynamics was studied using the impulse principle in [258], where the collision detection was performed with analytic geometry. Ma and Flores-Abad proposed a methodology to reduce the impact effect during a capturing process [259]. Their approach is first to predict the best capturing time and configuration such that the contact force resulting from the first physical contact will or nearly pass through the center of mass of the whole servicing system (including both the servicing satellite and the robot). Then an optimal trajectory of the manipulator was computed for the tip of the robot to reach the best capturing configuration at the best time. In this way, the attitude disturbance caused by the contact is zero or minimal. A contact dynamics analysis for space robotics applications was presented in [260]. The contact force direction was estimated based on the known geometries and motion states of the end-effector and the grapple fixture on the target. Using the estimated contact force and the observed target motion, an optimal capturing time and location were determined such that the resulting physical contact for capturing will cause minimal attitude impact to the base spacecraft. A recent adaptive reactionless control scheme to overcome the change in the dynamic parameters of the space manipulator system due to the capture of an unknown target was presented by Nguyen–Huynh and Sharf [261,262]. The algorithm is intended to provide minimum disturbances on the base satellite from the capturing phase until the unknown parameters are identified. The algorithm has the property of producing arm motions with minimum disturbance to the base after capture of an unknown tumbling target.

Multiple-arm systems. The use of multiple-arms manipulators (see for example, Fig. 14) also offers advantages in the capturing and post-capturing phases [263]. Because it allows a firmer grasping of the target. Thus, as early as 1989, JPL conducted lab experiments to perform dual-arm satellite grappling [264]. With the characteristic of reducing the effect of system's angular momentum change caused by the impact force during a capture operation and the burden of post impact control, a pre-impact configuration of a dual-arm space manipulator was introduced by Cong and Zhang [265,266]. The approach is based on the concept of generalized straight-arm capture, which was proposed initially for a single-arm system in [267].

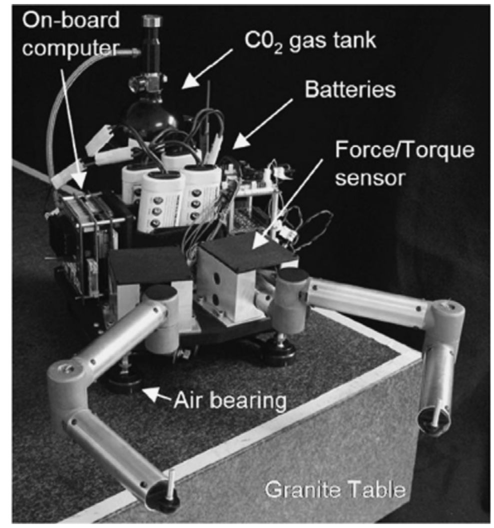

Fig. 14. MIT Space Laboratory's double-arm space manipulator [263].

6.2. Free-flying case

To allow larger displacements, free flying systems have also been proposed in the capturing and the post-capture phase. In this sense, impedance-based schemes are among the most preferred methods to handle the physical contact between the robot's end-effector and the target. An impedance control strategy has been developed for several cooperating manipulators [268] and also applied to a space robot with multiple arms [269,270], both the manipulator's end-effector and the capturing object are controlled to behave with the designated impedance in reaction to any disturbing external force on the object. Hence, a coordinated motion of the manipulator and the payload is achieved. With the objective of reducing the disturbances on the base spacecraft during a contact with the target, another control structure with force compensation for multi-arm cooperating manipulator was proposed in [271]. Methods in [226,246,268,269,271,272] assumed that the input force to the base from the robots can be controlled perfectly. However, the thrusters cannot provide accurate position control because the output forces of the thrusters are constant, and only the total impulse may be controlled by varying the thrusters durations [273]. Therefore, Nakanishi and Yoshida [274,275] presented a control method that does not require precision in the base control. The end-effector of the manipulator was controlled like a mass–damper–spring system fixed at a point in space regardless of the reactive motion of the base. An impedance controller based on the interaction torque between the robot tip and the target was analyzed in [276], where the impedance controller was achieved by introducing passive DOFs in the controller. The changes in orientation of the spacecraft were restored back using reaction wheels. Uyama et al. [277,278] proposed an impedance-based contact control utilizing a stiff manipulator with a compliant wrist. Their approach is based on the achievement of a desired coefficient of restitution and damping ratio between the manipulator hand and a contact point of the target.

Another possible solution for the capturing problem is from the viewpoint of angular momentum. Grasping a target without considering its momentum imposes difficulties for the post-impact control, and most likely the capturing operation will fail. One method utilizes a device with controllable momentum wheels (space leech), which has to be attached to the target and absorbs the angular momentum [279]. In [280] the idea of rotational motion-damper was proposed. Using a contact/push based method, the angular momentum from the target is partially transferred to the servicing satellite. However, this could result in separation from the target after each contact and therefore the usage of gas-jet thrusters for linear motion is unavoidable. This idea might be useful if the amount of angular momentum in the target is very large and direct capture is impossible. A similar method using *Impulsive Control* was proposed by Yoshikawa et al. [281]. An experimental verification of the strategy was reported in [282]. Nakamura et al. [283] utilized a “tethered retrieve” which was guided to the target through the tension force in the tether and thrusters positioned on the retriever. During the post-impact phase, the angular momentum of the target is absorbed in attitude devices positioned on the retriever. In [284] the service satellite makes a fly-around maneuver such that the capturing operation can be conducted with small relative motion between the two systems. The authors proposed a free-motion path method which enabled to completely ignore the nonlinearity effect in the dynamics by taking advantage of the conservative quantities of the system.

A capture strategy to minimize the base attitude disturbance from the viewpoint of angular momentum management was discussed in [285]. The technique is called *Bias Momentum*. Moreover, a method to control the transfer of the angular momentum from the target to the robot base by controlling the arm motion was proposed in [286]. A control method which can realize the consecutive contact so that the target is not pushed away and the suppression of the undesirable base rotation is required. Such a strategy was discussed in [287]. In order to guarantee conservation of contact, impedance control was utilized and the *Distributed Momentum Control* (DMC) was used for zero base rotation. Yoshida et al. [288] proposed a possible control sequence for the successful completion of a capturing operation. The authors used the bias momentum approach during the approaching phase, impedance control during the impact phase and DMC during the pos-impact phase. Inaba et al. [289] presented some design requirements when using a space robot to capture a satellite. Special attention was paid on the image processing for the visual servoing. In order to reduce and even eliminate the base reactions during a contact, control-moment reaction gyroscopes (CMGs) were proposed as actuators for space manipulators [290]. It was shown that the power consumption was the same as that of a robotic system driven by conventional joint motors.

In reality a time delay may occur when using an impedance control approach, which can cause the impulse of the contact to be very large. Therefore, in [291], experiments and numerical simulations were carried out to verify the effect of the time delay of impedance control. References [292,293] addressed an optimal control of a space manipulator in the post-capture phase to bring the tumbling non-cooperative satellite to rest in minimum time while ensuring that the magnitude of the interaction torque between the manipulator and the target remains below a prescribed threshold. A space robotic system that includes components to capture malfunctioning satellites in GEO (Geostationary Orbit) was proposed by Xu et al. [294]. In the work, 2-DOF docking and latching mechanisms similar to those used by the SMART-OLEV [295,296] were utilized for capture and docking of the target satellite.

Once a manipulator has captured a target satellite, the manipulator and the target become a single system with combined mass properties and dynamics characteristics. In order for the controller to handle these changes, an adaptation law may be designed. For this, Liang and Ma [297] introduced an adaptive control approach, which can be used to assist the control of a servicing satellite to rendezvous and dock with or capture a tumbling satellite. A Lyapunov-based tracking law and an adaptation law were proposed to guarantee the success of the nonlinear control for the post-capture stabilization of the combined two-satellite system.

Space structures assembly. Due to the need of handling large structures in space, using free-flying space manipulators has attracted the attention of some researchers. An example is the work presented by Senda and Matsumoto, where they conducted experiments for autonomous truss assembly by a space robot [298]. Different tasks were tested during this development, such as collision avoidance, manipulator berthing, components manipulation, visual servoing, task error recovering and structure construction. According to Whittaker et al. [299], the team members will be heterogeneous because the structural assembly tasks are too complex to be done by a single robot type (Fig. 15). The teams might include remote free-flying robots (with thrusters and manipulators), simple observation robots for sensing, and worker robots that can walk across structures and perform fine manipulation for the assembly and maintenance jobs [300].

Dubowsky and Boning [263] suggested employing a team of space robots for manipulation and assembly of large flexible structures (see Fig. 16). The approach uses linear quadratic optimal control methods to determine the forces needed to position the structures while minimizing the vibration. In this method, the vibration damping contribution should come primarily from the manipulators instead of from the thrusters. Then, the actuation effort for combined thrust and manipulation is calculated from the integral of the net forces applied to the structure by the robot. A reconfigurable brachiating space robot using handrails to inspect, repair and construct structures in orbit was proposed by Sawada and Matunga [301]. A method for micro-satellite assembly tasks in orbit using a two-arm robotic platform was presented in [302]. For that purpose, control strategies for fitting parts with almost no clearance and also dealing with flexible objects using visual and force feedback were developed. Tanaka et al. [303] proposed the use of a group of orbital servicing robots to provide assistance in different tasks, such as satellite assembly, disassembly, refueling, and reconfiguration. In [304] a strategy that used several robots was presented. Later [305], the authors calculated an optimal trajectory for reducing the fuel consumption. HEROS [306] (Heterogeneous Expert Robots for On-Orbit Servicing) is another concept that used a group of robots cooperatively performing servicing missions. The work reported in [305] addressed this type of application as well. The authors proposed a point-to-point trajectory tracking control of the passive object, while keeping limited trust firing. Later, the authors calculated an optimal trajectory to lower the fuel consumption. Rutkovsky et al. [307] also proposed the use of free-flying manipulators for on-orbit assembly. In this work a safety payload installation method was introduced. On the other hand, robots required for constructions of large space structures need to be precisely controlled. Inaccuracy in joint/actuator friction and spacecraft attitude control thrusters' inaccuracies can substantially degrade control system performance. Sensor-based control algorithms can be used to mitigate the effects of actuator error, but sensors can add substantially to a space system's weight, complexity, and cost, and reduce its reliability. Thus, it is desired having a reduced number of sensors. Boning and Dubowsky [308] presented a method called *space base sensor control*, which based on the kinematics configuration of the system uses the minimum number of sensors that can simultaneously compensate for errors and disturbance in aspace robot's joint actuators, spacecraft thrusters, and reaction wheels.

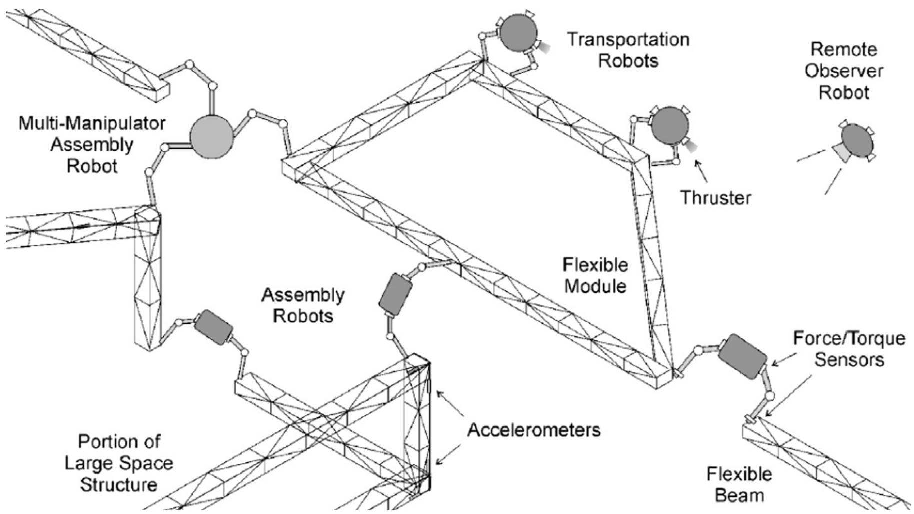

Fig. 15. Concept of heterogeneous robotic teams constructing large flexible space structures on-orbit [263].

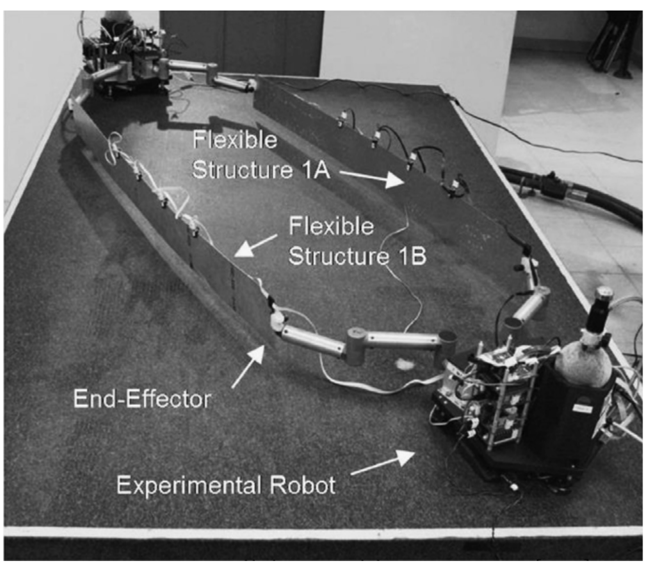

Fig. 16. Parallel assembly maneuver [263].

