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# Strategies for Control of Space Robots: A Review and Research Agenda

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*Abstract -* Modelling and control of space robots is not an easy task to perform, because the equations of motion that govern phenomenon are highly nonlinear. Furthermore, unlike fixed base manipulators a free-floating space robot exhibits non-holonomic behavior as a result of the non-integrability of the angular momentum conservation law. In recent days space robots are extensively used to play a significant role in space applications like, scheduled servicing of satellites and spacecrafts including refuelling tasks, inspection of remote sites or verification of structures, retrieval of tumbling tools or astronauts, and assembly or welding of space structures. In a large number of these applications, the manipulator endeffector is required to interact with the environment. Due to the interaction between the endeffector and the environment, the interaction torques act on the endeffector which gets transmitted through links to the base of the vehicle and the orientation of the vehicle changes. Hence, precise control of the manipulator's trajectory, attitude and impedance are critically important. This paper addressed the current state-oftheart in key areas of the space robotics by reviewing recently available literatures particularly on free flying and free floating space robots which help in summarizing various research outcomes in a structured manner.

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STRATEGIES FOR CONTROL OF SPACE ROBOTS A REVIEW AND RESEARCH AGENDA

*Strictly as per the compliance and regulations of :*

# Strategies for Control of Space Robots: A Review and Research Agenda

Migbar Assefa

*Abstract -* Modelling and control of space robots is not an easy task to perform, because the equations of motion that govern phenomenon are highly nonlinear. Furthermore, unlike fixed base manipulators a free-floating space robot exhibits non-holonomic behavior as a result of the non-integrability of the angular momentum conservation law. In recent days space robots are extensively used to play a significant role in space applications like, scheduled servicing of satellites and spacecrafts including refuelling tasks, inspection of remote sites or verification of structures, retrieval of tumbling tools or astronauts, and assembly or welding of space structures. In a large number of these applications, the manipulator endeffector is required to interact with the environment. Due to the interaction between the endeffector and the environment, the interaction torques act on the endeffector which gets transmitted through links to the base of the vehicle and the orientation of the vehicle changes. Hence, precise control of the manipulator's trajectory, attitude and impedance are critically important. This paper addressed the current state-of-the-art in key areas of the space robotics by reviewing recently available literatures particularly on free flying and free floating space robots which help in summarizing various research outcomes in a structured manner. This is by no means a complete survey but provides key references for future development.

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## I. Introduction

Robotics in general might be classified into five major areas: motion control, sensors and vision, planning and coordination, Artificial Intelligence and decision-making and man-machine interface. Without a good control strategy, a robotic device is ineffective. Since this paper is intended to provide an in-depth review of the control strategies of space robots, it is worthy to point out the difference between space environment and earth.

The peculiar features of space environment are:

1) The absence of gravity,
2) The absence of rigid base,
3) The limited amount of on-board fuel for actuation of the space robot system.

The absence of a rigid base imposes momentum constraints on the motion of the system. The limited amount of onboard fuel for actuation of the space robot system puts a limit on the use of thrusters for attitude control or for force and torque control (Pathak, 2004).

In recent years space missions and on-orbit tasks rely more and more on space robots, since these tasks are either hazardous to astronauts because of extremes of temperature and glare, and possible high level of radiation or very costly, due to safety support systems, or just physically impossible to be executed by humans (Tortopidis, I., Papadopoulos E. 2007; Vafa Z., Dubowsky S, 1990).

Repair, construction and maintenance of space stations and satellites have been performed by astronaut Extra Vehicular Activity (EVA), on-orbit servicing (OOS) and the maintenance of the International Space Station (Wang, 2011). Eliminating the need for astronaut EVA through the use of space manipulators would greatly reduce both mission costs and hazards to astronauts (Dubowsky , 1987).

Typical space applications require precise manipulator control, which is a difficult task to achieve due to free-floating base of the space robot and dynamic coupling between the manipulator and the base. The satellite's attitude stabilization is necessary in most cases for electrical power generation from solar panels and to retain the communication link (Pathak, 2004). P.M. Pathak in his PhD work explained space robot arm and vehicle dynamics by elaborating the mechanics of robot with vector notations, co-ordinate systems with specific assumptions. Euler junction structure, linear and angular dynamics for vehicle and link are the building blocks of total system dynamics. He also explained the bondgraph modeling of space robot by illustrating three degrees of freedom space robots and explained the submodels development for Euler junction, linear and angular dynamics.

