Teleoperation of Free-floating Space Manipulator Systems

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Abstract

Free-flying space robotic devices, in which manipulators are mounted on a thruster-equipped spacecraft, will assist in the construction, repair and maintenance of satellites and future space stations. Operation in a free-floating mode, in which spacecraft thrusters are turned off, increases a system's life. The teleoperation of free-floating systems is complicated due to the dynamic coupling between a system's manipulator and its spacecraft. Controlling such a system using visual feedback is not straightforward, especially when the task is to move the end-effector with respect to an inertially fixed target. In addition, free-floating systems are subject to path-dependent *Dynamic Singularities,* which restrict the paths by which *Path Dependent Workspace* points can be reached. These characteristics can result in increased operator burden during system teleoperation. A teleoperation planning system to assist the operator of a free-floating space robot is presented. Given an initial and a target end-effector location, and an optional connecting path, this system examines the feasibility of reaching the target from the initial location. If a problem is detected, the system proposes an alternative feasible path. An example demonstrates the value of such a teleoperator planning aid.

1. Introduction

The proliferation of satellites and the anticipated development of space stations and other space structures in orbit increases the need for inspection, maintenance and construction capabilities[1,2,3]. Astronaut Extra Vehicular Activities (EVA) will be valuable in all these operations. However, the cost of human life support facilities, the limited time available for astronaut EVA, and the high risks involved, make space robotic devices desired astronaut assistants or alternatives. To increase the mobility of such devices, *free-flying* systems in which one or more manipulators are mounted on a thruster-equipped spacecraft, have been proposed[4,5]. However, extended use of the thrusters severely limits the operational life of free-flyers[6].

Operation in a *free-floating* mode can increase a system's life[6, 7]. In this mode of operation, spacecraft thrusters are turned off, and the spacecraft is permitted to translate and rotate in response to manipulator motions. Additional benefits of this mode of operation include the smoothness of end-effector motions, which is particularly important when handling sensitive payloads, and the absence of thruster gases that disturb space structures and co-operating astronauts. Since the spacecraft thrusters are not in use during this mode of operation, a free-floating system must have zero linear and angular momentum to avoid uncontrolled drift or spin[7, 8]. Any nonzero momentum that may accumulate should be removed either by the use of reaction wheels and/or by using the system's thrusters.

Free-flying space robots will be initially under manual or supervisory control. An operator working in a short-sleeve environment will command such a robot receiving visual information from the worksite. However, the existence of a moving base (spacecraft), makes the dynamics and control of free-floating space robots more complicated than those of fixed-based systems[7, 8]. This is due to the dynamic coupling between the spacecraft and its manipulator; the spacecraft of a free-floating system will move in reaction of its manipulator motions. The dependent spacecraft motion introduces path dependent properties. For example, the spacecraft orientation which will result after reaching a target, will be different from the orientation which will result after reaching the same target, but following a different path than previously[8, 9].

In this paper, the teleoperation of free-floating systems is considered. The goal is to create a teleoperation environment which will allow an operator to control the space robot without having to think about its intrinsic dynamic and kinematic behavior. It is believed that in order to establish transparency in the control of such systems, a planner aware of the system kinematics and dynamics must be used. Such a planner will assist the operator in choosing appropriate end-effector paths, generate trajectories, avoid collisions with nearby objects, and display the simulated motion before it is executed. Therefore, as a first step in developing such an operator aid, the kinematic and dynamic nature of free-floating robotic systems is briefly discussed, and their fundamental nonholonomic behavior explained. It is shown that free-floating systems are subject to path-dependent *dynamic singularities*, which are functions of the system mass properties and cannot be predicted from their kinematic structure. *Path Dependent Workspaces* are defined in which locations may be reachable by specific only end-effector paths. These characteristics can result in increased operator burden during system teleoperation. A planning system to assist in the teleoperation of free-floating space manipulators by making their intricate dynamics transparent, is presented. Given an initial and a target end-effector location, and an optional connecting path, this system examines the feasibility of reaching the target from the initial location. If a problem is detected, the system proposes an alternative feasible path. An example demonstrates the value of such a teleoperator planner.

2. Teleoperation of Free-floating Manipulators

Typical teleoperation systems consist of local and remote nodes. A local node consists of an operator, of input command devices, of displays and other sensory feedback devises, and of operator support systems, like simulators, planners, etc. A remote node consists of a robotic system, including its sensors and control computers. The system's sensors may supply internal state information, for example joint angle/rate feedback provided by resolvers or tachometers, or external state information, for example end-effector position/orientation provided by video cameras[10, 11].

When a remote node's robotic system is a free-flying manipulator, the design of the teleoperation system must take into account the effect of the free-flyer's moving base. One can distinguish two modes of motion control of a free-flyer: The first, called Spacecraft-Referenced End-Point Motion Control[7], is the form of control in which the manipulator end-point is commanded to move to a location fixed to its own spacecraft, or when a simple joint motion is commanded, such as when the manipulator is to be driven at its stowed position, see Figure 1. The second, called Inertially-Referenced End-Point Motion Control, is when the manipulator end-point is commanded to move with respect to inertial space, see Figure 2.

