Payload Mass Identification of Space Robot

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Abstract

Future robotic manipulator systems will be required to perform complex tasks in space. In particular, the robotic manipulators will play important roles in future space missions such as retrieving, repairing, and servicing satellites in earth orbit. The dynamics of space robotic systems can be written complex and hence their control can be difficult. In this paper, particular attention is paid to free-floating space robots and only attitude-controlled robotic systems. These manipulators will encounter a number of kinematic, dynamic problems caused by the dynamic coupling between the manipulators and its spacecraft. This dynamic coupling also makes it difficult to analyze these systems. This paper reviews an analytical modeling method for space manipulators, called the Virtual Manipulator(VM) and presents a mass adaptation method of the unknown payload using the Virtual Manipulator concept.

1 Introduction

Space robotics is a special technological field. In future space development, robotization and automation will be key technology and contribute much to the success of space projects, reducing the workload and danger of astronauts and increasing operational efficiency. A major characteristic of these robots which are clearly distinguished from ground-based robots is the lack of a fixed base in space environment. There are a lot of past work to control space robots. Aong them, Vafa and Dubowsky proposed "Virtual Manipulator" concept in order to describe geometry of free-floating mechanical links. They applied it to analyze workspaces of space manipulators and to solve the inverse kinematics through a full comprehension both of position and attitude change of the satellite by the manipulator reaction([10], [11], [12], [1] [5]). Space Robotic manipulator systems are generally classified as three categories: free-flying manipulator system, the attitude controlled spacecraft/manipulator systems, a free-floating system. Once free-floating system is constructed and is available, it is very useful and attractive because it does not consume control fuel. The control problem for these kind of space/manipulator can be simplified using the VM concept ([11]). As mentioned above, attitude-controlled and free-floating space robot systems are very difficult in modeling and controling because the spacecraft moves due to the manipulator motions. If the VM method is applied to the attitude-controlled and free-floating space robot systems, they are represented by an ideal manipulator system, the VM, whose base is fixed in inertial space at a fixed point called the Virtual Ground(VG) ([12],[1]). However, the VM method is not always applied to the space robot systems. It is needed as prerequisite conditions for the VM to be applied to the space robot systems that the geometry and mass properties of space robot systems are exactly known in advance. The knowledge of mass property, is difficult to be satisfied when the spacecraft/manipulator system grasps some payloads of unknown mass. Vafa, Dubowsky, Papadopoulos, etc. dealt with the exactly known space robot itself and assumed that the payload mass property was exactly known when manipulator grasped payload and excluded the case of grasping unknown mass payloads. However, in actual cases, it is difficult to know the mass of payloads. Therefore, in this paper, we propose the mass adaptation method of unknown payloads using the VM method when the spacecraft/manipulator system grasps payloads.

2 Modeling

A space robot attached to a spacecraft in orbit is considered to be a free-flying free-floating sys-

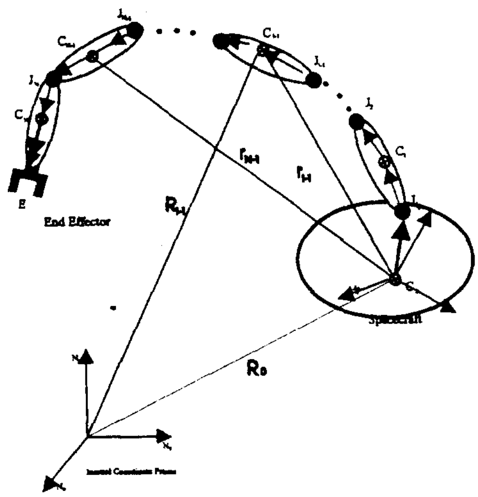

Figure 1: The Real Space Manipulator System

tem in the nongravitational environment. The system is modeled as a set of $(n+1)$ rigid bodies connected by n joints. Fig.1. show a general model of space robot system with a single manipulator arm, ,which is regarded as a free-flying or free-floating serial $(n+1)$ link system connected with n degrees of freedom active joints.