As briefly explained by Papadopoulos and Nanos (2004), space exploration is a relatively new field in science and engineering. In the case of robotic systems in orbit, robotic manipulators are mounted on a thruster equipped spacecraft, called free flying space manipulator systems. If the spacecraft thrusters are not operating, as for example during capture operations, then these systems are called free floating space manipulator systems. In free flying systems, thruster jets can compensate for manipulator induced disturbances, but their extensive use limits the system's useful life

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span. In free floating systems, dynamic coupling between the manipulator and the spacecraft exists, and manipulator motions induce disturbances to the system's spacecraft. In these cases, the spacecraft is permitted to translate and rotate in response to its manipulation motions. This mode of operation can be feasible when no external forces and torques act on the system and when the total momentum of the system is zero.

The concepts of free-flying and free-floating robots evolved in the early eighties. Unlike ground-base robot manipulator, the space manipulator has no fixed base. The dynamic reaction forces and moments due to the manipulator motion will disturb the space base, especially, when the space robot is in free-floating situation, The longer the motion time of space manipulator is, the greater the disturbance to the base will be. Hence, it is essential to resolve the attitude balance problem of a space robot during the manipulator operation (Papadopoulos and Konstantinos, 2004).

Vafa and Dubowsky have developed a technique called Virtual Manipulator (V.M.) method (Wang 2011). The kinematic and momentum equations of free-floating space manipulator systems were developed using this technique, which was subsequently used for path planning of such systems. Inspired by astronaut motions, they proposed a planning technique which employed small cyclical motions in the manipulator's joint space to modify its spacecraft's attitude.

The control strategies of space robots have been proposed by different authors and validate their results. The main objective of this paper is to address the research activities and accomplishments made in the area of trajectory, attitude and impedance control of space robotic systems.

## II. Trajectory Control

Since a space manipulator is a highly nonlinear system, computation of generalized efforts for a desired end effector trajectory becomes a difficult problem. The execution time for computing the generalized effort determines the feasibility of implementing the control scheme in real time. In many practical cases, position control of space manipulators is not enough and the manipulator's joints actually have to follow a time dependent desired trajectory to generate a specified time dependent path at the end effector.

A free-floating space robotic system is one in which the spacecraft's position and attitude are not actively controlled using external jets or thrusters, and it does not interact dynamically with the environment during manipulator motion. The spacecraft moves freely in response to the dynamical disturbances caused by the manipulator's motion. For such systems, the linear and angular momenta are conserved. This disturbance of the base results in deviation of the end-effector from the desired trajectory. Thus, it is very difficult to design a control strategy for a space robot end-effector trajectory control (Yoshihiko and Mukherjee, 1991). Moreover, the angular momentum conservation constraints are non integrable rendering the system nonholonomic. This property complicates the planning and control of such systems, which have been studied by a number of researchers.

Based on the insights developed from the bond graph modeling, Ghosh (1990) developed a robust overwhelming joint controller for a robotic manipulator, which does not require the knowledge of the robot parameters and the payload. Kumar (1994), Kumar and Mukherjee (1989) further developed the overwhelming control strategy and applied it for robust trajectory control of a two-link planar manipulator on a flexible foundation. The effect of the flexible foundation is compensated in the controller by providing the controller with the information of velocity of the foundation. Most robust robot trajectory control strategies assume the plant to be an ideal rigid manipulator. Thus, in the model for the controllers, it suffices to consider only the inertia of the manipulator. Due to the uncertainty in determining parameters of robot, in several cases it is not possible to find out accurately the Coriolis, centrifugal and gravity terms contribution in the dynamics of robot. Robust trajectory control algorithms are insensitive to variations in the manipulator parameters and retain the desired trajectory.

Pathak et al. (2008) extended the scheme for robust control of terrestrial manipulator with foundation compensation to space robots. In this work the authors proposed control scheme based on concept of robot foundation disturbance compensation, in this scheme no external jet/thrusters are were used. An example of three- link robot mounted on the free floating space platform is considered for demonstrating the efficacy of control scheme. For the purpose of modeling and simulation, bondgraph technique has been employed. Simulation results show that end-effector of space robot follows the reference velocity command effectively. Robustness of control scheme is guaranteed since the controller does not require the knowledge of the manipulator parameters.