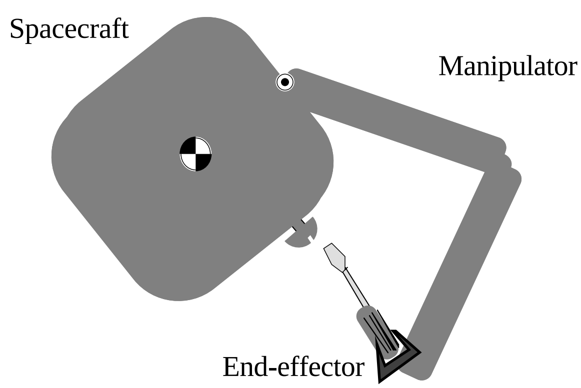
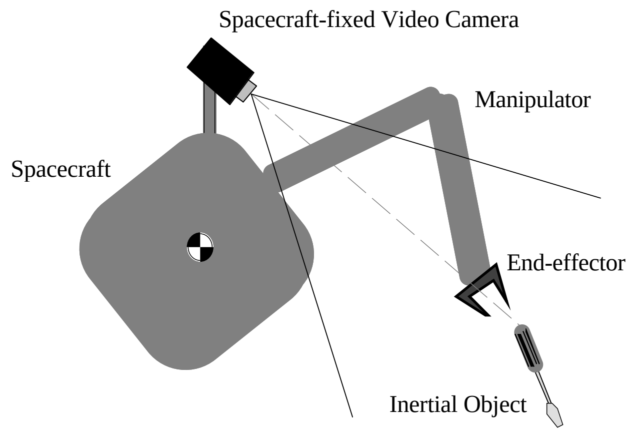


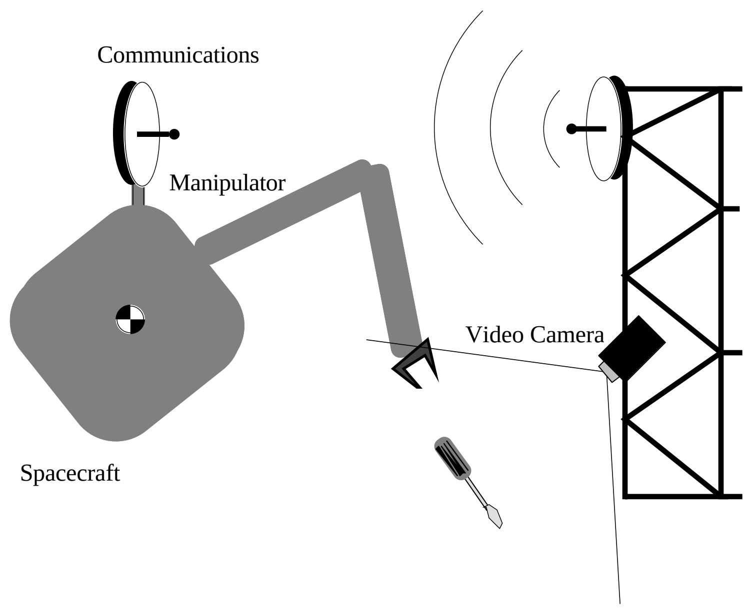
Figure 1. Spacecraft-Referenced End-Point Motion Control

The teleoperation of a free-flyer during the Spacecraft-Referenced End-Point Motion Control, is very similar to the teleoperation of a fixed-based robotic system. In fact, if the thruster jets are used to keep both the attitude and orientation of the spacecraft fixed, then this mode of control has identical requirements to those for a fixed-based system.

On the other hand, if the robotic system is free-floating, then the spacecraft will be reacting to the motions of the manipulator. The dynamic equations relating actuator torques to joint accelerations have the same structure to those for a fixed-based system, but the elements of the mass matrices are different. The result is that the profile of torques required for a particular motion of a free-floating system will not be the same to the profile required for a fixed-based system. However, the kinematics of both the free-floating and the fixed-based systems are the same. A camera fixed at some location of the spacecraft will provide the same picture as a camera fixed at an equivalent location of a fixed-based system. However, due to the motion of the spacecraft, background objects fixed in inertial space will appear to be moving on the operator's screen.



(a) Camera spacecraft-fixed.



(b) Camera inertially-fixed.

Figure 2. Inertially-Referenced End-Point Motion Control.

During Inertially-Referenced End-Point Motion Control, the teleoperation of a space robot whose spacecraft is fixed in space by virtue of its jet thrusters, has similar requirements to those for a system with a fixed base. However, the teleoperation of a free-floating system becomes a formidable task, because the operator will have to command the end-effector to move with respect to inertial space, while the base is itself moving, reacting to the manipulator's motions. Depending on the system configuration, the same displacement or rate command from the operator will not have the same effect to the inertial motion of the end-effector. If the manipulator is extended, its inertia will be large and will disturb the spacecraft significantly more than when it is folded. Therefore, the same operator command will result in different base motions which in turn will result in different end-effector motions. An additional problem exists when a video camera is fixed on the spacecraft, see Figure 2 (a). In such a case, the end-effector will appear in general to be moving at higher velocities, and unless the camera is reoriented, an inertially fixed target may disappear from the screen. These problems can increase the burden placed on the operator of such system.

One feasible way of reducing this burden it is to have a computer module plan and upon approval from the operator, execute a motion. Such a module must incorporate a detailed kinematic and dynamic model of the space robot. In addition, it must include planning aids that will suggest appropriate paths to the operator. In the next section we briefly present the fundamental kinematic and dynamic modeling of free-floating systems. The dynamic behavior of free-floating systems is discussed in Section 4, while the teleoperator planner is discussed in Section 5.

3. Free-floating Manipulator Modeling

The kinematic and dynamic equations needed to model a rigid free-floating manipulator system, see Figure 3, were obtained in detail in previous publications[7, 8]. A key feature of this modeling is expressing the kinematic and dynamic variables of the system as functions of a set of constant length, body-fixed barycentric vectors. The dynamics were written using a Lagrangian approach. Here the basic kinematic and dynamic equations are briefly reviewed.

