Robotica (2007) volume 25, pp. 537–547. © 2007 Cambridge University Press
doi:10.1017/S0263574707003438 Printed in the United Kingdom

Free-flying robots in space: an overview of dynamics modeling, planning and control

S. Ali A. Moosavian† and Evangelos Papadopoulos‡

†*Department of Mechanical Engineering, K. N. Toosi University of Technology PO Box 16765-3381, Tehran, Iran.*
E-mail: moosavian@kntu.ac.ir
‡*Department of Mechanical Engineering, National Technical University of Athens, 15780 Athens, Greece.*
E-mail: egpapado@central.ntua.gr

(Received in Final Form: January 24, 2007. First published online: March 6, 2007)

SUMMARY

Free-flying space manipulator systems, in which robotic manipulators are mounted on a free-flying spacecraft, are envisioned for assembling, maintenance, repair, and contingency operations in space. Nevertheless, even for fixed-base systems, control of mechanical manipulators is a challenging task. This is due to strong nonlinearities in the equations of motion, and consequently different algorithms have been suggested to control end-effector motion or force, since the early research in robotic systems. In this paper, first a brief review of basic concepts of various algorithms in controlling robotic manipulators is introduced. Then, specific problems related to application of such systems in space and a microgravity environment is highlighted. Basic issues of kinematics and dynamics modeling of such systems, trajectory planning and control strategies, cooperation of multiple arm space free-flying robots, and finally, experimental studies and technological aspects of such systems with their specific limitations are discussed.

KEYWORDS: Space robotics; Control algorithms; Force control; Impedance control; Dynamics modeling.

1. Introduction

As space commercialization expands, deployment of space structures and satellite launches will increase. Extending the life of such systems, and therefore reducing the associated costs, will require extensive inspection, assembly, capture, repair, and maintenance capabilities in orbit. Astronaut Extra Vehicular Activities (EVA) using Canada Arm can be valuable in meeting these requirements, Fig. 1. However, the cost of human life support facilities, the limited time available for the maneuver, and the high risks involved due to different hazards, are some serious restrictions for EVA. Therefore, it is expected that robotic devices will play a more important role in future missions.[1–3]

To increase the mobility of in-orbit robotic systems, Space Free-Flying Robots (SFFR), in which manipulators are mounted on a thruster-equipped spacecraft, have been proposed, Fig. 2.[4,5] Unlike fixed-based robots, the base body of SFFR is allowed to respond freely to dynamic reaction forces due to the arms motion. Hence, in order to control such a system, it is essential to consider the dynamic coupling between the arms and the base. Also it should be noted that the joint control torques are limited due to actuator weight constraints in space.[6]

Although dynamics modeling of SFFR is still an ongoing subject of research, control of these free-flying manipulators to perform precise tasks in space has also received some attention. Control techniques for space manipulators can be classified in three different categories. In the first category, both the position and attitude of the base are actively controlled (*free-flying mode*). In the second category, neither of them is controlled (*free-floating mode*), and finally, in the third category, only the base attitude is controlled. Clearly, a combination of these three modes can be employed during different phases of a mission. In this paper, first a brief review of different approaches to control *fixed-base manipulators* is introduced. Next, specific problems related to application of such systems in space and a *microgravity environment* will be addressed. Fundamental issues on the kinematics and dynamics modeling of such systems, trajectory planning and control strategies, and cooperation of multiple arm space free-flying robots will be discussed. Finally, experimental studies and technological aspects of such systems with their specific limitations will be shortly reviewed.

2. Robot Control Approaches

Due to strong nonlinearities in the equations of motion, control of mechanical manipulators is a complicated task. To control position, orientation, or the exerting force of the end-effector to do a desired action, different algorithms have been suggested. In this section, before considering specific problems in space applications, a brief review of these algorithms to control general *fixed-base manipulators* is introduced.

2.1. Position control[1]

Classic proportional—integral–derivative (PID) controllers at each joint of the manipulator are widely employed in industrial geared robots. Although these feedback controllers are designed on the basis of ignorance of the dynamics

---

[1] In this category, it is assumed that there is no force interaction between the end-effector and the environment.

Fig. 1. Hubble Space Telescope Servicing Mission using Canada Arm.

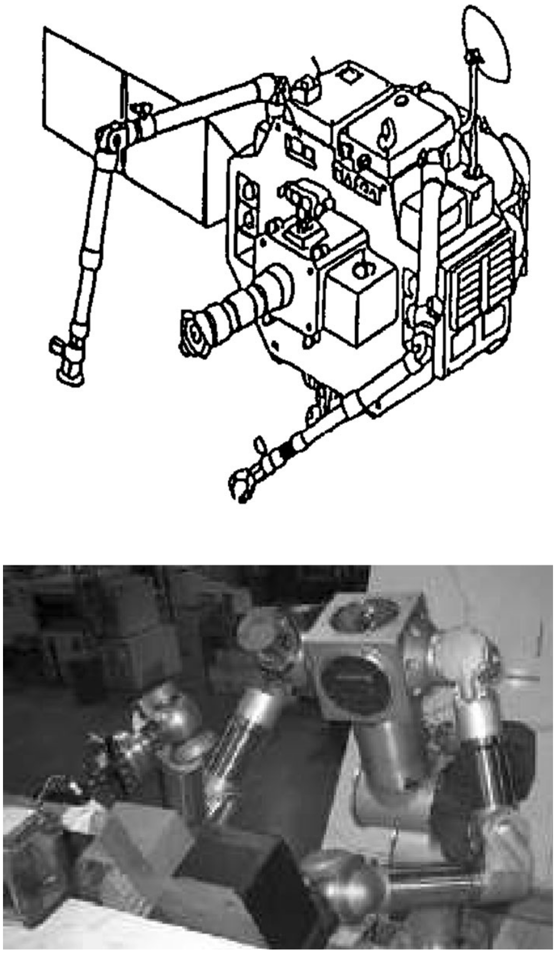

Fig. 2. Space Free-Flying Robots; *top*: The Orbital Servicing Vehicle, *bottom*: The University of Maryland Ranger.

coupling between the joints, they can effectively control the system.[7] High gear ratios reduce the computational complexity of system dynamics, but do not eliminate the requirement for the accurate modeling of system dynamics.[8] The *Computed Torque Method* employs such a model to compensate for the nonlinearities, and results in a linearized error behavior. Experimental studies have been presented, which compare the performance of independent joint control schemes (e.g., classic PID) to the computed torque method, implemented on direct drive manipulators.[9,10] These studies conclude the importance of compensating for the nonlinear *Coriolis* and *centrifugal* forces, even at low speeds of operation.

The application of *model-referenced adaptive control* to robotic manipulators is based on an adaptation algorithm, which changes the controller gains so that the real output follows the referenced model output within an accuracy bound.[11,12] The idea of *time delay control* has been suggested, which is a model-referenced algorithm for systems with unknown dynamics.[13] The basic function of the controller is to use observations of the system response to directly modify the control actions rather than adjusting the controller gains. The betterment process is based on a learning control approach, which improves the operation of a robot in the next cycle so that the motion trajectory eventually converges to the desired one.[14] Therefore this algorithm can be applied when repetitive operations are to be performed.

