The Kinematics, Dynamics, and Control of Free-Flying and Free-Floating Space Robotic Systems

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***Abstract*—The dynamics of space robotic systems can be quite complex and hence their control can be difficult. In this paper some important dynamics and control problems, unique to space robotic systems are discussed. Particular attention is paid to free-flying and free-floating space robots that might be used for such tasks as space station repair and construction. Recent advances made by the research community in solving these problems are briefly reviewed. Three examples of promising methods for planning and controlling the motion of space robotic systems are presented. It is suggested that a thorough understanding of the fundamental dynamics of these systems, will result in effective solutions to their control problems.**

I. Introduction

Autonomous robotic and telerobotic systems have been suggested for a number of important missions in space. Free-flying robotic and telerobotic systems have been considered for retrieving, repairing and servicing satellites in earth orbit, see Fig. 1(a). Highly dexterous robots carried by large articulated manipulator systems and transporter vehicles have been proposed to construct future space stations, see Fig. 1(b). Other systems have been considered for automating some of the routine functions of space station based scientific experiments. Roving robotics have also been considered for exploring the planets.

To date such technically ambitious systems have yet to be realized, in part, because new technology is needed to achieve the robotic system capabilities required for these missions. Some critical technical problems must be solved in a number of areas, including in dynamics and control. Many of these dynamics and control problems are not unique to *space* robotics. A number of the dynamics and control problems faced by the designers of space robotic systems are unique to this area, because of the distinctive and complex dynamics found in many potentially important space robotic applications. This paper focuses on these problems. The paper considers some representative types of space robotic and telerobotic systems, identifying some of their unique planning and control problems, with a particular focus on the very challenging problems posed by free-flying and free-floating space robots. It also briefly reviews certain accomplishments that have been made by the research community in the solution of some of these problems. Results from three example studies of planning and control problems unique to space robotics are presented. These examples illustrate the challenges of controlling space robots. They also suggest that the solutions to the problems of planning and control of space robotic systems lie in understanding the fundamental dynamic behavior of these systems.

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II. Future Space Robotic Systems and Their Control

A number of studies have proposed *free-flying* manipulator systems such as shown in Figure 1(a) for space missions [1], [4], [5], [7], [13], [40]. In a free-flying space manipulator system, and during the activity of its manipulator, the position and attitude of the system's spacecraft is controlled actively by reaction jets (thrusters). Such a system is clearly highly redundant giving it versatility, and a nearly unlimited workspace. However free-flying space systems present some unique control challenges. For example, the motions of the manipulator can disturb its spacecraft's position and attitude. These disturbances could result in the consumption of excessive amounts of reaction jet attitude control fuel. Attitude control fuel is a nonrenewable and expensive resource in space. Its excessive use could greatly limit a free-flying system's useful "on-orbit" life. Such problems represent challenging planning and control situations that must be addressed. As discussed below, while some important progress has been made, substantial work remains.

A *free-floating* space robotic system is one in which the spacecraft's position and attitude are not actively controlled during manipulator activity to conserve attitude control fuel. In which case the spacecraft will move freely in response to the dynamical disturbances caused by the manipulator's motions. Control algorithms for free-floating systems have been proposed to accommodate the uncontrolled spacecraft. Problems not found in terrestrial systems have surfaced. For example, these systems have been shown to exhibit previously unknown *dynamic singularities*, which can seriously degrade a free-floating system's performance [35], [36]. Even the kinematics of free-floating systems become quite complex. For example, as discussed below, defining the workspace of a free-floating system is not a simple matter.

The control of space robotic systems is made difficult by a number of factors. For example, the need for space systems to be light weight means that space robots will be flexible and have relatively small actuators. Hence, their control systems must handle the difficult problems of accommodating and compensating for low frequency resonances and nonlinear actuator saturation. Also, planetary exploration systems will be faced with the problems of controlling a system with long time-delays, while operating with a mobile compliant base in a highly unstructured environment with relatively limited sensing information for control.

Clearly, the dynamics and control of future robotic systems present difficult challenges to the research community. The following section briefly reviews some of the recent progress made in solving these problems. Then certain examples of what we believe are potentially effective approaches for planning and controlling the activities of space robotic are presented.

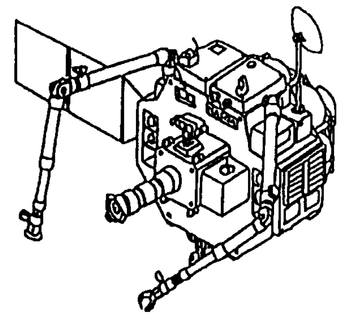
III. Current State of the Art—A Brief Review of the Literature

The difficulty of recreating space conditions on earth and the need for accurate simulation and prediction of the behavior of such systems makes the dynamic modeling of space robots important. As discussed later in the paper in some detail, a good understanding of a space robot's dynamics is essential in designing a system with a good basic dynamic behavior, and in designing and implementing its control and planning algorithms. The dynamics of multibody systems have been studied by researchers in both the robotics and aerospace communities. Robotics research has been mainly interested in fixed-based manipulator dynamics, with primary focus on Newton–Euler and Lagrangian formulations, and recently on Kane's method [29], [17], [24]. These methods can be extended to include the effects of a moving base [46].

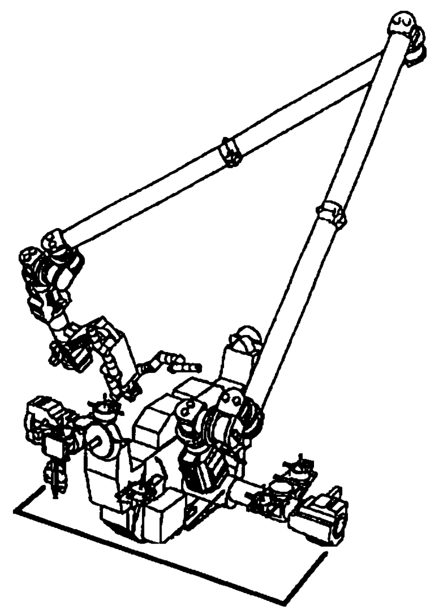
The main approaches in the aerospace literature that can be applied to the dynamic modeling of space robotic systems are reviewed in [21], [23], [27]. Newton–Euler approaches to multibody dynamics were pioneered by Hooker and Margulies, and by Roberson and Wittenburg [18], [41]. General characteristics of these methods are the use of a tree topology to describe open chains of multibody systems, the choice of the system Center of Mass (CM) to represent the translational DOF, and the introduction of the so-called *barycenters* and *augmented bodies* that simplify the systematic occurrence of certain weighted linear combinations. In the direct-path method employed by Ho, Frisch, and Hooker, a body of the system is chosen to be the home body and a point on it to represent the translational DOF of the system [16], [14], [19]. The equations that result are coupled but simpler to interpret. The Virtual Manipulator (VM) technique, proposed by Vafa, can be used to simplify the dynamics of space robotic systems [48]–[52]. The VM decouples the system CM translational DOF, and hence, it simplifies the equations of motion. The VM is discussed in some detail in Section IV of this paper.

Motion control implies that the manipulator moves its end-effector to specified locations in the inertial or spacecraft frames, without significant force interactions between its end-effector and its environment. A payload may be considered as part of its last link. A number of control techniques for space manipulators have been proposed, some of which are presented in [58]. These schemes can be classified in four categories. In the first category, the spacecraft position and attitude are fixed by compensating for any dynamic forces exerted on the spacecraft by its manipulator. In such case, control techniques for terrestrial manipulators can be used. For example, Dubowsky *et al.* proposed a time optimal trajectory planning technique that avoids the saturation of a spacecraft's thrusters [11]. However, the consumption of relatively large amounts of attitude control fuel, can limit a system's useful life. Based on a study of the dynamic characteristics of such systems, Dubowsky and Torres employed heuristic path planning methods, that can reduce the use of control fuel, and therefore extend a system's life [8], [9], [45]. This approach, called the Enhanced Disturbance Map (EDM), is discussed in further detail in Section V of this paper.