The manipulator joint angles and velocities are represented by the N×1 column vectors $\mathbf{q}$ and $\dot{\mathbf{q}}$. The spacecraft can translate and rotate in response to manipulator movements. The manipulator is assumed to have revolute joints and an open chain kinematic configuration so that, in a system with an N degree-of-freedom (DOF) manipulator, there will be 6+N DOF. Assuming that no external forces act on the system, the system center of mass (*CM*) does not accelerate, and the system linear momentum is constant. 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.

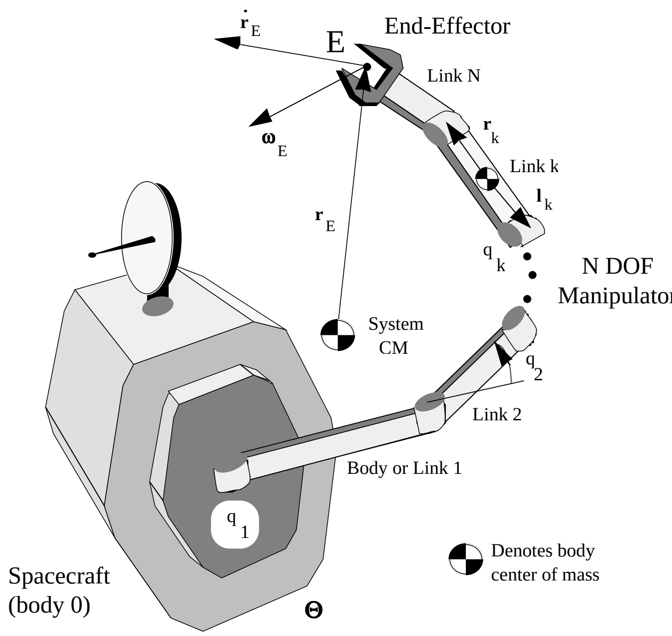


Figure 3. A spatial free-floating manipulator system.

It can be shown that in the absence of external torques, and for zero initial linear momentum, the conservation of momentum equation results[7] in:

$$^{0}\boldsymbol{\omega}_0 = - {}^{0}\mathbf{D}^{-1}\, {}^{0}\mathbf{D}_{\mathbf{q}}\, \dot{\mathbf{q}} \tag{1}$$

where $^{0}\boldsymbol{\omega}_0$ is the spacecraft angular velocity expressed in a frame fixed to it (frame 0), $^{0}\mathbf{D}$ is the 3×3 inertia matrix of the system expressed in a frame with the same orientation as frame 0 but located at the system *CM*, and $^{0}\mathbf{D}_{\mathbf{q}}$ is a 3×N mixed inertia matrix. Both $^{0}\mathbf{D}$ and $^{0}\mathbf{D}_{\mathbf{q}}$ are functions of the configuration $\mathbf{q}$ only, and they can be written as functions of the body-fixed barycentric vectors[7]. The inverse of $^{0}\mathbf{D}$ always exists because the system inertia matrix is positive definite.

The end-effector inertial linear and angular velocities, $\dot{\mathbf{r}}_E$, and $\boldsymbol{\omega}_E$, are functions of the joint rates $\dot{\mathbf{q}}$ and of the spacecraft angular velocity, $^{0}\boldsymbol{\omega}_0$. Equation (1) can be used to express $^{0}\boldsymbol{\omega}_0$ as a function of $\dot{\mathbf{q}}$, and hence to derive a free-floating system's Jacobian $\mathbf{J}^*$, defined by:

$$[\, \dot{\mathbf{r}}_E, \boldsymbol{\omega}_E \,]^T = \mathbf{J}^*\, \dot{\mathbf{q}} \tag{2}$$

where $\mathbf{J}^*$ is a function of the orientation $\mathbf{\Theta}$ of the spacecraft, and given by[8]

$$\mathbf{J}^*(\mathbf{\Theta},\mathbf{q}) = \mathrm{diag}(\mathbf{T}_0(\mathbf{\Theta}),\mathbf{T}_0(\mathbf{\Theta}))\ {}^0\mathbf{J}^*(\mathbf{q}) \tag{3}$$

$\mathbf{T}_0(\mathbf{\Theta})$ is a rotation matrix which describes the orientation of the spacecraft. Due to Equation (1), $\mathbf{J}^*$ depends not only on the kinematic properties of the system, but also on configuration dependent mass properties, i.e. inertias. Therefore, the singular configurations for a free-floating system, i.e. ones in which ${}^0\mathbf{J}^*$ has rank less than six, are not the same to the ones for fixed based systems, and they depend on the mass distribution.

The equations of motion for a free-floating system can be written in the form[7]:

$$\mathbf{H}^*(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{C}^*(\mathbf{q},\dot{\mathbf{q}})\,\dot{\mathbf{q}} = \boldsymbol{\tau} \tag{4}$$

where $\mathbf{H}^*(\mathbf{q})$, is the *reduced* system inertia matrix, $\mathbf{C}^*(\mathbf{q},\dot{\mathbf{q}})\,\dot{\mathbf{q}}$ contains the nonlinear centrifugal and Coriolis terms. The vector $\boldsymbol{\tau}$ is the torque vector equal to $[\tau_1, \tau_2, ..., \tau_N]^T$. It is easy to show that the system inertia matrix, $\mathbf{H}^*$, is an $N \times N$ positive definite symmetric inertia matrix, which depends on $\mathbf{q}$ and the system mass and inertia properties.

Based on the structural similarity of these equations to the ones derived for a fixed based system, it has been suggested[7] that if singularities of $\mathbf{J}^*$ can be avoided, nearly any control algorithm applied to fixed-based systems can be used in free-floating systems. The nature of free-floating system singularities and workspaces, in conjunction to the nonintegrability of the angular momentum, is addressed next.