Transpose Jacobian (TJ) control is a computationally simple algorithm, which has been arrived at intuitively.[15] The task error vector and its rate, both multiplied by relatively high gains and by the Jacobian transpose matrix, result in commands that push the end-effector in a direction which tends to reduce the tracking error. In the case of using an approximate Jacobian, it has been shown that the damping matrix and the position gain matrix of this controller play an important role in the stability condition.[16] The TJ algorithm does not fail when a singularity occurs,[17] and can be applied to redundant manipulators.[18] An extended TJ control algorithm has been developed to improve the performance of mobile manipulator systems,[19] and also to coordinate motion control of spacecraft/manipulator systems.[20]

2.2. *Force/Impedance control*[2]

Since both the end-effector position and interacting force cannot be controlled along a given direction, the idea of *hybrid position/force algorithm* has been suggested to control the end-effector position in some directions, and the contact forces in the other directions.[21] This approach has been successfully extended to a system of multiple manipulators.[22] Another approach of *operational space formulation* has been presented for motion and force control of robotic manipulators.[23] Defining generalized task specification matrices for motion and contact forces, and employing the nonlinear dynamic decoupling approach, a control architecture is presented with a slow computation of dynamics, and a fast servo level to compute the control command. Such different strategies in robot force control

---

[2] The interaction force between the end-effector and the environment, is to be controlled in this category.

have been compared and discussed, where some problems remained unsolved.[24]

The mechanics of coordinative manipulation by multiple robotic mechanisms, have been discussed taking the dynamics of object into consideration.[25] Assuming frictional grasp, a computational procedure is proposed to obtain optimal internal forces. A closed chain formulation in dynamic control of two cooperative manipulators with equal degrees of freedom (DOF) has been also presented.[26] Discussing different issues in the design of a multimanipulator control system, an environment for the programming and control of cooperative manipulators has been developed.[27] Also a distributed time-varying feedback control law has been presented for coordinating motions of multiple nonholonomic mobile robots to capture a target.[28]

Hogan has presented *impedance control*, for a single manipulator in dynamic interaction with its environment, to regulate the relationship between end-effector position and force.[29] Starting from basic concepts, and discussing different issues, a method is suggested to choose an appropriate manipulator impedance. This strategy has been extended for contact tasks involving multiple manipulators.[30,31] A Cartesian impedance controller has been presented to overcome the main problems encountered in fine manipulation, i.e., effects of friction (and unmodeled dynamics) on robot performances and occurrence of singularity conditions.[32] The implementation of a combined impedance and force control has been proposed to exert a desired force on the environment, and at the same time, generate a desired relationship between this force and the relative location of the point of interaction (contact) with respect to the commanded manipulator location.[33] Using an exact model of the manipulator, the algorithm is developed based on feedback and feedforward control theories. Adaptive schemes to make impedance control capable of tracking a desired contact force, which has been described as the main shortcoming of impedance control in an unknown environment, have also been presented.[34,35] One scheme is based on an online reference position generating procedure, as a function of force tracking errors. The second one is developed based on an online parameter estimation procedure to obtain the environmental unknowns, and compute the proper reference position for tracking a desired contact force. Experimental and simulation investigations into the performance of impedance control implemented on geared manipulators,[36] hydraulic robots,[37] master and slave teleoperation,[38] and elastic joints,[39] have shown the benefits of using this control strategy in compensating any undesirable effects.

As an extension of Hogan's impedance control concept, the *object impedance control* (OIC) has been developed for multiple robotic arms manipulating a common object.[40] A combination of feedforward and feedback control is employed to make the object behave like a reference impedance. Attempting to apply this controller when a flexible object interacts with the environment may lead to instability.[41] Based on the analysis of a representative system, it has been suggested that in order to solve the instability problem, one should either increase the desired mass parameters or filter and lower the frequency content of the estimated contact force. A framework for implementing coordinated object manipulation on industrial robots by taking advantage of the object-based reference frame has been presented.[42] Real-time trajectory modification and distributed control allow each robot to execute its own native low-level code, without the need for inter robot communication as the trajectories are executing, where a compliant controller around the basic motion is implemented.

The *multiple impedance control* (MIC) has been presented for several cooperating robotic systems manipulating a common object.[43] The MIC imposes a reference impedance on both the manipulator end points and the manipulated object. The general formulation of the MIC has been extended to fulfil a desired force-tracking task after impact,[44] which adds to the merits of the original algorithm. A vigorous stability analysis, based on the Liapunov Direct Method, besides error analysis has shown that under the MIC law, all participating manipulators and the manipulated object exhibit the same designated impedance behavior.

3. Space Robotic Systems

Dynamics and control of SFFR, unlike those for long reach space manipulators, are usually investigated under the assumption of rigid elements, which is the main focus in the following sections. To perceive different problems in flexible space manipulators one could see variant approaches of extensive series of studies.[45–52]

3.1. Kinematics and dynamics modeling

The kinematics and dynamics of a free-floating space manipulator system have been described using the virtual manipulator approach.[53,54] No external forces act on the system, and so the system center of mass is fixed in inertial space, enabling them to represent a free-floating system by one with a virtual fixed base. The barycentric vector approach has been employed to study kinematics and dynamics of a single arm SFFR in free-floating mode.[55] Taking the center of mass of the whole system as a representative point for the translational motion, and using barycentric vectors which reflect both geometric configuration and mass distribution of the system, results in decoupling the total linear and angular motion from the rest of the equations.

The generalized Jacobian matrix has been presented for a free-floating system.[56] Assuming that no external forces are applied on a rigid robotic system with revolute joints, a generalized Jacobian matrix reflects both momentum conservation laws and kinematic relations. The proposed generalized Jacobian matrix converges to the conventional Jacobian, when the base body is relatively massive. This generalized Jacobian has been employed to present solution algorithms to the inverse kinematics of a space manipulator mounted on a free-floating spacecraft.[57]

Two basic approaches for kinematics modeling of a multibody space robotic system has been developed.[58] Taking the center of mass of the whole system as a representative point for the translational motion, and using a set of the body-fixed vectors, forms the so-called *barycentric vector approach*. On the other hand, taking a point on the spacecraft as that representative point for the translational

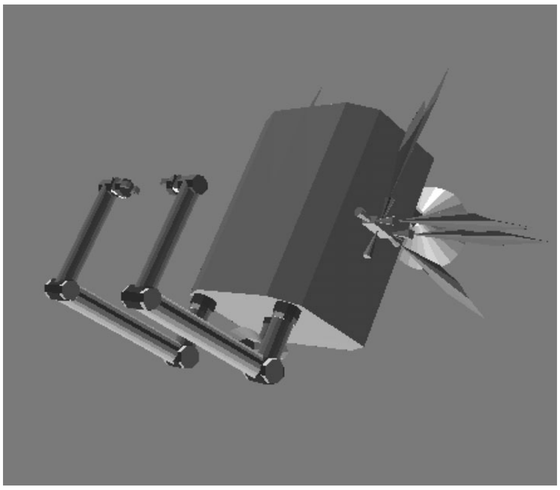

Fig. 3. Graphical view of a simulated SFFR with multiple manipulators.

motion, (preferably its CM), forms the so-called *direct path approach*, which results in more compact equations of motion. A solution of the inverse kinematics problem for space manipulators has been presented using optimization criteria rather than applying conventional schemes based on pseudo-inverse matrix methods.[59] The notion of kinematic redundancy in nonholonomic terrestrial and space robotic systems has been exploited to simplify the problem of controlling these systems and to enhance their performance capabilities.[60]

An explicit dynamics model of a multiple manipulator SFFR has been presented based on direct path kinematics approach.[61] Derivation of the equations of motion results in an explicit formulation of system's mass matrix, and of the vectors of nonlinear velocity terms and generalized forces. Unlike with recursive dynamics formulations, the obtained dynamics model is very useful for dynamics analyses, design studies, and the development of control algorithms for SFFRs. The obtained explicit dynamics model of a multiple manipulator SFFR, can be implemented either *numerically* or *symbolically.* The latter approach was followed, and the developed symbolic code for dynamics modeling, i.e., SPACEMAPLE, and its verification procedure were described. Exporting the dynamics model from this symbolic environment, simple case studies can be simulated in MATLAB, while a simulation code for general SFFR model has been developed in FORTRAN. Using Graphics Library commands, a graphical simulation code for SFFR maneuvers has been developed in C, which demonstrates the results of computational simulations. Running the code on an SGI Indigo 2, with a 4400 processor, yields a smooth animated picture of the maneuver, as Fig. 3 shows a snapshot of such maneuvers.