In the second category, a spacecraft's attitude is controlled, while its translation is not. Longman *et al.* proposed a control scheme that estimates the required moments to keep a



(a)



(b)

Fig. 1. Two proposed space robotic systems. (a) The Japanese Free-Flying ETS VII [56]. (b) The Canadian Special Purpose Dexterous Manipulator (SPDM) on the space station remote manipulator system (SSRMS).

spacecraft's orientation fixed, and uses reaction wheels to provide these moments to the spacecraft [28]. Walker and Wee designed an adaptive controller to achieve globally stable end-effector trajectory tracking [53]. In general, manipulator control of controlled-attitude space systems is somewhat more involved than that where both position and attitude are controlled. The VM technique can be used in path planning and workspace analysis of such systems [48]–[52].

In the third category, consisting of free-floating systems, the spacecraft is permitted to translate and rotate freely in response to manipulator motions. Reaction jet fuel is conserved, and sudden motions of the manipulator end-effector due to reaction jet firing are avoided. Clearly, this approach can only be used in the absence of external forces and torques. Momentum dump maneuvers need be employed to remove any accumulated momentum [36], [37]. The analysis of these systems, also can be simplified using the VM approach [48]–[52]. Alexander and Cannon proposed a control scheme based on the resolved acceleration algorithm, and used it to control successfully an experimental two-DOF planar free-floating system [2]. Their controller relied on end-point position feedback provided by a video camera mounted on the spacecraft. Umetani and Yoshida derived a Generalized Jacobian for a free-floating system and proposed a control algorithm based on the resolved rate algorithm [47]. Their experimental two-DOF planar system used end-point measurements provided by an inertially fixed video camera. Masutani *et al.* proposed a transposed Jacobian controller using a Jacobian derived for a fixed-based system [30]. This controller included end-point feedback and was capable of driving the end-effector to a desired location, provided that the spacecraft mass and inertia are large; otherwise, stability problems were encountered. Similar simplifying attempts are reported in [26], [32]. Papadopoulos and Dubowsky showed the existence of *Dynamic Singularities* (DS), whose location in the joint space depends on a system's mass properties. The location of the DS in the Cartesian space is *path dependent* [35], [37]. The fundamental dynamic nature of free-floating space robots was analyzed by Papadopoulos and Dubowsky who showed that nearly any control algorithm derived for terrestrial robotic systems, also can be employed in controlling free-floating systems, provided that the correct dynamic models are used and that dynamic singularities are avoided [36]. Path Independent Workspaces (PIW) were defined in which no such singularities occur [35], [37]. A brief review of this study is presented in Section VI in this paper.

In the fourth category, consisting of free-flying systems, the spacecraft's thrusters are used to reach some desired location and orientation in space, hence realizing a practically unlimited workspace. To reduce use of reaction fuel, Spofford and Akin proposed a free-flying system switching between free-flying and free-floating control modes [43]. During the free-flying mode, the system is controlled in a coordinated way as a redundant manipulator. Papadopoulos and Dubowsky designed a Coordinated Control algorithm that maintains a large workspace and allows the specification of a desired trajectory for both the end-effector and the spacecraft [33]. This algorithm fails gracefully in the case of conflicting trajectories. Coordinated control is briefly presented in Section VI of this paper.

The nonintegrability of the angular momentum in free-floating systems complicates their planning, but also offers the opportunity of achieving additional tasks. For example, Vafa proposed a self-correcting planning technique that allows the control of a spacecraft's orientation using a manipulator's joint motions [50], [52]. Nakamura and Mukherjee discussed the nonholonomic characteristics of free-floating space manipulators, and employed Lyapunov functions for path generation aiming at controlling both the manipulator configuration and the spacecraft orientation [31]. Yoshida *et al.* proposed that one of the manipulators of a free-flying system should move to compensate for the attitude disturbances created by the other [60]. To extend the useful workspace of a free-floating system, Papadopoulos proposed a planning algorithm that avoids dynamic singularities, and permits the manipulator's end-effector to move from any reachable workspace location to any other [38], [39]. However, the construction of paths that are optimal with respect to the execution time remains an open area of research.

Reliability in space robots is important. Clearly, increased reliability can be achieved by redundancy and proper design, see for example [57]. However, in some cases the dynamic characteristics of a system can be used to control a failed system. For example, Papadopoulos and Dubowsky proposed a Failure Recovery controller that, under certain conditions, allows the control of a manipulator failed joint using dynamic coupling between the failed and some operating joint [34]. Aiming to the design of more economical manipulator systems, Arai and Tachi reported a method of controlling a system with fewer actuators than joints, by using joint brake action [3]. The exploitation of the dynamical characteristics of a space system aiming at improving its control represents a promising area of future research.

Significant efforts have been placed in designing and building test beds that can be used in evaluating and verifying system designs and control techniques for space robots. One fundamental problem is the creation of weightless conditions in a laboratory environment. Simple experimental setups employ planar space robots floating on air bearings [2], [30], [47]. In spatial test beds, the effect of gravity is either eliminated in neutral buoyancy tanks, or estimated and subtracted in some way [15], [22], [42], [44], [54]. The forces required to cancel gravity are provided by suspension cables, other manipulators, servo drives, or by Stewart platforms [12], [15], [22], [42], [44], [56]. For example, the vehicle emulator system at MIT consists of a six-DOF Stewart mechanism that emulates the spacecraft (base) of a space robot, see Fig. 2. The gravitational forces and moments transmitted by the manipulator to its base are estimated as a function of its configuration and subtracted from the total transmitted forces and moments, allowing the base (emulated spacecraft) to move under the action of the dynamic forces only [10], [12], [54].

Several conclusions can be made from the above review of the literature. First, there is a relatively large amount of research being done in this field. The above discussion has been largely restricted to the dynamics and control of

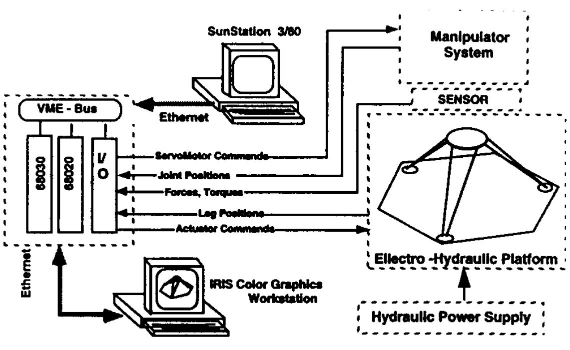


Fig. 2. The VES II Space Emulation System at MIT.