4. The Behavior of Free-floating Manipulators During Motion Control

4. 1. Nonintegrability of the Angular Momentum.

The angular momentum, given by Equation (1), cannot be integrated to yield the spacecraft's orientation $\mathbf{\Theta}$ as a function of the system's configuration, $\mathbf{q}$, with the exception of a planar two body system[12]. Obviously, 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. In other words, different paths in the joint space, with the same initial and final points, will result in different spacecraft orientations. Since the location of the end-effector is also a function of $\mathbf{\Theta}$, the same applies to workspace (Cartesian) paths, i.e. moving from one workspace location to another one via different paths results in different final spacecraft orientations. Therefore, closed joint space or workspace paths can change the spacecraft's orientation. This nonintegrability property introduces nonholonomic characteristics to free-floating systems. However, the nonholonomic behavior results from the particular *dynamic* structure of the system, and is not due to *kinematic* nonintegrable constraints, like the ones experienced by a rolling disk. The use of this nonholonomic behavior to achieve various tasks is described in the following sections.

4. 2. Spacecraft-Referenced End-Point Motion Control.

One typical task requires control of the system configuration $\mathbf{q}$. Since $\mathbf{H}^*$ is positive definite, the linearizing feedforward control law $\boldsymbol{\tau} = \mathbf{H}^*(\mathbf{q})\{\ddot{\mathbf{q}}_d + \mathbf{K}_d(\dot{\mathbf{q}}_d - \dot{\mathbf{q}}) + \mathbf{K}_p(\mathbf{q}_d - \mathbf{q})\} + \mathbf{C}^*(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}$, where $\mathbf{q}_d$ is the desired joint trajectory and $\mathbf{K}_d$ and $\mathbf{K}_p$ are diagonal gain matrices, reduces the equations of motion to a decoupled set of asymptotically stable second order equations, which guarantee that $\mathbf{q} \rightarrow \mathbf{q}_d$. It is expected that in space the kinematic and mass properties of all systems are known with sufficient accuracy. If this condition cannot be secured, and adaptive joint controller can be considered. The structure of any joint controller will be the same to the structure of a controller for a fixed-based system. However, since the elements of $\mathbf{H}^*$ are not the same to the elements of $\mathbf{H}$, which corresponds to a fixed base system, the torque vector $\boldsymbol{\tau}$ will have a different time profile from that obtained for a fixed-based system.

The motion of the base does not change the kinematics and differential kinematics of the manipulator if the task involves cartesian motion with respect to a frame fixed to the spacecraft. For example, the end-effector linear velocity will be given by: ${}^0\boldsymbol{V}_E = {}^0\mathbf{J}(\mathbf{q})\dot{\mathbf{q}}$, where ${}^0\mathbf{J}$ is the manipulator Jacobian when the base is fixed. Using ${}^0\mathbf{J}$ and $\mathbf{H}^*$ one can design an appropriate control algorithm without major complications.

4. 3. Inertially-Referenced End-Point Motion Control.

If the end-effector is moving with respect to an inertial frame, then its inertial velocity $\boldsymbol{V}_E$ is given by Equation (2). An inertially fixed camera would record $\boldsymbol{V}_E$. On the other hand, a spacecraft-fixed video camera would feed-back ${}^0\boldsymbol{V}_E = {}^0\mathbf{J}^*(\mathbf{q})\dot{\mathbf{q}}$. In both cases, the dynamics of the free-floating system will be described by Equation (4). Using Equations (2) and (4), one could design a linearizing and decoupling cartesian space controller[13]. However, since the rotation matrix $\mathbf{T}_0$ is not singular, (with the exception of possible representational singularities), such a controller would fail at all points where the Jacobian ${}^0\mathbf{J}^*(\mathbf{q})$ loses full rank, or for the case N=6 when:

$$\det[{}^0\mathbf{J}^*(\mathbf{q})] = 0 \tag{5}$$

The above condition shows that singularities in free-floating systems are fixed in joint space. Since ${}^0\mathbf{J}^*$ is a function of configuration dependent inertias, these singularities are different than the ones for fixed base systems, and their location in joint space depend in addition on the dynamic properties of the system; for these reasons, they were called *dynamic singularities*[8].

To find the location of the dynamic singularities in a system's workspace, we need a one to one correspondence from joint space to cartesian space. However, such a correspondence does not exist, even in the case of a six DOF manipulator, because its end-effector position $\mathbf{r}_E$, and orientation $\mathbf{\Theta}_E$, are not only functions of the system's configuration $\mathbf{q}$, but also of the path dependent spacecraft orientation, $\mathbf{\Theta}$. Out of all the pairs ($\mathbf{\Theta}$, $\mathbf{q}$) with which a workspace point can be reached, some may correspond to a singular configuration, $\mathbf{q}_s$. Then a workspace point may or may not induce a dynamic singularity, depending on the joint space path taken to reach it. It must be noted that under the assumptions for free-floating systems (zero total momentum), the speed of motion along a particular path time does not affect the feasibility of a particular path.

To resolve this ambiguity, *Path Dependent Workspaces* (PDW) were defined to contain all workspace locations that may induce a dynamic singularity[7, 8]. 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, i.e. R = R($\mathbf{q}$). This equation represents a spherical shell in the workspace. All the singular configurations $\mathbf{q}_s$ 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. If the system is in a dynamically singular configuration, the end-effector can move only along directions which lie in a subspace of dimension lower than six; some workspace points are not reachable with small $\delta\mathbf{q}$, whatever $\delta\mathbf{q}$ is. However, it may still be possible to reach any PDW point from any other workspace point, by choosing an appropriate path.