7. Flexibility and vibration suppression

It has been an increasing demand that space manipulators are lightweight and also capable of accurately performing autonomous manipulation tasks within an acceptable execution time. As a result, both link and joint flexibility effects become the main limitation to achieving a satisfactory performance of trajectory tracking. Thus, the study of this kind of flexibility effects become important [86,309].

To develop dynamics model of such flexible systems, various approaches have been used, including the Lagrange method, the Hamilton principle, and Newton–Euler equations. Torres and Dubowsky presented the *Coupling Map* to plan motions of elastically constrained space manipulator systems for lower vibration to robot's supporting elastic base [310]. A study on the dynamics and control of large flexible space structures was presented in [311], where the authors demonstrated their method using LQG/LTR and H_∞ controllers. Meirovitch and Lim [312] introduced a maneuvering and control method for flexible space robots. The robot was assumed to consist of a rigid base, two flexible arms and a rigid end-effector holding a payload. The rigid body maneuvers were addressed in an open loop configuration. However, the elastic motions were controlled using a closed loop LQR method. A study in the dynamics of space manipulators with an arbitrary number of slewing and deployable flexible links was performed in [313]. An order-N algorithm, based on the Lagrangian approach and velocities transformations, was used so that a parametric analysis of the system dynamics could be carried out to investigate the effects of initial disturbances, variation of system parameters and maneuver profiles. The study suggested a significant coupling between the rigid body motion and structural vibrations. Based on a nonlinear inversion technique, De Rivals-Mazres et al. [314] described the position and orientation of the base and the joint angles of a flexible manipulator by deriving a control law that controls the output variables. The concept of *Virtual Rigid Manipulator* was introduced in [315] to design a feed-back position controller for a space robot with flexible links. The stability of the controller was shown by Lyapunov's method. A command input shaping technique and a sliding mode control method with smooth joint friction compensation were applied in the control of flexible manipulators in [316]. Such a controller proved to be very efficient for tracking of reference trajectories in joint space. Zohoor and Khorsandijou [317] developed a nonlinear dynamic model of a flying manipulator with two revolute joints and two highly flexible links. Tension, compression, twisting and spatial deflections of each link are coupled to each other by some nonlinear terms. Another work dealing with links flexibility was reported in [318] where they approximated the bending due to the flexibility using the static bending curve of Shimoya. An optimal trajectory planning of a flexible dual-arm space robot with vibration reduction capability was presented by Wu et al. [319]. The authors used the Particle Swarm Optimization algorithm to describe the motion trajectory by the use of a fourth order B-spline with control points as the parameters to be optimized. For vibration reduction, the vibrations induced by the links flexibility are included in the performance index. With an objective of suppressing the vibrations due to the link flexibility in JEMRMS, Abiko and Yoshida [320] introduced an adaptive controller. Later the authors extended their work by using the reaction dynamics concept considering inaccuracy in kinematics and dynamics parameters [321]. Ma and Wang [87] presented a model reduction for impact-contact dynamics simulations of flexible manipulators. They first linearized the nonlinear contact force model and then applied the traditional modal analysis and reduction techniques to reduce the order of the resulting dynamics equations for more stable and efficient simulation process.

The latest generation of advanced space robots specifically designed for OOS operations is equipped with extremely lightweight joint mechanisms, including harmonic drives. These gear mechanisms have received increasing attention in robotic applications due to their attractive properties such as very high reduction ratio, compact size, low weight, and coaxial assembly. However, with harmonic drives, elastic vibrations of the flexspline becomes the main issue that significantly challenges control system development. As explained by Sweet and Good [322], joint stiffness coupled with damping at the joints can lead to strongly resonant behaviors when using rigid control schemes, unless the control bandwidth is severely restricted. In addition, when handling large payloads, joint or structural flexibility effect become even more important and can result in payload-attitude controller fuel-replenishing dynamic interactions. Although both joint and link flexibilities are influential to the performance of space manipulators, joint flexibility is often considered more influential than link flexibility. In [323] Sabatini et al. modeled the vibrations generated due to the flexibility in the links as well as in the joints of a manipulator and designed active damping strategies and devices that could be used to reduce the structural vibrations. Zarafshan and Moosavian studied the dynamics and control of space robotic systems with flexible members such as solar panels, appendages and flexible joints [324]. For a better analysis and control, the authors classified the flexible members into passive and active categories. The same authors proposed a fuzzy tuning manipulation control algorithm for the space robot with flexible members [325]. Masoudi and Mahzoon [326] presented a LQR regulator to suppress the vibration on a free-floating space robot with flexible arms. The governing equations were derived using Kane's method and the resulting nonlinear problem was separated into two sets of equations by a perturbation approach. One equation is for rigid-body maneuvering of the robot and the other for elastic vibrations suppression and rigid-body perturbation control. Ulrich and Sasiadek [327] developed an end-point tracking trajectory of a space robot considering the elastic vibrations occurring in the joints. Simulation results showed that in this scenario a better tracking performance can be achieved by an adaptive control scheme. Thus, the authors presented a direct adaptive controller [328] and a fuzzy logic adaptive controller [329] to maintain adequate performance regardless of parametric uncertainties and modeling errors in the plant (arising mainly from soft-windup and time-varying joint stiffness effects). Recently, Kumar et al. [330] developed a trajectory tracking control of a 2-DOF flexible space robot using the *Virtual Space Vehicle* concept. The flexible links were modeled as Euler–Bernoulli beams. Another important contribution of this work is that the authors used Bond-graphs to model the dynamics of the system and to devise the control strategy.

8. Ground verification

Just as any other space systems, a space manipulator and its associated control systems must pass all the verification tests on the ground before it can be launched to the space. For the dynamic test of control functions and performance, the test facility should be able to simulate reduced conditions and allow 6-DOF motions of the robotic system. Surveyed below are the different approaches employed to emulate zero-G conditions for the development and verification of space robotics for OOS missions.

Air-bearing supported floating. The most commonly used technology for emulating zero-G is to use an air-bearing based floating test facility. Such a system usually includes one or two mobile platforms floating on a flat floor through air bearing pads. It allows us to test a space manipulator or manipulators to operate in a simulated 0-G floating condition in a 2D space, which includes one rotational and two translational DOFs. More DOFs of maneuvering may be added by suspending the tested object with a multi-DOF mechanism but more massive support hardware has also to be added and thus the dynamics properties of the test system would also be altered. Such a method has been applied for testing the control algorithms of Japanese free-floating systems [331,332], and the free-flying experiments at Stanford University [333]. All the major space companies and some research groups in academia own this kind of facilities such as the ones described in [334–339].

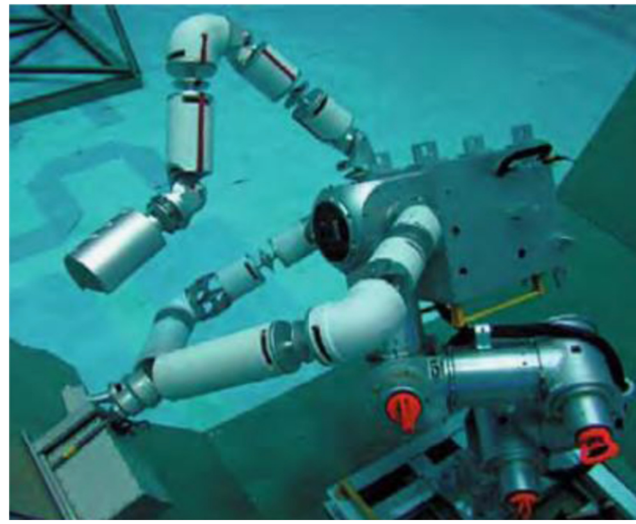

Fig. 17. Neutral buoyancy facility at University of Maryland [340].

Neutral buoyancy. Another technology for simulating reduced gravity is to use a water pool to achieve neutral buoyancy, so that the submerged body has an equal tendency to float as it would in space. This method has the advantages that an experiment can be carried out in a 6-DOF space without time constraints. MIT performed several tests of a teleoperated manipulator using NASA's neutral buoyancy lab (NBL) at NASA Johnson Space Center [340]. University of Maryland also owns such a facility and it has been used to explore the arm–base interaction for a multi-arm free-flying robot called Ranger [341] as depicted in Fig. 17. Researchers of the University of Padova have developed a free-flying robot prototype with one extended arm suitable for underwater conditions [342]. The neutral buoyancy technology suffers from the drag force induced by the water which does not exist in the space and it is also very expensive to operate. Moreover, all the tested hardware units must be made water proof or sealed, which means that the real space hardware cannot be tested as is.

Parabolic flight. An airplane flying in a parabolic trajectory can also achieve reduced gravity condition. In [343] a 4-DOF robotic arm was tested in a parabolic flight, under 0.02 g for a 20 s generated by an MU-300 aircraft. Menon et al. [344] carried out two flights of 30 parabolas each. Parabolic flight tests were performed to evaluate an attitude controller for a tethered robot in [345]. This reduced gravity simulation technology suffers several obvious drawbacks such as short time duration (10–30 s) of microgravity or reduced-gravity condition, limited work space due to the small volume inside an aircraft, and non-smooth or jittering working environment due to the aircraft dynamic motion [346]. It is also an expensive technology for operation.

Free fall. A microgravity environment can be generated by free-falling experiments as well. Iwata et al. [347] achieved 3×10^{-3} g for 10 s from a distance of 710 m, and Watanabe et al. [348] obtained 1×10^{-3} g for 10 s by a free falling experiment from a vertical distance of 490 m. Both experiments were performed at the Japan Microgravity Center (JAMIC). The time interval of zero-G condition using this method is even less than the parabolic flight and, if it is not performed very carefully, the robot can be easily damaged. Therefore, this technology is not very suitable for testing robotic operations.

Force compensation. The gravity force may also be compensated by a suspension system or a balancing mechanism for zero or reduced gravity testing of a space manipulator [349]. Such a system generates compensating forces of the same amplitude but in the opposite direction as the gravity force of the tested robot. Sato et al. [350] developed an experiment to test a free-floating space manipulators using such a method. Brown and Dolan [351] suspended a robot with a cable from an electromechanical system that passively generates mechanical counterbalance forces. White and Xu [352] also developed an active gravity compensation system. Their testbed utilizes lightweight cables passing through several pulleys before terminating in the counterweight that has the same effective mass as the simulated robot. Menon et al. [338] suspended the base of a robot employing an inextensible cable fixed in the vertical projection of its center of mass, while the arm links are suspended by springs. The main drawback of this technology is obviously a static balancing of the gravity force and thus the system cannot preserve the true microgravity dynamics of a space manipulator as it would experience in the space. Further, all the suspension cables, as long as they are not perfectly vertical during a test, apply extra tensions to the tested robot in non-vertical directions which can significantly alter the multi-DOF dynamic behavior of the tested space robot. This problem may be solved by the method of using a multi-DOF statically balanced mechanism as the one proposed by Ma et al. [353]. The mechanism employs springs to achieve multi-DOF gravity balancing at each configuration within the workspace of the mechanism.

Hardware-in-the-loop systems. The combination of hardware test and computer simulation is an attractive approach for verification of space robots performing complicated contact tasks. Since the technology involves both hardware test and software simulation, it is called hardware-in-the-loop (HIL) simulation or hybrid simulation. With this technology, a high-bandwidth hardware robotic system is employed to mimic the dynamic behavior of the simulated space manipulator by strictly following the 3D motion commands generated by software that simulates the dynamics of the space manipulator working in the space environment [354]. Such a system helps to simulate not only the approaching phase but also the capturing/docking phase. The first hybrid simulator reported was developed by Shimoshi et al. [231]. They combined numerical simulation and servo mechanisms. The system consisted of a facility robot, a 5-DOF translational target, and software simulating the dynamics of the space robot. Agrawal et al. [355] proposed two possible laboratory setups to achieve the relative motion of a free-floating robot with respect to the space target. In both cases, the target is mounted on the end-effector of the facility robot. CSA developed a sophisticated HIL simulation system called STVF (SPDM Task Verification Facility), shown in Fig. 18, to simulate the dynamic behavior of the space robot SPDM performing maintenance on the ISS [356]. The simulation facility has been accepted as the formal verification tool for the SPDM. The space robot has been successfully launched to the ISS and is currently performing its regular services there.