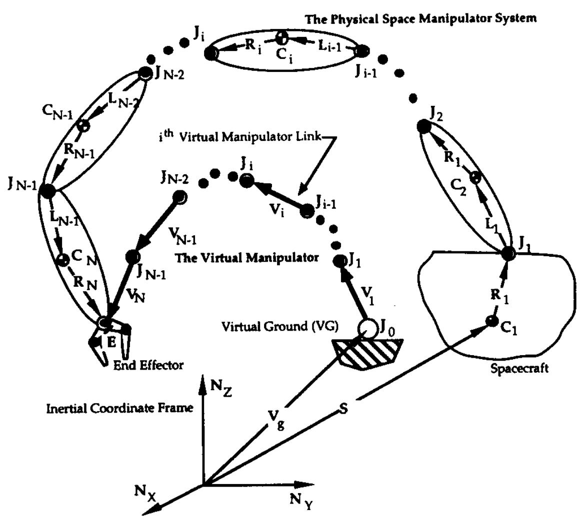


Fig. 3. A serial space robotic manipulator system and its Virtual Manipulator.

rigid systems, in near earth orbit, performing relatively simple motion tasks. Even so, the review could only touch on a few of the studies that have been reported in the literature. Second, the problems being treated are quite difficult. From a dynamics and controls point of view, robots in space offer some very challenging problems due to their unique dynamics. Problems that are far from being solved. Finally, the control studies that seem to have the largest degree of success are based on a solid understanding of the dynamic characteristics of these systems. In the following sections, a few of these studies are briefly reviewed.

IV. The Virtual Manipulator Model—With an Application to Workspace Analysis

As discussed above, the motions of a space manipulator, if not controlled, will disturb the attitude and position of its spacecraft. Due to the lack of a fixed base, planning and controlling the motions of such systems is difficult. This section reviews a very effective analytical modeling method for space manipulators called the Virtual Manipulator (VM). The kinematics and dynamics of a free-floating space manipulator system, can be described relatively easily using the VM. As a result, the planning and control of these systems can be made far easier. A more complete description of the VM and its applications can be found in references [49]–[52].

The VM is an ideal kinematic chain connecting its base, the virtual base (VB) to any point on a free-floating manipulator. This point can be chosen as the manipulator's end effector. As the real manipulator moves, the end of the VM remains coincident with the selected point on the real manipulator, and its base remains attached to a fixed point in inertial space, called a virtual ground (VG). It can be shown that the joint displacements of the real manipulator and those of the VM are equal for revolute joints, and they are simply related for prismatic joints. The VG is located at the CM of the manipulator-spacecraft system. The VM gives system analysts and designers the ability to represent a free-floating system by a much simpler fixed system. In this section the VM is described and applied in studying space manipulator workspaces.

A. The Virtual Manipulator Structure And Its Construction

The 1st VM link corresponds to the spacecraft, and its orientation corresponds to the spacecraft's attitude, see Fig. 3. This link is attached to the fixed VG by a spherical joint that permits the three spacecraft rotations with respect to inertial space. The end of the virtual manipulator terminates at the end-effector of the real manipulator, point E, fixed in the Nth link. A VM can be constructed to any point in the real manipulator, a useful fact in writing the dynamic equations for the system [50]. The ith VM joint will be a revolute or a prismatic joint depending upon whether the ith joint of the real manipulator is revolute or prismatic joint. The axis of rotation for a revolute VM joint is parallel to the axis of the real manipulator joint J_i. Similarly the translational axis of prismatic VM joints is parallel to the corresponding axis of the real manipulator prismatic joints.

Virtual manipulators exist for different manipulator structures, such as open or closed chains, or multiple arms. Here the analytical construction of the virtual manipulator is given for an N body serial manipulator system, see Fig. 3. The ith joint is referred to as J_i, and C_i is the CM of the ith body. The first body is the spacecraft, and the Nth body is a combination of the end effector and its payload. The body fixed vectors $\boldsymbol{R}_i$ and $\boldsymbol{L}_i$ are defined in Fig. 3. The vector $\boldsymbol{R}_N$ connects $\boldsymbol{C}_N$ to the end effector, E. The ith link in this system's virtual manipulator, shown in Fig. 3, is defined by the vector $\boldsymbol{V}_i$, where

$$\begin{aligned} \boldsymbol{V}_1 &= \boldsymbol{D}_1 \\ \boldsymbol{V}_2 &= \boldsymbol{H}_1 + \boldsymbol{D}_2 \\ \boldsymbol{V}_i &= \boldsymbol{H}_{i-1} + \boldsymbol{D}_i \\ \boldsymbol{V}_N &= \boldsymbol{H}_{N-1} + \boldsymbol{D}_N \end{aligned} \tag{1}$$

where $\boldsymbol{D}_i$ and $\boldsymbol{H}_i$ are given by

$$\boldsymbol{D}_i = \left[\sum_{q=1}^{i} M_q / \sum_{q=1}^{N} M_q\right] \boldsymbol{R}_i \quad i = 1, \cdots, N \tag{2}$$

$$H_i = \left[\sum_{q=1}^{i} M_q / \sum_{q=1}^{N} M_q\right] L_i \quad i = 1, \cdots, N-1. \quad (3)$$

The VG is located at the CM of the system and given by

$$V_g = (m_1 S + m_2(S + R_1 + L_1) + \cdots + m_N(S + R_1 + L_1 + \cdots + R_{N-1} + L_{N-1}))/(m_1 + m_2 + \cdots + m_N). \quad (4)$$

where S is the vector locating the spacecraft CM, see Fig. 3.

Equations (1) through (4) specify a VM in a position corresponding to the initial position of the real system. The VM will move as the joints of the real manipulator move. The angular rotations of the VM revolute joints, from their initial position, are equal to the angular rotations of the corresponding revolute joints of the real manipulator. The prismatic virtual joint translations are ratios of the corresponding real prismatic joint translations. For the end effector VM, the translation of the virtual joint, P_j, is given by

$$P_j/T_j = \sum_{q=1}^{N} M_q / \sum_{q=1}^{N} M_q \qquad i = 1, \cdots, N-1 \quad (5)$$

where T_j is the translation of the jth real prismatic joint.

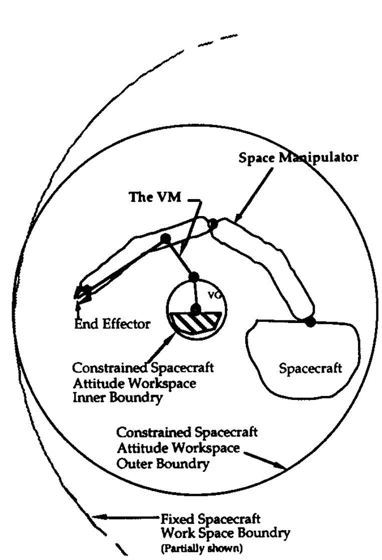


Fig. 4. Space system with its fixed and constrained spacecraft attitude work spaces.

B. Workspace Analysis: An Example Application of the VM Approach

The virtual manipulator approach can be applied to a number of space manipulator problems. VMs can be used to simplify the inverse kinematics of manipulators, calculate the workspace of the system, to aid in path planning analysis, design, and control synthesis, and to formulate the equations of motion, see references [51]–[53]. It should be noted that these problems are far more difficult for manipulators in space than for standard manipulators with fixed bases. The use of the VM in calculating the workspaces of a free-floating system is briefly presented in this section to demonstrate its utility.

First, three different types of space manipulator workspaces need to be defined. These depend on whether the system uses reaction jets, reaction wheels or neither to control its spacecraft. If reaction jets keep the spacecraft stationary, the system workspace is simply the same as it would be on earth, called here the fixed spacecraft workspace. Clearly, conventional workspace analysis methods, such as described in [59], can be used to solve this problem. If neither reaction jets nor reaction wheels are used, the spacecraft will move, and this will affect the manipulator end-effector's location in inertial space. Hence, a free-floating manipulator will not be able to reach all the points that could be reached by the same manipulator with a fixed base. This reduced workspace is called the Free Spacecraft Workspace, or the Free Workspace. Finally in cases where the attitude, but not the location, of the spacecraft can be controlled, say by reaction wheels, a third workspace called the Constrained Spacecraft Attitude Workspace results, or the Constrained Workspace. These latter two more complex workspaces can be understood and found quite easily using the VM approach. First, a system's VM is found. Any joint limits of the real manipulator are transformed into VM joint limits. The Constrained Workspace can be found directly from applying conventional analysis methods to this VM representation because, in this case, all the links of the VM, including the first, are controlled. This workspace will in general be a spherical shell due to the three possible rotations of the spacecraft.