Another important characteristic of free-floating systems under Inertially-Referenced End-Point Motion Control is that the size of the PIW, PDW, and reachable workspaces depends on the system mass properties. It can be shown that the size of all these workspaces is proportional to m_0/M, where m_0 is the spacecraft mass and M is the total mass of the system[14]. If the manipulator mass is very small compared to the mass of the spacecraft, the size of the reachable workspace is approximately equal to the size of the fixed-based system. On the other hand, if the manipulator is moving a big payload, the total mass increases drastically, and the system workspaces shrink considerably. In the limit, they become zero; the end-effector cannot move a big payload with respect to an inertially fixed frame. Any attempted motion of the manipulator will result in moving its spacecraft!

It becomes obvious that finding an end-effector path under Inertially-Referenced End-Point Motion Control is not an easy task and can increase the burden on an operator. An alternative to a trial-and-error search for an appropriate path is to have a planner sub-module compute a feasible path and suggest it to the operator. After approval, the path can be converted to a trajectory and executed by the robotic system. In the next section, the principles on which the planner sub-module is based are described briefly.

5. A Planner for a Free-floating Space Manipulator

5. 1. Planner PDW Module

As discussed above, motion control in the PIW can be achieved with relative ease, since all paths are feasible. The operator can either command the end-effector by means of a joystick, or can specify the desired path by means of a mouse or keyboard. In the later case, a trajectory would be generated, and if required, the motion of the system would be simulated and previewed. Finally, following operator approval, the motion would be executed.

However, if the target is in the PDW of the system, and the operator commands the end-effector by means of a joystick, it is possible that the system will reach a dynamic singularity and stop. To move away from the singular configuration, the system would have to be commanded in joint space till it is away from the problematic area. A new trajectory would be subsequently tried, but another singularity can appear. This trial and error sequence may never lead to a feasible path, and the operator burden will definitely increase. Similar frustration is experienced by new car drivers trying to park. In both cases, the nonholonomic behavior of these systems makes their control complicated. Although a car driver can find a standard maneuver to accomplish the task, it is rather doubtful that the operator of a free-floater can do the same. For this reason, a planner which would aid an operator control a free-floating manipulator is appropriate.

Creating a planner sub-module that can suggest feasible paths connecting points in the PDW hinges on following three properties:

(a) Motions in the joint space are singularity free. Dynamic singularities restrict the feasible cartesian motions, only.
(b) Motions in the PIW are singularity free.
(c) Cyclical motions of the end-effector in cartesian space can change the orientation of the spacecraft.

The third property is a direct outcome of the non-integrability of the angular momentum. This property is further discussed next.

If a spacecraft's orientation is described by the 3-2-1 Euler angles, $\mathbf{\Theta} = [\theta_1,\theta_2,\theta_3]^T$, then $\dot{\mathbf{\Theta}}$ is written using Equation (1) as[15]:

$$\dot{\mathbf{\Theta}} = -\mathbf{S}^{-1}(\mathbf{\Theta})\,\boldsymbol{\omega}_0 = \mathbf{G}(\mathbf{\Theta}, \mathbf{q})\dot{\mathbf{q}} \qquad (6)$$

where $\mathbf{S}^{-1}(\mathbf{\Theta})$ is a nonsingular matrix, except at some isolated points, and $\mathbf{G}(\mathbf{\Theta}, \mathbf{q}) = -\mathbf{S}^{-1}(\mathbf{\Theta})\ \mathbf{T}_0\,{}^0\mathbf{D}^{-1}\ {}^0\mathbf{D}_{\mathbf{q}}$. For small changes in the configuration $\mathbf{q}$, Equation (6) is written as:

$$\delta\mathbf{\Theta} = \mathbf{G}(\mathbf{\Theta}, \mathbf{q})\delta\mathbf{q} \qquad (7)$$

where $\mathbf{G}$ is a 3×N matrix. It can be shown that Equation (7) is non integrable[6,9,12]. The result of this property is that closed paths in the joint space will result in general in a net change in the orientation of the spacecraft. The vector $\delta\mathbf{q}$ in Equation (7) can be expressed as a function of a small change in the end-effector position and orientation, $\delta\mathbf{x}_E = \delta[\mathbf{r}_E,\mathbf{\Theta}_E]^T$, inverting Equation (2):

$$\delta\mathbf{q} = \left\{\mathrm{diag}(\mathbf{I},\mathbf{S}^{-1}(\mathbf{\Theta}_E))\mathbf{J}^*\right\}^{-1}\delta\mathbf{x}_E \qquad (8)$$

Combining Equations (7) and (8) results in the following expression for $\delta\mathbf{\Theta}$:

$$\delta\mathbf{\Theta} = \mathbf{G}(\mathbf{\Theta},\mathbf{q})\left\{\mathrm{diag}(\mathbf{I},\mathbf{S}^{-1}(\mathbf{\Theta}_E))\mathbf{J}^*\right\}^{-1}\delta\mathbf{x}_E = \mathbf{G}^*(\mathbf{\Theta},\mathbf{x}_E)\delta\mathbf{x}_E \qquad (9)$$

The 3×6 matrix $\mathbf{G}^*$ is written as a function of $\mathbf{\Theta}$, and $\mathbf{x}_E$, because if these are given, and N=6, then $\mathbf{q}$ can be found uniquely. Note that Equation (9) has the same structure to Equation (7), although more complicated. If cyclical motions in the PIW are employed, then $\mathbf{J}^*$ is invertible and $\mathbf{G}^*$ exists. Equation (9) is also non-integrable and therefore, closed paths in cartesian space will result in net changes in the spacecraft's attitude.

