

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

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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 control¹

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.

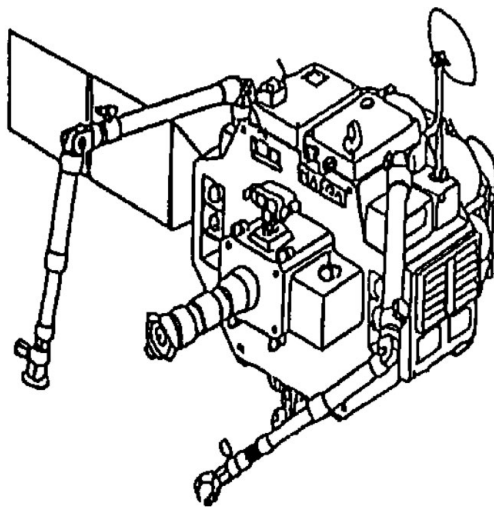


Fig. 2. Space Free-Flying Robots; *top*: The Orbital Servicing Vehicle, *bottom*: The University of Maryland Ranger.

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 control²

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

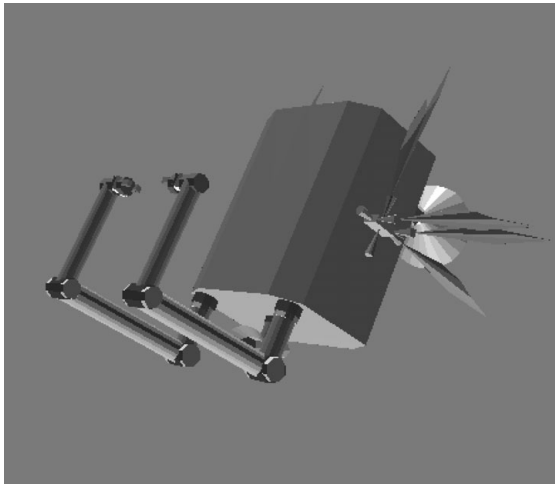


Fig. 3. Graphical view of a simulated SFFR with multiple manipulators.

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 joint⁵⁴ 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

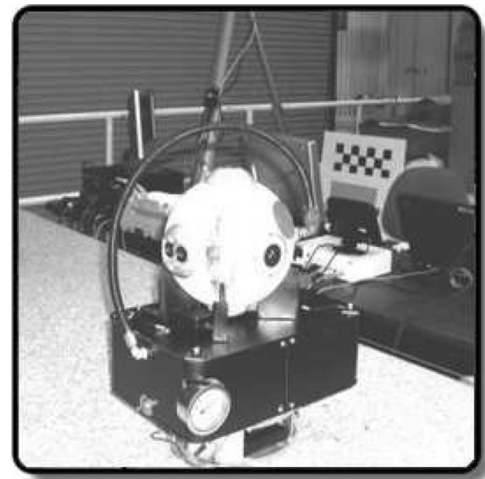


Fig. 4. Autonomous Extravehicular Robotic Camera (AERCAM), a free-flying camera platform developed by NASA; courtesy Robotic Systems Technology Branch, NASA Johnson Space Center.

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.

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

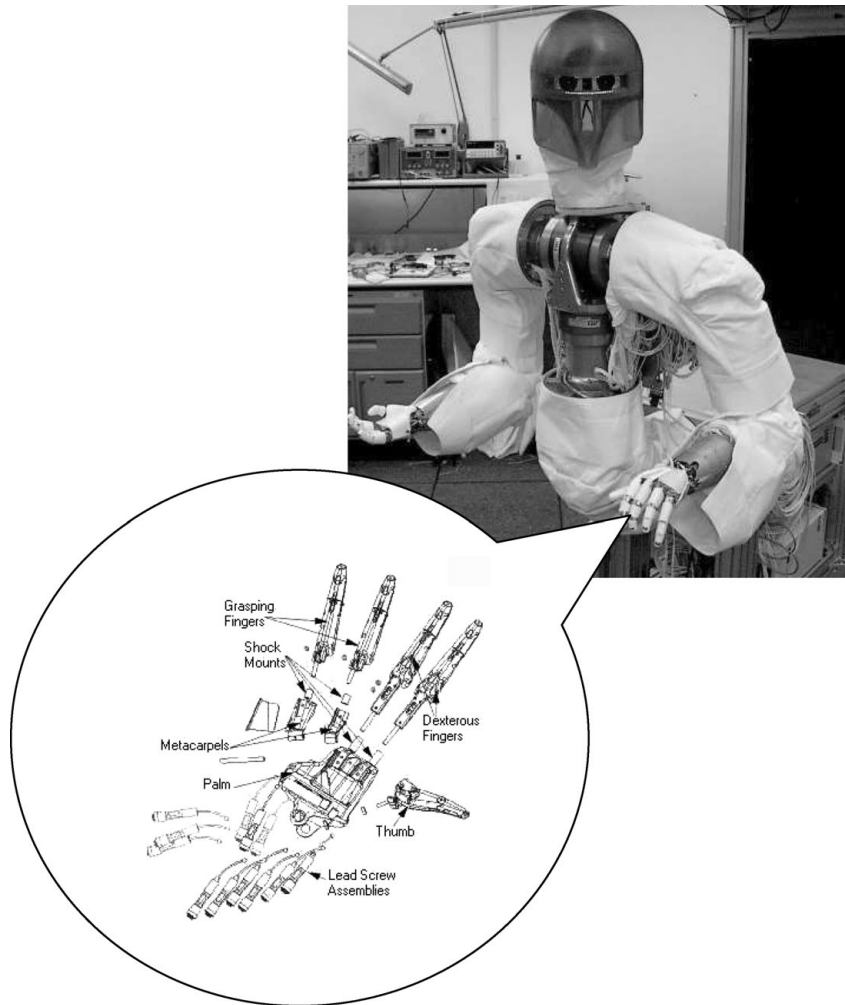


Fig. 5. Robonaut, a humanoid free-flying robot developed by NASA, and its hand details; courtesy Robotic Systems Technology Branch, NASA Johnson Space Center.

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

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

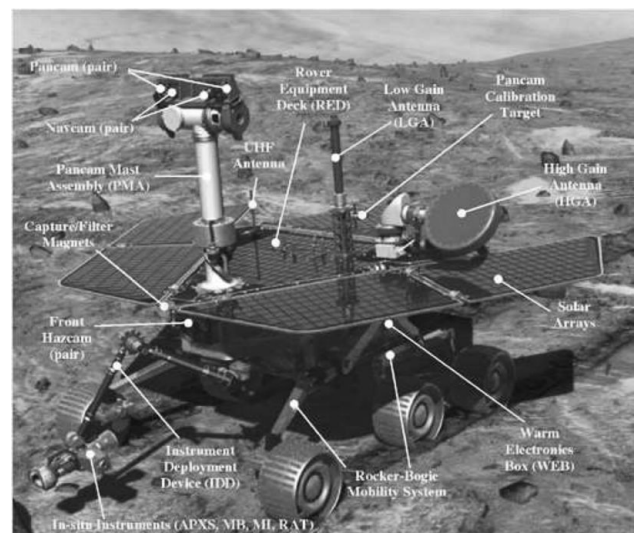


Fig. 6. Spirit and Opportunity, two mobile robotic systems developed by NASA for Mars explorations.

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.

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