Dubowsky et al. implemented a dual-robot HIL simulation system named Vehicle Emulation System (VES) and VES II, which consists of a PUMA manipulator mounted on a Stewart platform to simulate the base spacecraft motion. The emulation was done using admittance control, so that the Stewart platform moved according to the desired admittance model [357]. A dual-manipulator-based system for capturing operations was built by Matunaga et al. [358]. Emulation of zero-G was obtained at CSA using a controlled manipulator by Aghili [359]. Another HIL facility developed at CSA for testing autonomous capturing of a tumbling satellite was presented in [360]. The facility consists of a dual manipulator system that simulates the tracking and capture scenario; the manipulator on the left is equipped with a hand, and the manipulator on the right holds a mock-up satellite to simulate its tumbling motion. DLR recently developed a dual-robot HIL simulation system called European Proximity Operations Simulator (EPOS) [361]. In the system, two KUKA industrial robots are employed, one of which behaves as a servicing satellite and the other as a target satellite. The system is capable of simulating proximity rendezvous and docking of two spacecraft. Such a test bed is currently being used to support the development of the DEOS and other future OOS missions [55]. Takahashi et al. [362] also developed a hybrid system by using a 14-DOF dual-arm robot and a 9-DOF motion table (including a 6-DOF parallel robot) to verify orbital operations. Some other test facilities that are also based on the idea of HIL were presented in [43,363–367], and a

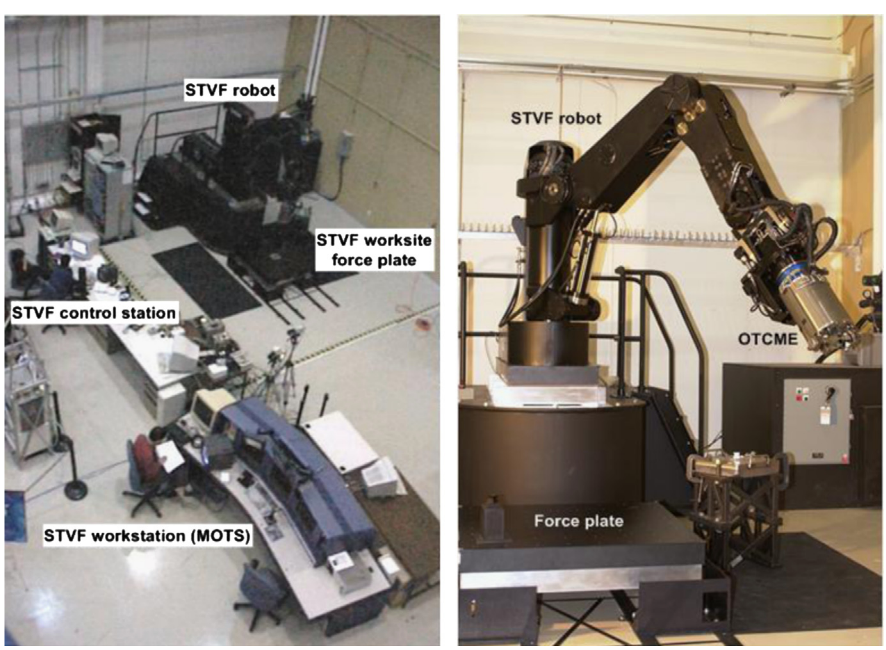

Fig. 18. SPDM Task Verification Facility (STVF) [354].

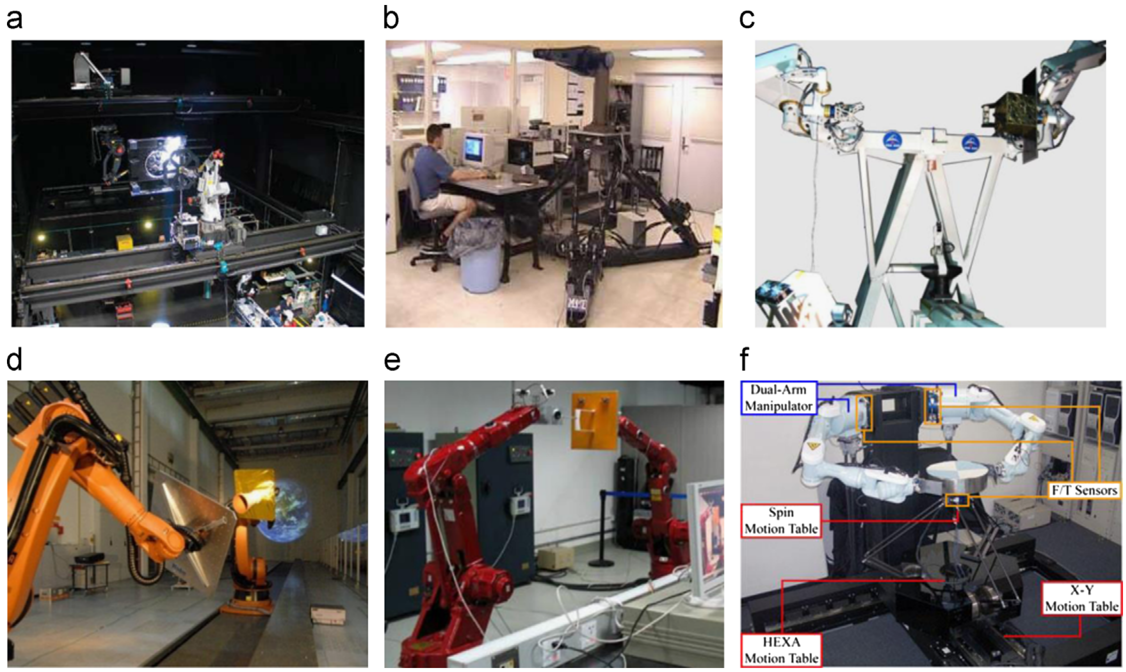

Fig. 19. Facilities for testing a space robotic system to capture a free-flying satellite or object in space using the HIL concept: (a) NRL's facility for autonomous docking experiments [43], (b) MIT's VES system [357], (c) CSA's Experimental facility for autonomous capturing [360], (d) DLR's EPOS for proximity operations and docking/capturing experiments [361], (e) Shenzhen Space Technology Center's ground experimental system [365] and (f) Tohuku University's hybrid simulator for orbital operations experiments [370].

system that combines air bearing table with HIL concept was developed by Tsinghua University [368]. HIL simulation is powerful for testing complex space systems for complicated robotic tasks but it also suffers some drawbacks. First, since the system is driven by simulation, the mathematical model of the spacecraft or space robot has to be accurate and the simulation must be performed in real time for interacting with hardware. Second, the hardware part of the system must have sufficient bandwidth and proper impedance, so that the active hardware system can produce dynamic behavior close enough to the real space robot. Finally, the system has to be able to deal with the inevitable time delay from a hardware contact to the corresponding simulation-driven reaction at the tip of the facility robot (not the immediate and passive reaction of the facility robot). Nevertheless, some researchers have proposed techniques to handle the HIL time delay problem [369,370]. Fig. 19 shows some of the above-described HIL simulation facilities.

9. Conclusions

It has been shown that on-orbit services (OOS) such as docking, berthing, refueling, repairing, upgrading, transporting, rescuing, and orbit cleanup are of increasing interest to the space industry because of their high economical potential and also the strategic benefits. As a result, many enabling techniques for OOS missions have been developed by the academia and space industry across the world in the past two decades. These development works reported in 370 publications have been reviewed with an emphasis on the key areas of kinematics, dynamics, trajectory planning, control, and ground-based task verification. In addition, several technology demonstration missions have been successfully accomplished. A review of these accomplished missions revealed that all of them were designed to service perfectly known and cooperative targets only. Servicing a non-cooperative satellite or space object in orbit such as a tumbling satellite or a piece of space debris with unknown properties by a space robot or multiple robots is still an untested mission facing many technical challenges. This review also found that there are still many challenges in the development and operation of space robots for OOS missions which requires further development, such as motion estimation and prediction of the target object, kinematics and dynamics models uncertainties, on-orbit model parameters identification, safe and reliable capture mechanisms and strategies, contact dynamics modeling and simulation of capturing operations, reduction of disturbances to the base spacecraft caused by robot motion, smart grasping of natural objects (not designed for grasping), dexterous and efficient manipulation, time delay and sensor errors in feedback controls, compliance and intelligent controls, multi-arm coordinated controls and operations, safety when operated near human, physical simulation of 6-DOF microgravity operation for system level test and verification, among others. Therefore, further research and development of these robotics technologies and other related technologies such as the sensing, actuation, and communication technologies definitely need to be further advanced.

References

[1] Sullivan B, Akin D. A survey of serviceable spacecraft failures. In: AIAA space conference and exposition, vol. 4540, Albuquerque, NM; 2001.
[2] Ellery A, Kreisel J, Sommer B. The case for robotic on-orbit servicing of spacecraft: spacecraft reliability is a myth. Acta Astronaut 2008;63 (5):632–48.
[3] Landis G, Bailey S, Tischler R. Causes of power-related satellite failures. In: IEEE fourth world conference on photovoltaic energy, vol. 2, Waikoloa, HI; 2006. p. 1943–5.
[4] Martin D. Communication satellites. American Institute of Aeronautics & Astronautic; 2000.
[5] Waltz DM, Cepollina F. On-orbit servicing of space systems. Krieger Publishing Company; 1993.
[6] Davinic N, Chappie S, Arkus A, Greenberg J. Spacecraft modular architecture design study–cost benefit analysis of on-orbit satellite servicing. In: IAF—international astronautical congress, Turin, Italy; 1997.
[7] Leisman G, Wallen A, Kramer S, Murdock W. Analysis and preliminary design of on-orbit servicing architectures for the GPS constellation. In: AIAA space technology conference and exposition; 1999.
[8] Saleh JH, Lamassoure E, Hastings DE. Space systems flexibility provided by on-orbit servicing: part 1. J Spacecr Rockets 2002;39(4):551–60.

Please cite this article as: Flores-Abad A, et al. A review of space robotics technologies for on-orbit servicing. Progress in Aerospace Sciences (2014), http://dx.doi.org/10.1016/j.paerosci.2014.03.002