Based on the three above properties, a planning algorithm to move the end-effector without encountering dynamic singularities from an initial point A to a final point D, can be the following[12]:

(a) Start from the final desired spacecraft orientation and end-effector position/orientation, and move under joint space control to some point C of the PIW. Such a motion is not subject to the effects of dynamic singularities, because these affect cartesian motions, only. (Cartesian paths can also be used, if no singularities are encountered). Record the path taken. The system reaches point C with $\mathbf{q}_{DC}$ and $\mathbf{\Theta}_{DC}$.
(b) Start from the initial desired spacecraft orientation and end-effector position/orientation, and move under joint space control to some point B of the PIW. The system reaches point C with $\mathbf{q}_{AB}$ and $\mathbf{\Theta}_{AB}$. Note that other points B or C located outside the PIW can be used also, if they are reachable from A, and D at configurations "sufficiently" away from singular ones. Such points can be useful in the event that the PIW is zero.
(c) Move from point B to point C, using any path. The system reaches point C with $\mathbf{q}_{AC}$ and $\mathbf{\Theta}_{AC}$. In general, these are different than $\mathbf{q}_{DC}$ and $\mathbf{\Theta}_{DC}$.
(d) Using small cyclical motions of the end-effector, change the spacecraft orientation from $\mathbf{\Theta}_{AC}$ to $\mathbf{\Theta}_{DC}$. The configuration changes from $\mathbf{q}_{AC}$ to $\mathbf{q}_{DC}$, since the end-effector moves around some fixed point in cartesian space.
(e) Use the recorded path during step (a), to move to point D.

5. 2. A Planner for Operator Assistance

One possible teleoperation scenario for a free-floating manipulator might be the following. The operator has visual feedback provided by video-cameras mounted on the end-effector, the spacecraft and in some cases on the target itself (space station, other space vehicle, etc.) Assuming that the position and orientation of all the objects including the target are known, the operator can specify a target end-effector frame, see Figure 4, either from a keyboard or by means of a pointing device. The planner first checks if the target can be reached by moving the manipulator only. If not, then the spacecraft thrusters must be used to move the system center of mass so that the target is in the reachable workspace of the system. Control strategies which can be applied for such motions are described in the literature[16,17].

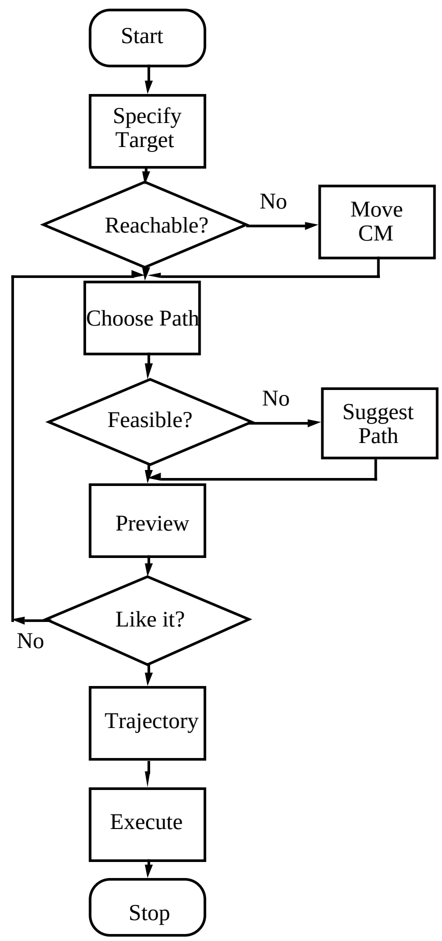


Figure 4. Planner flowchart.

It is obviously beneficial to move the free-flying system so that the target is in the system's PIW. However, it is conceivable that after some time the end-effector may be required to reach another target which is located in the PDW. For this motion, the operator specifies a desirable path and the planner checks if this path can be followed by the end-effector without passing close to or through a singularity. If this is the case, the path is converted to a trajectory and executed by the system, after previewing and approval by the operator.

On the other hand, if the operator-specified path is not feasible due to dynamic singularities, then the planner suggests a feasible path to the operator. If the operator is satisfied, the path is converted to a trajectory and executed, otherwise the planner suggests a different path.

The planner flowchart, see Figure 4, assumes that *reaching* a target and not the *path* to the target is of primary importance. However, if the end-effector must follow a prescribed path, then the free-floating system must be moved so that the desired path lies entirely in the system's PIW. Note also that the planner could check for collisions with known objects in the vicinity of the system using the known kinematics of the free-floater. However, the collision avoidance sub-module is not considered in this work.

6. Example

As an example of the teleoperation planner aid described above, we consider the teleoperation of a planar two DOF manipulator mounted on a 3 DOF spacecraft, shown in Figure 5. Its mass and inertia properties are given in Table I.

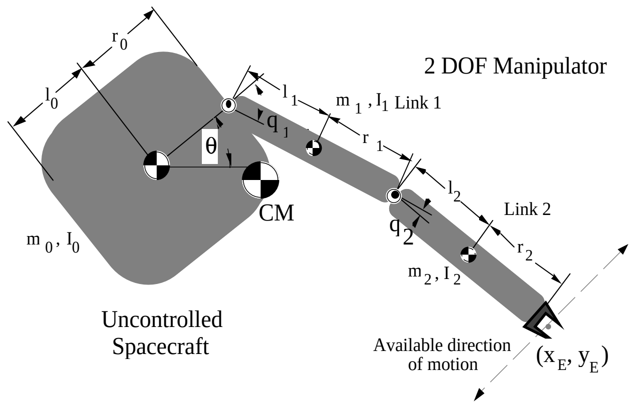


Figure 5. A planar free-floating manipulator, shown in a dynamically singular configuration.

Table I. The system parameters.

