Abstract

In this paper, the contact motion between robotic manipulator under impedance control and rigid body floating in space is modeled and analyzed.

The contact motion between rigid bodies floating in space is formulated and dynamic conditions were investigated in order to capture a non-cooperative satellite. The equivalent mass of the tip of manipulator come from impedance control is discussed. The simulation model of contact motion between a floating target and a manipulator under impedance control is established. For validation of this model, experiment with a robotic arm and a pendulum is carried out. Using the simulation model, it is inspected that the influence of the damping factor, the control time delay and the contact stiffness between the chaser hand and the target on the VMI.

1 INTRODUCTION

In order to reduce the risk of collision between satellites and space debris, it is very important to keep orbital environment clean. Satellite servicing is one of the biggest key technology for such problem. Satellites on-orbit with potential becoming space debris should be captured, and then should be repaired, sent into the Earth’s atmosphere (deorbit) or sent into a so-called graveyard orbit.

On-orbit demonstration of robotics and rendezvous-docking technologies was carried out by the Engineering Test Satellite VII (ETS-VII) of the National Space Development Agency, Japan from 1997 to 1999 [1]. In this demonstration, a sub-satellite (target) was approached and successfully docked with by a main satellite (chaser). However, the target was stabilized its attitude. Moreover it had dedicated fixture and optical markers. Such target is called “cooperative.” In contrast, the satellites already existing in orbit and requiring service are “non-cooperative” targets with no such features.

The present paper considers a case of a non-cooperative target, having no dedicated grapple fixtures. Figure 1 is a schematic of the docking mechanism used by ETS-VII. This mechanism squeezes the grapple fixture on the target with the end effector on the chaser. The end effector forms a closed space around the grapple fixture before making contact, then gradually narrows the space to grasp the fixture. This prevents the target from pushed off due to the collision when the end effector and the grapple fixture come into contact. ETS-VII has three sets of this type of mechanism and fixes the target securely by three-point clamping.

A key idea here is to form a physical enclosure by the end effector before contacting the fixture. Contact without enclosure is referred to as “open contact.” Open contact can push the target away from the chaser during the grappling process.

Unlike the ETS-VII sub-satellite, most existing satellites in orbit do not have dedicated grappling fixtures. Among common features in the mechanical design of conventional satellites the Payload Attach Fitting (PAF) and the nozzle cone of an apogee kick motor are good candidates to be grasped [3]. The PAF is a high-strength structure that is used to connect the satellite to the launch vehicle. The mounting base of apogee kick motor has high strength. Therefore, the grappling inside of the nozzle cone with a probe is effective [2] [3]. Figure 2, 3 show the concept of PAF and nozzle cone grappling. As the figures show, PAF and nozzle cone grappling inherently require open contact.

For safe capture by open contact, it is necessary to discusses the dynamic conditions in order to pre-
vent a chaser robot from pushing a target away from the chaser under the open contact. The dynamic conditions can vary due to the impedance control of the chaser’s arm. The contact motion between rigid body systems floating in space is formulated using an impedance model. The equivalent mass of the chaser is suggested using the impedance model in order to clarify the conditions of impedance control so as not to deflect the target away from the chaser. The equivalent mass is defined by the impedance characteristic and specific angular frequency. It is difficult to define the angular frequency in case of that the impedance control include the damping factor and time delay. The presented paper discusses the influences of the damping factor, the control time delay and the contact stiffness between the chaser hand and the target on the equivalent mass.

2 CONTACT DYNAMICS OF A SPACE ROBOT

2.1 Contact Model

Figure 4 shows a model in which two satellites come into contact. The robot satellite on the left (hereinafter, referred to as the chaser) has a manipulator arm that allows impedance control attached to a base of mass \( m_0 \). The satellite on the right is the target of capture (hereinafter, referred to as the target) that is modeled as a floating rigid body of mass \( m_t \). When the robot hand is in contact with the target, mechanical impedance (contact impedance) is defined between both parties.

The present paper considers the influences of the impedance at the robot hand on the target motion using this model. The impedance is subject to the (passive) mechanical properties of the system as well as the characteristics of the (active) impedance control.

2.2 Basic Equations of a Space Robot

The equation of motion of a free-floating space robot is expressed by Equation (1):

\[
\tau = H^* \phi - J^{*T} F_e + c
\]  

(1)

where \( \phi \) is the joint angle, \( \tau \) is the joint torque, \( F_e \) is the external force on the hand, \( c \) is the nonlinear velocity term, and \( J^* \) and \( H^* \) are the generalized Jacobian [4] and generalized inertia [5] matrices of the floating link system.

2.3 Impedance Control of a Space Robot

Impedance control of the robot arm allows the inertial characteristics of the hand to vary over a wide range.