Patolia et al (2010) presented a trajectory planning strategy for a dual arm planar space robot in workspace that is intended to minimize vehicle attitude disturbance that may occur due to dynamic coupling between the arms and the vehicle of the space robot. The strategy used by the authors was based on the principle of dynamic coupling between the tip motion and the vehicle motion of the space robot. This strategy uses the two arms of manipulator. One arm, called the mission arm, achieves the trajectory control task while the other arm, called the balance arm, moves in such a

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way as to reduce the attitude of the vehicle. A bond graph has been adopted as the modeling tool, as it facilitates the system modeling from the physical paradigm itself and it is easy to develop various control strategies by modifying the physical paradigm.

## III. Attitude Control

In space robots, the change of position of center of mass (CM) of space vehicle, due to manipulator reaction does not produce serious errors, compared to the attitude change. The attitude change is more serious because it effects the orientation of satellite antennas whose disorientation disrupts the communication link between the ground control and the satellite.

There are some basic requirements which an attitude controller must fulfill. The attitude controller must be simple and precise. It must be stable both for long term and for short term. Reaction wheels are used only during flying operation. They must be switched off at the manipulation, otherwise interference between wheel control force and contact force control will exist. Targets of free flying space robots such as space stations and satellites are usually rotating around the pitch axis according to the robot motion to keep the yaw axis towards center of earth. Thus the space robot has to rotate its attitude to keep relative attitude to the target.

Papadopoulos and Dubowsky (1991) suggested that any control algorithm that can be used for fixed based manipulators can also be used in the control of free floating space manipulators systems, with the additional conditions of estimating or measuring a spacecraft's orientation, and of avoiding dynamic singularities. They suggested that spacecraft attitude can be measured by an inertially fixed camera mounted on some space structure. Papadopoulos and Dubowsky (1993) also showed the occurrence of dynamic singularities in free-floating space manipulators systems when the spacecraft moves in response to manipulator motions when no attitude controller is used. At a dynamic singularity, the manipulator is unable to move its end effector in certain inertial directions. The dynamic singularity exists due to dynamic coupling between link motion and spacecraft. They concluded that, for a free-floating manipulator, singularities in work space are path dependent.

As addressed by Pathak (2004), there are many advantages of reaction wheels as an attitude controller. The attitude control logic for satellite application provides stability against disturbance torque using the momentum bias/gyroscopic rigidity principle analogously to the spinning of an entire space craft. It is a low cost attitude control system. It can have mixture of attitude determination and control capacity, minimize mass and power and enhance reliability. In this system each wheel is to be independently instrumented and uses its own separate drive circuitry. All electronics, including power converter, commutation, speed monitoring, current control and telemetry collection are housed within the assembly. Both types (i) current (torque) controller and (ii) speed (momentum) controller may be used. It has low residual imbalance.

However there are some disadvantages in using the reaction wheel as an attitude controller. It is heavy, complicated having small control torque capability (about 0.2 Nm). The reaction wheel output torque is not as large as the robot arm's reaction torque. However in order to save attitude control fuel, reaction wheel is used when the robot arm's reaction is not large. For a large space platform such as the space station, a controlled moment gyro (CMG), which is a momentum wheel on a gimbaled platform and which can generate a larger reaction torque is used (Pathak, 2004).

Rajkumar Jain and P.M. Pathak (2008) developed path planning of robot tip with minimum disturbance in base. In this paper bond graphs are used to model the dynamics of the space robot as it offers flexibility in modeling and formulation of system equations. To minimize the base disturbance the authors make use of attitude controller device such as thrusters and reaction wheels by developing an approach to move the tip from starting position to target position with minimum disturbance in base, without using attitude controller device.

Pathak etal (2006) presented new torque generation device that can be used to control the attitude of space robots. The device is based on the concept of variable transmission. The advantage and limitations of the device were also discussed by the authors. The advantage of this device is that the system is a multi-input system, and hence many control strategies are possible to control the platform rotation. The control strategies for platform rotation could be (i) motor voltage control (ii) transmission ratio control or (iii) control by generator resistance.