[9] Lamassoure E, Saleh JH, Hastings DE. Space systems flexibility provided by on-orbit servicing: part 2. J Spacecr Rockets 2002;39(4):561–70.
[10] Miller R. Minsky M, Smith D. Space applications of automation, robotics and machine intelligence systems (ARAMIS), vol. 1: executive summary. Technical Report NASA-CR 162079, NASA; 1982.
[11] Dubowsky S. Advanced methods for the dynamic control of high performance robotic devices and manipulators with potential for applications in space. Technical Report NASA-CR-181061, NASA; 1987.
[12] NASA. On-orbit satellite servicing study project report. Technical Report, NASA; 2010.
[13] Fehse W. Automated rendezvous and docking of spacecraft, vol. 16. Cambridge University Press; 2003.
[14] Rembala R, Ower C. Robotic assembly and maintenance of future space stations based on the ISS mission operations experience. Acta Astronaut 2009;65(7):912–20.
[15] Salaberger C. Canadian space robotic activities. Acta Astronaut 1998;41 (4):239–46.
[16] Bonnet RM. Ten years hubble space telescope. SPATIUM Mag 2004;12:1–26.
[17] Sato N, Doi S. JEM remote manipulator system (JEMRMS) human-in-the-loop test. In: The 22nd international symposium on space technology and science, Morioka, Japan; 2000. p. 1195–9.
[18] Laryssa P, Lindsay E, Layi O, Marius O, Nara K, Aris L, et al. International space station robotics: a comparative study of ERA, JEMRMS and MSS. In: The seventh ESA workshop on advanced space technologies for robotics and automation eASTRA, ESTEC, Noordwijk; 2002.
[19] Didot G, Oort M, Kouwen J, Verzijden P. The ERA system: control architecture and performance results. In: International symposium on artificial intelligence, robotics and automation in space, Montreal, Canada; 2001.
[20] Hirzinger G, Brunner B, Dietrich J, Heindl J. ROTEX—the first remotely controlled robot in space. In: IEEE international conference on robotics and automation, San Diego, CA; 1994. p. 2604–11.
[21] Hirzinger G, Landzettel K, Reintsema D, Preusche C, Albu-Schäffer A, Rebele B, et al. ROKVISS—robotics component verification on ISS. In: Artificial intelligence, robotics and automation in space, San Diego, CA; 2005.
[22] Hirzinger G, Landzettel K, Brunner B, Fischer M, Preusche C, Reintsema D, et al. DLR's robotics technologies for on-orbit servicing. Adv Robot 2004;18(2):139–74.
[23] Guizzo E. Humanoid robot justin learning to fix satellites. URL 〈http://spectrum.ieee.org/automaton/robotics/industrial-robots/humanoid-robot-justin-learning-to-fix-satellites〉; 2010.
[24] Bluethmann W, Ambrose R, Diftler M, Askew S, Huber E, Goza M, et al. Robonaut: a robot designed to work with humans in space. Auton Robots 2003;14(2):179–97.
[25] Diftler M, Mehling J, Abdallah M, Radford N, Bridgwater L, Sanders A, et al. Robonaut 2—the first humanoid robot in space. In: IEEE international conference on robotics and automation, Shanghai, China; 2011. p. 2178–83.
[26] Diftler M, Ahlstrom T, Ambrose R, Radford N, Joyce C, De La Pena N, et al. Robonaut 2—initial activities on-board the ISS. In: IEEE aerospace conference, Big Sky, MT; 2012. p. 1–12.
[27] Bekey G, Ambrose R, Kumar V, Lavery D, Sanderson A, Wilcox B, et al. Robotics: state of the art and future challenges. Imperial College Press; 2008.
[28] Peuter W. Development program on space automation and robotics. In: International symposium on artificial intelligence, robotics and automation in space, Toulouse, France; 1992.
[29] Acquatella P. Development of automation and robotics in space exploration. In: The fourth annual international planetary probe workshop, Pasadena, CA; 2006.
[30] Syromiatnikov V. Manipulator system for module redocking on the MIR orbital complex. In: IEEE international conference on robotics and automation, Nice, France; 1992. p. 913–8.
[31] Kulakov F. Some Russian research on robotics. Robot Auton Syst 1996;18 (13):365–72.
[32] Putz P. Space robotics in Europe: a survey. J Robot Auton Syst 1998;23(1–2):3–16.
[33] Gillett R, Ken A, Sallaberger C, Maharaj D, Martin E, Richards R, et al. A hybrid range imaging system solution for in-flight space shuttle inspection. In: Canadian conference on electrical and computer engineering, Niagara Falls, Ontario; 2004.
[34] Salaberger C, Fulford P, Ower C, Ghafoor N, McCoubrey R. Robotic technologies for space exploration at MDA. In: International symposium on artificial intelligence, robotics and automation in space, Munich, Germany; 2005.
[35] NASA NEWS, NASA's robotic refueling mission practices new satellite-servicing tasks@ONLINE. URL 〈http://www.nasa.gov/mission_pages/station/research/news/rrm_practice.html〉; May 2013.
[36] Oda M, Kibe K, Yamagata F. ETS-VII, space robot in-orbit experiment satellite. In: IEEE international conference on robotics and automation, vol. 1, Minneapolis, MN; 1996. p. 739–44.
[37] Yoshida K. Contact dynamics and control strategy based on impedance matching for robotic capture of a non-cooperative satellite. In: The 15th CISM-IFToMM symposium on robot design, dynamics and control—ROMANSY, St-Hubert, Canada; 2004.
[38] Penin LF, Matsumoto K, Wakabayashi S. Force reflection for ground control of space robots. IEEE Robot Autom Mag 2000;7(4):50–63.
[39] Friend RB. Orbital express program summary and mission overview. In: SPIE defense and security symposium, CA: San Diego; 2008. 〈http://dx.doi.org/10.1117/12.783792〉.
[40] Mulder T. Orbital express autonomous rendezvous and capture flight operations. In: AIAA/AAS astrodynamics specialist conference and exhibit, Honolulu, Hawaii; 2008.
[41] Bosse A, Barnds W, Brown M, Creamer N, Feerst A, Henshaw C, et al. SUMO: spacecraft for the universal modification of orbits. In: SPIE 2004, vol. 5419; 2004. p. 36–46.
[42] Creamer N, Arnold S, Butcher S, Henshaw C, Kelm B, Oppenheimer P, et al. Laboratory demonstration of a prototype geosynchronous servicing spacecraft. NRL Rev—Space Res 2006:1–3.
[43] Kelm B, Angielski J, Butcher S, Creamer N, Harris K, Henshaw C, et al. FREND: pushing the envelope of space robotics. NRL Rev—Space Res 2008:239–41.
[44] Debus TJ, Dougherty SP. Overview and performance of the front-end robotics enabling near-term demonstration (FREND) robotic arm. In: AIAA infotech@ aerospace conference, Seattle, Washington; 2009. p. 1–12.
[45] Thronson HA, Akin D, Grunsfeld J, Lester D. The evolution and promise of robotic in-space servicing. In: AIAA SPACE conference & exposition, Pasadena, CA; 2009. p. 1–6.
[46] TSullivan B, Hunter R, Bruhn J, Fowler E, Hoag L, Chappie S, et al. Phoenix project status 2013. In: AIAA SPACE conference & exposition, San Diego, CA; 2013. p. 1–17.
[47] Krolikowski A, David E. Commercial on-orbit satellite servicing: national and international policy considerations raised by industry proposals. New Space 2013;1(1):29–41.
[48] Office DTT. DARPA phoenix satellite servicing. URL 〈http://www.darpa.mil/Our_Work/TTO/Programs/Phoenix.aspx〉; May 2013 [online; accessed 25.06.13].
[49] Grossman E, Costa K. Small, experimental satellite may offer more than meets the eye. URL 〈http://www.globalsecurity.org/org/news/2003/031204-asat.htm; 2003.
[50] Rumford T. Demonstration of autonomous rendezvous technology (DART) project summary. In: SPIE defense and security symposium, vol. 5088; 2003. p. 10–9.
[51] Croomes S. Overview of the dart mishap investigation results. NASA Report 2006:1–10.
[52] Sommer B. Automation and robotics in the german space program-unmanned on-orbit servicing (OOS) & the TECSAS mission. In: IAF 55th international astronautical congress, Vancouver, Canada; 2004.
[53] Reintsema D, Thaeter J, Rathke A, Naumann W, Rank P, Sommer J. DEOS the German robotics approach to secure and de-orbit malfunctioned satellites from low earth orbit. In: International symposium on artificial intelligence, robotics and automation in space, Sapporo, Japan; 2010. p. 244–51.
[54] Reintsema D, Sommer B, Wolf T, Thaeter J, Radthke A, Naummann W, et al. DEOS-the in-flight technology demonstration of Germans robotics approach to dispose malfunctioned satellites. In: ESA workshop on advanced space technologies for robotics and automation, ESTEC, Noordwijk, The Netherlands; 2011.
[55] Rupp T, Boge T, Kiehling R, Sellmaier F. Flight dynamics challenges of the German on-orbit servicing mission DEOS. In: The 21st international symposium on space flight dynamics, Toulouse, France; 2009.
[56] Wingo D. Orbital recovery's responsive commercial space tug for life extension missions. In: AIAA second responsive space conference, Los Angeles, San Diego, CA; 2004.
[57] Williams M. SpaceX capsule: NASA astronauts enter the dragon after historic docking@ONLINE. URL 〈http://www.guardian.co.uk/science/2012/may/26/spacex-capsule-nasa-dragon-iss〉; May 2012.
[58] Longman R, Lindererg R, Zedd M. Satellite-mounted robot manipulators—new kinematics and reaction moment compensation. Int J Robot Res 1987;6:87–103.
[59] Vafa Z, Dubowsky S. On the dynamics of manipulators in space using the virtual manipulator approach. In: IEEE international conference on robotics and automation, vol. 4, Raleigh, NC; 1987. p. 579–85.
[60] Alexander HL, Cannon Jr. RH. Experiments on the control of a satellite manipulator. In: American control conference, Minneapolis, MN; 1987.
[61] Longman R. The kinetics and workspace of a satellite-mounted robot, space robotics: dynamics and control. Springer; 1992; 27–44.
[62] Vafa Z, Dubowsky S. The kinematics and dynamics of space manipulators: the virtual manipulator approach. Int J Robot Res 1990;9(4):3–21.
[63] Dubowsky S, Vance E, Torres M. The control of space manipulators subject to spacecraft attitude control saturation limits. In: NASA conference on space telerrobotics, JPL, Pasadena, CA, p. 409–18.
[64] Papadopoulos E, Dubowsky S. Dynamic singularities in free-floating space manipulators, space robotics: dynamics and control. Springer; 1992; 77–100.
[65] Lampariello R, Agrawal S, Hirzinger G. Optimal motion planning for free-flying robots. In: IEEE international conference on robotics and automation, vol. 3, Taipei, Taiwan; 2003. p. 3029–35.
[66] Umetani Y, Yoshida K. Continuous path control of space manipulators mounted on OMV. Acta Astronaut 1987;15(12):981–6.
[67] Nenchev D, Umetani Y, Yoshida K. Analysis of a redundant free-flying spacecraft/manipulator system. IEEE Trans Robot Autom 1992;8(1):1–6.
[68] Saha SK. A unified approach to space robot kinematics. IEEE Trans Robot Autom 1996;12(3):401–5.
[69] Liang B, Xu Y. Bergerman M. Mapping a space manipulator to a dynamically equivalent manipulator. J Dyn Syst Meas Control 1998;120(1):1–7 . 〈http://dx.doi.org/10.1115/1.2801316〉.
[70] Parlaktuna O, Ozkan M. Adaptive control of free-floating space manipulators using dynamically equivalent manipulator model. Robot Auton Syst 2004; 46(3):185–93.
[71] Pazelli T, Terra M, Siqueira A. Adaptive robust controller designs applied to free-floating space manipulators in task space, robot manipulators, trends and development. InTech; 2010. p. 232–47.