Let link 0 denote a satellite main body(base frame), link $i(i = 1, 2, \cdots, n)$ the $i_t h$ link of the manipulator and joint j a joint connecting link $(i-1)$ and link i. The total kinetic energy of the whole system is defined by summing up the translational energy and rotational energy of each body ([9]).

$$T \equiv \frac{1}{2}\sum_{i=0}^{n}(\Omega_i^T I_i{}^B + m_i V_i^T V_i) \qquad (1)$$

In case of free-floating, the linear and angular momenta are conserved at zero. Substituting momentum conservation equations into equation (??), we obtain the reduced form

$$T = \frac{1}{2}\dot{q}^T \hat{H}(q)\dot{q}, \qquad (2)$$

In above equations, concrete parameter meanings are referred to ref([9]).

It is easy to prove the reduced inertia matrix $\hat{H}(q)$ to be symmetric and positive definite ([9]). Therefore, the equation of motion for the reduced form can be derived in the same way as conventional robotics. If the Lagrangian formulation is applied, the general form of dynamics equation can be obtained as follows:

$$\hat{H}(q)\ddot{q} + B(q, \dot{q})\dot{q} = \tau \qquad (3)$$

3 The Mass Adaptation of unknown mass payloads

The attitude-controlled and free-floating space manipulator systems are very difficult to control because the base of the system is freely floating. But the motion control of them can be simplified by applying the VM method to those systems. But we need the prerequisite conditions for the Virtual Manipulator method to be applied to space robot systems :the geometric parameters and mass property are exactly known. In general, the geometric parameters and mass property are well known for the space robot system itself. However, above prerequisite conditions are not satisfied when the space robot system grasps some payloads of unknown mass. This problem is fatal to the application of the Virtual Manipulator approach to the space robot systems. In the control of space robot systems through the Virtual Manipulator approach, past researchers considered above unknown payload grasping cases as exceptional cases. But the above case is very important for the wide application of space robot systems using the Virtual Manipulator approach. So, we need a new mass adaptation methods that can be applied to the space robot systems. First, consider the construction of VM,that is, (N+1) link open chain rigid bodies formed by a spatial manipulator composed of N revolute joints and its supporting vehicle shown in Fig.2. The first VM link represents the vehicle's orientation. This link is attached to the VG by a spherical joint which permits the three vehicle rotations with respect to inertial space.

When space manipulator grasps payload whose mass is δm_p , the Virtual link lengths and Virtual Ground(VG) are changed due to the addition of payload mass. The payload can be considered as a part of the last link., the length of only the last link among vectors representing its mass center at each link, $R_n.L_n$, are changed. The Virtual link lengths for the new space manipulator system with unknown mass payload are

$$V_{p0} = R_0 \frac{m_0}{M_{tot} + \delta m_p} \qquad (4)$$

$$V_{p1} = L_1 \frac{m_0}{M_{tot} + \delta m_p} + R_1 \frac{(m_0 + m_1)}{M_{tot} + \delta m_p} \qquad (5)$$

$$\cdots \qquad (6)$$

$$V_{p(n)} = L_{new(n)} \frac{m_0 + \cdots + m_{n-1}}{M_{tot} + \delta m_p} + R_{new(n)} \qquad (7)$$

where we assume that the last link is straight. If the last link is bended link, it can be divided into

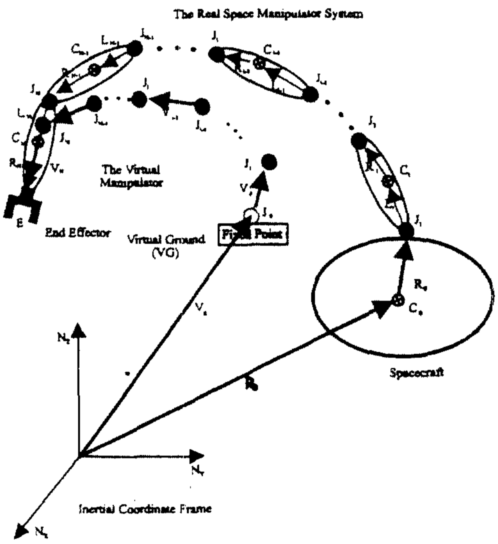

Figure 2: The Real and Virtual Manipulator System

two straight links. Therefore, it is valid that the last link is assumed to be straight. The new Virtual Ground(VG) when the payload is grasped is

$$VG_p = \frac{(VG \times M_{tot} + P \times \delta m_p)}{M_{tot} + \delta m_p} \tag{8}$$

where

$$R_{new(n)} = \frac{m_n}{m_n + \delta m_p}\frac{l_n}{2},$$
$$L_{new(n)} = (1 + \frac{\delta m_p}{m_n + \delta m_p})\frac{l_n}{2} \tag{9}$$

and P is initial payload position when payload is grasped. When manipulator grasps a payload, the lengths of only the last link vector, R_n, L_n among vectors representing the center of mass in each of link are changed . When space manipulator grasps a payload, Virtual link lengths are different from those of Virtual links without payload such that the position of the real manipulator end-effector is not coincident to the position of Virtual manipulator end-effector without payload. Now, consider the mass adaptation method of unknown payload. First, we consider payload mass adaptation method under a few assumptions.