Fig. 4 shows the fixed spacecraft, and Constrained Spacecraft Attitude Workspaces for a simple planar manipulator system. As can be seen in Fig. 4, the Fixed Workspace is quite large. The Constrained Spacecraft Attitude Workspace, found using the VM, is substantially smaller.

In finding the workspace of a completely free-floating manipulator system, it needs to be recognized that the spacecraft attitude affects which points the manipulator can reach. Since this attitude is not controlled, the free workspace is the region in inertial space that the manipulator is able to reach, *without regard* to its spacecraft attitude. This workspace can be found by first finding all VM workspaces corresponding to all fixed spacecraft attitudes, such as the one shown in Fig. 5. These are found relatively easily using the conventional methods with the first link of the VM held stationary with an orientation corresponding to the assumed spacecraft attitude. The intersection of all of these workspaces forms the Free Workspace. Any point in this region can be reached without consideration of the spacecraft attitude. Fig. 5 shows the Free Workspace of the simple manipulator shown in Fig. 4. Additional analysis of the workspaces for free-floating systems will be given in Section VI.

In this section, the concept of the Virtual Manipulator, an approach based on the fundamental mechanics of space robotic systems, has been introduced and shown that can be useful in analyzing and understanding the complex kinematic and

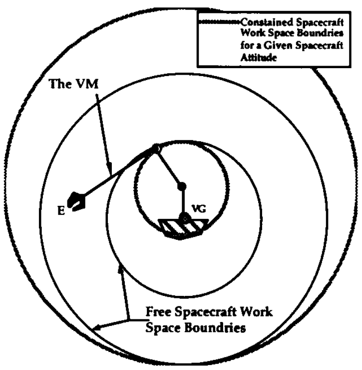


Fig. 5. Finding a system's free spacecraft work space using its Virtual Manipulator.

dynamic characteristics of space robotic systems. In the cited references it has been shown also to be effective for treating a number of other planning, design and control problems.

V. Path Planning—Finding Manipulator Motions to Reduce Spacecraft Attitude Disturbances

As discussed above, the dynamic disturbances of a space manipulator's motions to a system's attitude and position can be controlled using its attitude control reaction jets. However, the control fuel required could limit the life of the system [5]. Planning algorithms to minimize the dynamic disturbances have been proposed [6], [9], [11], [32], [45], [46], [48], [50]. In this section a method, called the Enhanced Disturbance Map (EDM), is briefly described. Its use for planning the motions of a redundant space manipulator to reduce attitude fuel usage is outlined.

A. The Enhanced Disturbance Map (EDM)

Consider an N-DOF rigid manipulator mounted on a spacecraft. The spacecraft's inertial position and orientation in body fixed axes are $\boldsymbol{X}_b = [x, y, z]^T$, and $\boldsymbol{\Theta}_b = [\phi, \theta, \psi]^T$, respectively. The manipulator joint angles are $\boldsymbol{q} = [q_1, q_2, \cdots, q_n]^T$. Infinitesimal changes in the spacecraft's attitude measured with respect to its body-fixed axes, $\delta\boldsymbol{\Theta}_b$, can be expressed as a function of infinitesimal manipulator joint motions, $\delta\boldsymbol{q}$, as $\delta\boldsymbol{\Theta}_b = \boldsymbol{G}(\boldsymbol{q})\delta\boldsymbol{q}$, where $\boldsymbol{G}$ is a 3 by N disturbance sensitivity matrix [50]. The vector $\delta\boldsymbol{\Theta}_b$ is defined as the instantaneous disturbance.

Singular value decomposition of $\boldsymbol{G}(\boldsymbol{q})$ gives the directions and magnitudes of the maximum and minimum spacecraft disturbances in joint space. These directions are orthogonal in joint space, and in some cases the magnitude of the minimum disturbance is exactly zero. In the original disturbance map these maximum disturbances were mapped onto each point $\boldsymbol{q}$ in joint space, [48], [50]. The more effective EDM [45], [46], [8], [9] can be found by writing the system's generalized momentum vector, $\boldsymbol{\pi}$, as

$$\boldsymbol{\pi} = H(\boldsymbol{\xi})\dot{\boldsymbol{\xi}} = \begin{bmatrix} \boldsymbol{A} & \boldsymbol{B} \\ \boldsymbol{C} & \boldsymbol{D} \end{bmatrix} \quad (6)$$

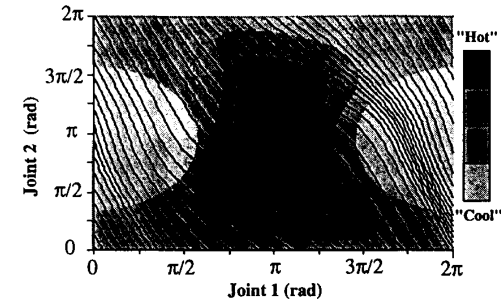


Fig. 6. An Enhanced Disturbance Map.

where $\boldsymbol{\xi}$ is $[\boldsymbol{X}_b^T, \boldsymbol{\Theta}_b^T, \boldsymbol{q}^T]^T$, $\boldsymbol{H}(\boldsymbol{\xi})$ is an $N+6$ by $N+6$ symmetric, positive definite inertia matrix, and the elements of $\boldsymbol{\pi}$ are $\pi_x, \pi_y, \pi_z, \pi_\phi, \pi_\theta, \pi_\psi, \pi_1, \pi_2, \cdots, \pi_n$. The π_x, π_y, and π_z terms are the x, y, z linear momentum components of the CM of the spacecraft; and π_ϕ, π_θ,and π_ψ, are the components of the angular momentum of the spacecraft, all measured with respect to the spacecraft fixed axes. The $\pi_1, \pi_2, \cdots, \pi_n$ terms are the generalized momentum components in the direction of each of the manipulator's respective joint axes. The submatrices $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$, and $\boldsymbol{D}$ are defined in [46]. Assuming zero external forces or moments, and a system initially at rest, $\boldsymbol{\pi}$ is equal to zero, and (6) yields

$$[\dot{\boldsymbol{X}}_b^T, \dot{\boldsymbol{\Theta}}_b^T]^T = -\boldsymbol{A}^{-1}\boldsymbol{B}\dot{\boldsymbol{q}} \quad (7)$$

A discussion of the validity and utility of the above assumption in fuel minimization path planing is contained in [45]. Replacing the derivative operation by a variation, letting $\boldsymbol{Z} = [\boldsymbol{z}_1^T, \boldsymbol{z}_2^T]^T = -\boldsymbol{A}^{-1}\boldsymbol{B}$, and noting that $\boldsymbol{z}_1$ and $\boldsymbol{z}_2$ are 3 by N matrices, (7) becomes

$$\begin{bmatrix} \delta\boldsymbol{X}_b \\ \delta\boldsymbol{\Theta}_b \end{bmatrix} = \begin{bmatrix} \boldsymbol{Z}_1 \\ \boldsymbol{Z}_2 \end{bmatrix} \delta\boldsymbol{q}. \quad (8)$$

Equation (8) gives a relationship between the changes in orientation of the base $\delta\boldsymbol{\Theta}_b$ and motion of the manipulator joints $\delta\boldsymbol{q}, \delta\boldsymbol{\Theta}_b = \boldsymbol{z}_2\delta\boldsymbol{q}$. So $\boldsymbol{G}$ required for the EDM is simply $\boldsymbol{z}_2$, a submatrix of $-\boldsymbol{A}^{-1}\boldsymbol{B}$, which can be computed easily [46]. Singular value decomposition of the matrix $\boldsymbol{z}_2$ gives the directions and magnitudes of maximum and minimum disturbances (usually zero). The EDM shows the directions of minimum disturbances at an arbitrary point in joint space, $\boldsymbol{q}$. In the map, these directions are jointed into lines of minimum disturbance, such as shown in Fig. 6. Manipulator motions on a path following these lines will not disturb the attitude of its spacecraft. The lines are colored proportionally to the maximum disturbance magnitude that would result for joint motions perpendicular to the line.

