Simulation study of the space robot dynamics using virtual manipulator approach

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Abstract - The attempt of this simulation study was to test the capability of the Virtual Manipulator (VM) ideas as originally proposed by Vafa and Dubowsky, (1987, 1988, 1990). It was observed that the base-fixed manipulator's dynamic formulations are not suitable for the space manipulator consideration. The dynamic problems of the space manipulator requires a unique solution to be undertaken. The dynamic formulations for these systems are complex. Several simulation tests were performed over the free-floating space robotics system, whereby the spacecraft's angular velocity was fixed. The most beneficial knowledge of this simulation test was the total understanding of the dynamic behavior of these systems that comprises of space manipulator and the space platform. It appears that the proposed Virtual Manipulator concepts had further enhanced the understanding of space manipulator systems.

Keywords: **Space Robotics, Dynamics, Virtual Manipulator, free-floating robot.**

I. INTRODUCTION

The control of space manipulators poses planning and control problems that are not found in terrestrial fixed-base manipulators due to the dynamic coupling of space manipulators and its spacecraft. There have been several control techniques that has been proposed by previous researchers, which can be subdivided into three categories. In the first category, the spacecraft position and attitude are controlled by reaction jets to compensate for any manipulator dynamics forces exerted on the spacecraft. In this case, the control laws for earth-bound manipulators can be used. However, the utility of such systems can be limited. This is because the manipulator's motions can both saturate the reaction jet system and consume relatively large amount of attitude control flue, limiting the usefulness of the system [1]. In the second category, the spacecraft attitude is controlled, using reaction wheels or attitude control jets in a non-translation manner [2][3][4]. The control problem of these systems can be simplified using the Virtual Manipulator (MV) technique [4][5]. The third proposed category assumes a free-floating system in order to conserve fuel or electrical power [5][7]. Such a system permits the spacecraft to move freely in response to manipulator motions. This mode becomes feasible when no external forces and torques act on the system, and when its total momentum is negligible, since the spacecraft's attitude control system does not operate during this mode of space manipulation. In practice, momentum dump maneuvers would be employed to remove any momentum that may accumulate [8][9]. In this light, two identification methods for space robots can be used. In the first method the space robot manipulators can be considered on an inertial fixed base [10]. The dynamic parameters of these space robots can be determined from the relations between motions of a manipulator and applied joint forces and/or torques. In the second method, a novel identification method for space robots can be proposed which can freely move in both translational and rotational directions. This method is based upon the conservation laws of linear and angular momentum of a space robot. 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. The 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 cases where there are external forces and torques acting on the system, such as forces caused by reaction jets or by contact with external object the VB will accelerate and change its position in inertial space. The VB accelerations are proportional to the external forces on the manipulator/spacecraft. The forces and torques will also rotate the system about the center of mass. The systems considered are assumed to be free-floating, and hence the virtual manipulator base will be a VG as shown in Fig. 1.

II. DYNAMIC OF BASE-FIXED MANIPULATOR

Kinematic and kinetic (dynamic) characteristics of a manipulator will have a major influence on the base-fixed manipulator operation. The physical and geometric parameters such as masses, moments of inertias and link dimensions are used to identify the dynamics parameters of a base-fixed robot. The equation of motion of free-floating systems with no external forces or moments can be formulated as,

$$\tau = M(q)(\ddot{q}) + h(q,\dot{q}) \tag{1}$$

where $M(q)(\ddot{q})$ is the inertia matrix and $h(q,\dot{q})$ is the centrifugal and Coriolis term.

The dynamic analysis of a base-fixed manipulator can be achieved by considering a satellite base fixed on an inertial foundation with two links of the manipulator moving in a plane. The first and second joint angles are denoted as $q=(q_1,q_2)^T$ and its corresponding joint torques as $\tau=(\tau_1,\tau_2)^T$. The superscript T indicates the transpose of a vector. Again by adding the joint frictional resistant torque the dynamic equations of motion of the manipulator can be re-described as follows:

$$M(q)\ddot{q}+h(q,\dot{q})+f_f=\tau \tag{2}$$

where

$$M(q)=\begin{bmatrix} m_{11}+2m_c\cos q_2 & m_{22}+m_c\cos q_2 \\ m_{22}+m_c\cos q_2 & m_{22} \end{bmatrix} \tag{3}$$

is the inertial matrix of the manipulator. The vector $h(q,\dot{q})$ represents the centrifugal and Coriolis' forces:

$$h(q,\dot{q})=\begin{bmatrix} -m_c Sin\,q_2\,.\dot{q}_2^2-2m_c Sin\,q_2\,.\dot{q}_1\dot{q}_2 \\ m_c Sin\,q_2\,.\dot{q}_2 \end{bmatrix} \tag{4}$$

