The Analysis on the Contact Dynamics between a Robotic Manipulator and a Non-Cooperative Satellite using an Air-floating Testbed

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Abstract : This paper presents the analysis on the contact dynamics between a robotic manipulator under impedance control and a floating target in space. After the contact of two free-flying bodies in space, both parties are easily bounced away and start rotating by the contact force. In order to reduce the contact force in satellite capture, the dynamic conditions between the manipulator under impedance control and a free flying target are investigated. As a evaluation criteria, the equivalent mass of the tip of the manipulator coming from the impedance control is discussed. The influence of the impedance characteristics and the control time delay upon the equivalent mass are evaluated using experiments and numerical simulations. To replicate microgravity environment, a airfloating testbed on a stone surface plate is used.

空気浮上実験装置を用いた非協力衛星とマニピュレータとの接触力学解析

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概要： 宇宙空間において，ターゲットを捕獲する場合，初期接触でターゲットを弾き飛ばさないことが必須である．手先インピーダンス制御を用いて手先の見かけの慣性特性をコントロールすることによって接触力を減少させることが可能であるが，実際の宇宙空間では接触時間が非常に短く，また，ロボットの制御時間遅れや敏捷性が影響するために，ターゲットとの接触を維持することは容易ではない. 本論文では，フリーフライングロボットにおける手先インピーダンス制御を用いたロボットアームと二次元微小重力環境を模擬できる空気浮上型実験装置を用いて接触力学解析を行を行う.

1 Introduction

One of the most important phases of satellite servicing operations by a space robot is the contact phase. During the contact between the end-effector and grasping point, there is a risk that the target and the robot can be pushed away from each other by the contact force.

An On-orbit demonstration of robotics and rendezvous-docking technologies was carried out by ETS-VII of NASDA, Japan from 1997 to 1999 [1]. In this demonstration, a sub-satellite (target) was approached and successfully docked with by a main robotic satellite (chaser). However, the target equiped dedicated docking instrumens (grapple fixture, optical marker, etc.) suiting for the chaser satellite. These equipments prevented the target from being pushed off due to the collision when the end effector and the grapple fixture come into contact. 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 contact motion between rigid body systems floating in space can be formulated using an impedance model. The equivalent mass of the chaser was 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 [2]. The equivalent mass is defined by the impedance characteristics. However, in real contact phenomena, contact forces depend on a lot of facters (ex. dynaminc condition at the contact, the control time delay of the chaser, mechanical characteristics of the materials, mechanical impedance of system and so on.) [3] These facters make the estimation of the equivalent mass more diffiuclt. To velify the effect of the impedance control in experiment, a method to replicate the target floating in space more strictly should be carried

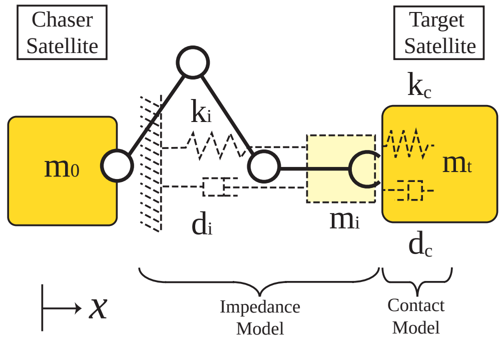


Figure 1: Satellite capture model

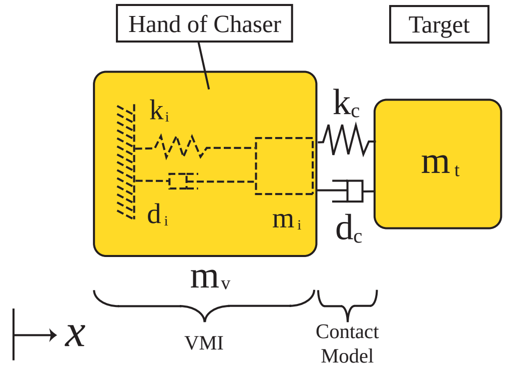


Figure 2: Impedance control model

out.

In earlier study, a hybrid simulator was used as a floating target. Using force data from a sensor, satellite motions were simulated on the manipulator. In such cases, the control time delay of the manipulator is unavoidable. Therefore, this method cannot play the target strictly.

In this papar, a testbed that can replicate microgravity environment by air injection method is used as a floating target. This method can simulate more strictly satellite motions because it doesn't include the control time delay. The analysis of the collision motion and the contact force when the cahser under impedance control with the time delay collides with the testbed is discussed, and the influences of the impedance characteristics and the control time delay of the chaser on the equivalent mass is also discussed.