3.2. Trajectory/Path and strategy planning

Planning techniques for space robots is a very important subject that has received some attention recently. These include planning in the presence of nonholonomy, planning during the satellite approach phase, and force planning during capture of a satellite by a multimanipulator system. Free-floating systems exhibit nonholonomic behavior that can be used to control not only manipulator joints, but also the attitude of the system base. This is achieved by small cyclical motions in the joint[54] or Cartesian space of the manipulator.[62] The drawback of these techniques is that they are time consuming. A fast and computationally inexpensive method developed for terrestrial mobile manipulator systems has been further improved to be of potential use in space free-flyers.[63] The developed method uses smooth and continuous functions such as polynomials to construct trajectory inputs that drive both the manipulator and its platform to a final configuration without violating the constraints. The idea employed is to construct a transformation that maps the nonholonomic constraint associated with a given platform point from the Cartesian space to a space where it can be satisfied trivially. The proposed transformation is obtained through a systematic methodology that can also be applied directly to other more complex systems. Since the mapping is smooth and planning in this new space is achieved using polynomial trajectories, the resulting Cartesian paths and trajectories are also smooth.

The main issues associated with catching a free-floating object have been discussed assuming that the object is initially out of reach of the robot.[64] Trajectory requirements for catching a moving object were described and a dual-arm two-link planar space manipulator was simulated using a computed torque algorithm. The virtual manipulator approach has been employed in path planning of space manipulators to minimize spacecraft attitude disturbances.[65] Early planning work during the approach phase and just before target capture used heuristics, while recent work is focusing on optimizing performance metrics.[66] Capturing techniques include matching of end-effector motion to target motion,[67] reconfigurable chasers,[68] and hardware architectural improvements.[69]

Finding the maximum force that can be applied in some direction was addressed in the context of cooperating robots,[70] and generation of large forces by multilimbed robots was also studied.[71] Redundancy resolution criteria were introduced based on force task requirements.[72] The concept of force workspace was introduced and used to plan force tasks in multilimb robotic systems,[73] while a min–max optimization method was employed to maximize the force capabilities of a manipulator with a movable base.[74] Impacts in terrestrial systems,[75] and between free-flyers and payloads were analyzed using the concept of extended–inversed inertia tensor.[76] The dynamics of impacts in long reach spaceborne manipulators was also studied.[77]

Various approaches have been presented for the control of robot teams acting in cooperation with potential applications to planetary exploration and satellite inspection or maintenance.[78] A measure of dynamic coupling in free-floating space robotic systems has been presented based on momentum conservation laws.[79] The dynamic coupling factor is defined based on the matrix, which relates the end-effector motion and the base body motion, and can be employed in planning robot motions. A trajectory planning scheme has been presented that exploits the nonholonomic redundancy of SFFR to avoid joint limits and obstacles.[80] This scheme is developed using a 6-DOF SFFR, and simulation results are included. A path planning scheme has been presented for a single arm of a free-floating satellite, which is equipped with momentum wheels.[81] This method utilizes the angular momentum of the base, without causing its nutation, which occurs unless the attitude of the final satellite is the same as the initial one. A capture strategy has been presented to retrieve a tumbling free-flying object.[82] A simplified dynamics model of the object attitude motion is used to approximate a complex nutation motion by a superposition of rotational motions with constant angular velocities, and capture planning is introduced based on the proposed model. The TJ controller is used for the manipulator control, in both simulation and experimental studies.

3.3. Control

Most of the reported studies have focused on the motion (position) control of a single-arm manipulator in free-floating mode, i.e., an end-effector moves toward a target in the inertial or spacecraft body-fixed frame with no significant force interactions between the environment and any part of the system. A payload can be considered as a known disturbance added to the last link at the time of capture,[83,84] while coordination and control of the base and its multiple arms to capture and manipulate space objects has not received enough attention.

To achieve the goal of capturing and manipulating space objects (whether passive or include some internal momentum source), exploiting multiple manipulators is required. Therefore, dynamics modeling of multiple-arm SFFR, and motion control of the end-effectors coordinated with the base, to chase a moving object have been developed.[85–87] To ensure smooth operation and reduce disturbances on both the spacecraft and the object just before grasping, appropriate trajectories for the spacecraft/manipulators motion are planned, which lead to capture of moving objects in space. These trajectories take into account the relative target motion and thruster/actuator saturation limits. Model-based control algorithms, based on an Euler angle and an Euler parameter description of the orientation, and a transposed Jacobian (TJ) control algorithm were developed. These algorithms permit control of both the spacecraft and its appendages in their task space. Euler angle model-based control algorithm presents the inconvenience of representational singularities, while Euler parameter model-based control algorithm overcomes these nonphysical singularities. The developed control laws were evaluated using three manipulator/appendages free-flyer examples, in both planar and three-dimensional maneuvers. Comparing the performance of the TJ algorithm to those of different model-based algorithms, shows the eligibility of this simple algorithm to be employed in the control of highly nonlinear and complex systems, with many DOF. This result motivates further work on this algorithm, aiming at overcoming the lack of information about the dynamics of the system, a problem which appears more clearly in tracking fast trajectories. The modified transpose Jacobian (MTJ) algorithm, which yields an improved performance over the standard algorithm by employing stored data of the previous time step control command, was presented.[88,89] This new algorithm was based on an approximation of feedback linearization methods, with no need of *a priori* knowledge of the plant dynamics terms. Its performance is comparable to that of model-based algorithms but with a reduced computational burden, which is a crucial factor in space. Stability analysis, based on Lyapunov's theorems, shows that both the standard and the MTJ algorithms are asymptotically stable. Simulation results were presented that compare the performance of the MTJ to that of the TJ and model-based algorithms.

A motion control technique has been developed based on the general three-dimensional equations of motion of an n link manipulator mounted on a spacecraft.[90] Instead of performing a single inverse kinematic calculation at the beginning of a movement in order to determine the required joint setpoints, multiple inverse kinematic updates based on an optimal algorithm have been done throughout a movement. The derived motion control technique incorporates the base motion without base motion control. Employing the generalized Jacobian matrix approach, the kinematics of space manipulators has been described not by positions or angles but by their motion rates.[91] Consequently, the inverse kinematics problem is solved analytically, and a *resolved motion rate control* is developed to compensate for spacecraft motion. This method has been applied to the control of a multiple-arm system.[92] To control the motion of an SFFR, an algorithm has been developed called the *extended operational-space method*, and both simulation and experimental results were presented.[93] In this algorithm, actuator torque vector for the manipulator is calculated based on a reference model, where the spacecraft position and attitude actuators are assumed to be "off" or else to be given and known to the manipulator controller. Another control strategy has been performed to make the position and velocity of the end-effector coincide with those of a moving object, in free-floating mode.[94] In general, it has been suggested that nearly any control algorithm, which can be used for fixed-based manipulators can also be employed in the control of free-floating systems, provided that the unique dynamics problems of these systems are considered.[55]

Efficient algorithms have been studied for computing the generalized Jacobian matrix, and the *resolved acceleration control* for multiarm space robots has been presented.[95] In this algorithm, introducing a modified Newton–Euler recursive method, all computations start from the end-effector, so as not to compute the actual acceleration of the spacecraft; parallel computations of multiple arms also become possible. Focusing on the dynamics and control problems unique in rigid space robotic systems, some of the efforts being done in this field have been discussed.[96]

Control strategies for changing the configuration of all joints of an underactuated space manipulator have been studied.[97] This study reveals the conditions for controlling only the actuated joints, and all the joints of the system, separately. A planar three-link underactuated space manipulator was simulated to demonstrate the application of the obtained results. Various mathematical models have been developed for different motion primitives in space.[98] Propulsion, collision, catching, and assembly operations were discussed, and some simulation results for a dual-arm space robot in planar motion were presented. The dynamics of contact between space robots have been studied, and an algorithm has been proposed to achieve both trajectory tracking and impulse minimization.[99] The problem of estimating and minimizing the impulsive reaction force both at the end-effector and the base have also been studied.[100] Based on the null-space of the system inertia matrix, they try to find out proper manipulator configurations, to achieve a safe capture and minimize the impact.