B. Reducing Spacecraft Disturbance Path Planning

A number of methods using the EDM to suggest paths which result in reduced rotational spacecraft disturbances have been developed and studied in detail [8], [9], [45], [46]. The exact relationship between reduced rotational spacecraft disturbances and minimizing total fuel usage is not simple, see [45]. However, it generally is the case that a manipulator path

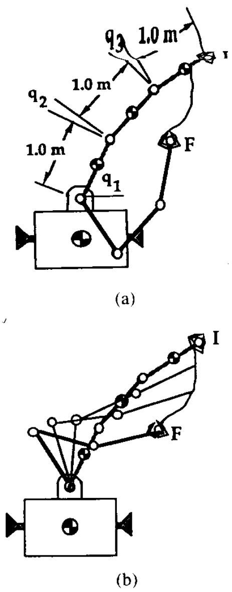


Fig. 7. Redundant manipulator paths-common inertial space end-points. (a) An arbitrary path. (b) Minumm disturbance path.

that results in a low disturbance, will result in relatively low fuel usage.

Here, an example of using an EDM to find minimum disturbance paths for a redundant manipulator, is briefly outlined. Consider the three-link redundant manipulator, shown in Fig. 7(a), moving in a planar space from inertial point I to inertial point F.

The three-dimensional EDM for this system is shown in Fig. 8. For this redundant manipulator, paths of minimum angular disturbance motion lie on two dimensional manifolds, or surfaces in the EDM, rather than on lines as is the case for nonredundant manipulators. The minimum disturbance surface passing through the initial configuration of system, see Fig. 8, can be found by the direct application of the above equations and singular value decomposition. Because the manipulator is redundant, the final position of the end effector in inertial space, F, maps into a locus of points, a curved line, in the EDM. If the final EDM position is chosen as the intersection of the minimum disturbance surface passing through the initial configuration and this locus, and if the path from the initial to final configuration is chosen to lie in the minimum disturbance surface, then manipulator motion will not result in any angular disturbance to the spacecraft. This can be computed relatively easily [45].

Fig. 8 shows two EDM paths. The first is the minimum disturbance path computed as described above. The second joint path to the final inertial end-point position is selected arbitrarily, and does not lie on the minimum disturbance surface passing from the initial configuration. These two paths are shown in inertial space in Fig. 7. The motions along the two paths were simulated allowing reaction jets to compensate for any dynamic disturbance, and the fuel usage was recorded. The velocity profile along the path was chosen to be a half sinusoidal wave with initial and final velocities equal to zero,

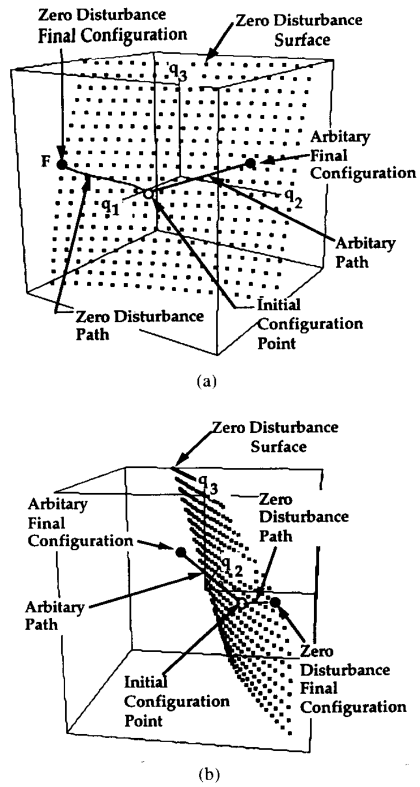


Fig. 8. Redundant manipulator EDM paths. (a) Front view. (b) Back view.

and with a maneuvers time of 2 seconds. For the arbitrary path, the total angular and linear fuel required was 0.587 units of fuel. The minimum disturbance path required only 0.160 units, a substantial reduction. This minimum disturbance path fuel was required mostly to compensate for the translational disturbances to the spacecraft.

Planning the motions of space manipulators involves problems such as the minimization of dynamic disturbances, not found in conventional robotic systems. However, methods such as the Enhanced Disturbance Map can be developed to aid in understanding these problems, and in generating solutions. The EDM has evolved from studying the fundamental dynamic properties of space robotic systems. A more complete description of the EDM and its applications can be found in references [8], [9], [45], [46]

VI. The Control of Free-Flying/ Floating Space Robots—A Fundamental Approach

A. Free-Flying Space Robots

In free-flying space robots, spacecraft thrusters can be used to either maintain a constant spacecraft position and orientation, or track a prescribed one, despite any dynamic disturbances induced by a system's manipulator. Since both a manipulator and its spacecraft can be controlled, system safety can be improved by commanding trajectories that avoid collisions with other neighboring objects. In addition, by controlling a spacecraft's position and orientation, the end effector can reach its target with the manipulator in a predetermined desired configuration, i.e., a configuration suitable for applying some prescribed forces, or in one that is away from singularities. For the above reasons, it is advantageous to be able to control simultaneously both a free-flying system's spacecraft and its manipulator. To this end, a dynamic model describing the behavior of the free-flying system as a whole, is required. This is addressed next.

B. Dynamic Modeling of a Free-Flying Space Manipulator

Constructing a dynamic model can be achieved in many ways depending on the principles used, coordinates used, etc. Here, a quasi-Lagrangian method is used to reveal the structure of the system equations of motion. The system CM is chosen to represent the translational motion of the system. This choice has the advantage of decoupling the translational variables from the rotational variables. The resulting equations readily yield the conservation of momentum equations when the spacecraft's actuators are not in use and the system is free-floating. In the following sections, left superscripts correspond to the frame in which a vector or matrix is written. A missing left superscript implies a vector or matrix expressed in the inertial frame.