Body	l_i (m)	r_i (m)	m_i (Kg)	I_i (Kg m^2)
0	.5	.5	400	66.67
1	.5	.5	40	3.33
2	.5	.5	30	2.50

For this system, the dynamic singularities in joint space are found using Equation (5), and shown in Figure 6. For more details, please refer to previous publications. It can be seen that unlike fixed-based kinematic singularities (q_2 = 0°, ±180°) infinite more singular pairs (q_1,q_2) exist. Figure 5 depicts the example system in a typical dynamically singular configuration with (q_1,q_2) = (-65°, -11.41°). For this system, the PIW is represented by the light gray hollow disk, shown in Figure 7. The dark area hollow disks correspond to the PDW.

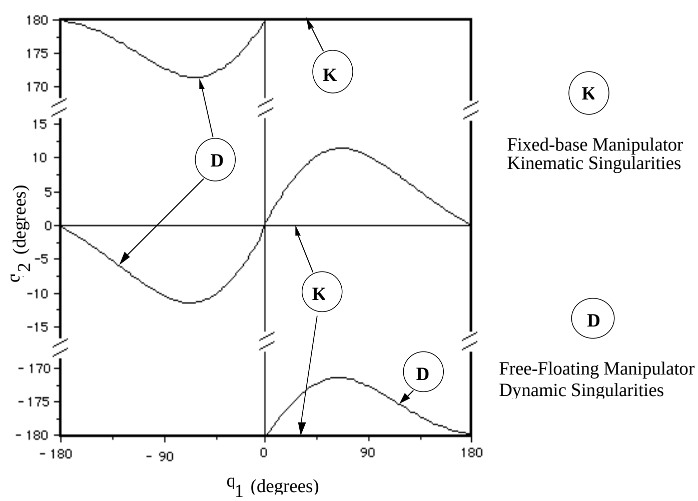


Figure 6. Dynamically singular configurations for the system shown in Figure 5.

Let the system's end-effector initially be at point A: (x,y) = (2,0), which belongs in the system's PDW, see Figure 7. The initial configuration of the system is (q_1,q_2) = (-58°, 60.3°) which corresponds to an initial spacecraft orientation θ = 21°. Assume an operator commands the end-effector to reach point D: (x,y) = (1.5,1.5), following a straight line path. The planner calculates the reachable, PIW and PDW spaces, and detects that the path is in the PDW. Next, the system Jacobian is computed along the straight-line path and a dynamic singularity is detected at point E, where (θ, q_1, q_2) = (-32.4°, 74.24°, 10.6°). Since the inverse of the system Jacobian does not exist at a singularity, a resolved rate-type controller would fail at such a point and the system would have to be commanded in joint space in order to be moved away from the singularity. On the other hand, if a transposed Jacobian-type of control algorithm is used, the end-effector will deviate from the straight line path and result is large errors[7]. Other than straight-line paths can be tried, but singularities eventually re-appear at other locations.

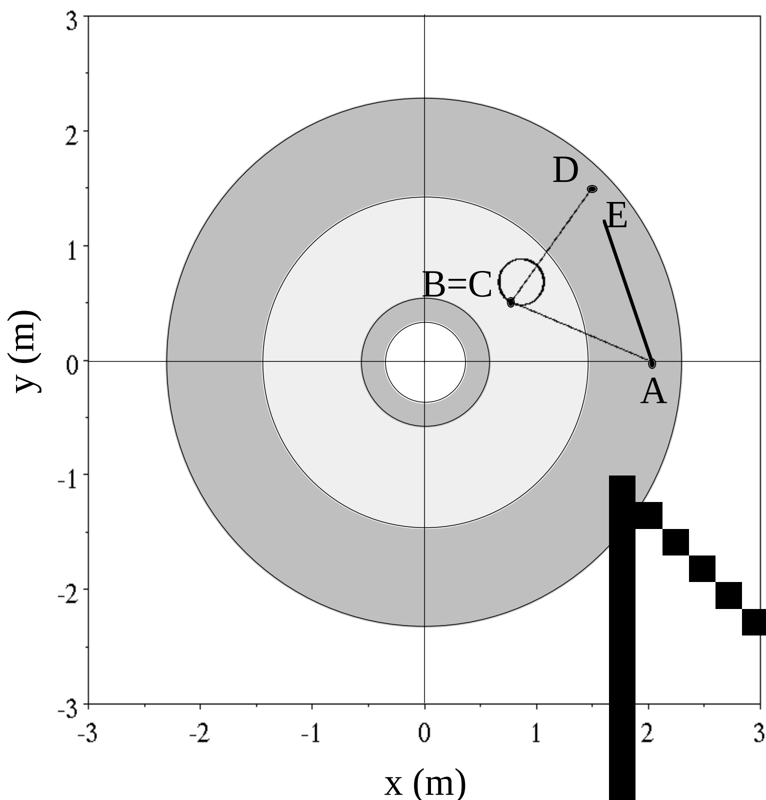


Figure 7. A Dynamic Singularity at point E does not allow the e[redacted]-effector to move from [redacted]int A to D. The teleoperator planner suggests path ABCD wh[redacted]h avoids singularities.

The planner must now suggest an alternative path. Since there is some free[redacted]m in the construction of the[redacted]ath, the operator can also specify the final desired spacecraft orientation, for example θ 3°[redacted]f the end-effector is at point [redacted] and θ 3°, the planner finds the corresponding configuration to be (q_1,q_2) = (39.4°, 22.2°). To find such a path the planner follows the steps of the algorithm described in Section 5.1.