To control the system after grasping the object, an adaptive approach has been employed considering the flexibility of the transported object.[101] Inverse dynamics controllers with motive force compensation have been developed for the cooperating fixed-base, free-floating, and free-flying space manipulator systems.[102] The new multiple impedance control (MIC) has been developed, which enforces a controlled impedance of both the manipulator end-points and of the manipulated object.[103] To reveal the merits of this new algorithm, a simple linear system has been considered to present a thorough comparison analysis between the MIC and object impedance control (OIC). Then, application of the MIC law in a system of two cooperating two-link manipulators with an RCC attached to the second end-effector, has been simulated. Next, the MIC algorithm was applied in space robotic systems to manipulate space objects.[104,105] Error analysis and stability analysis have shown that under the MIC law, all participating manipulators, the free-flyer base, and the manipulated object exhibit the same impedance behavior.

3.4. *Experimental studies*

Experimental studies of space robotic systems are faced with the difficulty of generating a microgravity environment on earth. Therefore, these studies are implemented during planar maneuvers, in horizontal plane with zero friction condition on the test bed. Consequently, most of the rotational dynamics effects cannot be investigated on these test beds, which in turn necessitates developing vigorous simulation codes.

A control algorithm has been developed and implemented to provide accurate end-effector tracking for structurally flexible space manipulators.[106] Instead of linearizing the system equations about the desired trajectory and considering a time-varying system, a series of steady-state time-invariant regulators are utilized to reduce computational requirements and make it easier to handle different trajectories. The algorithm is implemented on a two-link planar manipulator, tracking circular and square paths, and the obtained experimental results are compared to those of independent joint PID control implementations. Another test bed has been developed for space robot technologies, and some experimental results of a satellite berthing maneuver with a two-armed space robot have been presented. A conceptual representation of the reality and a laboratory simulator have been developed to achieve the relative motion of a free-floating robot with respect to space target.[107] Another free-floating planar system has been developed to be used as a test bed for investigation of efficient and autonomous satellite capture in space.[108]

A summary of theoretical and experimental space robotic research activities has been presented, using the Experimental Free-Floating Robot Satellite (EFFORTS-I and -II) simulators.[109] The test bed can mechanically simulate the planar floating dynamics of a single- or double-arm system. The experimental results and post-flight analysis of the ETS-VII Japanese space robot was also presented. The focus has been made on reactionless manipulation, and the identification of the dynamics parameters such as mass, moment of inertia, and product of inertia. Focusing on capturing a satellite, a criterion has been presented as "impedance matching" to recognize if the contact is maintained with a target or the target is pushed away.[110,111] Developing *decentralized object impedance control*, some experimental results have been presented for the capture, transportation, and docking of an object by two free-flying robots in planar motion.[112] The algorithm is an extension of OIC, as discussed in the previous section, to maneuvers with multiple participating robots.

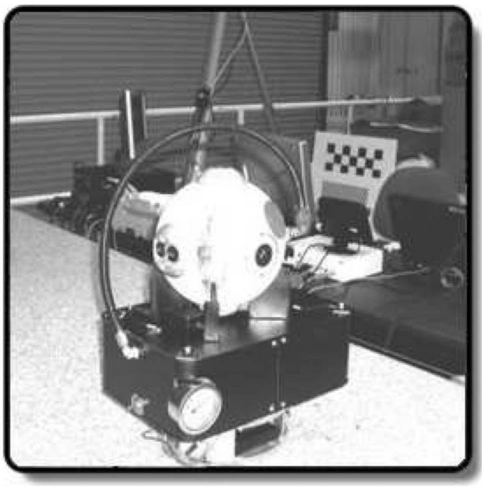

Fig. 4. Autonomous Extravehicular Robotic Camera (AERCam), a free-flying camera platform developed by NASA; courtesy Robotic Systems Technology Branch, NASA Johnson Space Center.

3.5. *Technological aspects*

The technology related to the capture of satellites and on-orbit servicing has been widely addressed.[113–118] NASA has developed the Autonomous Extravehicular Robotic Camera (AERCam) (see Fig. 4) as a free-flying vehicle capable of performing inspections and monitoring missions in support of the International Space Station (ISS) operations.[119] AERCam will be able to provide additional external views unavailable from the ISS or space shuttle cameras, also capable of flying to areas around the ISS difficult to reach by a space walk.

A humanoid robot called *Robonaut* has been designed by the Robot Systems Technology Branch at NASA's Johnson Space Center in a collaborative effort with DARPA. The Robonaut project demonstrates a robotic system that can be used for EVA tasks, i.e., those which were not specifically designed for robots. However, it still keeps the human operator in the control loop through its remote control system. The Robonaut arm and dexterous hand are human scale manipulators designed to fit within the exterior volume of an astronaut's suit, and have been developed with a substantial investment in mechatronics design (Fig. 5).

Spirit and Opportunity, NASA's twin robot geologists for Mars explorations, were launched toward Mars on June 10