[72] Pazelli T, Pazelli F, Terra M, Siqueira A. Neural network robust controllers applied to free-floating space manipulators in task space. In: American control conference, Baltimore, MD; 2010. p. 3648–53.
[73] Pazelli TF, Terra MH, Siqueira AA. Experimental investigation on adaptive robust controller designs applied to a free-floating space manipulator. Control Eng Pract 2011;19(4):395–408.
[74] From P, Pettersen KY, Gravdahl JT. A singularity free formulation of the dynamically equivalent manipulator mapping of space manipulators. In: AIAA space conference and exposition. AIAA, Long Beach, CA; 2011. p. 1–10.
[75] Schäfer B, Krenn R, Rebele B. On inverse kinematics and kinetics of redundant space manipulator simulation. J Comput Appl Mech 2003;4(1):53–70.
[76] Xu W, Liang B, Xu Y. Practical approaches to handle the singularities of a wrist-partitioned space manipulator. Acta Astronaut 2011;68(1):269–300.
[77] Ellery A. An introduction to space robotics. Chichester, United Kingdom: Praxis Publishing Ltd; 2000.
[78] Yoshida K, Kurazume R, Umetani Y. Dual arm coordination in space free-flying robot. In: IEEE international conference on robotics and automation, Sacramento, CA; 1991. p. 2516–21.
[79] Ellery A. Space robotics, part 2: space-based manipulators. Int J Adv Robot Syst 2004;1(3):213–6.
[80] Moosavian SAA, Papadopoulos E. On the kinematics of multiple manipulator space free-flyers and their computation. J Robot Syst 1998;15(4):207–16.
[81] Moosavian SAA, Papadopoulos E. Explicit dynamics of space free-flyers with multiple manipulators via SPACEMAPLE. Adv Robot 2004;18(2):223–44.
[82] Nakamura Y, Yamane K. Dynamics computation of structure-varying kinematic chains and its application to human figures. IEEE Trans Robot Autom 2000;16(2):124–34.
[83] Lampariello R, Abiko S, Hirzinger G. Dynamics modeling of structure-varying kinematic chains for free-flying robots. In: IEEE international conference on robotics and automation, Pasadena, CA; 2008. p. 1207–12.
[84] Wee L, Walker M. On the dynamics of contact between space robots and configuration control for impact minimization. IEEE Trans Robot Autom 1993;9(5):581–91.
[85] Ma O. Contact dynamics modelling for the simulation of the space station manipulators handling payloads. In: IEEE international conference on robotics and automation, vol. 2, Nagoya, Japan; 1995. p. 1252–8.
[86] Ma O, Buhariwala K, Roger N, MacLean J, Carr R. MDSF—a generic development and simulation facility for flexible, complex robotic systems. Robotica 1997;15(01):49–62.
[87] Ma O, Wang J. Model order reduction for impact-contact dynamics simulations of flexible manipulators. Robotica 2007;25(4):397–408.
[88] Shibli M, Aghili F, Su C. Modeling of a free-flying space robot manipulator in contact with a target satellite. In: Proceedings of IEEE conference on control applications, Toronto, Canada; 2005. p. 559–64.
[89] Nenchev D, Yoshida K. Impact analysis and post-impact motion control issues of a free-floating space robot subject to a force impulse. IEEE Trans Robot Autom 1999;15(3):548–57.
[90] Ma O, Flores-Abad A, Boge T. Use of industrial robots for hardware-in-the-loop simulation of satellite rendezvous and docking. Acta Astronaut 2012;81(1):335–47.
[91] Abiko S, Uyama N, Ikuta T, Nagaoka K, Yoshida K, Nakanishi J, et al. Contact dynamic simulation for capture operation by snare wire type of end effector. In: International symposium on artificial intelligence, robotics and automation in space, Turin, Italy; 2012.
[92] Uyama N, Nagaoka K, Yoshida K. Experimental evaluation of contact-impact dynamics between a space robot with compliant wrist and a free-flying object. In: International symposium on artificial intelligence, robotics and automation in space, Turin, Italy; 2012.
[93] Sawada H, Szuki S, Oda M. A contact dynamics analysis of spacecraft capturing and rigidizing. In: The 17th workshop on JAXA astrodynamics and flight mechanics; 2007.
[94] Gilardi G, Sharf I. Literature survey of contact dynamics modelling. Mech Mach Theory 2002;37(10):1213–39.
[95] Nagamatsu H, Kubota T, Nakatani I. Capture strategy for retrieval of a tumbling satellite by a space robotic manipulator. In: IEEE international conference on robotics and automation, vol. 1, Minneapolis, MI; 1996. p. 70–5.
[96] Huang P, Xu Y, Liang B. Tracking trajectory planning of space manipulator for capturing operation. Int J Adv Robot Syst 2006;3(3):211–8.
[97] Thienel JK, Sanner RM. Hubble space telescope angular velocity estimation during the robotic servicing mission. J Guid Control Dyn 2007;30(1):29–34.
[98] Thienel JK, VanEepoel JM, Sanner RM. Accurate estimation and tracking of a non-cooperative target vehicle. In: AIAA guidance, navigation, and control conference, Keystone, CO; 2006. p. 5511–22.
[99] Masutani Y, Iwatsu T, Miyazaki F. Motion estimation of unknown rigid body under no external forces and moments. In: IEEE international conference on robotics and automation, San Diego, CA; 1994. p. 1066–72.
[100] Lichter M, Dubowsky S. State, shape, and parameter estimation of space objects from range images. In: IEEE international conference on robotics and automation, vol. 3, New Orleans, USA; 2004. p. 2974–9.
[101] Hillenbrand U, Lampariello R. Motion and parameter estimation of a free-floating space object from range data for motion prediction. In: International symposium on artificial intelligence, robotics and automation in space, Munich, Germany; 2005.
[102] Inaba N, Oda M, Hayashi M. Visual servoing of space robot for autonomous satellite capture. Trans Jpn Soc Aeronaut Space Sci 2003;46(153):173–9.
[103] Kelsey JM, Byrne J, Cosgrove M, Seereeram S, Mehra RK. Vision-based relative pose estimation for autonomous rendezvous and docking. In: Aerospace conference, 2006 IEEE, Big Sky, MT; 2006.
[104] Xu W, Liu Y, Liang B, Xu Y, Qiang W. Autonomous path planning and experiment study of free-floating space robot for target capturing. J Intell Robot Syst 2008;51(3):303–31.
[105] Xu W, Liang B, Li C, Liu Y, Xu Y. Autonomous target capturing of free-floating space robot: theory and experiments. Robotica 2009;27(3):425.
[106] Aghili F. Optimal control of a space manipulator for detumbling of a target satellite. In: IEEE international conference on robotics and automation, Kobe, Japan; 2009. p. 3019–24.
[107] Tzschichholz T, Ma L, Schilling K. Model-based spacecraft pose estimation and motion prediction using a photonic mixer device camera. Acta Astronaut 2011;68(7):1156–67.
[108] Petit A, Marchand E, Kanani K. Vision-based space autonomous rendezvous: a case study. In: IEEE/RSJ international conference on intelligent robots and systems, San Francisco, CA; 2011. p. 619–24.
[109] Petit A, Marchand E, Kanani K. Tracking complex targets for space rendezvous and debris removal applications. In: IEEE/RSJ international conference on intelligent robots and systems, Vilamoura, Portugal; 2012. p. 4483–8.
[110] Aghili F, Kuryllo M, Okouneva G, English C. Fault-tolerant position/attitude estimation of free-floating space objects using a laser range sensor. IEEE Sens J 2011;11(1):176–85.
[111] English C, Okouneva G, Saint-Cyr P, Choudhuri A, Luu T. Real-time dynamic pose estimation systems in space: lessons learned for system design and performance evaluation. Int J Intell Control Syst 2011;16(2):79–96.
[112] Shi Y, Liang B, Wang X, Xu W, Liu H. Modeling and simulation of space robot visual servoing for autonomous target capturing. In: International conference on mechatronics and automation, Chengdu, China; 2012. p. 2275–80.
[113] Shi Y, Liang B, Wang X, Xu W, Liu H. Study on intelligent visual servoing of space robot for cooperative target capturing. In: International conference on information and automation, Shenyang, China; 2012. p. 733–8.
[114] Tweddle BE. Relative computer vision based navigation for small inspection spacecraft. In: AIAA guidance, navigation, and control conference, Portland, Oregon; 2011.
[115] O'Connor MC, Tweddle BE, Katz JG, Saenz-Otero A, Miller DW, Makowka K. Visual-inertial estimation and control for inspection of a tumbling spacecraft: experimental results from the international space station. In: AIAA guidance, navigation, and control conference, Minneapolis, MN; 2012.
[116] Fourie D, Tweddle BE, Ulrich S, Saenz-Otero A. Vision-based relative navigation and control for autonomous inspection of a tumbling spacecraft. In: AIAA guidance, navigation, and control conference, Boston, MA; 2013.
[117] Sabatini M, Monti R, Gasbarri P, Palmerini G. Deployable space manipulator commanded by means of visual-based guidance and navigation. Acta Astronaut 2013;83:27–43.
[118] Sabatini M, Monti R, Gasbarri P, Palmerini GB. Adaptive and robust algorithms and tests for visual-based navigation of a space robotic manipulator. Acta Astronaut 2013;83:65–84.
[119] Katoh R, Sakon H, Yamamoto T. A control method for space manipulator mounted on a free-flying robot by using parameter identification. In: Asian-Pacific vibration conference; 1993. p. 1205–9.
[120] Murotsu Y, Tsujio S, Senda K, Ozaki M. Parameter identification of unknown object handled by free-flying space robot. In: Guidance, navigation and control conference, vol. 1, Hilton Head Island, SC; 1992.
[121] Murotsu Y, Senda K, Ozaki M, Tsujio S. Parameter identification of unknown object handled by free-flying space robot. J Guid Control Dyn 1994;17(3):488–94.
[122] Yoshida K, Abiko S. Inertia parameter identification for a free-flying space robot. In: AIAA guidance, navigation, and control conference, Monterey, CA; 2002.
[123] Lampariello R, Hirzinger G. Freeflying robots-inertial parameters identification and control strategies. In: Advance space technologies for robotics automation (ASTRA), vol. 1, Noordwijk, Netherlands; 2000.
[124] Lampariello R, Hirzinger G. Modeling and experimental design for the on-orbit inertial parameter identification of free-flying space robots. In: ASME international design engineering technical conferences and computers and information in engineering conference, Long Beach, CA; 2005. p. 1–10.
[125] Ma O, Dang H, Pham K. On-orbit identification of inertia properties of spacecraft using robotics technology. J Guid Control Dyn 2008;31(6):1761–71.
[126] Fitz-Coy N, Liu M. A modified proportional navigation scheme for rendezvous and docking with tumbling targets: the planar case. In: Flight mechanics/estimation theory symposium, vol. 1; 1995. p. 243–52.
[127] Nakasuka S, Fujiwara T. New method of capturing tumbling object in space and its control aspects. In: IEEE international conference on control applications, vol. 2, Kohala Coast, HI; 1999. p. 973–8.
[128] Tsuda Y, Nakasuka S. New attitude motion following control algorithm for capturing a tumbling object in space. Acta Astronaut 2003;53(11):847–61.
[129] Matsumoto S, Jacobsen S, Dubowsky S, Ohkami Y. Approach planning and guidance for uncontrolled rotating satellite capture considering collision avoidance. In: International symposium on artificial intelligence, robotics and automation in space, Nara, Japan; 2003.
[130] Ma Z, Ma O, Shashikanth B. Optimal approach to and alignment with a rotating rigid body for capture. J Astronaut Sci 2007;55(4):407–19.
[131] Breger L, How J. Safe trajectories for autonomous rendezvous of spacecraft. J Guid Control Dyn 2008;31(5):1478–89.

Please cite this article as: Flores-Abad A, et al. A review of space robotics technologies for on-orbit servicing. Progress in Aerospace Sciences (2014), http://dx.doi.org/10.1016/j.paerosci.2014.03.002

[132] Boyarko G, Yakimenko O, Romano M. Optimal rendezvous trajectories of a controlled spacecraft and a tumbling object. J Guid Control Dyn 2011;34 (4):1239–52.

[133] Boyarko G, Yakimenko O, Romano M. Optimization of a spacecraft maneuver to dock with a tumbling object. In: AAS/AIAA astrodynamics specialist conference, Pittsburgh, Pennsylvania; 2009.

[134] Pearson D. The glideslope approach. In: AAS/NAS international symposium, Greenbelt, Maryland; 1989.

[135] Hablani HB, Tapper ML, Dana-Bashian D. Guidance and relative navigation for autonomous rendezvous in a circular orbit. J Guid Control Dyn 2002;25 (3):553–62.

[136] Sultan C, Seereram S, Mehra R. Deep space formation flying spacecraft path planning. Int J Robot Res 2007;26:405–30.

[137] Fejzic A. Development of control and autonomy algorithms for docking to complex tumbling satellites. Technical Report, Massachusetts Institute of Technology, Department of Aeronautics and Astronautics; 2008.

[138] Xu W, Liang B, Li C, Xu Y. Autonomous rendezvous and robotic capturing of non-cooperative target in space. Robotica 2010;28(05):705–18.

[139] Xin M, Pan H. Nonlinear optimal control of spacecraft approaching a tumbling target. Aerosp Sci Technol 2011;15(2):79–89.

[140] Masutani Y, Miyazaki F, Arimoto S. Sensory feedback control for space manipulators. In: IEEE transactions on robotics and automation, Scottsdale, AZ; 1989. p. 1346–51.

[141] Vafa Z, Dubowsky S. On the dynamics of space manipulators using the virtual manipulator, with applications to path planning. Space Robot Dyn Control 1992:45–76.

[142] Dubowsky S, Torres M. Path planning for space manipulators to minimize spacecraft attitude disturbances. In: IEEE transactions on robotics and automation, Sacramento, CA; 1991. p. 2522–8.

[143] Nakamura Y, Mukherjee R. Nonholonomic path planning of space robots. In: IEEE transactions on robotics and automation, Scottsdale, AZ; 1989. p. 1050–5.

[144] Dubowsky S, Torres M. Path planning for space manipulators to minimize the use of attitude control fuel. In: International symposium on artificial intelligence, robotics and automation in space, Kobe, Japan; 1990.

[145] Zappa B, Legnani G, Adamini R. Path planning of free-flying space manipulators: an exact solution for polar robots. Mech Mach Theory 2005;40 (7):806–20.

[146] Nakamura Y, Mukherjee R. Exploiting nonholonomic redundancy of free-flying space robots. IEEE Trans Robot Autom 1993;9(4):499–506.

[147] Papadopoulos E. Path planning for space manipulators exhibiting nonholonomic behavior. In: IEEE/RSJ international conference on intelligent robots and systems, Raleigh, North Carolina; 1992. p. 7–10.

[148] Mukherjee R, Chen D. Control of free-flying underactuated space manipulators to equilibrium manifolds. IEEE Trans Robot Autom 1993;9(5):561–70.

[149] De Silva C. Trajectory design for robotic manipulators in space applications. J Guid Control Dyn 1991;14(3):670–4.

[150] Pandey S, Agrawal S. Path planning of free floating prismatic-jointed manipulators. Multibody Syst Dyn 1997;1(1):127–40.

[151] Lampariello R, Deutrich K. Simplified path planning for free-floating robots. Technical Report, DLR; 1999.

[152] Nenchev D, Yoshida K, Uchiyama M. Reaction null-space based control of flexible structure mounted manipulator systems. In: IEEE decision and control conference, vol. 4, Kobe, Japan; 1996. p. 4118–23.

[153] Nenchev DN, Yoshida K, Vichitkulsawat P, Uchiyama M. Reaction null-space control of flexible structure mounted manipulator systems. IEEE Trans Robot Autom 1999;15(6):1011–23.

[154] Piersigilli P, Sharf I, Misra A. Reactionless capture of a satellite by a two degree-of-freedom manipulator. Acta Astronaut 2010;66(1):183–92.

[155] Fukazu Y, Hara N, Kanamiya Y, Sato D. Reactionless resolved acceleration control with vibration suppression capability for JEMRMS/SFA. In: IEEE international conference on robotics and biomimetics, 2008, Bangkok, Thailand; 2009. p. 1359–64.

[156] Xu W, Liang B, Li C, Xu Y, Qiang W. Path planning of free-floating robot in cartesian space using direct kinematics. Int J Adv Robot Syst 2007;4 (1):17–26.

[157] Fernandes C, Gurvits L, Li Z. Near-optimal nonholonomic motion planning for a system of coupled rigid bodies. IEEE Trans Autom Control 1994;39 (3):450–63.

[158] Fernandes C, Gurvits L, Li Z. Attitude control of space platform/manipulator system using internal motion. Space Robot Dyn Control 1992:131–63.

[159] Yamada K. Arm path planning for a space robot. In: IIEEE/RSJ international conference on intelligent robots and systems, vol. 3, Yokohama, Japan; 1993. p. 2049–55.

[160] Yamada K, Yoshikawa S, Fujita Y. Arm path planning of a space robot with angular momentum. Adv Robot 1994;9(6):693–709.

[161] Suzuki T, Nakamura Y. Planning spiral motion of nonholonomic space robots. In: IEEE international conferences on robotics and automation, vol. 1, Minneapolis, Minnesota; 1996. p. 718–25.

[162] Yoshida K, Hashizume K, Abiko S. Zero reaction maneuver: flight validation with ETS-VII space robot and extension to kinematically redundant arm. In: IEEE international conferences on robotics and automation, vol. 1, Piscataway, NJ; 2001. p. 441–6.

[163] Papadopoulos E, Poulakakis I, Papadimitriou I. On path planning and obstacle avoidance for nonholonomic platforms with manipulators: a polynomial approach. Int J Robot Res 2002;21(4):367–83.

[164] Papadopoulos E, Tortopidis I, Nanos K. Smooth planning for free-floating space robots using polynomials. In: IEEE international conference on robotics and automation, Barcelona, Spain; 2005. p. 4272–7.

[165] Tortopidis I, Papadopoulos E. On point-to-point motion planning for underactuated space manipulator systems. Robot Auton Syst 2007;55(2):122–31.

[166] Belousov I, Estevès C, Laumond J, Ferré E. Motion planning for the large space manipulators with complicated dynamics. In: IEEE/RSJ international conference on intelligent robots and systems; 2005. p. 2160–6.