Denoting \( \vec{x} \) as the hand position in the inertial frame, the impedance characteristics \( M_i, D_i, \) and \( K_i \) are assigned as shown in Equation (2). Here, the orientation of the hand is excluded for simplicity.

\[
M_i \ddot{x} + D_i \dot{x} + K_i x = F_e
\]  

(2)

The joint torque to realize such impedance characteristics is theoretically obtained by Equation (3) [6].

\[
\tau = -H^* J^{*T} \{ J^* \dot{\phi} + M_i^{-1}(D_i \Delta \dot{x} + K_i \Delta x) \} + (H^* J^{*T} M_i^{-1} - J^{*T}) F_e + c
\]  

(3)

Due to the limitation of the control bandwidth, however, the above equation is not easy to apply to a practical system. In the experiments described later, we use a position control based approach to stably realize the impedance control which is equivalent to Equation (3) under the bandwidth of a practical controller.
3 VIRTUAL MASS BASED ON IMPEDANCE

3.1 Definition of VMI

Here, for simplicity, only a uniaxial component of hand impedance is considered. The satellite capturing model shown in Figure 4 is modified to Figure 5, where, $m_i$, $d_i$ and $k_i$ are the values of $m_v$, $D_i$ and $k_i$, respectively, projected onto a single axis.

We propose the Virtual Mass based on Impedance (VMI) $m_v$. It characterize the inertia-based impedance property of the chaser’s hand which is under the impedance control:

$$m_v \equiv m_i + \frac{d_i}{s} + \frac{k_i}{s^2}$$

where $s$ is the Laplace operator.

The VMI is rearranged by using the relationship of $s = j\omega$ ($j$: imaginary unit, $\omega$: specific angular frequency) to obtain Equation (6).

$$m_v = \left| m_i - \frac{k_i}{\omega^2} - j\frac{d_i}{\omega} \right|$$

$$= \sqrt{\left(m_i - \frac{k_i}{\omega^2}\right)^2 + \left(\frac{d_i}{\omega}\right)^2}$$

3.2 Modeling of Collision Motion Using VMI

Here, we consider a collision motion in which an impedance-controlled chaser’s hand contacts a target with a relative velocity.

Using the above VMI model, the chaser’s hand can be modeled as a virtual point mass having an equivalent mass $m_v$. Consider the case in which the hand with initial velocity $v_h$ collides the target with velocity $v_t$. Then the post-collision velocities $v_h'$ and $v_t'$ can be calculated using the coefficient of restitution $e$ as follows:

$$v_h' = \frac{m_vv_h + m_tv_t - m_te(v_h - v_t)}{m_v + m_t}$$

$$v_t' = \frac{m_vv_h + m_tv_t + m_ve(v_h - v_t)}{m_v + m_t}$$

3.3 $\omega$ in VMI

In theory, Equation (6) is valid in the frequency domain and may not be used in a transient phenomena such as collisions. However, even in collision, the contact duration is not infinitesimal but rather has a finite time. And for this finite time, a specific angular frequency $\omega$ can be defined as a specific angular frequency of the coupled mass-spring system showed in Figure 5 when $d_i = 0$. However, in case that the impedance control include the high damping factor or the control time delay, it is difficult to define the specific angular frequency.

The following section, it is inspected how the damping factor and the control time delay affect the VMI using the numerical simulation.
In order to investigate the effects of time delay and damping factor, we constructed a simulation model based on the spring-dumper model in Figure 5. Chaser’s manipulator under impedance control is represented as a mass-spring-dumper model connected with a wall. There is spring and dumper between the mass of impedance model and mass of the target. The wall is moving at a constant velocity, and then the mass of impedance becomes contact with the target through the spring of the contact model. The block diagram of this model is shown in Figure 8.

In order to realize this model on numerical calculation, the block diagram Figure 8 is constructed on MATLAB/SIMULINK. The input is the contact force between the chaser’s manipulator and the target. The force is transferred into position of the manipulator through the second-order transfer function including time delay. Next, the position of the manipulator is compared with the target surface. If the manipulator lodges in the target surface, the force is output in proportion to the sinkage quantity. This proportional constant is the stiffness of the contact point. Using the force data and target’s mass, the target position is updated.

5 EXPERIMENTAL VERIFICATION

5.1 Experimental Setup

For verification of the simulation model, we carried out an experiment. In this experimental set, a 7-DOF manipulator arm (Mitsubishi Heavy Industries, PA-10) were used as a chaser’s manipulator. And a pendulum (wire:10[m], total weight:130[kg]) were used as a target. Figure 9 is the concept of the experimental set.

A force/torque sensor was attached to the wrist of the chaser arm. Using force data from this sensor, impedance of the arm was controlled. Behind the target, there were laser range sensor. Figure 10 shows the control block diagrams of the chaser arm.

In this experiment, the endtip of the chaser arm under impedance control was collided with the target. After collision, the target starts swing. By measuring the width of the swing, the velocity of the floating target in space after collision with the manipulator can be expected.