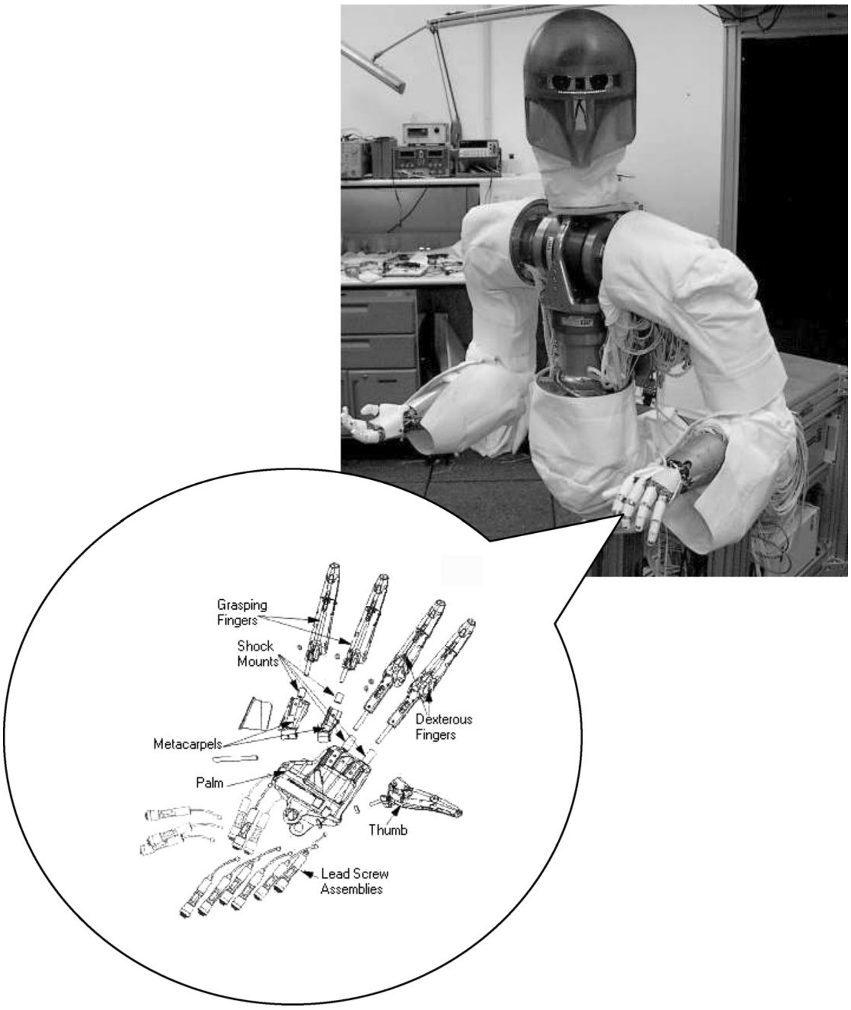

Fig. 5. Robonaut, a humanoid free-flying robot developed by NASA, and its hand details; courtesy Robotic Systems Technology Branch, NASA Johnson Space Center.

and July 7, 2003, and landed on Mars on January 3 and January 24, 2004, respectively. The Mars Exploration Rover mission is part of NASA's Mars Exploration Program, a long-term effort of robotic exploration of the red planet. Both Rovers have begun surface operations once they completed the egress phase. As shown in Fig. 6, the rovers parts are similar to what any living creature would need to keep it "alive" and able to explore. This is a significant progress toward exploiting mobile autonomous robotic system for space explorations.[120]

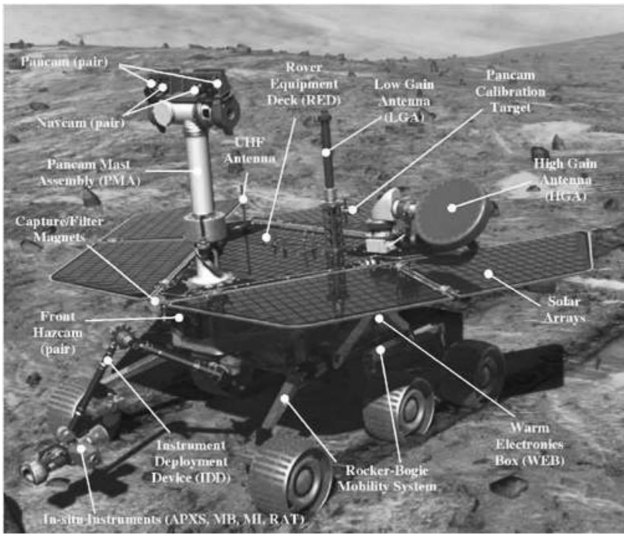

Fig. 6. Spirit and Opportunity, two mobile robotic systems developed by NASA for Mars explorations.

4. Conclusions

To implement assembling, maintenance, repair, and contingency operations in space, the notion of free-flying space manipulator systems, in which robotic manipulators are mounted on a free-flying spacecraft, was discussed. Unlike fixed-based robots, the base of space robotic systems is allowed to respond freely to dynamic reaction forces due to the arms motion. Hence, in order to control such systems, it is essential to consider the dynamic coupling between the arms and the base. To this end, a brief review of basic concepts of different algorithms for controlling mechanical manipulators and the end-effector motion/force was presented. Next, specific problems related to application of robotic systems in space were highlighted, and variant issues on the dynamics and control of multiple-arm space free-flying robots were detailed. In particular, kinematics and dynamics of such systems, trajectory planning and control strategies, experimental studies, and technological issues were discussed.

Acknowledgment

The second author would like to acknowledge support by the EPAN Cooperation Program 4.3.6.1.b (Greece-USA 035) of the Hellenic General Secretariat for Research and Technology.