2 Contact Dynamics of a Space Robot

2.1 Satellite Capture Model

Figure 1 shows a uniaxial component model in which two satellites come into contact. The robot satellite on the left 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 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 and the control time delay of the robot hand on the motion of the target using this model.

2.2 Basic Equations of a Space Robot

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

$$\boldsymbol{\tau} = \boldsymbol{H}^* \ddot{\boldsymbol{\phi}} - \boldsymbol{J}^{*T} \boldsymbol{F}_e + \boldsymbol{c} \tag{1}$$

where $\boldsymbol{\phi}$ is the joint angle, $\boldsymbol{\tau}$ is the joint torque, $\boldsymbol{F}_e$ is the external force on the hand, $\boldsymbol{c}$ is the nonlinear velocity term, and $\boldsymbol{J}^*$ and $\boldsymbol{H}^*$ 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 $\boldsymbol{x}$ as the hand position in the inertial frame, the impedance characteristics $\boldsymbol{M}_i$, $\boldsymbol{D}_i$, and $\boldsymbol{K}_i$ are assigned as shown in Equation (2). Here, the orientation of the hand is excluded for simplicity.

$$\boldsymbol{M}_i \ddot{\boldsymbol{x}}_h + \boldsymbol{D}_i \Delta \dot{\boldsymbol{x}}_h + \boldsymbol{K}_i \Delta \boldsymbol{x}_h = \boldsymbol{F}_e \tag{2}$$

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

$$\begin{aligned} \boldsymbol{\tau} \;\; = \;\; & \boldsymbol{H}^* \boldsymbol{J}^{*-1} \{ \boldsymbol{M}_i^{-1} (\boldsymbol{D}_i \Delta \dot{\boldsymbol{x}}_h + \boldsymbol{K}_i \Delta \boldsymbol{x}_h - \boldsymbol{F}_e) \} \\ & - \dot{\boldsymbol{J}}^* \dot{\boldsymbol{\phi}} - \ddot{\boldsymbol{x}}_{gh} \} - \boldsymbol{J}^{*T} \boldsymbol{F}_e + \boldsymbol{c} \end{aligned} \tag{3}$$

3 Equivalent Mass Based on Impedace

3.1 Definiton of Equivalent Mass

Figure 2 shows a model in which the chaser using impedance control and the terget includeing contact impedance are collided. The Equivalent Mass m_v based on Impedance is denied by Eqation (4) [2]. It characterizes the inertia-based impedance property of the chaser's hand which is under the impedance control

$$m_v \equiv \left| m_i + \frac{d_i}{s} + \frac{k_i}{s^2} \right| \tag{4}$$

where s is the Laplace operator.

3.2 Modeling of Collision Motion Using Equivalent Mass

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

$$v_t' = \frac{m_v v_h + m_t v_t + m_v e(v_h - v_t)}{m_v + m_t} \tag{5}$$

In case of $v_t = 0$ and $e = 1$, if $m_v \leq m_t$,

$$v_h \geq v_t' \tag{6}$$

that is to say that the target velocity after contact is smaller than the approaching velocity of the chaser. In this case, It is easy to keep contact after contact as long as the chaser hand is controled to keep the approaching velocity.

On the other hand, if $m_v > m_t$,

$$v_h < v_t'$$

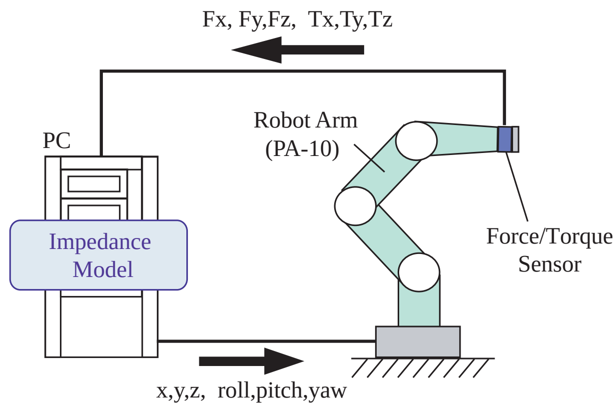
The target velocity is larger than the approaching velosity of the target hand. This means that the target pushed away from the chaser hand after contact.

Therefore, the condition to prevent a chaser from pushing the target away is to control the manipulator so that its m_v is smaller than the mass of the target.