The vector f_f is the joint frictional resistant torque defined as

$$f_f=\begin{bmatrix} f_{v1}\dot{q}_1 \\ f_{v2}\dot{q}_2 \end{bmatrix}+\begin{bmatrix} f_{c1} \\ f_{c2} \end{bmatrix} \tag{5}$$

The first term of the right hand side of the equation denotes viscous damping torques and the second term the Coulomb damping torques m_{11}, m_{22} and m_c which are the dynamic parameters of the manipulator. Note that the f_{v1}, f_{v2}, f_{c1} and f_{c2} are the frictional parameters.

In the analysis, the base reactions of a space manipulator are directly transmitted to the supporting structure, which is generally part of the space vechicle or space station. These base reaction forces are in fact disturbance that can have significant adverse effects on the control and performance of the space robot. Clearly, it is not trivial to take into account the reaction force on the space structure in the associated control schemes. Furthermore, since the coupling between the manipulator and the space structure is dynamic in nature, the performance of the manipulator will also be affected by these dynamic interactions. It follows that, ideally, one would desire zero base reactions for robot manipulators used in space applications.

III. DYNAMIC OF FREE-FLOATING SPACE ROBOTS

Consider a platform/manipulator system as shown in Fig. 1. Suppose there are no external forces acting on the system, the system CM does not accelerate, and the system linear momentum is constant, i.e., ${}^0\dot{r}_{cm}=0$. 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.

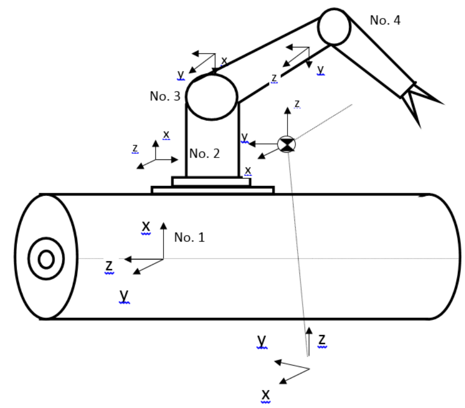

Fig. 1. Satellite platform and the manipulator arm.

The spacecraft's initial 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 $q=[q_1,q_2,\ldots,q_n]^T$. 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, δq, as $\delta\boldsymbol{\theta}_b=\boldsymbol{G}(q)\delta q$, where $\boldsymbol{G}$ is a 3 by N disturbance sensitivity matrix [1]. The vector $\delta\boldsymbol{\theta}_b$ is defined as the instantaneous disturbance.

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, ${}^0\omega_0$, as,

$$[\dot{r}_E,\omega_E]^T=J^*\dot{q} \tag{6}$$

The conservation of angular momentum is,

$${}^o\omega_0=-{}^0D^{-1}\ {}^0D_q\dot{q} \tag{7}$$

where ${}^0D$ is the 3 by 3 system inertia matrix with respect to the system CM, and as such it is a positive definite symmetric matrix. The ${}^0D_q$ is a 3 by N matrix. The matrices ${}^0D$ and ${}^0D_q$ are the functions of the configuration q. The inverse of ${}^0D$ always exist because the system inertia matrix is positive definite. Equation (7) can be used to express ${}^o\omega_0$, from

$$v_E=J^+v=[\dot{r}_E^T,\omega_E^T]^T \tag{8}$$

where v_E is the end-effector velocity and J^+ is the 6 by N+6 nonsquare matrices, even when N=6. Again, ${}^o\omega_0$ is a function of $\dot{q}$, which can be used to derive a free-floating system's Jacobian J^*, defined by,

$$[\dot{r}_E,\omega_E]^T=J^*\dot{q} \tag{9}$$

where J^* is a 6xN matrix given by,

$$J^*(\boldsymbol{\theta}_s, q) = \mathrm{diag}(T_0(\boldsymbol{\theta}_s), T_0(\boldsymbol{\theta}_s))^0 J^*(q) \tag{10}$$