Assumptions when the manipulator end-effector grasps a payload :

1. the position of unknown payloads can be measured or known.

2. payloads are assumed to be rigid and fixed to the manipulator end-effector.

Procedure of the mass adaptation of payload will be explained next. The Virtual Manipulator without payload is constructed. And the estimated Virtual Manipulator for the estimated payload mass is constructed when manipulator grasps payload. Real manipulator end-effector is moved from initial payload position to generate position error between real manipulator end-effector position and estimated Virtual Manipulator end-effector position when the payload is grasped. Payload mass adaptation process is performed using the Virtual Manipulator approach.

This process requires end-effector position error which is calculated or measured from external sensor system only one times. In this process, joint angles are fixed as joint angles when manipulator is moved at one times after grasping payload. Therefore, in the process of mass adaptation joint angles are time-invariant constant values and only Virtual link lengths and estimated payload mass are time-varying variables. Now, consider concrete mathematical process. When payload is grasped, actual Virtual Manipulator with payload is as above and estimated Virtual Manipulator with payload is

$$\begin{aligned}
V_{est0} &= R_0\frac{m_0}{M_{tot} + \delta m_{est}} \\
V_{est1} &= L_1\frac{m_0}{M_{tot} + \delta m_{est}} + R_1\frac{(m_0 + m_1)}{M_{tot} + \delta m_{est}} \\
&\dots \\
V_{est(n)} &= L_{est(n)}\frac{m_0 + m_1 + \cdots + m_{n-1}}{M_{tot} + \delta m_{est}} \\
&\quad - R_{est(n)}
\end{aligned} \tag{10}$$

Virtual Ground(VG) is

$$VG_{est} = \frac{(VG \times M_{tot} + P \times \delta m_{est})}{M_{tot} + \delta m_{est}} \tag{11}$$

where

$$R_{est(n)} = \frac{m_n}{m_n + \delta m_{est}}\frac{l_n}{2},$$
$$L_{est(n)} = (1 + \frac{\delta m_{est}}{m_n + \delta m_{est}})\frac{l_n}{2} \tag{12}$$

For fixed joint angles, time derivatives of estimated Virtual Ground and Virtual link length are

$$\begin{aligned}
\dot{VG}_{est} &= -(VG_{est} - P)\frac{\delta \dot{m}_{est}}{M_{tot} + \delta m_{est}} \\
\dot{V}_{est0} &= -\frac{\delta \dot{m}_{est}}{(M_{tot} + \delta m_{est})}V_{est0} \\
\dot{V}_{est1} &= -\frac{\delta \dot{m}_{est}}{(M_{tot} + \delta m_{est})}V_{est1} \\
&\dots \\
\dot{V}_{est(n-1)} &= -\frac{\delta \dot{m}_{est}}{(M_{tot} + \delta m_{est})}V_{est(n-1)}
\end{aligned} \tag{13}$$

and for the last link

$$V_{estn} = (\frac{l_n}{2})\frac{m_0+\cdots+m_{n-1}}{M_{tot}+\delta m_{est}} + \frac{M_{tot}}{M_{tot}+\delta m_{est}}(\frac{l_n}{2})$$

$$\dot{V}_{estn} = -\frac{\delta\dot{m}_{est}}{M_{tot}+\delta m_{est}}V_{estn} \quad (14)$$

As we know from above time-derivatives, all estimated Virtual Manipulator link lengths are shortened with estimated payload mass increased. End-point of estimated Virtual Manipulator with payload is

$$x_{est} = VG_{estx} + V_0cos(q_0) + \cdots + V_ncos(q_0+\cdots+q_n)$$

$$y_{est} = VG_{esty} + V_0sin(q_0) + \cdots + V_nsin(q_0+\cdots+q_n) \quad (15)$$