In the early study, a manipulator was used as a floating target. Using force data from sensor, satellite motions were simulated on the manipulator. In such case, the time delay of the manipulator is unavoidable. Therefore, this method cannot play the target strictly. On the other hand, the method of pendulum gives accurate data after contact because it is a real phenomenon. Of course, chaser’s hand has also time delay. In this case, the time delay should be analyzed instead of prevention because the chaser in real mission has also time delay.

Note here that in space the base of the manipulator arm also moves due to the reaction of the manipulator motion. However, in the experiments, the position of the hand (or contact probe) x is controlled on a fixed base. Equation (3) gives an exact motion in which the base reaction is accounted for. In practice, the base reaction can be compensated in the loop of hand position feedback in the block diagram of Figure 10.

5.2 Experimental Results

Typical results of the experiments is shown in Table 1. In this case, the impedance ratio of $m_i$, $d_i$, and $k_i$ are 1:50:5.

5.2.1 Estimate of Contact Stiffness

For the simulation, the contact stiffness between chaser and target have to be known. In theory, the contact stiffness is given by the material characteris-
Table 1: Comparison between the experimental result and the simulation result

<table>
<thead>
<tr>
<th>Condition</th>
<th>Impedance</th>
<th>Experiment</th>
<th>Simulation</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$m_i$</td>
<td>$d_i$</td>
<td>$k_i$ [mm/s]</td>
<td>$v_h$ [mm/s]</td>
</tr>
<tr>
<td>5</td>
<td>250</td>
<td>25</td>
<td>20</td>
<td>19.72</td>
</tr>
<tr>
<td>7</td>
<td>350</td>
<td>35</td>
<td>20</td>
<td>21.50</td>
</tr>
<tr>
<td>10</td>
<td>500</td>
<td>50</td>
<td>20</td>
<td>23.57</td>
</tr>
<tr>
<td>30</td>
<td>1500</td>
<td>150</td>
<td>20</td>
<td>29.00</td>
</tr>
<tr>
<td>7</td>
<td>350</td>
<td>35</td>
<td>5</td>
<td>5.32</td>
</tr>
<tr>
<td>0.7</td>
<td>35</td>
<td>3.5</td>
<td>5</td>
<td>5.50</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>5</td>
<td>5</td>
<td>6.38</td>
</tr>
</tbody>
</table>

6 ANALYSIS OF DAMPING AND TIME DELAY

In this section, we discuss the effect of damping factor, time delay and contact stiffness on the VMI. Basically, the higher damping factor, the higher VMI. However, damping exerts a different influence according to the other conditions, especially contact stiffness and control time delay. The influence of control time delay is also different according to the contact stiffness.

6.1 Damping vs Contact Stiffness

At first, we investigated the effect of the damping factor on VMI under the various condition of contact stiffness. The relation between damping factor $d_i$ and the Contact stiffness $k_c$ is shown in Figure 11. In that case, the other condition is as follows: $m_i = 10$[kg], $k_i = 50$[N/m], $k_c = 50000$-$500000$[N/m], and no time delay. The x-axis is the value of the damping factor $d_i$ and y-axis is the value of VMI.

The obtained result show that the higher contact stiffness, the lower effect of damping on VMI. It is considered that the reason of the result is as follows: The damping factor $d_i$ is multiplied by the velocity of tip of the hand $\dot{x}$ in Equation (2). When the contact stiffness is high, $\dot{x}$ is reduced and become 0 in very short time. Therefore, the effect of the velocity term in Equation (2), namely damping factor, become lower.

6.2 Time Delay vs Contact Stiffness

Here, it is investigated that the effect of time delay on VMI under the different contact stiffness. Figure 12 is the result of the simulation. The obtained result show that the time delay make VMI larger in higher contact stiffness case than in lower case. The contact stiffness is the higher, the shorter contact time. Therefore, relative uncontrollable time of impedance increases and give large impact to the target.
6.3 Damping vs Time Delay

Here, the relationship between the damping factor and the control time delay is analyzed. Figure 13 is the result of the simulation in case of $k_c = 20000$ [N/m]. Basically, the obtained result show that the longer time delay, the slightly higher effect of damping on VMI.

It is considered that the reason of the result is as follows: Long time delay means long inactive time of impedance control. The contact force (strain energy) increase when the impedance control is inactive. The higher contact force, the chaser’s hand move the more quickly. Therefore, the longer time delay, the higher $\dot{x}$ in (2) and become the higher influence of the damping factor.

7 Conclusion

In this paper, the contact motion between robotic manipulator under impedance control and rigid body floating in space was modeled and analyzed. We suggested the virtual mass based on the impedance control VMI. The simulation model of contact motion between a floating target and a manipulator under impedance control is established. For validation of this model, experiment carried out with a robotic arm and a pendulum. Using the simulation model, It was investigated the influence of the damping factor, the control time delay and the contact stiffness between the chaser hand and the target on the VMI.

Acknowledgement

This study was jointly conducted by Tohoku University and Japan Aerospace Exploration Agency (JAXA).

References