Since Eq. (6) 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 configuration 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 equal to zero. The resulting equation becomes,

$$\tau = M(q)(\ddot{q}) + h(q,\dot{q}) \tag{11}$$

where $M(q)(\ddot{q}) \equiv {}^0D_q - {}^0D_q^T \; {}^0D^{-1} \; {}^0D_q$ is the reduced system inertia matrix, and $h(q,\dot{q})$ contains the non-linear centrifugal and Coriolis terms. The vector τ is the manipulator joint force/torque vector $[\tau_1, \tau_1, \ldots, \tau_N]^T$. Therefore, $M(q)(\ddot{q})$ is the *N* x *N* positive definite symmetric inertia matrix, which depends on *q* and the system mass properties, as defined in Eq. (3).

IV. SIMULATION RESULTS

A simulation study was conducted by considering the Puma 560 robot structure shown in Table 1. The VM to an arbitrary point on the real manipulator body, and end-effector VM coincide with the real manipulator end-effector. These VM constructions enable the dynamic motions of a space manipulator system to be described by the motions of its Virtual Manipulator representation that has its base at the VG.

TABLE I
The Puma 560 robot's parameter.

i	q_i	a_i (cm)	a_i (deg)	d_i (cm)	Rotor Inertia (kgm^2)	M_i (Kg)
1	var	0	-90	60	2.5×10^{-2}	1.5
2	var	175	0	0	2.5×10^{-3}	1.3
3	var	266	0	0	2.5×10^{-3}	1.2
4	var	0	90	0	1.5×10^{-4}	0.25
5	var	20	0	-55	1.5×10^{-4}	0.12
6	var	0	90	0	7.8×10^{-5}	0.05

The systems Jacobian can be calculated from the Eq. (9) as,

$$\dot{x} = \dot{r}_E = \frac{d}{dt}[x,y,z]^T = J^*\dot{q} \tag{12}$$

where, $x = r_E = [x, y, z]^T$ and

$$q = [q_1, q_2, q_3, q_4, q_5, q_6]^T$$

Thus the J^* is,

$$J^*(\theta, q) = T_0(\theta)^0 J^*(q) \tag{13}$$

The transformation matrices ${}^0T_i$ are found according to,

$$\begin{aligned}
{}^0T_1 &= \mathrm{Rot}(q_1) \\
{}^0T_2 &= \mathrm{Rot}(q_1)\mathrm{Rot}(q_2) \\
{}^0T_3 &= \mathrm{Rot}(q_1)\mathrm{Rot}(q_2)\mathrm{Rot}(q_3) \\
{}^0T_6 &= \mathrm{Rot}(q_1) \;\ldots\;\ldots\; \mathrm{Rot}(q_5)\mathrm{Rot}(q_6)
\end{aligned} \tag{14}$$

Finally the system Jacobian J^* is,

$$\begin{aligned}
{}^0J^*(q) &= \mathrm{Diag}(T_0, T_0)^0 J^*(q) \\
&\equiv \begin{bmatrix} -{}^0J_{11}\,{}^0D^{-1} \;\; {}^0D_q + {}^0J_{12} \\ -{}^0D^{-1} \;\; {}^0D_q + {}^0J_{22} \end{bmatrix}
\end{aligned} \tag{15}$$

where ${}^0D_j$ are the inertia matrices corresponding to the scalars ${}^0d_{ij}$ for the planar robot. Thus, the matrices can be given by,

$$\begin{aligned}
{}^0D_j &\equiv D_j = \sum_{i=0}^{6} {}^0d_{ij} \qquad (j = 0, 1\ldots5, 6) \\
D &\equiv D = D_0 + D_1 + \ldots + D_5 + D_6 \\
{}^0D_q &= [D_1 + D_2 + \ldots\ldots + D_5 + D_6]
\end{aligned} \tag{16}$$

Finally, from the above Eqs. (13 – 16), the system Jacobian J^* is assembled.