References

1. A. Ollero, G. Morel, P. Bernus, S. Y. Nof, J. Sasiadek, S. Boverie, H. Erbe and R. Goodall, "Milestone report of the manufacturing and instrumentation coordinating committee: From MEMS to enterprise systems," *Annu. Rev. Control* **26**(2), 151–162 (2002).
2. G. Bertoni, "Automatic Control in Aerospace," *Proceedings of 15th IFAC Symposium on Automatic Control in Aerospace*, Bologna/Forli, Italy (2001).
3. S. Dubowsky, "A perspective of the advancement of robotic systems during the past 15 years," *J. Annu. Rev. Control* **22**, 111–119 (1998).
4. M. A. Bronez, M. M. Clarke and A. Quinn, "Requirements Development for a Free-Flying Robot—The ROBIN," *Proceedings of the IEEE International Conference on Robotics and Automation*, San Francisco, CA (1986) pp. 667–672.
5. G. J. Reuter *et al.*, "An intelligent, free-flying robot, in space station Automation IV," (W. C. Chiou ed.) *SPIE Proceedings Series* **1006**, 20–27 (1995).
6. S. Rondeau, "Space Robotics," *Proceedings of the IFAC Workshop*, St-Hubert, Quebec, Canada (1998).
7. S. Kawamura, F. Miyazaki and S. Arimoto, "Is a Local Linear PD Feedback Control Law Effective for Trajectory Tracking of Robot Motion?," *Proceedings of the IEEE International Conference on Robotics and Automation*, Philadelphia, PA (1988) pp. 1335–1340.
8. M. B. Leahy Jr. and G. N. Saridis, "Compensation of industrial manipulator dynamics,"*Int. J. Robot. Res.* **8**(4), 73–84 (1989).
9. P. K. Khosla and T. Kanade, "Real-time implementation and evaluation of computed torque scheme," *IEEE Trans. Robot. Autom.* **5**(2), 245–253 (1989).
10. C. H. An, C. G. Atkeson, J. D. Griffiths and J. M. Hollerbach, "Experimental evaluation of feedforward and computed torque control," *IEEE Trans. Robot. Autom.* **5**(3), 368–373 (1989).
11. S. Dubowsky and D. T. Des Forges, "The application of model-referenced adaptive control to robotic manipulators," *ASME J. Dynam. Syst., Meas. Control* **101**, 193–200 (1979).
12. J. J. E. Slotine and W. Li, "Adaptive Robot Control: A New Perspective," *Proceedings of the 26th IEEE Conference on Decision and Control*, Los Angeles, CA (1987) pp. 192–198.
13. K. Youcef-Toumi and O. Ito, "Controller Design for Systems With Unknown Dynamics," *Proceedings of the American Control Conference*, Minneapolis, MN (1987) pp. 836–844.
14. S. Arimoto and F. Miyazaki, "Can Mechanical Robots Learn by Themselves?," *Proceedings of the 2nd International Symposium on Robotics Research*, Kyoto, Japan (1984) pp. 127–134.
15. J. Craig, *Introduction to Robotics, Mechanics and Control* (Addison Wesley, Reading, MA, (1989).
16. F. Miyazaki, Y. Masutani and S. Arimoto, "Sensor Feed–back Using Approximate Jacobian," *Proceedings of the USA–Japan Symposium on Flexible Automation—Crossing Bridges, Advances in Flexible Automation and Robotics*, Minneapolis, MN (1988) pp. 139–145.
17. S. Chiaverini, L. Sciavicco and B. Siciliano, "Control of robotic systems through singularities," *Proceedings of the International Workshop on Nonlinear and Adaptive Control: Issues in Robotics*, Grenoble, France, Nov. 1990; *Advanced Robot Control, Lecture Notes in Control and Information Sciences 162*, (C. Canudas de Wit ed.). Springer-Verlag, Berlin, D (1991), pp. 285–295.
18. Y. Asari, H. Sato, T. Yoshimi and K. Tatsuno, "Development of a Model-Based Remote Maintenance Robot System (IV)—A Practical Stiffness Control Method for Redundant Robot Arm," *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Yokohama, Japan (1993) pp. 1245–1251.
19. N. A. M. Hootsmans and S. Dubowsky, "Large Motion Control of Mobile Manipulators Including Vehicle Suspension Characteristics," *Proceedings of the IEEE International Conference on Robotics and Automation*, Sacramento, CA (1991) pp. 2336–2341.
20. E. Papadopoulos and S. Dubowsky, "Coordinated Manipulator/Spacecraft Motion Control for Space Robotic Systems," *Proceedings of the IEEE International Conference on Robotics and Automation* (1991) pp. 1696–1701.
21. M. H. Raibert and J. J. Craig, "Hybrid position/force control of manipulators," *ASME J. Dynam. Syst., Meas. Control* **126**, 126–133 (Jun. 1981).
22. S. Hayati, "Hybrid Position/Force Control of Multi-Arm Cooperating Robots," *Proceedings of the IEEE International Conference on Robotics and Automation*, San Francisco, CA (1986) pp. 82–89.
23. O. Khatib, "A unified approach for motion and force control of robot manipulators: The operational space formulation," *IEEE J. Robot. Autom.* **3**(1), 43–53 (1987).
24. D. E. Whitney, "Historical perspective and state of the art in robot force control," *Int. J. Robot. Res.* **6**(1), 3–14 (1987).
25. Y. Nakamura, K. Nagai and T. Yoshikawa, "Mechanics of Coordinative Manipulation by Multiple Robotic Mechanisms," *Proceedings of the IEEE International Conference on Robotics and Automation* (1987) pp. 991–998.
26. T. J. Tarn, A. K. Bejczy and X. Yun, "Design of Dynamic Control of Two Cooperating Robot Arms: Closed Chain Formulation," *Proceedings of IEEE International Conference on Robotics and Automation* (1987) pp. 7–13.
27. V. Hayward and S. Hayati, "KALI: An Environment for the Programming and Control of Cooperative Manipulators," *Proceedings of the American Control Conference*, Piscataway, NJ (1988) pp. 473–478.
28. H. Yamaguchi, "A distributed motion coordination strategy for multiple nonholonomic mobile robots in cooperative hunting operations," *J. Robot. Autonom. Syst.* **43**(4), 257–282 (2003).
29. N. Hogan, "Impedance control: An approach to manipulation—a three part paper," *ASME J. Dynam. Syst., Meas. Control* **107**, 1–24 (1985).
30. F. Caccavale and L. Villani, "Impedance Control for Multi-Arm Manipulators," *Proceedings of the IEEE International Conference on Decision and Control*, Australia (2000) pp. 3465–3470.
31. F. Caccavale and L. Villani, "An Impedance Control Strategy for Cooperative Manipulation," *Proceedings of the IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Italy (2001) pp. 343–348.
32. L. Biagiotti, H. Liu, G. Hirzinger and C. Melchiorri, "Cartesian Impedance Control for Dexterous Manipulation," *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Las Vegas, NV (2003) pp. 3270–3275.
33. A. A. Goldenberg, "Implementation of Force and Impedance Control in Robot Manipulators," *Proceedings of the IEEE International Conference on Robotics and Automation*, Philadelphia, PA (1988) pp. 1626–1632.
34. H. Seraji and R. Colbaugh, "Force Tracking in Impedance Control," *Proceedings of the IEEE International Conference on Robotics and Automation*, Atlanta, GA (1993) pp. 499–506.
35. S. Jung and T. C. Hsia, "Stability and Convergence Analysis of Robust Adaptive Force Tracking Impedance Control of Robot

Manipulators," *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Korea (1999) pp. 635–640.