Fig. 9 shows a free-flying space robot consisting of a spacecraft (body 0), and an N -DOF manipulator (bodies $1, \cdots, N$) with revolute joints, in an open chain kinematic configuration. The manipulator joint angles are described by the $N \times 1$ vector $\boldsymbol{q}$. The system CM linear velocity ${}^0\dot{\boldsymbol{r}}_{\rm cm}$, the spacecraft angular velocity expressed in the spacecraft's frame ${}^0\boldsymbol{\omega}_0$, and the manipulator joint rates $\dot{\boldsymbol{q}}$ are chosen as the system independent velocities, and are grouped in vector $\boldsymbol{v} \equiv [{}^0\dot{\boldsymbol{r}}_{\rm cm}^T, {}^0\boldsymbol{\omega}_0^T, \dot{\boldsymbol{q}}^T]^T$, see Fig. 9. The linear and angular velocity of point m in body $k, \boldsymbol{v}_{k,m}$, is given by

$$\begin{aligned}\boldsymbol{v}_{k,m} &= [\dot{\boldsymbol{r}}_{k,m}^T, \boldsymbol{\omega}_k^T]^T = \boldsymbol{J}_{k,m}^+ \boldsymbol{v} \\ &= \mathrm{diag}(\boldsymbol{T}_0, \boldsymbol{T}_0)^0\boldsymbol{J}_{k,m}^+(\boldsymbol{q})\boldsymbol{v} \end{aligned} \tag{9}$$

where $\boldsymbol{T}_0$ is a rotation matrix that describes the orientation of the spacecraft, and $\boldsymbol{J}_{k,m}^+$ and ${}^0\boldsymbol{J}_{k,m}^+$ are 6 by $N+6$ nonsquare matrices, even when $N = 6$. This underlines the redundant nature of such a system. Since any position or orientation can be reached by moving the spacecraft alone, the rank of these Jacobians is always six [33], [37]. For the end-effector velocity $\boldsymbol{v}_E$, we write simply

$$\boldsymbol{v}_E = [\dot{\boldsymbol{r}}_E^T, \boldsymbol{\omega}_E^T]^T = \boldsymbol{J}^+ \boldsymbol{v}. \tag{10}$$

The equations of motion for the system shown in Fig. 9, are written using a Lagrangian approach. The potential energy due to gravity is zero and since the system is assumed to be rigid, the potential energy due to strain is also zero. Hence, the system Lagrangian is equal to the system kinetic energy given by [33], [37]

$$T = \frac{1}{2}\boldsymbol{v}^T \boldsymbol{H}^+(\boldsymbol{q})\boldsymbol{v} \tag{11}$$

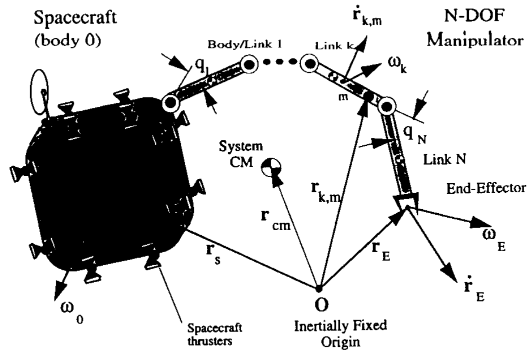


Fig. 9. A free-flying space manipulator system.

where $\boldsymbol{H}^+(\boldsymbol{q})$ is a $N+6$ by $N+6$ positive definite symmetric inertia matrix, given by

$$\boldsymbol{H}^+(\boldsymbol{q}) = \begin{bmatrix} M\mathbf{1} & 0 & 0 \\ 0 & {}^0\boldsymbol{D}(\boldsymbol{q}) & {}^0\boldsymbol{D}_q(\boldsymbol{q}) \\ 0 & {}^0\boldsymbol{D}_q(\boldsymbol{q})^T & {}^0\boldsymbol{D}_{qq}(\boldsymbol{q}) \end{bmatrix} \tag{12}$$

where $\mathbf{1}$ is the unit 3 by 3 matrix, 0 a zero matrix of appropriate size, and M the system total mass. ${}^0\boldsymbol{D}$ is the 3 by 3 system inertia matrix with respect to the system CM, and as such it is a positive definite symmetric matrix. ${}^0\boldsymbol{D}_q$ is a 3 by N matrix, and ${}^0\boldsymbol{D}_{qq}$ is an N by N matrix. The matrices ${}^0\boldsymbol{D}, {}^0\boldsymbol{D}_q$ and ${}^0\boldsymbol{D}_{qq}$ are functions of the configuration $\boldsymbol{q}$ only, and they can be expressed as functions of the body-fixed barycentric vectors [55], [37]. The inverse of ${}^0\boldsymbol{D}$ always exists because the system inertia matrix is positive definite. The $N + 6$ equations of motion are, see [33], [37]

$$\boldsymbol{H}^+(\boldsymbol{q})\dot{\boldsymbol{v}} + \boldsymbol{C}^+(\boldsymbol{q}, {}^\circ\omega_0, \dot{\boldsymbol{q}}) = \boldsymbol{Q}_c + \boldsymbol{Q}_d \tag{13}$$

where the term $\boldsymbol{C}^+$ contains the nonlinear terms of the equations of motion, $\boldsymbol{Q}_d$ is a disturbance vector, and $\boldsymbol{Q}_c$ is a control force vector, given by

$$\boldsymbol{Q}_c = \boldsymbol{J}_q^T[{}^0\boldsymbol{f}_S^T, {}^0\boldsymbol{n}_S^T, \boldsymbol{\tau}^T]^T. \tag{14}$$

The control forces $\boldsymbol{Q}_c$ include the spacecraft forces ${}^0\boldsymbol{f}_S$ that can be generated by thruster actuators, the spacecraft torques ${}^0\boldsymbol{n}_S$ which can be generated by thruster actuators, momentum gyros or reaction wheels, and the manipulator joint torques, $\boldsymbol{\tau}$. The transmission Jacobian, $\boldsymbol{J}_q$, is square and always invertible.

C. Control of Free-Flying Systems

To control the end-effector and the spacecraft Cartesian position and orientation, $\boldsymbol{z} = [\boldsymbol{r}_E^T, \boldsymbol{\Theta}_E^T, \boldsymbol{r}_S^T, \boldsymbol{\Theta}_S^T]^T$, in a coordinated way, a relation between the independent velocities $\boldsymbol{v}$, and the output velocities $\dot{\boldsymbol{z}}$, is required. To this end, the Euler angle rates of the k^{th} body, $\dot{\boldsymbol{\Theta}}_k$, are expressed as functions of the corresponding $\boldsymbol{\omega}_k$

$$\dot{\boldsymbol{\Theta}}_k = \boldsymbol{S}^{-1}(\boldsymbol{\Theta}_k)\boldsymbol{\omega}_k \quad k = 0, \cdots, N \tag{15}$$

where $\boldsymbol{S}$ is an invertible matrix, except at some isolated points. Using (9) written for the spacecraft CM, and (10) and (15), an expression for the output velocities, $\dot{\boldsymbol{z}}$, is obtained

$$\dot{\boldsymbol{z}} \equiv [\dot{\boldsymbol{r}}_E^T, \dot{\boldsymbol{\Theta}}_E^T, \dot{\boldsymbol{r}}_S^T \dot{\boldsymbol{\Theta}}_S^T]^T = \boldsymbol{J}_z \boldsymbol{v} \tag{16}$$

where J_z is a 12 by 12 Jacobian matrix ($N = 6$). Neglecting the nonphysical representational singularities, J_z is an invertible matrix, unless the manipulator is kinematically singular.