The attitude of a space robot is corrected using internal actuators such as reaction wheels, control moment gyros or by external actuators such as reaction jets. In case of attitude control by reaction wheels, three reaction wheels may be used, with one reaction wheel in each direction. Usually in the three reaction wheel approach for satellite attitude control, the control of each axis of rotation is designed independently of the other two. In this approach it is assumed that the control dynamics of each axis has no influence on the others. This assumption is not always valid. There can be significant gyroscopic coupling, which is prominent when the wheels are spinning at high spin rates.

In case of space robots, due to a floating base, the movement of robot arm causes attitude disturbance of the base, which also leads to end-effector trajectory errors. Various researchers have attempted to address this problem. Approximate solution to this problem is provided by a disturbance map. The disturbance map is based on the principle that there are some combinations of the joint velocities, which leads to a zero angular velocity of the robot base. It identifies the direction of joint movements, which results in minimum and maximum disturbances of the spacecraft attitude due to manipulator movement. The concept of disturbance map and its use in non-holonomic motion planning of space robots with minimum attitude change was proposed by Dubowsky and Torres (1991). They named the graphical tool as Enhanced Disturbance Map (EDM).

The EDM was used as an aid in developing control algorithms to minimize the base disturbances. They used EDM, also to find near optimal paths which minimizes these dynamic disturbances. Legnani et al. (1999) proposed the approximate solution for the problem of space robot base motion due to joint motion, using the concept of the disturbance map. They showed that design of the robot introduces some dynamic singularities which, when used in conjunction with the disturbance map solves the problem of moving the robot without rotating its base.

## IV. Impedance Control

Space manipulator tasks can be divided into two different categories. In the first category, the manipulator end-effector is under position or trajectory control. These types of tasks are called motion control tasks. An example of this is when the manipulator grasps an object and moves it to a desired position. The second category of task is called force/torque control tasks. These involve a significant force/torque interaction between the space manipulator and its environment. An example of this type of task is when the manipulator performs an operation on an external object, such as disconnecting a cable or turning a knob from a satellite. The typical tasks to be performed by space robots would be deploying or assembling space platforms, space stations, large antennas or solar power stations and servicing and maintenance of satellites. The environment, in which space robot work is unstructured in nature. These manipulators must ensure safe and reliable interaction with objects or environment in their workspace (Pathak, 2004).

Robots are subjected to interaction forces whenever they perform tasks involving motion, which is constrained by the environment. These interaction forces/moments must be accommodated and restricted so as to comply with the environmental constraints. Control of spacecraft and manipulators during capture or manipulation of object has not been given adequate attention. Successful performance of a compliant motion is very important for space robots. Force control of space manipulator is required for fine manipulation such as in space structure assemblies which require insertion, push etc. There are two main difficulties with the force control of space manipulators. First is that space robot has no fixed point in the inertial space, and moves when a manipulator applies a force or torque on an environment. Secondly, the physical properties of the environment on which the manipulator applies force are not well known. The first problem can be overcome by using a thruster if force control of the robot is desired, while torque control can be achieved by use of thruster pairs or an attitude controller. The second problem can be overcome by assuring that the force controller is robust against the physical properties of the environment and by providing a passive compliance between the end-effector and manipulator. The passive compliance mechanism can absorb an impulse force acting on the end-effector and align the end-effector along an inclined surface. Two broad approaches for achieving compliant motion are described in literature. These approaches are (i) Hybrid position and force control, and (ii) Impedance control. The Hybrid position/force control approach [19] is based on the fact that when the robot end-effector is in contact with the environment, the Cartesian space of the end-effector coordinate may be naturally decomposed into a position control subspace and a force control subspace.

The position control subspace corresponds to the Cartesian directions in which the end-effector is free to move, while the constrained directions correspond to the force control subspace. The hybrid position/force control approach to compliant motion is to track a position/ orientation trajectory in the position subspace, and a force/moment trajectory in the force subspace by using separate position and force controllers. On the other hand, the impedance control approach proposes that the control objective should not be tracking of position/force trajectories, but rather should involve the regulation of the mechanical impedance of the robot end-effector which relates velocity and force (Pathak, 2004).

Thus, the objective of impedance controller is to reduce very high contact impedance of the position controlled robot by controlling dynamic robot reaction to the external contact forces in order to compensate for uncertainties and tolerances in the relative robot/environment position, while maintaining acceptable force magnitudes. The interaction force between the robot and a fixed environment depends on the robot motion and the achieved target impedance. Under certain circumstances the impedance control may also be applied to realize a desired force, too. To ensure a successful accomplishment of a constrained motion task, the stiff robot position control behavior must be replaced with a compliant target impedance model.