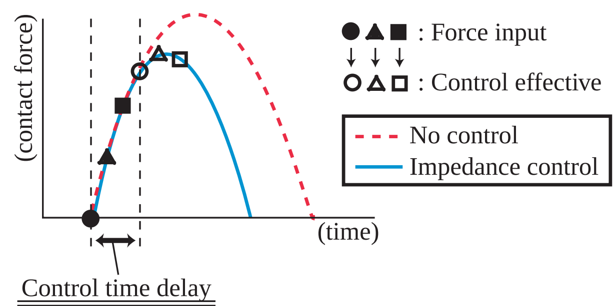
4 Control Time Delay

The control time delay occurs because of degitalization time of data from a froce-torque sensor, data communication time and caluculation time for objective position. This depends on performance of its systems, but any control system has time delay necessarily.

Figure 3-(b) shows a relation of contact force and time delay of impedance control. Because of the control time delay, it takes a little time from the chaser receiving force inputs to starting the motion according to the impedance control. The chaser under no



(a) Control time delay of robot arm



(b) Control time delay and contact force

Figure 3: Schematic of the control time delay

control continues to push the target during the period.

5 Experimental Setup

Figure 4 shows the schematic of the experimental setup. A 7-DOF manipulator arm (Mitsubishi Heavy Industries, PA-10) is used as a chaser's manipulator. A force-torque sensor mounted on the end tip of the chaser measures contact forces and moments, and the impedance control is applied using these.

An air-floating testbed as a target is shown in Figure 5. On the precision surface plate, aminiature model of a spacecraft has been set. The testbed floats slightly on the plate supported by a thin layer of air leaking from the bottom of the model. The friction between the precision surface plate and the bottom of the spacecraft model become nearly zero. Hence the micro gravity environment in two dimension is obtained. Two air tanks (Maximum pressure of 0.7[MPa]) mounted on the testbed allow it to main-

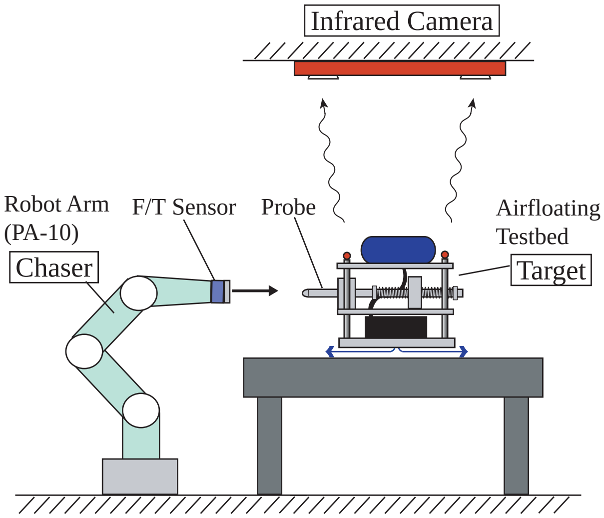
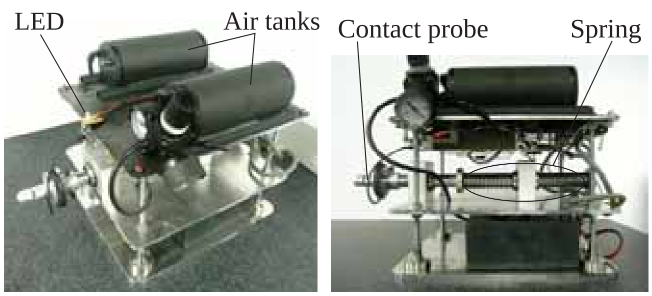


Figure 4: Experimental setup



(a) All view (b) Side view

Figure 5: Airfloating Testbed (Target)

tain one minute floating. A shaft is mounted on the center of the testbed as a contact probe to the end tip of the chaser. The contact probe has a exchangeable spring at the root of it in order to change the mechanical impedance of the contact point.

In order to obtain the position data of the testbed, there is a infrared camera on the ceiling over the experimental setup which track infrared LEDs on the testbed.

6 Contact Experiment about the Impedance Characteristics

This experiment investigates whether the end tip of the chaser under the impedance control can continue to keep in contact with the target when the chaser is controlled with various impedance characteristics. To continue to keep in contact is to satisfy the Equation (6). In other words, the relative velocity of the end tip of the chaser and the target after the collision is less than 0[cm/s].