The equations of motion (13) and the Jacobian given by (16) can be used to implement various motion control techniques in a way similar to the operational space approach, where a Jacobian relating generalized joint velocities to operational velocities is used to design controllers in the operational space [25]. The equations of motion in the z space can be found by substituting (16) into (13) to obtain the form

$$\tilde{H}\ddot{z} + \tilde{C} = (J_z^{-1})^T Q_c \quad (17)$$

where $\tilde{C}$ contains the nonlinear terms, and $\tilde{H} = (J_z^{-1})^T H^+ J_z^{-1}$ is positive definite if J_z is nonsingular. If z is provided by inertial feedback, and the desired end-effector and spacecraft inertial trajectory, z_{des}, is provided by a trajectory planner or a system operator, a tracking error e can be defined as $e \equiv z_{des} - z$. When the manipulator is not kinematically singular, the control law

$$Q_c = J_z^T\{\tilde{H}(K_p e + K_d \dot{e} + \ddot{z}_{\text{des}}) + \tilde{C}\} \quad (18)$$

where K_p and K_d are positive definite diagonal matrices, reduces the error dynamics to a set of 12 homogeneous linear decoupled second order equations. Therefore, the tracking error converges to zero exponentially. Since this algorithm is based on a transposed Jacobian, it will fail gracefully in case of conflicting trajectories for the spacecraft and the end-effector. The spacecraft forces and moments and the joint torques can be found by inverting J_q in (14). This is possible since this Jacobian is always nonsingular. Equation (18) permits the coordinated control of both the spacecraft and its manipulator, based on inertial measurements of the spacecraft and end-effector locations and orientations. If no such measurements are available, then the error e can be estimated by integrating the equations of motion in real time, but then errors due to model uncertainties will be introduced. A small disturbance will result in a small steady state error since this controller is of PD type.

To demonstrate the coordinated control law, a planar 5-DOF free-flying system is simulated [33]. Fig. 10 shows the motion of the free-flying system in inertial space. The end-effector converges almost along a straight line to the desired point, while the spacecraft assumes the desired position and attitude. Note that if the spacecraft were fixed at its initial position, the end-effector would have reached point B in an almost singular configuration.

D. Free-Floating Space Robots

Free-flying space robots have the disadvantage of a limited life because of the use of jet fuel. To increase a system's life, a free-floating mode can be employed. Operation in a free-floating mode is also advantageous during the capture of fragile payloads. If no external forces act on the system, the system CM does not accelerate, and the system linear momentum is constant, i.e., ${}^0\dot{r}_{\text{cm}} = 0$. With the further assumption of zero initial momentum, the system CM remains fixed in inertial space, and can be taken as the origin of a fixed frame of reference.

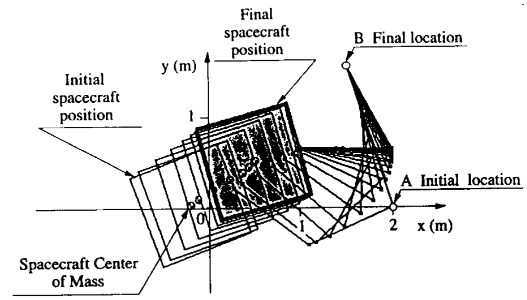


Fig. 10. Coordinated spacecraft/manipulator motion in the inertial space.

E. Dynamic Modeling of a Free-Flying Space Manipulator

The end-effector inertial linear and angular velocities, $\dot{r}_E$, and ω_E, are functions of the joint rates $\dot{q}$ and of the spacecraft angular velocity, ${}^0\omega_0$, see (10). It can be shown that under the above assumptions, the conservation of angular momentum can be written as [35]–[37]

$${}^0\omega_0 = -{}^0D^{-1}\,{}^0D_q\dot{q} \quad (19)$$

Equation (19) is used to express ${}^0\omega_0$ in (10) as a function of $\dot{q}$, and hence to derive a free-floating system's Jacobian J^*, defined by

$$[\dot{r}_E, \omega_E]^T = J^*\dot{q} \quad (20)$$

where J^* is a $6 \times N$ matrix given by

$$J^*(\Theta_S, q) = \operatorname{diag}(T_0(\Theta_S), T_0(\Theta_S))\,{}^0J^*(q). \quad (21)$$

Since (19) was used in constructing J^*, this Jacobian depends not only on the kinematic properties of the system, but also on configuration dependent inertias. Therefore, the singular configurations for a free-floating system, i.e., ones in which ${}^0J^*$ has rank less than six, are not the same to the ones for fixed based systems, as they depend on the mass distribution.

The equations of motion for a free-floating system can be found either using a Lagrangian approach or by setting all external forces and moments in (13) equal to zero, and by subsequent elimination of ${}^0\omega_0$ [36]. The resulting equations are

$$H^*(q)\ddot{q} + C^*(q, \dot{q})\dot{q} = \tau \quad (22)$$

where $H^*(q) \equiv {}^0D_{qq} - {}^0D_q^T\,{}^0D^{-1}\,{}^0D_q$ is the *reduced* system inertia matrix, and $C^*(q, \dot{q})\dot{q}$ contains the nonlinear centrifugal and Coriolis terms. The vector τ is the manipulator joint torque vector equal to $[\tau_1, \tau_2, \cdots, \tau_N]^T$. It is easy to show that the system inertia matrix, H^*, is an N by N positive definite symmetric inertia matrix, which depends on q and the system mass properties [36], [37]. Some fundamental characteristics of free-floating systems are discussed next.

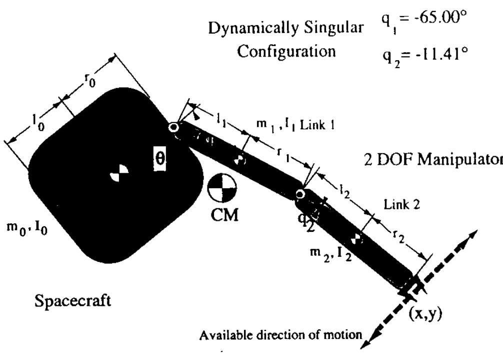


Fig. 11. A free-floating manipulator in a dynamically singular configuration.

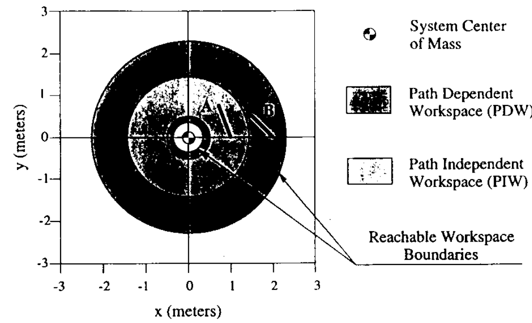


Fig. 12. The reachable, Path Independent and Path Dependent Workspaces for the system shown in Fig. 11. Paths like A cannot induce dynamic singularities, while paths like B can.

F. Path Dependence and Dynamic Singularities

The angular momentum, given by (19), cannot be integrated to yield the spacecraft's orientation $\boldsymbol{\Theta}_S$ as a function of the system's configuration, $\boldsymbol{q}$, with the exception of a planar two body system [37]–[39]. This equation can be integrated numerically, but in such case the resulting final spacecraft orientation will be a function of the path taken in the joint space. Joint space paths that start and end at the same joint space points, but otherwise are different, will result in different final spacecraft orientations. In addition, since the inertial location of the end-effector is a function of $\boldsymbol{\Theta}_S$, moving from one workspace location to another through different paths results in different final spacecraft orientations $\boldsymbol{\Theta}_S$, and different final configurations $\boldsymbol{q}$. Clearly, the nonintegrability introduces nonholonomic characteristics to free-floating systems. However, these are due to the dynamic structure of the system, and not to *kinematic* constraints, as the ones experienced by a rolling disk.

On the basis of the structural similarity of (20) and (22) to the ones derived for a fixed based system, [36] suggested that if singularities of $\boldsymbol{J}^*$ can be avoided, nearly any control algorithm applied to fixed-based systems can be used in free-floating systems. Therefore, the nature of the singularities of $\boldsymbol{J}^*$ is briefly reviewed here. Since the rotation matrix $\boldsymbol{T}_0$ in (21) is in general not singular, then a square $\boldsymbol{J}^*$ loses its full rank when

$$\det[{}^0\boldsymbol{J}^*(\boldsymbol{q})] = 0. \tag{23}$$

This condition shows that free-floating system singularities are fixed in joint space. Since ${}^0\boldsymbol{J}^*$ is a function of configuration dependent inertias, these singularities are different from the ones for fixed-based systems, while their location in joint space depends on the dynamic properties of the system; for these reasons, they were called *dynamic singularities* [35]–[37]. If the system is in a dynamically singular configuration, the end-effector can move only along directions that lie in a subspace of dimension lower than six ($N = 6$); some workspace points may not be reachable with whatever small $\delta\boldsymbol{q}$. Fig. 11 depicts a planar space manipulator in a dynamically singular configuration. This characteristic represents a physical limitation of free-floating systems, and must be considered in designing and controlling such systems.