Manipulation fundamentally requires the manipulator to be mechanically coupled to the object being manipulated; the manipulator may not be treated as an isolated system. The three-part papers published by Neville Hagan (1985) addressed an approach to the control of dynamic interaction between a manipulator and its environment. The first part presented a unified approach to manipulation termed "impedance control" by addressing theoretical reasoning and fundamental mechanics of interaction. Part II presented techniques for implementing desired manipulator impedance and the last part presented a technique for choosing the impedance appropriate to a given application using optimization theory.

Impedance control provides a fundamental approach for controlling a stiff industrial robot to interact with the environment. Impedance control mainly addresses the contact tasks for which the control of interaction force is not essential for the successful task execution. These contact tasks, such as an insertion task, require a specific motion of the work piece to be realized closely to external constraints in the presence of possible contact with the environment. This kind of motion is referred to as constrained or compliant robot motion. In essence, compliant motion tasks concern motion control problems.

Pathak et al (2005) presented a methodology for force control by impedance control at the interaction point between the space robot tip and the environment. The impedance control of a space robot is achieved by a virtual foundation. The effectiveness of the scheme is demonstrated through simulation and animation results. The impedance is shown to depend upon a compensation gain for the dynamics of the passive degree of freedom. It is observed that the controller is able to limit the interaction forces within the commanded value. In this paper, due to the interaction between the robot tip and the environment, the interaction forces act on the tip gets transmitted through links to the base of the vehicle and the orientation of the vehicle changes. If the simulation is extended over time, it is observed that the tip is not able to follow the trajectory due to change of CM location of the vehicle.

Pathak et al. (2009) presented a torque control strategy using impedance control at the interface of the end-effector and a space structure. The impedance control is achieved by the introduction of passive degrees of freedom called virtual foundation in the controller of the robotic system. When torque control is achieved, the vehicle attitude changes. The vehicle attitude is restored by an attitude controller. In this paper the authors used a methodology for torque control by impedance control at the interaction point between the robot tip and the environment is illustrated. The impedance control of a space robot is achieved by a virtual foundation. The efficiency of the scheme is demonstrated through simulation and animation results. It is observed that the controller is able to limit the interaction torques within the commanded value. This torque changes the attitude of space vehicle. The attitude is restored back to the initial value using a reaction wheel as an attitude controller.

Depending on the features of the robotic system the implementation is usually reduced to the two basic operating procedures (Miomir et al 2009):

- Position based impedance control and
- force based impedance control

Position-based impedance control: this control scheme is feasible to implement in commercial robotic systems. Position based impedance control is most reliable and suitable for implementation in industrial robot control systems since it does not require any modification of conventional position controller.

Force-based impedance control: Most of the impedance control algorithms utilize the computed torque method to cancel the nonlinearity in robot dynamics in order to achieve linear target impedance behavior. This popular approach requires computation of a complete dynamic model of the robot's constrained motion, which makes its realization rather complex. An important drawback of this approach is also the sensitivity to model uncertainties and parameter variations. Performance improvements that can be achieved with the algorithms in industrial robotics are not in proportion to the implementation efforts.

Satoko et al (2006) addressed an impedance control for a free-floating space robot in the grasping of a tumbling target with model uncertainty. In this paper the authors presented a novel and very simple method to derive a dynamic model for a free-floating robot in operational space, necessary for the desired control implementation. Furthermore, they derived an impedance control theory based on feedback linearization, to account for target parameter uncertainty.

## V. Conclusion

Over the last decade, we have seen tremendous progress in science exploration of Mars through use of robotics systems. The systems have enabled extended missions on a faraway planet without deployment of astronauts. More recently, robots have also been deployed on the international space station to explore how some of the menial tasks can be performed by a robot in comparison to use of astronauts. Repetitive, high-precision, and extended tasks are all examples of where a robot may offer an advantage over use of humans. This paper is devoted to review the control strategies for trajectory, attitude and impedance control of space robots. The paper addressed the state-of-the-art in the three main control strategies, trajectory control, attitude control and, impedance control of space robot.

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