36. N. Tischler and A. A. Goldenberg, "Stiffness Control for Geared Manipulators," *Proceedings of the IEEE International Conference on Robotics and Automation*, Korea (2001) pp. 3042–3046.
37. B. Heinrichs and N. Sepehri, "Relationship of Position-Based Impedance Control to Explicit Force Control: Theory and Experiments," *Proceedings of the American Control Conference*, California (1999) pp. 2072–2078.
38. L. J. Love and W. J. Book, "Force reflecting teleoperation with adaptive impedance control," *IEEE Trans. Syst., Man, Cybern.—Part B: Cybern.* **34**(1), 159–165 (2004).
39. R. Ozawa and H. Kobayashi, "A New Impedance Control Concept for Elastic Joint Robots," *Proceedings of the IEEE International Conference on Robotics and Automation*, Taiwan (2003) pp. 3126–3131.
40. A. Schneider and R. H. Cannon, "Object impedance control for cooperative manipulation: Theory and experimental results," *IEEE Trans. Robot. Autom.* **8**(3), pp. 383–394 (1992).
41. D. W. Meer and S. M. Rock, "Coupled-System Stability of Flexible-Object Impedance Control," *Proceedings of the IEEE International Conference on Robotics and Automation*, Nagoya, Japan (1995) pp. 1839–1845.
42. B. M. Braun, G. P. Starr, J. E. Wood and R. Lumia, "A framework for implementing cooperative motion on industrial controllers," *IEEE Trans. Robot. Autom.* **20**(3) 583–589 (2004).
43. S. Ali A. Moosavian and E. Papadopoulos, "Multiple Impedance Control for Object Manipulation," *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Victoria, Canada (1998) pp. 461–466.
44. S. Ali A. Moosavian and R. Rastegari, "Multiple-arm space free-flying robots for manipulating objects with force tracking restrictions," *J. Robot. Autonom. Syst.* **54**(10), 779–788 (2006).
45. Y. Murotsu, K. Senda, A. Mitsuya, K. Yamane, M. Hayashi and T. Nunohara, "Theoretical and Experimental Studies for Continuous Path Control of Flexible Manipulators Mounted on a Free-Flying Space Robot," *Proceedings of the AIAA Guidance, Navigation and Control Conference*, Monterey, CA (1993) pp. 1458–1471.
46. E. Martin, E. Papadopoulos and J. Angeles, "On the Interaction of Flexible Modes and On-Off Thrusters in Space Robotic Systems," *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Pittsburgh, PA (1995) pp. 65–70.
47. E. Martin, E. Papadopoulos and J. Angeles, "A Control Scheme for the Reduction of Thruster-Manipulator Interaction in Space Robotic Systems," *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Victoria, Canada (1998) pp. 1352–1357.
48. Y. Hu and G. Vukovich, "Modeling and Control of Free-Flying Flexible Joint Coordinated Robots," *Proceedings of the IEEE International Conference on Robotics and Automation*, Monterey, CA (1997) pp. 1013–1020.
49. H. A. Talebi, R. V. Patel and H. Asmer, "Dynamic Modeling of Flexible-Link Manipulators Using Neural Networks with Application to the SSRMS," *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Victoria, Canada (1998) pp. 673–678.
50. G. de Rivals-Mazères, W. Yim, F. Mora-Camino and S.N. Singh, "Inverse control and stabilization of free-flying flexible robots," *Robotica* **17**(3), 343–350 (1999).
51. M. Yamano, A. Konno, M. Uchiyama and T. Miyabe, "Capturing a Spinning Object by Two Flexible Manipulators," *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Takamatsu, Japan (2000) pp. 2036–2041.
52. M. Caron, V. J. Modi and A. K. Misra, "Dynamics of a multimodule variable geometry manipulator," *Acta Astronaut.* **50**(10), 587–595 (2002).
53. Z. Vafa and S. Dubowsky, "On the Dynamics of Manipulators in Space Using the Virtual Manipulator Approach," *Proceedings of the IEEE International Conference on Robotics and Automation* (1987) pp. 579–585.
54. Z. Vafa and S. Dubowsky, "The kinematics and dynamics of space manipulators: The virtual manipulator approach," *Int. J. Robot. Res.* **9**(4), 3–21 (1990).
55. E. Papadopoulos and S. Dubowsky, "On the nature of control algorithms for free-floating space manipulators," *IEEE Trans. Robot. Autom.* **7**(6), 750–758 (1991).
56. Y. Umetani and K. Yoshida, "Continuous path control of space manipulators mounted on OMV," *Acta Astronaut.* **15**(12), 981–986 (1987).
57. F. Caccavale and B. Siciliano, "Kinematic control of redundant free-floating robotic systems", *J. Adv. Robot.* **15**, 429–448 (2001).
58. S. Ali A. Moosavian and E. Papadopoulos, "On the kinematics of multiple manipulator space free-flyers," *J. Robot. Syst.* **15**(4), 207–216 (1998).
59. B. Schäfer, R. Krenn and B. Rebele, "On inverse kinematics and kinetics of redundant space manipulator simulation," *J. Comput. Appl. Mech.* **4**(1), 53–70 (2003).
60. R. Colbaugh, M. Trabatti and K. Glass, "Redundant nonholonomic mechanical systems: characterization and control," *Robotica* **17**(02), 203–217 (1999).
61. S. Ali A. Moosavian and E. Papadopoulos, "Explicit dynamics of space free-flyers with multiple manipulators via SPACEMAPL," *J. Adv. Robot.* **18**(2), 223–244 (2004).
62. E. Papadopoulos, "Nonholonomic Behaviour in Free-floating Space Manipulators and its Utilization," **In**: *Nonholonomic Motion Planning* **192** (Li Z. and Canny J.F., eds.) (Kluwer Academic, Boston, MA, (1993) pp. 423–445.
63. E. Papadopoulos, I. Poulakakis and I. Papadimitriou, "On path planning and obstacle avoidance for nonholonomic mobile manipulators: A polynomial approach," *Int. J. Robot. Res.* **21**(4), 367–383 (2002).
64. M. Ullman and R. H. Cannon, "Experiments in Global Navigation and Control of a Free-Flying Space Robot," *Proceedings of the ASME WAM* **15**, San Francisco (1989) pp. 37–43.
65. S. Dubowsky and M. Torres, "Path Planning for Space Manipulators to Minimize Spacecraft Attitude Disturbances," *Proceedings of IEEE International Conference on Robotics and Automation* (1991) pp. 2522–2528.
66. S. Jacobsen, C. Zhu, C. Lee and S. Dubowsky, "Planning of Safe Kinematic Trajectories for Free-Flying Robots Approaching an Uncontrolled Spinning Satellite," *Proceedings of the ASME 2002 Design Engineering Technical Conferences*, Montreal, Canada (Sep. 29–Oct. 2, DETC2002/MECH-34336, 2002).
67. N. Inaba and M. Oda, "Autonomous Satellite Capture by a Space Robot," *Proceedings of the IEEE International Conference on Robotics and Automation* **2**, San Francisco (2000) pp. 1169–1174.
68. S. Nakasuka and T. Fujiwara, "New Method of Capturing Tumbling Object in Space and Its Control Aspects," *Proceedings of the IEEE International Conference on Control Applications*, Kohala Coast, Hawaii (Aug. 22–27, 1999) pp. 973–978.
69. S. Matsumoto, *et al.*, "Satellite Capturing Strategy Using Agile Orbital Servicing Vehicle, Hyper-OSV," *Proceedings of the IEEE International Conference on Robotics and Automation*, Washington, DC (2002) pp. 2309–2314.
70. Z. Li, T. J. Tarn and A. Bejczy, "Dynamic workspace of multiple cooperating robot arms," *IEEE Trans. Robot. Autom.* **7**(5), 589–596 (1991).
71. Y. F. Zheng and Q. Yin, "Coordinating Multilimbed Robots for Generating Large Cartesian Force," *Proceedings of the IEEE International Conference on Robotics and Automation*, Cincinnati, OH (1990) pp. 1653–1658.
72. H. Seraji, "Task-based configuration control of redundant manipulators," *J. Robot. Syst.* **9**(3), 411–451 (1992).