It is interesting to examine the location of the dynamic singularities in a system's workspace. To this end, we need a one to one correspondence from the joint space to the Cartesian workspace. However, such correspondence does not exist, even in the case of a six-DOF manipulator, because the end-effector position $\boldsymbol{r}_E$ and orientation $\boldsymbol{\Theta}_E$, are not only functions of the system's configuration $\boldsymbol{q}$, but also of the path dependent spacecraft orientation, $\boldsymbol{\Theta}_S$. Out of all the pairs $(\boldsymbol{\Theta}_S, \boldsymbol{q})$ with which a particular workspace point can be reached, some will correspond to a singular configuration, $\boldsymbol{q}_s$. In other words, a workspace point may or may not induce a dynamic singularity, depending on the joint space path taken to reach it.

To resolve this ambiguity, Path Dependent Workspaces (PDW) were defined to contain all workspace locations that may induce a dynamic singularity [35], [36]. To find these points, note that the distance of a workspace location from the system CM, R, does not depend on the spacecraft's orientation, but is only a function of the configuration $\boldsymbol{q}$, i.e., $R = R(\boldsymbol{q})$. This equation represents a spherical shell in the workspace. All the singular configurations $\boldsymbol{q}_s$ are mapped to a set of shells, whose union gives the PDW. If we subtract the PDW from the reachable workspace, we get the Path Independent Workspace, (PIW). All points in the PIW are guaranteed not to induce dynamic singularities. Then, any point in the PIW can be reached from all other points in the PIW, by any path that belongs entirely to the PIW. It can be shown that the PIW is a subset of the Free Workspace discussed in Section IV, see also [37]. Fig. 12 shows the PIW and PDW for the system depicted in Fig. 11.

G. Control in the Joint and Cartesian Space

Assume that one task requires control of the manipulator configuration $\boldsymbol{q}$, only. This is the case of Spacecraft-Referenced End-Point Motion Control, where the manipulator is commanded to move with respect to its floating base, [36]. Since $\boldsymbol{H}^*$ is positive definite, a linearizing feedforward control law $\boldsymbol{\tau} = \boldsymbol{H}^*(\boldsymbol{q})\boldsymbol{u} + \boldsymbol{C}^*(\boldsymbol{q}, \dot{\boldsymbol{q}})\boldsymbol{q}$, where $\boldsymbol{u} \in \boldsymbol{R}^N$ is an auxiliary control input, reduces the equations of motion to a decoupled second order controllable system.

Assume next that the task is to move the end-effector to some inertially fixed position and orientation, and for sim-

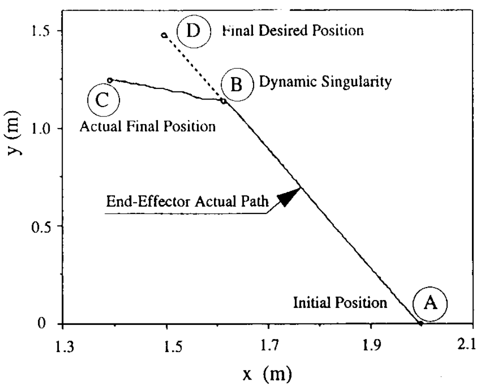


Fig. 13. Due to a dynamic singularity at B, the end-effector misses point D and moves to point C, which is an equilibrium point.

plicity, that $N = 6$. This is the case of Inertially-Referenced End-Point Motion Control, and is required in inspection or capture tasks, [36]. As shown in the same reference, almost any controller can be used, provided that $\boldsymbol{J}^*$ is not singular. If a controller based on the inverse of this Jacobian is used, then the control algorithm will fail computationally at a dynamic singularity. A controller based on a transposed Jacobian will result in large errors. For example, Fig. 13 shows the path taken by a system's end-effector when commanded to move from point A to point C. A simple transposed Jacobian control law is used

$$\boldsymbol{\tau} = \boldsymbol{J}^{*T}\{\boldsymbol{K}_p(\boldsymbol{x}_{\text{des}} - \boldsymbol{x}) - \boldsymbol{K}_d\dot{\boldsymbol{x}}\}. \tag{24}$$

where $\boldsymbol{x}$ represents the Cartesian location of the end-effector, and $\boldsymbol{x}_{\text{des}}$ the desired location. Since this Cartesian path lies in the PDW of the free-floating system, a dynamic singularity occurs at point B, and the end-effector diverges to point C, which is an equilibrium point. This does not mean that point C is not reachable from point A. In fact, as shown in [38], a path to point D can be constructed by exploiting the properties of the PIW and PDW. An example of such a path is depicted in Fig. 14(a). Fig. 14(b) shows the change of the spacecraft orientation when the end-effector follows the path shown in Fig. 14(a). It can be seen that the effect of path ABC is to gradually change the spacecraft orientation to one from which point D is reachable.

This section demonstrated some of the complex dynamics and control challenges unique in free-flying and free-floating space robotic systems. It was shown that a thorough understanding of the dynamics of such systems is a prerequisite in solving the associated control and planning problems.

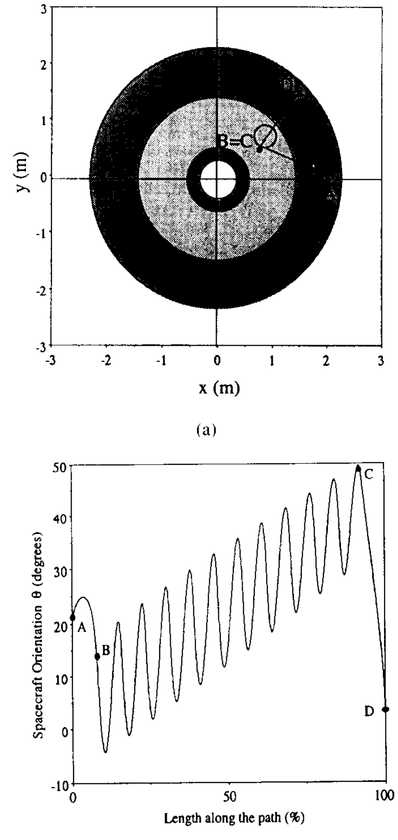


Fig. 14. (a) Path ABCD avoids singularities by employing small circles at point B. (b) The orientation of the spacecraft θ as a function of the path ABCD, in Fig. 6(a).

VII. Conclusion

Autonomous robotic and telerobotic systems have been proposed for a number of important missions in space. However, these ambitious systems will require the solution of a number of critical dynamics and control problems, some of which are unique to space robotics. These problems are also challenging, principally because the dynamics of these systems are complex. This paper has attempted to give a sense of some of the planning and control problems posed by free-flying and free-floating space robotic systems. Clearly there are many other important, unsolved problems, not discussed. Many of these have not even been recognized yet. Some of the accomplishments of the research community have been briefly reviewed, and three specific examples of space robotics problems and their solutions have been presented. These suggest that the key to solving the problems of planning and control of space robotic systems lies in understanding the fundamental dynamic behavior of these systems.

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