[167] Franch J, Agrawal S, Oh S, Fattah A. Design of differentially flat planar space robots: a step forward in their planning and control. In: IEEE/RSJ international conference on intelligent robots and systems, vol. 4, Las Vegas, Nevada; 2003. p. 3053–8.

[168] Agrawal SK, Pathak K, Franch J, Lampariello R, Hirzinger G. A differentially flat open-chain space robot with arbitrarily oriented joint axes and two momentum wheels at the base. IEEE Trans Autom Control 2009;54 (9):2185–91.

[169] Xu W, Liu Y, Liang B, Xu Y, Li C, Qiang W. Non-holonomic path planning of a free-floating space robotic system using genetic algorithms. Adv Robot 2008;22(4):451–76.

[170] Xu W, Li C, Liang B, Xu Y, Liu Y, Qiang W. Target berthing and base reorientation of free-floating space robotic system after capturing. Acta Astronaut 2009;64(2):109–26.

[171] Nanos K, Papadopoulos E. On cartesian motions with singularities avoidance for free-floating space robots. In: IEEE international conference on robotics and automation; 2012. p. 5398–403.

[172] Cocuzza S, Pretto I, Debei S. Novel reaction control techniques for redundant space manipulators: theory and simulated microgravity tests. Acta Astronaut 2011;68(11):1712–21.

[173] Cocuzza S, Pretto I, Debei S. Least-squares-based reaction control of space manipulators. J Guid Control Dyn 2012;35(3):976–86.

[174] Umetani Y, Yoshida K. Resolved motion rate control of space manipulators with generalized Jacobian matrix. IEEE Trans Robot Autom 1989;5(3):303–14.

[175] Caccavale F, Siciliano B. Kinematic control of redundant free-floating robotic systems. Adv Robot 2001;15(4):429–48.

[176] Nenchev D. A controller for a redundant free-flying space robot with spacecraft attitude/manipulator motion coordination. In: IEEE/RSJ international conference on intelligent robots and systems, vol. 3, Yokohama, Japan; 1993. p. 2108–14.

[177] Xu Y. The measure of dynamic coupling of space robot systems. In: IEEE international conference on robotics and automation, Atlanta, USA; 1993. p. 615–20.

[178] Xu Y, Shum H. Dynamic control and coupling of a free-flying space robot system. J Robot Syst 1994;11(7):573–89.

[179] Matsuno F, Saito K. Attitude control of a space robot with initial angular momentum. In: IEEE international conference on robotics and automation, vol. 2, Seoul, Korea; 2001. p. 1400–5.

[180] Zhaobin H, Li C. Attitude control of a space robot with initial angular momentum using time-state control form. In: Chinese control conference, Harbin, China; 2006. p. 1538–42.

[181] Kai T, Tamaki K. 3D attitude near-optimal control of a universal joint space robot model with initial angular momentum. In: IEEE international conference on control and automation, New Zealand; 2009. p. 2335–40.

[182] Nanos K, Papadopoulos E. On the use of free-floating space robots in the presence of angular momentum. Intell Serv Robot 2011;4(1):3–15.

[183] Walker MW, Wee L-B. Adaptive control of space-based robot manipulators. IEEE Trans Robot Autom 1991;7(6):828–35.

[184] Gu Y, Xu Y. A normal form augmentation approach to adaptive control of space robot systems. Dyn Control 1995;5(3):275–94.

[185] Parlaktuna O, Ozkan M. Adaptive control of free-floating space robots in cartesian coordinates. Adv Robot 2004;18(9):943–59.

[186] Wee L, Walker M, McClamroch N. An articulated-body model for a free-flying robot and its use for adaptive motion control. IEEE Trans Robot Autom 1997;13(2):264–77.

[187] Sanner RM, Vance EE. Adaptive control of free-floating space robots using neural networks. In: American control conference, vol. 4, Seattle, WA; 1995. p. 2790–4.

[188] de FPA Taveira T, Siqueira AA, Terra H. Adaptive nonlinear H_∞ controllers applied to a free-floating space manipulator. In: IEEE international conference on control applications, Munich, Germany; 2006. p. 1476–81.

[189] McCourt R, de Silva C. Autonomous robotic capture of a satellite using constrained predictive control. IEEE/ASME Trans Mechatron 2006;11 (6):699–708.

[190] Abiko S, Hirzinger G. An adaptive control for a free-floating space robot by using inverted chain approach. In: IEEE/RSJ international conference on intelligent robots and systems, San Diego, CA; 2007. p. 2236–41.

[191] Abiko S, Hirzinger G. Adaptive control for a torque controlled free-floating space robot with kinematic and dynamic model uncertainty. In: IEEE/RSJ international conference on intelligent robots and systems, St. Louis, USA; 2009. p. 2359–64.

[192] Wang H. On adaptive inverse dynamics for free-floating space manipulators. Robot Auton Syst 2011;59(10):782–8.

[193] Liu S, Ma C, Luo C, Wang X. Adaptive control of free-floating space robot with disturbance based on robust fuzzy compensator. In: The second international conference on intelligent human–machine systems and cybernetics (IHMSC), 2010, vol. 1; 2010. p. 23–8.

[194] Wang H, Xie Y. Passivity based adaptive Jacobian tracking for free-floating space manipulators without using spacecraft acceleration. Automatica 2009;45(6):1510–7.

[195] Shibli M. Unified modeling approach of kinematics, dynamics and control of a free-flying space robot interacting with a target satellite. J Intell Control Autom 2011;2(1):8–23.
[196] Wang H, Xie Y. Prediction error based adaptive Jacobian tracking for free-floating space manipulators. IEEE Trans Aerosp Electron Syst 2012;48(4):3207–21.
[197] Xu Y, Gu Y, Wu Y, Sclabassi R. Robust control of free-floating space robot systems. Int J Control 1995;61(2):261–77.
[198] Li C. Adaptive and robust composite control of coordinated motion of space robot system with prismatic joint. In: World congress on intelligent control and automation, Shanghai, China; 2002. p. 1255–9.
[199] Guo Y, Chen L. Robust adaptive composite control of dual-arm space robot system in inertial space. In: IEEE international conference on intelligent systems design and applications, vol. 3, Jian, China; 2006. p. 115–9.
[200] Guo Y, Chen L. Robust control of dual-arm space robot system with two objects in joint space. In: IEEE/RSJ international conference on intelligent robots and systems, Beijing, China; 2006. p. 5091–5.
[201] Huang P, Yan J, Yuan J, Xu Y. Robust control of space robot for capturing objects using optimal control method. In: IEEE international conference on information acquisition, Seogwipo-si, South Korea; 2007. p. 397–402.
[202] Chen Z, Chen L. Robust adaptive composite control of space-based robot system with uncertain parameters and external disturbances. In: IEEE/RSJ international conference on intelligent robots and systems, St. Louis, MO; 2009. p. 2353–8.
[203] Pathak PM, Kumar RP, Mukherjee A, Dasgupta A. A scheme for robust trajectory control of space robots. Simul Modell Pract Theory 2008;16(9):1337–49.
[204] Tang X, Tang C-k, Li H. A backstepping robust control method for free-floating space robot system with dual-arms. In: IEEE international conference on robotics and biomimetics, Phuket, Thailand; 2011. p. 761–5.
[205] Xu G, Zhang M, Wang H. Robust controller design for one arm space manipulator with uncertainties compensated. In: Informatics in control, automation and robotics. Springer; 2012. p. 59–66.
[206] Oki T, Nakanishi H, Yoshida K. Time-optimal manipulator control of a free-floating space robot with constraint on reaction torque. In: IEEE/RSJ international conference on intelligent robots and systems, Nice, France; 2008. p. 2828–33.
[207] Flores-Abad A, Ma O. Control of a space robot for minimal attitude disturbance to the base satellite for capturing a tumbling satellite. In: SPIE sensors and systems for space applications V, vol. 8385, Baltimore, USA; 2012.
[208] Papadopoulos E, Dubowsky S. On the nature of control algorithms for free-floating space manipulators. IEEE Trans Robot Autom 1991;7(6):750–8.
[209] Dubowsky S, Papadopoulos E. The dynamics and control of space robotic systems. IEEE Trans Robot Autom 1993;9(5):531–43.
[210] Xu Y, Kanade Ye. Space robotics: dynamics and control, vol. 188. Springer; 1993.
[211] Bronez M, Clarke M, Quinn A., Requirements development for a free-flying robot—the "Robin". In: IEEE international conference on robotics and automation, vol. 3, San Francisco, CA; 1986. p. 667–72.
[212] Reuter G, Hess C, Rhoades D, McFadin L, Healey K, Erickson J. An intelligent, free-flying robot. In: SPIE, space station automation IV, vol. 1006; 1988. p. 20–7.
[213] Ellery A. An engineering approach to the dynamic control of space robotic on-orbit servicers. Proc Inst Mech Eng, Part G: J Aerosp Eng 2004;218(2):79–98.
[214] Papadopoulos E, Dubowsky S. Coordinated manipulator/spacecraft motion control for space robotic systems. In: IEEE international conference on robotics and automation, Sacramento, CA; 1991. p. 1696–701.
[215] Xu Y, Shum H, Lee J, Kanade T. Adaptive control of space robot system with an attitude controlled base. Space Robot Dyn Control 1992:229–68.
[216] Oda M. Coordinated control of spacecraft attitude and its manipulator. In: IEEE international conference on robotics and automation, vol. 1. Minneapolis, MN; 1996. p. 732–8.
[217] Oda M, Ohkami Y. Coordinated control of spacecraft attitude and space manipulators. Control Eng Pract 1997;5(1):11–21.
[218] Carter F, Cherchas D. Motion control of non-fixed base robotic manipulators. Robotica 1999;17(2):143–57.
[219] Oda M. Attitude control experiments of a robot satellite. J Spacecr Rockets 2000;37(6):788–93.
[220] Aghili F. A prediction and motion-planning scheme for visually guided robotic capturing of free-floating tumbling objects with uncertain dynamics. IEEE Trans Robot Autom 2012;28(3):634–49.
[221] Agrawal SK, Shirumalla S. Planning motions of a dual-arm free-floating manipulator keeping the base inertially fixed. Mech Mach Theory 1995;30(1):59–70.
[222] Yale GE, Agrawal BN. Lyapunov controller for cooperative space manipulators. J Guid Control Dyn 1998;21(3):477–84.
[223] Yokokohji Y, Toyoshima T, Yoshikawa T. Efficient computational algorithms for trajectory control of free-flying space robots with multiple arms. IEEE Trans Robot Autom 1993;9(5):571–80.
[224] Papadopoulos E, Moosavian SAA. Dynamics and control of multi-arm space robots during chase and capture operations. In: IEEE/RSJ international conference on intelligent robots and systems, Germany: Munich; 1994. p. 1554–61.
[225] Papadopoulos E, Moosavian SAA. Dynamics and control of space free-flyers with multiple arms. J Adv Robot 1995;9:603–24.
[226] Moosavian SAA, Papadopoulos E. Control of space free-flyers using the modified transpose Jacobian algorithm. In: IEEE/RSJ international conference on intelligent robots and systems, Grenoble, France; 1997. p. 1500–5.
[227] Huang P, Xu Y, Liang B. Dynamic balance control of multi-arm free-floating space robots. Int J Adv Robot Syst 2006;2(2):117–24.
[228] Huang P, Xu Y. Attitude compensation of space robots for capturing operation. In: Mobile robots toward new applications; 2006. p. 499–512.
[229] Chen L, Guo Y. Adaptive control of dual-arm space robot system in joint space. In: IEEE/RSJ international conference on intelligent robots and systems, Beijing, China; 2006. p. 5096–9.
[230] Xu W, Liu Y, Xu Y. The coordinated motion planning of a dual-arm space robot for target capturing. Robotica 2012;30(5):755–71.
[231] Shimoji H, Inoue M, Tsuchiya K, Niomiya K, Nakatani I, Kawaguchi J. Simulation system for a space robot using six-axis servos. Adv Robot 1991;6(2):179–96.
[232] Cyril X, Jaar G, Misra A. The effect of payload impact on the dynamics of a space robot. In: IEEE/RSJ international conference on intelligent robots and systems, Yokohama, Japan; 1993. p. 2070–5.
[233] Yoshida K, Sashida N, Kurazume R, Umetani Y. Modeling of collision dynamics for space free-floating links with extended generalized inertia tensor. In: IEEE international conference on robotics and automation, Nice, France; 1992. p. 899–904.
[234] Yoshida K, Sashida N. Modeling of impact dynamics and impulse minimization for space robots. In: IEEE/RSJ international conference on intelligent robots and systems, vol. 3, Yokohama, Japan; 1993. p. 2064–9.
[235] Yoshikawa S, Yamada K. Impact estimation of a space robot at capturing a target. In: IEEE/RSJ international conference on intelligent robots and systems, Munich, Germany; 1994. p. 1570–7.
[236] Yoshikawa S, Yamada K. On the dynamics of a space robot at capturing a target. In: The 20th international symposium on space technology and science, Gifu, Japan; 1996. p. 492–7.
[237] Yoshida K, Mavroidis C, Dubowsky S. Experimental research on impact dynamics of spaceborne manipulator systems. Exp Robot 1997;IV:436–47.
[238] Yoshida K, Mavroidis C, Dubowsky S. Impact dynamics of space long reach manipulators. In: IEEE international conference on robotics and automation, vol. 2, Minneapolis, MN; 1996. p. 1909–16.
[239] Yoshida K, Nenchev D. Space robot impact analysis and satellite-base impulse minimization using reaction null-space. In: Proceedings of the IEEE international conference on robotics and automation, Nagoya, Japan; 1995. p. 1271–1277.
[240] Cyril X, Jaar G, Misra A. Dynamical modelling and control of a spacecraft-mounted manipulator capturing a spinning satellite. Acta Astronaut 1995;35(2):167–74.
[241] Cyril X, Ingham M, Jaar GJ, Misra AK. Postcapture dynamics of a spacecraft-manipulator-payload system. J Guid Control Dyn 2000;23(1):95–100.
[242] Papadopoulos E, Paraskevas I. Design and configuration control of space robots undergoing impact. In: ESA conference on guidance, navigation and control systems, ESA, Loutraki, Greece; 2006.
[243] Huang P, Xu Y, Liang B. Contact and impact dynamics of space manipulator and free-flying target. In: IEEE/RSJ international conference on intelligent robots and systems, Edmonton, Canada; 2005. p. 1181–6.
[244] Huang P, Yuan J, Xu Y, Liu R. Approach trajectory planning of space robot for impact minimization. In: IEEE international conference on information acquisition, Veihai, China; 2006. p. 382–7.
[245] Huang P, Xu W, Liang B, Xu Y. Configuration control of space robots for impact minimization. In: IEEE international conference on robotics and biomimetics, China; 2006. p. 357–62.
[246] Taniwaki S, Matunaga S, Tsurumi S, Ohkami Y. Coordinated control of a satellite-mounted manipulator with consideration of payload flexibility. Control Eng Pract 2001;9(2):207–15.
[247] Raibert M, Craig J. Hybrid position/force control of manipulators. In: American society of mechanical engineers, winter annual meeting, Chicago, IL; 1980.
[248] Hogan N. Impedance control: an approach to manipulation. In: American control conference, 1984, San Diego, CA; 1984. p. 304–13.
[249] Yoshida K, Nakanishi H. Impedance matching in capturing a satellite by a space robot. In: IEEE/RSJ international conference on intelligent robots and systems, vol. 4, Las Vegas, Nevada; 2003. p. 3059–64.
[250] Yoshida K, Nakanishi H, Ueno H, Inaba N, Nishimaki T, Oda M. Dynamics, control and impedance matching for robotic capture of a non-cooperative satellite. Adv Robot 2004;18(2):175–98.
[251] Nakanishi H, Uyama N, Yoshida K. Virtual mass of impedance system for free-flying target capture. In: IEEE/RSJ international conference on intelligent robots and systems, Taipei, Taiwan; 2010. p. 4101–6.
[252] Ma O. CDT—a general contact dynamics toolkit. In: Proceedings of the 31st international symposium on robotics, Montreal, Canada; 2000. p. 468–73.
[253] Ma O, Crabtree D, Jones H, Yang G, Martin E, Carr R, Piedboeuf J. Development and applications of a simulink-based satellite docking simulator with generic contact dynamics capabilities. In: IAF world space congress, Houston, TX; 2002.
[254] Diao X, Ma O, Liu M. Dynamics of a robotics-based hardware-in-the-loop simulator for verifying microgravity contact dynamics. In: Proceedings of SPIE, vol. 6221, Orlando, FL; 2006. p. 30–41.
[255] Liu S, Wu L, Lu Z. Impact dynamics and control of a flexible dual-arm space robot capturing an object. Appl Math Comput 2007;185(2):1149–59.
[256] Zhao Y, Wei C, Wang H. Tracking control in space robot grasping a floating object. In: IEEE international conference on robotics and biomimetics, Guangxi, China; 2009. p. 2194–8.