Theorem 1 *Assume that real manipulator is moved after payload grasped such that real manipulator end-point is not included to the line between the VG without payload and the initial payload position when the payload is grasped.*

If adaptation law

$$\delta\dot{m}_{est} = Kp \times [e_x(x_{est}-P_x) + e_y(y_{est}-P_y)]$$

where Kp is adaptation gain, $e_x = x_p - x_{est}, e_y = y_p - y_{est}$ *,* x_p *and* y_p *are real manipulator end-effector position with payload and* x_{est} *and* y_{est} *are estimated VM end-effector position for the estimated payload mass, is applied to the estimated VM,*
then it is guaranteed that estimated payload mass converges to exact payload mass and end-point error between real manipulator with payload and estimated Virtual Manipulator with payload converges to zero.

Proof
Let Lyapunov function be

$$v = \frac{1}{2}e^Te$$

where P_x and P_y are the initial position of payload when it is not grasped by the manipulator. First, it is needed that only payload mass is time-varying variable and that joint angles are not time-varying variables during the process of payload mass adaptation. Time-derivative of Lyapunov function is

$$\dot{v} = e^T\frac{de}{dt} = -e^T\frac{\partial x_e}{\partial\delta m_{est}}\delta\dot{m}_{est} \quad (16)$$

where

$$\frac{dx_{est}}{dt} = -(x_{est}-P_x)\frac{\delta\dot{m}_{est}}{M_{tot}+\delta m_{est}}$$

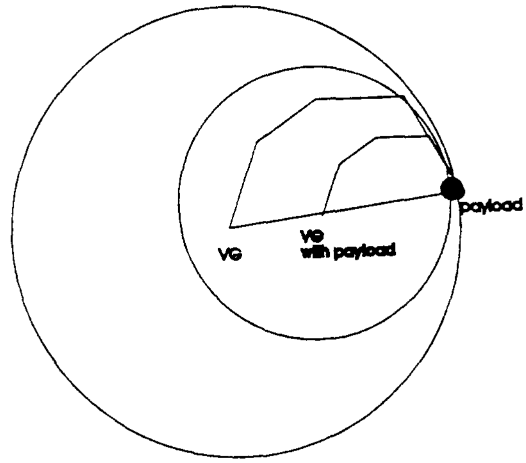

Figure 3: The Virtual Manipulator with Payload

$$\frac{dy_{est}}{dt} = -(y_{est}-P_y)\frac{\delta\dot{m}_{est}}{M_{tot}+\delta m_{est}} \quad (17)$$

As a result

$$\dot{v} = -e^T\begin{pmatrix} x_{est}-P_x \\ y_{est}-P_y \end{pmatrix}\frac{\delta\dot{m}_{est}}{M_{tot}+\delta m_{est}} \quad (18)$$

proposed adaptation law $\delta\dot{m}_{est}$ is substituted for $\delta\dot{m}_{est}$ of above time-derivative Lapunov equation

$$\dot{v} = -Kp\times(e_x(x_{est}-P_x)^2+e_y(y_{est}-P_y)^2)\frac{1}{M_{tot}+\delta m_{est}} \quad (19)$$

Therefore if $(x_{est}, y_{est}) \neq P$, then error $e = (x_p - x_{est}, y_p - y_{est})$ will converge to zero. If real manipulator end-effector x_p is not included in the line between the VG and the position of real manipulator end-effector at the time that payload is grasped, then the position of estimated virtual manipulator end-effector is not coincident with the position of real manipulator end-effector at the time that payload is grasped. Above fact can be easily proved by geometric viewpoint, which will be shown in Fig.3 and Fig.6 in simulation result. Therefore, it is guaranteed that estimated payload mass will converge the exact payload mass and that end-effector error in inertial space will be converge to zero.

4 Simulation

Consider the simple planar space robot system. The mass of spacecraft is 100(Kg) and for the first and second link, 30(Kg),30(Kg). The length of spacecraft is 10(m) and for the first and second link, 10(m),8(m). AT first, payload mass is assumed to be the mass of total system,160(Kg).