6.1 Condition of the Experiment

The chaser under the impedance control moves in a straight line with constant speed $v_h = 3$[cm/s], and collides with the static target. The target mass $m_t = 30$[kg].

The impedance ratio of m_i, d_i, and k_i are 1:100:2, and the proportional constant a determines the impdedance characteristics.

$$\begin{bmatrix} m_i & d_i & k_i \end{bmatrix} = a \cdot \begin{bmatrix} 1 & 100 & 2 \end{bmatrix} \tag{7}$$

In this experiment, the profiles of the contact force and the motion of target are investigated when $a =$ 0.0675, 1.125, and 3.6.

6.2 Experimental Result

Figure 6 and 7 show the profiles of contact force and velocity of the target when the impedance characteristics $a = 0.675$(low), 1.125(proper), and 3.6(high). The higher a, the longer the contact time and the faster the velocity of target after the collision. The waveform of contact force changes from about 30[ms], which is the control time delay of this system. The reason of the result is as follows: In any impedance characteristic a, the chaser keeps pushing the terget with the mechanical impedance of the manipulator because the control effect has not appared yet during the control time delay. Hence, the total impulse which the chaser get during the control time delay is constant. In this case, the m_v in Equation (5) is the time average of the equivalent mass under time delay and the one under impedance control.

When a is 2.6, the velocity of target after collision is 3[cm/s]. That means the relative velocity of the chaser and the target is 0[cm/s], and the chaser can continue to keep in contact with the target when a is lower than 2.6.

6.3 Relation with the Equivalent Mass

The equation for m_v can be obtained by using Equation (5) as follows:

$$m_v = \frac{m_t(v_t - v_t')}{v_t' - (1+e)v_h + ev_t} \tag{8}$$

The value of m_v is obtained by assigning the experimental conditions m_t=30[kg], v_h=3[cm/s], v_t=0[cm/s], and e=1 and the experimental result v_t' to Equation (8).

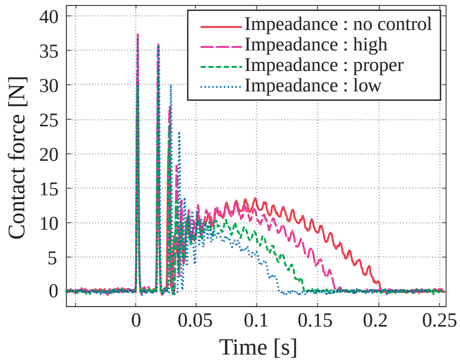


Figure 6: Contact force

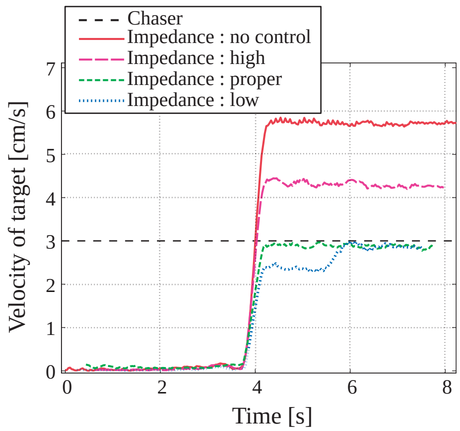


Figure 7: Velocity of Target

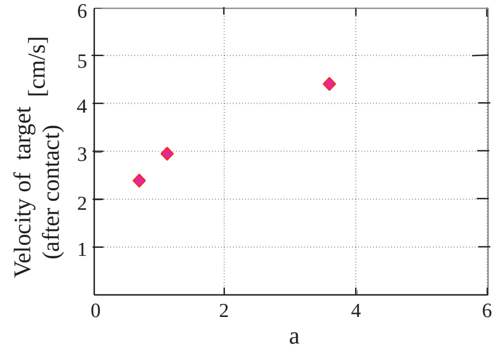


Figure 8: Relation between a and velocity

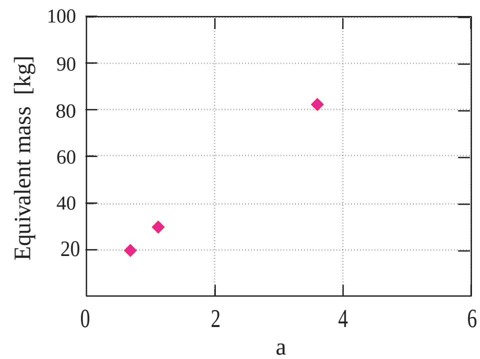


Figure 9: Relation between a and m_v

The velocity of target v_t' after contact are shown in Figure 8, and the m_v obtained by Equation (8) are shown in Figure 9. These results show the equivalent mass depend heavily on the impedance characteristics.