To demonstrate this space robot dynamic algorithm, the manipulator end-point is commanded to reach the workspace point (200cm, 340cm, 100cm) starting from the initial location of (100cm, 300cm, 300cm) with initial attitude of joint angles. A constant spacecraft angular velocity was considered at the rate of 100 cm/sec. The simulated control algorithm calculates the end-effector inertial position and velocity, x and $\dot{x}$, by using the control law,

$$\tau = J^{*T}\{K_p(x_{\mathrm{des}} - x) - K_d\dot{x}\} \tag{17}$$

Where, *x* represents the Cartesian location of the end-effector, and, x_{des} is the inertial desired point location. The gain matrices K_p and K_d are diagonal. Note that this algorithm will specify the desired end-effector location. The path of the end-effector to the desired location is not specified in advance. If the control gains are large enough, then the motion of the end-point will be a straight line. The torque vector τ is nonzero until the $(x_{\mathrm{des}} - x)$ and $\dot{x}$ are zero with the vector in the brackets of Eq. (17) being in the null space of J^{*T}. In this space robot dynamic simulations test the control gain matrices used are $K_p = \mathrm{Diag}(25, 25, 25, 5, 5, 5)$ and $K_d = \mathrm{diag}(100, 80, 60, 30, 10, 10)$.

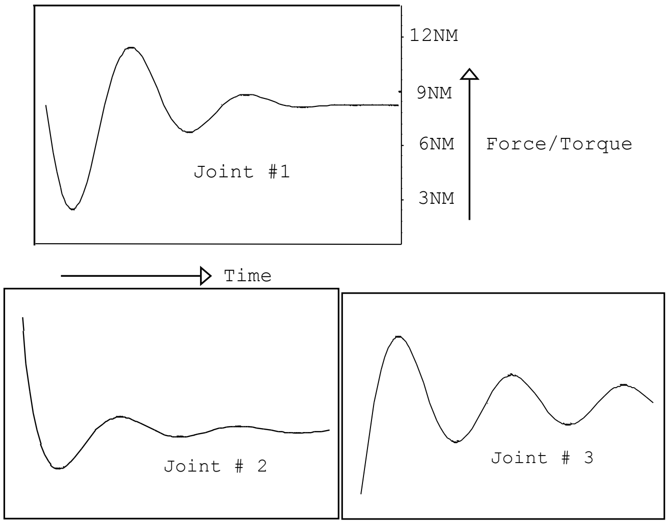

Fig. 2(a,b,c). The force/torque profile of joints 1, 2 and 3

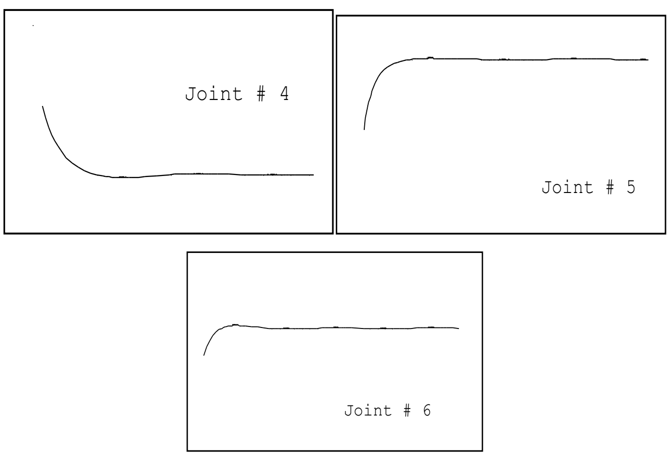

Fig. 3(a,b,c). The force/torque profile of joints 4,5 and 6

The initial joint position of the space manipulator was $(0^0, 90^0, -90^0, 0^0, 0^0, 0^0)$, which reaches the commanded position with the following configuration of $(10^0, -30^0, -15^0, -50^0, 45^0, 25^0)$. The control gain matrices parameters K_p and K_d has significant effects on the final force/torque value. The space manipulator's system Jacobian was calculated with consideration of the spacecraft angular velocity. The Fig. 2(a,b,c) and Fig. 3(a,b,c) shows the force/torque profiles of the six joints.

V. CONCLUSION

The attempt of this simulation study was to test the capability of the Virtual Manipulator (VM) ideas as originally proposed by Vafa and Dubowsky [1][7]. It was observed that the base-fixed manipulator's dynamic formulations are not suitable for the space manipulator consideration. The dynamic problems of the space manipulator requires a unique solution to be undertaken. The dynamic formulations for these systems are complex. Several simulation tests were performed over the free-floating space robotics system, whereby the spacecraft's angular velocity was fixed. The most beneficial knowledge of this simulation test was the total understanding of the dynamic behaviour of these systems. It appears that the proposed Virtual Manipulator concepts had further enhanced the understanding of space manipulator systems.

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