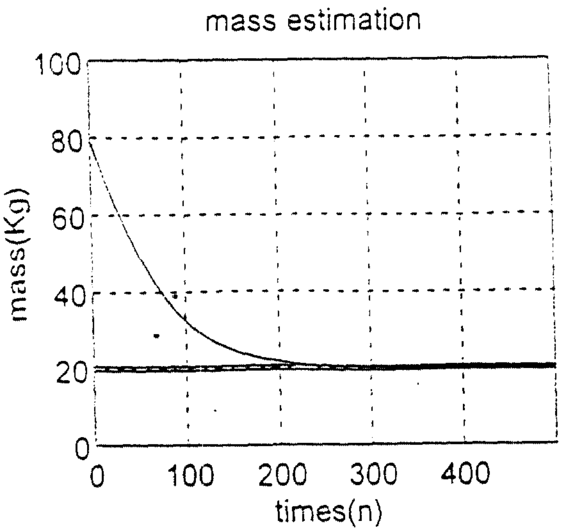

Figure 4: The Payload Mass Adaptation

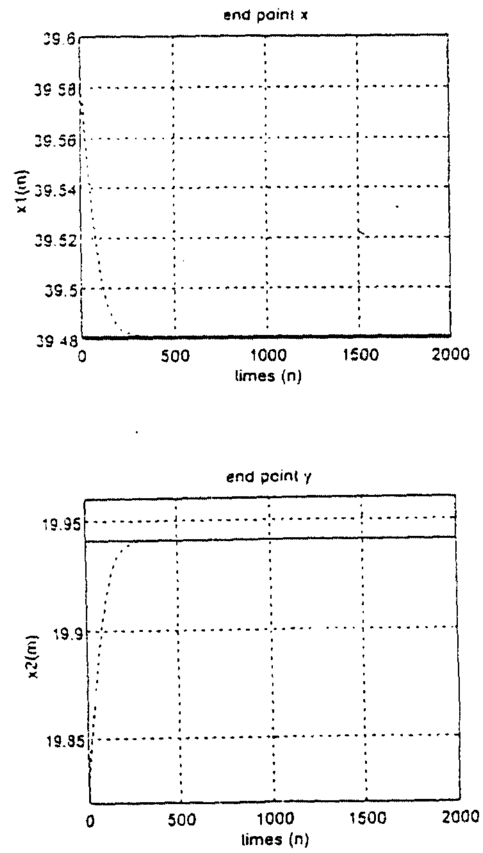

Figure 5: The End Point during Payload Mass Adaptation

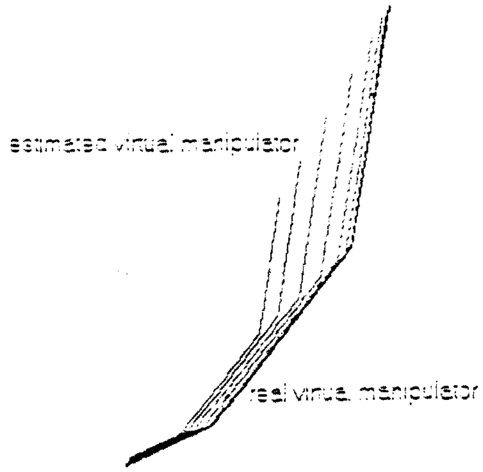

Figure 6: The Snap Shot of VM configuration

Fig.4 shows the payload mass adaptation and shows that the estimated payload mass converges to exact payload. And Fig.5 shows that the end-effector position of estimated virtual manipulator converges that of real virtual manipulator when the manipulator grasps the unknown payload. Fig.6 shows the configuration of the estimated virtual manipulator during mass adaptation process when payload is grasped. Above simulation results show that the estimated payload mass converges to exact payload mass if the proposed mass adaptation method is used.

5 Conclusion

In this paper, we considered the mass adaptation method of payload for the attitude-controlled and free-floating space manipulator systems when the space manipulator grasped some payloads. In general the conventional adaptive control method cannot be used in the free-floating space manipulator systems. So we cannot adapt the payload mass using the conventional adaptive control method. If we cannot adapt the payload mass, the VM approach which will solve many difficult and important problems in attitude-controlled and free-floating space manipulator systems such as workspace analysis and inverse kinematics cannot be used. So the motion control problem, which can be simplified by the VM approach, will be remained original difficult problem. However, if the proposed mass adaptation method of payload is used, the motion control problem will be again solved simply because the VM can be constructed for the new space manipulator system with payload. As a result, we can apply the VM approach the attitude-controlled and free-floating space manipulator system whether the manipulator grasps some payloads or not.

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