73. A. Madhani and S. Dubowsky, "The force workspace: A tool for the design and motion planning of multi-limb robotic systems," *ASME J. Mech. Des.* **119**(2), 218–225 (1997).
74. E. Papadopoulos and Y. Gonthier, "A framework for large-force task planning of mobile redundant manipulators," *J. Robot. Syst.* **16**(3), 151–162 (1999).
75. I. D. Walker, "Impact configurations and measures for kinematically redundant and multiple armed robot systems," *IEEE Trans. Robot. Autom.* **10**(5), 670–683 (1994).
76. K. Yoshida, "Impact Dynamics Representation and Control With Extended–Inversed Inertia Tensor for Space Manipulators," *Proceedings of the 6th International Symposium on Robotics Research*, Pittsburgh, PA (1994) pp. 453–463.
77. K. Yoshida, C. Mavroidis and S. Dubowsky, "Experimental Research on Impact Dynamics of Spaceborne Manipulator Systems," *Proceedings of the 4th International Symposium on Experimental Robotics*, Stanford, CA (Jun. 30–Jul. 2, 1995). [Also published as Experimental Robotics IV, Control and Information Science Series 223 (O. Khatib and J. K. Salisbury eds.) (Springer-Verlag, Germany) pp. 436–447.]
78. J. Sequeira, P. Lima, M. I. Ribeiro and J. Sentieiro, "Behavior-Based Cooperation With Application to Space Robots," *Proceedings of the 6th ESA Workshop on ASTRA*, The Netherlands (2000) pp. 1–7.
79. Y. Xu, "The Measure of Dynamic Coupling of Space Robot Systems," *Proceedings of the IEEE International Conference on Robotics and Automation*, Atlanta, GA (1993) pp. 615–620.
80. Y. Nakamura and R. Mukherjee, "Exploiting nonholonomic redundancy of free-flying space robots," *IEEE Trans. Robot. Autom.* **9**(4), 499–506 (1993).
81. K. Yamada, S. Yoshikawa and Y. Fujita, "Arm path planning of a space robot with angular momentum," *J. Adv. Robot.* **9**(6), 693–709 (1995).
82. H. Nagamatsu, T. Kubota and I. Nakatani, "Capture Strategy for Retrieval of a Tumbling Satellite by a Space Robotic Manipulator," *Proceedings of the IEEE International Conference on Robotics and Automation* (1996) pp. 70–75.
83. G. Jaar, X. Cyril and A. K. Misra, "Dynamical Modeling and Control of a Spacecraft-Mounted Manipulator Capturing a Spinning Satellite," *Proceedings of the 43rd Congress of the International Astronautical Federation*, IAF-92-0029, 1992.
84. S. Taniwaki, S. Matunaga, S. Tsurumi and Y. Ohkami, "Coordinated control of a satellite-mounted manipulator with consideration of payload flexibility," *J. Control Eng. Pract.* **9**, 207–215 (2001).
85. E. Papadopoulos and S. Ali A. Moosavian, "Dynamics and Control of Multi-Arm Space Robots During Chase and Capture Operations," *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Munich, Germany (1994) pp. 1554–1561.
86. E. Papadopoulos and S. Ali A. Moosavian, "A Comparison of Motion Control Algorithms for Space Free-flyers," *Proceedings of the 5th International Conference on Adaptive Structures*, Sendai, Japan (1994) pp. 501–516.
87. E. Papadopoulos and S. Ali A. Moosavian, "Dynamics and control of space free-flyers with multiple arms," *J. Adv. Robot.* **9**(6), 603–624 (1995).
88. S. Ali A. Moosavian and E. Papadopoulos, "Control of Space Free-Flyers Using Modified Transpose Jacobian Algorithm," *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Grenoble, France (1997) pp. 1500–1505.
89. S. Ali A. Moosavian and E. Papadopoulos, "Modified Transpose Jacobian control of Robotic systems," *Automatica* (2007) to be published.
90. F. M. Carter and D. B. Cherchas, "Motion control of non-fixed base robotic manipulators," *Robotica* **17**(2), 143–157 (1999).
91. Y. Umetani and K. Yoshida, "Resolved motion rate control of space manipulators with generalized Jacobian matrix," *IEEE Trans. Robot. Autom.* **5**(3), 303–314 (1989).
92. K. Yoshida, R. Kurazume and Y. Umetani, "Dual Arm Coordination in Space Free-Flying Robot," *Proceedings of the IEEE International Conference on Robotics and Automation* (1991) pp. 2516–2521.
93. H. Alexander and R. Cannon, "An extended operational-space control algorithm for satellite manipulators," *J. Astronaut. Sci.* **38**(4), 473–486 (1990).
94. H. Fujii, T. Murayama, K. Nakajima and S. Anazawa, "Capture Control for Manipulator Arm of Free-flying Space Robot," *AIAA-90-3432-CP* (1990).
95. Y. Yokokohji, T. Toyoshima and T. Yoshikawa, "Efficient computational algorithms for trajectory control of free-flying space robots with multiple arms," *IEEE Trans. Robot. Autom.* **9**(5), 571–580 (1993).
96. S. Dubowsky and E. Papadopoulos, "The dynamics and control of space robotic systems," *IEEE Trans. Robot. Autom.* **9**(5), 531–543 (1993).
97. R. Mukherjee and D. Chen, "Control of free-flying underactuated space manipulators to equilibrium manifolds," *IEEE Trans. Robot. Autom.* **9**(5), 561–570 (1993).
98. S. K. Agrawal and G. Desmier, "Models of Assembly Primitives for Free-Floating Robots," *Proceedings of the International Conference on Intelligent Robots and Systems*, Yokohama, Japan (1993) pp. 2041–2048.
99. L. B. Wee and M. W. Walker, "On the dynamics of contact between space robots and configuration control for impact minimization," *IEEE Trans. Robot. Autom.* **9**(5), 581–591 (1993).
100. K. Yoshida and D. N. Nenchev, "Space Robot Impact Analysis and Satellite-Base Impulse Minimization Using Reaction Null-Space," *Proceedings of the IEEE International Conference on Robotics and Automation*, Nagoya, Japan (1995) pp. 1271–1277.
101. V. Yu. Rutkovsky, V. M. Sukhanov, V. M. Glumov, S. D. Zemlyakov and S. D. Dodds, "Computer simulation of an adaptive control system for a free-flying space robotic module with flexible payload's transportation," *J. Math. Comput. Simulation* **58**, 407–421 (2002).
102. A. K. Swain and A. S. Morris, "Dynamic control of multi-arm co-operating manipulator systems," *Robotica* **22**(3), 271–283 (2004).
103. S. Ali A. Moosavian and E. Papadopoulos, "On the Control of Space Free-Flyers Using Multiple Impedance Control," *Proceedings of the IEEE International Conference on Robotics and Automation*, Albuquerque, NM, USA (1997) pp. 853–858.
104. S. Ali A. Moosavian, R. Rastegari and E. Papadopoulos, "Multiple impedance control for space free-flying robots," *AIAA J. Guid., Control, Dynam.* **28**(5), 939–947 (2005).
105. R. Rastegari and S. Ali. A. Moosavian, "Multiple Impedance Control of Space Free-Flying Robots Using Virtual Object Grasp," *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Beijing, China (Oct. 9–15, 2006) pp. 3125–3130.
106. J. Carusone, K. S. Buchan and G. M. T. D'Eleuterio, "Experiments in end-effector tracking control for structurally flexible space manipulators," *IEEE Trans. Robot. Autom.* **9**(5), 553–560 (1993).
107. S. K. Agrawal, G. Hirzinger, K. Landzettel and R. Schwertassek, "A new laboratory simulator for study of motion of free-floating robots relative to space targets," *IEEE Trans. Robot. Autom.* **12**(4), 627–633 (1996).
108. M. Annapragada and S. K. Agrawal, "Design and experiments on a free-floating planar robot for optimal chase and capture operations in space," *Robot. Autonom. Syst.* **26**, 281–297 (1999).
109. K. Yoshida, "Experimental study on the dynamics and control of a space robot with experimental free-floating robot satellite (EFFORTS) simulators," *J. Adv. Robot.* **9**(6), 583–602 (1995).
110. K. Yoshida and H. Nakanishi, "Impedance Matching in Capturing a Satellite by a Space Robot," *Proceedings of the*

IEEE/RSJ International Conference on Intelligent Robots and Systems, Las Vegas, NV (2003) pp. 3059–3064.

111. K. Yoshida, H. Nakanishi, H. Ueno, N. Inaba, T. Nishmaki and M. Oda, "Dynamics, control and impedance matching for robotic capture of a non-cooperative satellite," *J. Adv. Robot.* **18**(2), 175–198 (2004).
112. C. Dickson and R. H. Cannon, "Experimental Results of Two Free-Flying Robots Capturing and Manipulating a Free-Flying Object," *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Pittsburgh, PA (1995) pp. 51–58.
113. D. M. Waltz, *On-Orbit Servicing of Space Systems* (Krieger, Malabar, FL, (1993).
114. C. R. Carignan and D. L. Akin, "The reaction stabilization of on-orbit robots," *IEEE Control Syst. Mag.* **20**(6), 19–33 (2000).
115. C. R. Carignan, J. C. Lane and P. J. Churchill, "Controlling robots on-orbit," *Proceedings of the IEEE International Symposium on Computational Intelligence in Robotics and Automation* (2001) pp. 314–319.
116. A. Ellery, "Handling Technology for On-Orbit Servicing," *Proceedings of the 1st Bilateral DLR-CSA Workshop on On-Orbit Servicing of Space Infrastructure Elements via Automation and Robotics Technologies*, DLR, Cologne, Germany (Nov. 25–26, 2002) pp. 1–5.
117. G. Hirzinger, B. Brunner, R. Lampariello, K. Landzettel, J. Schott and B.M. Steinmetz, "Advances in Orbital Robotics," *Proceedings of the IEEE International Conference on Robotics and Automation*, San Francisco, CA (2000) pp. 898–907.
118. G. Hirzinger, K. Landzettel, B. Brunner, M. Fischer, C. Preusche, D. Reintsema, A. Albu-Schäffer, G. Schreiber and B.M. Steinmetz, "DLR's robotics technologies for on-orbit servicing," *J. Adv. Robot.* **18**(2), 139–174 (2004).
119. C. W. Borst and R. A. Volz, "Telerobotic ground control of a free-flying space camera," *Robotica* **18**(4), 361–367 (2000).
120. P. Arena, P. Di Giamberardino, L. Fortuna, F. La Gala, S. Monaco, G. Muscato, A. Rizzo and R. Ronchini, "Toward a mobile autonomous robotic system for Mars exploration," *J. Planet. Space Sci.* **52**(1–3), 11–21 (2004).