The path is found as follows: The planner first chooses some random point C in the PIW. The end-effector is moved from the desired point D, to point C: (0.8, 0.5), see path DC in Figure 7. Although a straight line motion is used here, in general a joint space path guarantees the avoidance of singularities. The spacecraft angle θ_{DC} by which point C is reached is calculated and found equal to 49.1°. Next, the end-effector is moved from the initial point A, to point B, which for simplicity is taken as point C. The end-effector reaches point B: (0.8, 0.5) with (θ,q_1,q_2) = (14.5°, -49.4°, 145.9°). The next task is to change the orientation of the spacecraft, from θ_{AC}=14.5°, to θ_{DC}=49.1°. To this end, the end-effector is commanded to follow circular paths, with radius .2m, as shown in Figure 7. The circular paths stop when the orientation θ changes to 48.9°. It was found that 11 such circles are required. Next, the end-effector is moved to D, following the prerecorded path DC in the opposite direction, and reaches D with (θ,q_1,q_2) = (3.3°, 38.9°, 22.7°). Note that not only the destination point D, but also the desired final spacecraft orientation has been reached. If a closer match in orientation is required, a smaller circle radius and more circles can be employed. However, the process will take more time to be completed.

Next, the planner simulates the motion of the system and asks the operator for approval. Once this path is approved by the operator, the planner generates the desired trajectory, which is executed subsequently. The operator is only supervising the system's motion.

7. Conclusions

In this paper, the teleoperation of free-floating systems is considered. The kinematic and dynamic nature of such systems was briefly discussed, and their fundamental nonholonomic behavior explained. Controlling such a system using visual feedback is not straightforward, especially when the task is to move the end-effector with respect to an inertially fixed target. In addition, free-floating systems are subject to path-dependent *dynamic singularities*, which restrict the paths by which points in the *Path Dependent Workspace* can be reached. These characteristics can result in increased operator burden during system teleoperation. A teleoperation planning system which can assist the operator of a free-floating robot is presented. Given an initial and a target end-effector location, and an optional connecting path, this system examines the feasibility of reaching the target from the initial location. If a problem is detected, the system proposes an alternative feasible path, which is executed upon approval from the operator.

8. Acknowledgments

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9. References

1. Jenkins, L., "Space Telerobotic Systems: Applications and Concepts," *Proc. of the Workshop on Space Telerobotics,* NASA-JPL, Pasadena, CA, 1987.
2. Weisbin, C.R. and Montermelo, M.D., "NASA's Telerobotics Research Program," *Proc. IEEE Int. Conf. on Robotics & Automation*, Nice, France, May 1992.
3. Ono, M., Machida, K., and Nagayama, H., "Advanced Space Telerobotics: Concept and Applications," *Proc. i-SAIRAS '90*, Kobe, Japan, 1990.
4. Bronez, M. A., Clarke, M. M., and Quinn A., "Requirements Development for a Free-Flying Robot - the ROBIN," in *Proc. of the IEEE International Conference on Robotics and Automation*, San Fransisco, CA, April 1986.
5. Erickson, J.D., et al., "Technology for an Intelligent, Free-flying Robot for Crew and Equipment Retrieval in Space," *Proc. Space Operations Automation and Robotics Conf. and Workshop*, JSC, Houston, TX, July 1989.
6. Vafa, Z. and Dubowsky, S., "On the Dynamics of Space Manipulators Using the Virtual Manipulator, with Applications to Path Planning," *J. Astr. Sciences,* Vol. 38, No. 4, October-December 1990, pp. 441-472.
7. Papadopoulos, E. and Dubowsky, S., "On the Nature of Control Algorithms for Free-floating Space Manipulators," *IEEE Trans. on Robotics and Automation*, Vol. 7, No. 6, Dec. 1991, pp. 750-758.
8. Papadopoulos E. and Dubowsky, S., "Dynamic Singularities in the Control of Free-Floating Space Manipulators," accepted for publication in the *ASME Journal of Dynamic Systems, Measurement and Control*, (in press).
9. Nakamura, Y. and Mukherjee, R., "Nonholonomic Path Planning of Space Robots via Bi-directional Approach," *Proc. IEEE Int. Conf. on Robotics & Automation*, Cincinnati, OH, May 1990.
10. Bejcy, A., Venema, S., and Kim, W.S., "Role of Computer Graphics in Space Telerobotics: Preview and Predictive Dispalys", *SPIE Cooperative Robotics in Space*, Vol. 1387, SPIE 1990, pp.365-377.
11. Kalaycioglu, S. and Seifu, S., "Ground-Based Control of Space Station Freedom-Based Robots," *Proc. IEEE Int. Conf. on Robotics & Automation*, Nice, France, May 1992.
12. Papadopoulos, E., "Path Planning for Space Manipulators Exhibiting Nonholonomic Behavior," *Proc. of the Int. Conf. on Intelligent Robots and Systems*, IROS '92, Raleigh, NC, July 1992.
13. Khatib, O., "A Unified Approach for Motion and Force Control of Robot Manipulators: The Operational Space Formulation," *IEEE J. of Robotics and Automation*, Vol. RA-3, No. 1, Feb. 1987, pp. 43-53.
14. Papadopoulos, E., "On the Dynamics and Control of Space Manipulators," Ph.D. Thesis, Department of Mechanical Engineering, MIT, October 1990.
15. Hughes, P., *Spacecraft Orientation Dynamics*, John Wiley, New York, NY, 1986.

16. Spofford, J.P. and Akin, D.L., "Redundancy Control of a Free-flying Telerobot," *J. Guidance*, Vol. 13, No. 3, May-June 1990, pp. 515-522.
17. Papadopoulos, E. and Dubowsky, S., "Coordinated Manipulator/Spacecraft Motion Control for Space Robotic Systems," *Proc. IEEE Int. Conf. on Robotics and Automation*, Sacramento, CA, April 1991.