[257] Cheng W, Tianxi L, Yang Z. Grasping strategy in space robot capturing floating target. Chin J Aeronaut 2010;23(5):591–8.
[258] Chen G, Jia Q, Sun H, Wang J. Modeling and simulation on impact motion of space robot for object capturing. In: IEEE conference on industrial electronics and applications, Taichung, Taiwan; 2010. p. 1885–90.
[259] Ma O, Flores-Abad A, Pham K. Control of a space robot for capturing a tumbling object. In: International symposium on artificial intelligence, robotics and automation in space, Turin, Italy; 2012.
[260] Krenn R, Hirzinger G. Contact dynamics simulation for space robotics applications. In: IEEE/RSJ international conference on intelligent robots and systems; 2008.
[261] Nguyen-Huynh T-C, Sharf I. Adaptive reactionless motion for space manipulator when capturing an unknown tumbling target. In: IEEE international conference on robotics and automation, Minnesota, USA; 2011. p. 4202–7.
[262] Nguyen-Huynh TC, Sharf I. Adaptive reactionless motion and parameter identification in postcapture of space debris. J Guid Control Dyn 2013:1–11.
[263] Dubowsky S, Boning P. The coordinated control of space robot teams for the on-orbit construction of large flexible space structures. In: IEEE international conference robotics and automation, Rome, Italy; 2007.
[264] Wilcox B, Tso K, Litwin T, Hayati S, Bon B. Autonomous sensor-based dual-arm satellite grappling. In: NASA-conference on space telerobotics, Pasadena, CA, Citeseer; 1989.
[265] Cong P-C, Zhang X. Preimpact configuration analysis of a dual-arm space manipulator with a prismatic joint for capturing an object. Robotica 2013:1–8.
[266] Cong P, Sun Z. Preimpact configuration analysis of dual-arm space manipulator capturing object. J Aerosp Eng 2010;23(2):117–23.
[267] Zhaowei CPS. The research of impact issues during single-arm space manipulator capturing object. J Dyn Control 2009;1:1–10.
[268] Moosavian SAA, Rastegari R, Papadopoulos E. Multiple impedance control for space free-flying robots. J Guid Control Dyn 2005;28(5):939.
[269] Rastegari R, Moosavian SAA. Multiple impedance control of space free-flying robots using virtual object grasp. In: IEEE/RSJ international conference on intelligent robots and systems, Beijing, China; 2006. p. 3125–30.
[270] Moosavian SAA, Rastegari R. Multiple-arm space free-flying robots for manipulating objects with force tracking restrictions. Robot Auton Syst 2006;54(10):779–88.
[271] Swain A, Morris A. Dynamic control of multi-arm co-operating manipulator systems. Robotica 2004;22(3):271–83.
[272] Moosavian SAA, Rastegari R. Force tracking in multiple impedance control of space free-flyers. In: IEEE/RSJ international conference on intelligent robots and systems, vol. 3, Takamatsu, Japan; 2000. p. 1646–51.
[273] Sidi M. Spacecraft dynamics and control: a practical engineering approach, vol. 7. Cambridge University Press; 2000.
[274] Nakanishi H, Yoshida K. Impedance control for free-flying space robots-basic equations and applications. In: IEEE/RSJ international conference on intelligent robots and systems, Beijing, China; 2006. p. 3137–42.
[275] Nakanishi H, Yoshida K. Impedance control of free-flying space robot for orbital servicing. J Robot Mechatron 2006;8(5):608–17.
[276] Pathak PM, Mukherjee A, Dasgupta A. Interaction torque control by impedance control of space robots. Simulation 2009;85(7):451–9.
[277] Uyama N, Hirano D, Nakanishi H, Nagaoka K, Yoshida K. Impedance-based contact control of a free-flying space robot with respect to coefficient of restitution. In: IEEE/SICE international symposium on system integration, Kyoto, Japan; 2011. p. 1196–201.
[278] Uyama N, Nakanishi H, Nagaoka K, Yoshida K. Impedance-based contact control of a free-flying space robot with a compliant wrist for non-cooperative satellite capture. In: IEEE/RSJ international conference on intelligent robots and systems, Algarve, Portugal; 2012. p. 4477–82.
[279] Walker M, Kim D. Satellite stabilization using space leeches. In: American control conference, San Diego, CA; 1990. p. 1314–9.
[280] Matunaga S, Kanzawa T, Ohkami Y. Rotational motion-damper for the capture of an uncontrolled floating satellite. Control Eng Pract 2001;9(2):199–205.
[281] Yoshikawa S, Yamada K. Impulsive control for angular momentum management of tumbling spacecraft. Acta Astronaut 2007;60(10):810–9.
[282] Kawamoto S, Matsumoto K, Wakabayashi S. Ground experiment of mechanical impulse method for uncontrollable satellite capturing. In: International symposium on artificial intelligence, robotics and automation in space, Montreal, Canada; 2001.
[283] Nakamura Y, Sasaki F, Nakasuka S. Guidance and control of tethered retriever with collaborative tension-thruster control for future on-orbit service missions. In: International symposium on artificial intelligence, robotics and automation in space; 2005. p. 5–8.
[284] Tsuda Y, Nakasuka S. New attitude motion following control algorithm for capturing tumbling object in space. Acta Astronaut 2003;53(11):847–61.
[285] Dimitrov D, Yoshida K. Utilization of the bias momentum approach for capturing a tumbling satellite. In: IEEE/RSJ international conference on intelligent robots and systems, vol. 4, Sendai, Japan; 2004. p. 3333–8.
[286] Dimitrov D, Yoshida K. Momentum distribution in a space manipulator for facilitating the post-impact control. In: IEEE/RSJ international conference on intelligent robots and systems, vol. 4, Sendai, Japan; 2004. p. 3345–50.
[287] Oki T, Nakanishi H, Yoshida K. Whole-body motion control for capturing a tumbling target by a free-floating space robot. In: IEEE/RSJ international conference on intelligent robots and systems, San Diego, CA; 2007. p. 2256–61.
[288] Yoshida K, Dimitrov D, Nakanishi H. On the capture of tumbling satellite by a space robot. In: IEEE/RSJ international conference on intelligent robots and systems, Beijing, China; 2006. p. 4127–32.
[289] Inaba N, Nishimaki T, Asano M, Oda M. Rescuing a stranded satellite in space-experimental study of satellite captures using a space manipulator. In: IEEE/RSJ international conference on intelligent robots and systems, vol. 4, Las Vegas, Nevada; 2003. p. 3071–6.
[290] Carpenter M, Peck M. Reducing base reactions with gyroscopic actuation of space-robotic systems. IEEE Trans Robot 2009;25(6):1262–70.
[291] Nakanishi H, Kodama M, Yoshida K. Influence of control time delay on the dynamics of satellite capture. Trans Jpn Soc Aeronaut Space Sci Space Technol Jpn 2009;7:29–34.
[292] Aghili F. Coordination control of a free-flying manipulator and its base attitude to capture and detumble a noncooperative satellite. In: IEEE/RSJ international conference on intelligent robots and systems, San Louis, USA; 2009. p. 2365–72.
[293] Aghili F, Parsa K. An adaptive vision system for guidance of a robotic manipulator to capture a tumbling satellite with unknown dynamics. In: IEEE/RSJ international conference on intelligent robots and systems, Nice, France; 2008. p. 3064–71.
[294] Xu W, Liang B, Gao D, Xu Y. A space robotic system used for on-orbit servicing in the geostationary orbit. In: IEEE/RSJ international conference on intelligent robots and systems, Taipei, Taiwan; 2010. p. 4089–94.
[295] Kaiser C, Rank P, Krenn R, Landzettel K. Simulation of the docking phase for the smart-OLEV satellite servicing mission. In: International symposium on artificial intelligence, robotics and automation in space; 2008. p. 26–9.
[296] Kaiser C, Sjöberg F, Delcura JM, Eilertsen B. SMART-OLEV-An orbital life extension vehicle for servicing commercial spacecrafts in GEO. Acta Astronaut 2008;63(1):400–10.
[297] Liang J, Ma O. Angular velocity tracking for satellite rendezvous and docking. Acta Astronaut 2011;69(11):1019–28.
[298] Senda K, Matsumoto T. Truss assembly by space robot and task error recovery via reinforcement learning. In: IEEE/RSJ international conference on intelligent robots and systems, Takamatsu, Japan; 2000. p. 410–5.
[299] Whittaker W, Staritz P, Ambrose R, Kennedy B, Fredrickson S, Parrish J, et al. Robotic assembly of space solar-power facilities. J Aerosp Eng 2001;14(2):59–64.
[300] Ueno H, Nishimaki T, Oda M, Inaba N. Autonomous cooperative robots for space structure assembly and maintenance. In: International symposium on artificial intelligence, robotics and automation in space; 2003.
[301] Sawada H., Matunaga S. Dynamics and control of space robot brachiating motion using handrails. In: IEEE/RSJ international conference on intelligent robots and systems, vol. 4. 2003; p. 3065–70.
[302] Ozaki F, Machida K, Oaki J, Iwata T. Robot control strategy for in-orbit assembly of a micro satellite. Adv Robot 2004;18(2):199–222.
[303] Tanaka H, Yamamoto N, Yairi T, Machida K. Reconfigurable cellular satellites maintained by space robots. J Robot Mechatron 2006;18(3):356.
[304] Rekleitis G, Papadopoulos E. Towards passive object on-orbit manipulation by cooperating free-flying robots. In: IEEE international conference on robotics and automation; 2010. p. 2247–52.
[305] Rekleitis G, Papadopoulos E. On on-orbit passive object handling by cooperating space robotic servicers. In: IEEE/RSJ international conference on intelligent robots and systems; 2011. p. 595–600.
[306] Tatsch A, Fitz-Coy N, Edmonson W. Heterogeneous expert robots for on-orbit servicing: a new paradigm. In: AIAA infotech@ aerospace. AIAA, Arlington, Virginia; 2005. p. 595–600.
[307] Rutkovsky V, Sukhanov V, Glumov V. Free-flying manipulation robot using for in-orbit assembly of large space structures. In: International conference on recent advances in space technologies, Istanbul, Turkey; 2011. p. 808–13.
[308] Boning P, Dubowsky S. A kinematic approach to determining the optimal actuator sensor architecture for space robots. Int J Robot Res 2011;30(9):1194–204.
[309] Vaillancourt C, Gosselin G. Compensating for the structural flexibility of the SSRMS with the SPDM. In: International advanced robotics program, second workshop on robotics in space, Montreal, Canada; 1994.
[310] Torres M, Dubowsky S. Path-planning for elastically constrained space manipulator systems. In: IEEE international conference on robotics and automation, Atlanta, GA; 1993. p. 812–7.
[311] Grewal A, Modi V. Dynamics and control of flexible multibody systems: an application to orbiting platforms. In: IEEE international conference on systems, mans and cybernetics, vol. 3, Vancouver, BC; 1995. p. 2093–8.
[312] Meirovitch L, Lim S. Maneuvering and control of flexible space robots. J Guid Control Dyn 1994;17(3):520–8.
[313] Caron M, Modi V, Misra A. Order-n formulation and dynamics of multi-unit flexible space manipulators. Nonlinear Dyn 1998;17(4):347–68.
[314] de Rivals-Mazeres G, Yim W, Mora-Camino F, Singh S. Inverse control and stabilization of free-flying flexible robots. Robotica 1999;17(3):343–50.
[315] Senda K, Murotsu Y. Methodology for control of a space robot with flexible links. IEE Proc—Control Theory Appl 2000;147(6):562–8.
[316] Romano M, Agrawal BN, Bernelli-Zazzera F. Experiments on command shaping control of a manipulator with flexible links. J Guid Control Dyn 2002;25(2):232–9.
[317] Zohoor H, Khorsandijou SM. Dynamic model of a flying manipulator with two highly flexible links. Appl Math Modell 2008;32(10):2117–32.
[318] Otsuki M. Flexible space robotic manipulator with passively switching free joint to drive joint. In: IEEE international conference on robotics and automation, Anchorage, Alaska; 2010. p. 1169–74.
[319] Wu H, Sun F, Sun Z, Wu L. Optimal trajectory planning of a flexible dual-arm space robot with vibration reduction. J Intell Robot Syst 2004;40(2):147–63.