7 Contact Experiment about the Control Time Delay

This experiment investigates the effects of control time delay on the contact force and the motion of the chaser.

7.1 Condition of the Experiment

the chaser under the impedance control moves in a straight line with constant speed 3[cm/s], and collides with the static target. The target mass m_t =30[kg].

In this experiment, $a = 1.125$(const) and the control time delay of each case is about 30, 60 and 90[ms].

7.2 Experimental Result

Figure 10 and 11 show the profiles of contact force and velocity of target. The longer the time delay, the longer the contact time and the faster the velocity of target after collision. The waveform of contact force changes respectively from about its time delay. Therefore, the longer the time delay, the bigger the total impulse to the target during time delay of each case.

7.3 Relation with the Equivalent Mass

The value of m_v is obtained by assigning the experimental conditions m_t=30[kg], v_h=3[cm/s], v_t=0[cm/s], and e=1 and the experimental result v_t' to Equation (8).

The velocity of target after contact are shown in Figure 12, and the m_v obtained by Equation (8) are shown in Figure 13. These results show that the longer the time delay, the m_v of chaser works more

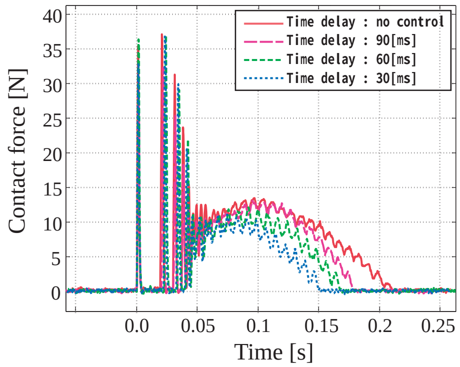


Figure 10: Contact force with time delay

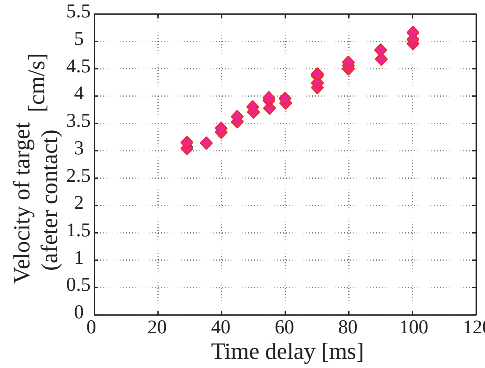


Figure 12: Relation between time delay and velocity

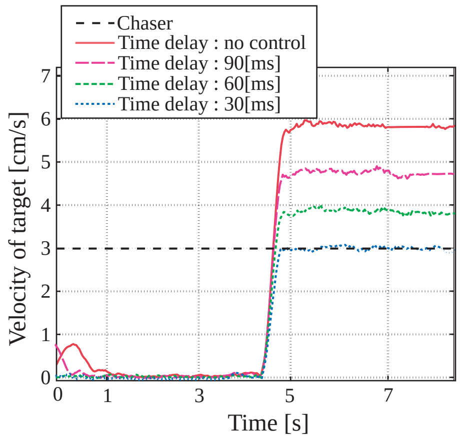


Figure 11: Velocity of target with time delay

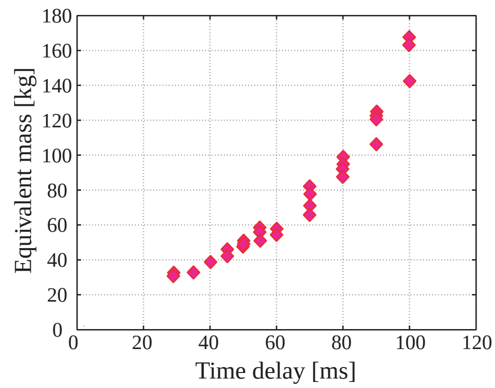


Figure 13: Relation between time delay and m_v

heavier.

8 Conclusion

In this paper, the contact motion between a robotic manipulator under impedance control and a floating target in space was analyzed. The equivalent mass based on the impedance control and the time delay which any cotrol system has necessarily were formulated. To investigate the influence of the impdence characteristics and the time delay of the chaser on the contact motion, the experiment using a robotic arm and a airfloating testbed was carried out.

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