Please cite this article as: Flores-Abad A, et al. A review of space robotics technologies for on-orbit servicing. Progress in Aerospace Sciences (2014), http://dx.doi.org/10.1016/j.paerosci.2014.03.002

[320] Abiko S, Yoshida K. An adaptive control of a space manipulator for vibration suppression. In: IEEE/RSJ international conference on intelligent robots and systems, Alberta, Canada; 2005. p. 2167–72.
[321] Abiko S, Yoshida K. Adaptive reaction control for space robotic applications with dynamic model uncertainty. Adv Robot 2010;24(8–9):1099–126.
[322] Sweet L, Good M. Re-definition of the robot motion control problem: effects of plant dynamics, drive system constraints, and user requirements. In: The 23rd IEEE conference on decision and control, Las Vegas, Nevada; 1984.
[323] Sabatini M, Gasbarri P, Monti R, Palmerini G. Vibration control of a flexible space manipulator during on orbit operations. Acta Astronaut 2011;73:109–21.
[324] Zarafshan P, Moosavian SAA. Control of a space robot with flexible members. In: IEEE international conference on robotics and automation, Shanghai, China; 2011. p. 2211–6.
[325] Zarafshan P, Moosavian SAA. Fuzzy tuning manipulation control of a space robot with passive flexible solar panels. In: International conference on mechatronics and automation, Beijing, China; 2011. p. 404–9.
[326] Masoudi R, Mahzoon M. Maneuvering and vibrations control of a free-floating space robot with flexible arms. J Dyn Syst Meas Control 2011;133:5. ⟨http://dx.doi.org/10.1115/1.4004042⟩.
[327] Ulrich S, Sasiadek JZ. Trajectory tracking control of flexible-joint space manipulators. Can Aeronaut Space J 2012;58(1):47–59.
[328] Ulrich S, Sasiadek JZ, Barkana I. Modeling and direct adaptive control of a flexible-joint manipulator. J Guid Control Dyn 2012;35(1):25–39.
[329] Ulrich S, Sasiadek JZ. Direct fuzzy adaptive control of a manipulator with elastic joints. J Guid Control Dyn 2013;36(1):311–9.
[330] Kumar A, Pathhak P, Sukavanam N. Trajectory control of a two dof rigid flexible space robot by a virtual space vehicle. Robot Auton Syst 2013;61:473–82.
[331] Umetani Y, Yoshida K. Experimental study on two-dimensional free-flying robot satellite model. In: NASA conference on space telerobotics, vol. 5, Pasadena, CA; 1989. p. 215–24.
[332] Yoshida K. Experimental study on the dynamics and control of a space robot with experimental free-floating robot satellite (EFFORTS) simulators. Adv Robot 1995;9(6):583–602.
[333] Ullman M, Cannon R. Experiments in autonomous navigation and control of a multi-manipulator, free-flying space robot, space robotics: dynamics and control. Springer; 1992. p. 269–84.
[334] Ballhaus WL, Alder LJ, Chen VW, Dickson WC. Stanford aerospace robotics laboratory research overview. In: NASA sixth annual workshop on space operations applications and research, Houston, TX; 1992. p. 54–65.
[335] LeMaster EA, Schaechter D, Carrington CK. Experimental demonstration of technologies for autonomous on-orbit robotic assembly. In: AIAA space, San Jose, CA; 2006. p. 1–13.
[336] Romano M, Friedman DA, Shay TJ. Laboratory experimentation of autonomous spacecraft approach and docking to a collaborative target. J Spacecr Rockets 2007;44(1):164–73.
[337] Schwartz J, Peck M, Hall C. Historical review of airbearing spacecraft simulators. J Guid Control Dyn 2003;26(4):513–22.
[338] Menon C, Busolo S, Cocuzza S, Aboudan A, Bulgarelli A, Bettanini C, et al. Issues and solutions for testing free-flying robots. Acta Astronaut 2007;60(12):957–65.
[339] Toglia C, Kennedy F, Dubowsky S. Cooperative control of modular space robots. Auton Robots 2011;31(2):209–21.
[340] Akin D, Bowden M, Spofford J. Neutral buoyancy evaluation of technologies for space station external operations. In: XXXV congress of the international astronautical federation, Switzerland; 1984.
[341] Carignan C, Akin D. The reaction stabilization of on-orbit robots. IEEE Control Syst 2000;20(6):19–33.
[342] Akin D, Bowden M, Spofford J. The ranger telerobotic shuttle experiment: Implications for operational EVA/robotic cooperation. In: SAE 30th international conference on environmental systems, Toulouse, France; 2000. p. 7–31.
[343] Sawada H, Ui K, Mori M, Yamamoto H, Hayashi R, Matunaga S, et al. Micro-gravity experiment of a space robotic arm using parabolic flight. Adv Robot 2004;18(3):247–67.
[344] Menon C, Aboudan A, Cocuzza S, Bulgarelli A, Angrilli F. Free-flying robot tested on parabolic flights: kinematic control. J Guid Control Dyn 2005;28(4):623–30.
[345] Nohmi M, Yamamoto T, Takagi Y. Microgravity experiment for attitude control of a tethered body by arm link motion. In: IEEE international conference on mechatronics and automation, Harbin, China; 2007. p. 3519–24.
[346] Martin PK. Review of NASA's microgravity flight services. Technical Report, NASA, IG-10-015; 2010.
[347] Iwata T, Kodama K, Numajiri F, Kiku Y, Murakami H. Experiment of robotic motion using drop shaft. J Robot Soc Jpn 1995;13(8):1206–9.
[348] Watanabe Y, Nakamura Y. Experiments of a space robot in the free-fall environment. In: International symposium on artificial intelligence, robotics and automation in space, Paris, France; 1999. p. 601–7.
[349] Lu Q, Ortega C, Ma O. Passive gravity compensation mechanisms: technologies and applications. Recent Pat Eng 2011;5(1):32–44.
[350] Sato Y, Ejiri A, Iida Y, Kanda S, Maruyama T, Uchiyama T, et al. Micro-G emulation system using constant-tension suspension for a space manipulator. In: IEEE international conference on robotics and automation. Sacramento, CA; 1991. p. 1893–900.
[351] Brown H, Dolan J. A novel gravity compensation system for space robots. In: Proceedings of the ASCE specialty conference on robotics for challenging environments; 1994. p. 250–8.
[352] White G, Xu Y. An active vertical-direction gravity compensation system. IEEE Trans Instrum Meas 1994;43(6):786–92.
[353] Ma O, Lu Q, McAvoy J, Ruble K. Concept study of a passive reduced-gravity simulator for training astronauts. In: ASME international design engineering technical conferences and computers and information in engineering conference (IDETC/CIE). Montreal, Canada; 2010. p. 655–64.
[354] Ma O, Wang J, Misra S, Liu M. On the validation of SPDM task verification facility. J Robot Syst 2004;21(5):219–35.
[355] Agrawal S, Hirzinger G, Landzettel K, Schwertassek R. A new laboratory simulator for study of motion of free-floating robots relative to space targets. IEEE Trans Robot Autom 1996;12(4):627–33.
[356] Piedbœuf J, De Carufel J, Aghili F, Dupuis E. Task verification facility for the Canadian special purpose dextrous manipulator. In: IEEE international conference on robotics and automation, vol. 2, Detroit, Michigan; 1999. p. 1077–83.
[357] Dubowsky S, Durfee W, Corrigan T, Kuklinski A, Muller U. A laboratory test bed for space robotics: the VES II. In: IEEE/RSJ international conference on intelligent robots and systems, vol. 3. Munich, Germany; 1994. p. 1562–9.
[358] Matunaga S, Yoshihara K, Takahashi T, Tsurumi S, Ui K. Ground experiment system for dual-manipulator-based capture of damaged satellites. In: IEEE/RSJ international conference on intelligent robots and systems, vol. 3, 2000; p. 1847–52.
[359] Aghili F. A robotic testbed for zero-g emulation of spacecraft. In: IEEE/RSJ international conference on intelligent robots and systems; 2005. p. 3654–61.
[360] Rekleitis I, Martin E, Rouleau G, L'Archevêque R, Parsa K, Dupuis E. Autonomous capture of a tumbling satellite. J Field Robot 2007;24(4):275–96.
[361] Boge T, Ma O. Using advanced industrial robotics for spacecraft rendezvous and docking simulation. In: IEEE international conference on robotics and automation, Shanghai, China; 2011. p. 1–4.
[362] Takahashi R, Ise H, Konno A, Uchiyama M, Sato D. Hybrid simulation of a dual-arm space robot colliding with a floating object. In: IEEE international conference on robotics and automation, Pasadena, CA; 2008. p. 1201–6.
[363] Roe F, Howard R, Murphy L. Automated rendezvous and capture system development and simulation for NASA. In: SPIE defense and security. 2004. p. 118–25.
[364] Wei R, Jin M, Xia J, Xie Z, Shi J, Liu H. High fidelity distributed hardware-in-the-loop simulation for space robot on can-based network. In: IEEE/RSJ international conference on intelligent robots and systems, Beijing, China; 2006. p. 5106–11.
[365] Xu W, Liang B, Xu Y, Li C, Qiang W. A ground experiment system of free-floating robot for capturing space target. J Intell Robot Syst 2007;48(2):187–208.
[366] Aghili F, Namvar M. Scaling inertia properties of a manipulator payload for 0-g emulation of spacecraft. Int J Robot Res 2009;28(7):883–94.
[367] Liu H, Liang B, Xu W, Di Z, Wang X. A ground experiment system of a free-floating robot for fine manipulation. Int J Adv Robot Syst 2012;9(183):1–10.
[368] Xiao W, Fuchun S, Huaping L. Design and development of a ground experiment system with free-flying space robot. In: IEEE conference on industrial electronics and applications, Beijing, China; 2011. p. 2101–6.
[369] Krenn R, Schäfer B. Limitations of hardware-in-the-loop simulations of space robotics dynamics using industrial robots. In: International symposium on artificial intelligence, robotics and automation in space, Noordwijk, The Netherlands; 2004. p. 118–25.
[370] Osaki K, Konno A, Uchiyama M. Delay time compensation for a hybrid simulator. Adv Robot 2010;24(8–9):1081–98.

Please cite this article as: Flores-Abad A, et al. A review of space robotics technologies for on-orbit servicing. Progress in Aerospace Sciences (2014), http://dx.doi.org/10.1016/j.paerosci.2014.03.002