A Contact Dynamics For Spacecraft Capturing and Rigidizing by End-Effector of Space Manipulator

Hirotaka Sawada [(1)], Satoshi Szuki [(2)], Mitsushige Oda [(1)]

[(1)]Japan Aerospace Exploration Agency
2-1-1 Sengen, Tsukuba-shi, Ibaraki-ken, 305-8505, JAPAN,
Email: sawada.hirotaka@jaxa.jp

[(2)] Advanced Engineering Services
1-6-1 Takezono, Tsukuba-shi, , Ibaraki-ken, 305-0032, JAPAN,

Abstract

A space robotic manipulator operated practically in orbit, for example, Space Station Remote manipulator System (SSRMS), Shuttle RMS (SRMS), has a similar end-effector (EE) to capture a specified interface called Grapple Fixture (GF), and the Japan Experimental Module (JEM) Remote Manipulator System (JEMRMS) has a same EE. Therefore, dynamics analysis of capturing operation using space robotic manipulator and the specified EE considering a contact dynamics between a manipulator/EE and captured objective is very important for future missions applying RMS in orbit.

We focus the contact dynamics of an interface of EE and GF in order to analyze a behavior of space robotic manipulator and a target object, and set up a high-fidelity simulator that using an industrial manipulator and 6-axis force/torque sensor. In this paper we assumed the target object is a large spacecraft that weights approximately 1.3ton similar to HII-A Transfer Vehicle (HTV). We report results of dynamics simulation and experiment to measuring a constraint condition of the target spacecraft that is captured by manipulator/EE.

1. Introduction

A spacecraft capture task using a space robotic manipulator in orbit is a key technology for ISS or JEM operation/construction, and furthermore, for a future mission, for example, Space Solar Power System (SSPS) construction or assembly other huge space structure. Therefore, we consider it is significant that a dynamics simulation of both behavior of a manipulator and a captured target during/after capturing operation, applying contact dynamics model. The present, a EE applied tree-wired mechanism shown in Fig.1 is practically adapted, which grapples a specified interface, that is, the pin of GF (illustrated in Fig.2) by snaring and rigidizing using three wires mechanism. Thus, it is probable that a contact characteristic of contact point is very complicated.

The behavior of the target vehicle after making contact during the capturing process is very difficult to predict, since the contact dynamics are influenced by a complicated condition as above. In these capturing cases, contact will occur due to residual relative motion between the EE and the GF pin on the target spacecraft. Relative motion of these two vehicles after an uncontrolled contact may ultimately cause a serious collision. Therefore, we need to conduct a various cases simulation to predict behavior of the manipulator and the target spacecraft with high precision. However, that requires much time and computing power. Thus, we have been researching an effective modelling method that describes the dynamics simply and precisely is required. Research on the dynamics of space manipulators [2-4] and theoretical research aimed at describing contact phenomena [5] have been widely conducted, and practical models integrating these approaches have been prepared.

In addition, we set up a 1/2 scale mockup of EE mechanism model so that we can make a simulation model more accurate by measuring contact and constraint conditions between snare-wire and GF pin in ground experiments.

Fig.1 Three-Wired EE

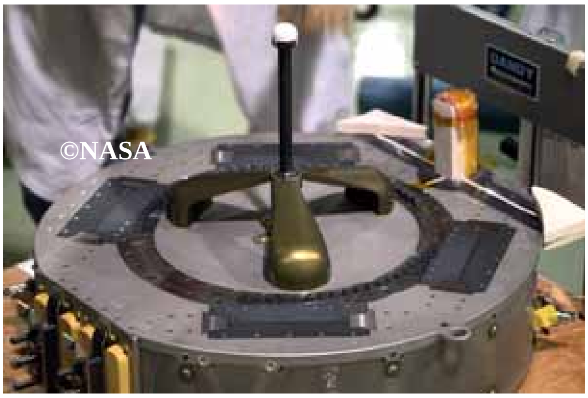


Fig.2 GF Pin

2. Numerical Simulation

We focus the case that a capturing operation of a heavy spacecraft which has a similar weight to HTV by a large manipulator, such as SSRMS as shown in Fig.3.

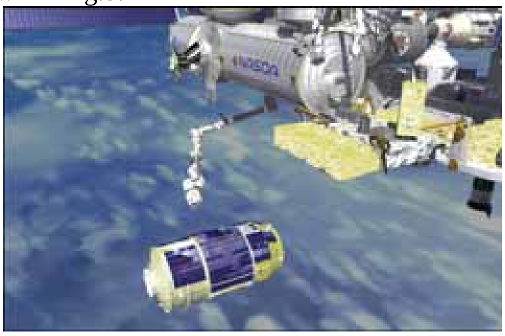
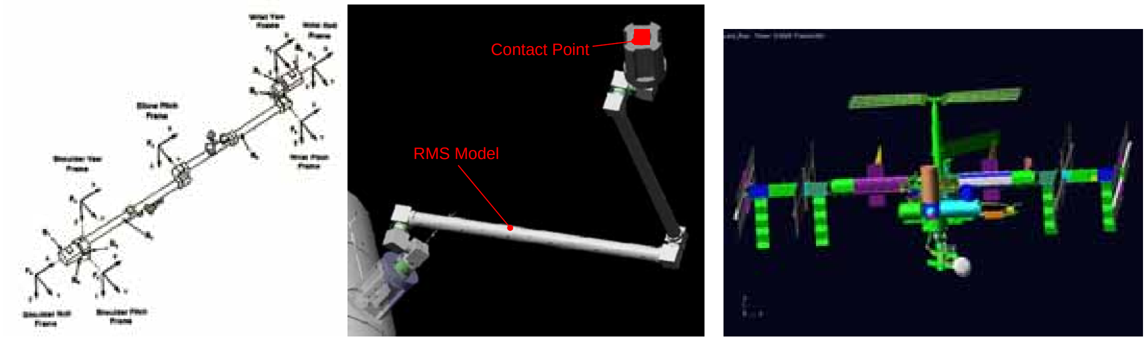


Fig.3 Spacecraft Capturing Case

2.1 Simulation Model

We set up a large RMS simulation model using a general-purpose mechanical analyze tool. The RMS model has similar physical specification[1] to the SSRMS(Fig.4(a)), and the RMS model is attached to ISS model that has similar feature of weight and inertia parameter to ISS as shown in Fig.4(b).



(a) RMS Simulation Model (b) ISS Simulation Model

Fig.4 RMS Simulation Model

Fig.5 indicates a target spacecraft, which has approximately 1.3ton and similar inertia parameters to HTV. The GF model is attached the target spacecraft, which is defined as a contact point to EE during being captured.

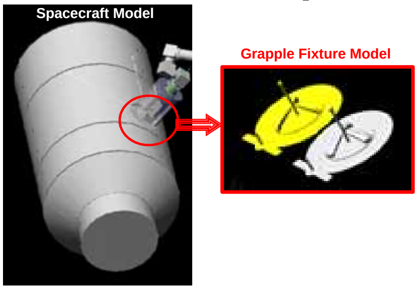


Fig.5 Target Spacecraft Model

2.2 Joint of RMS Model

The RMS simulation model has 7-DOF as same as SSMRS. We apply stiffness and friction model to those joint and the stiffness contain backlash model as illustrated in Fig.6.

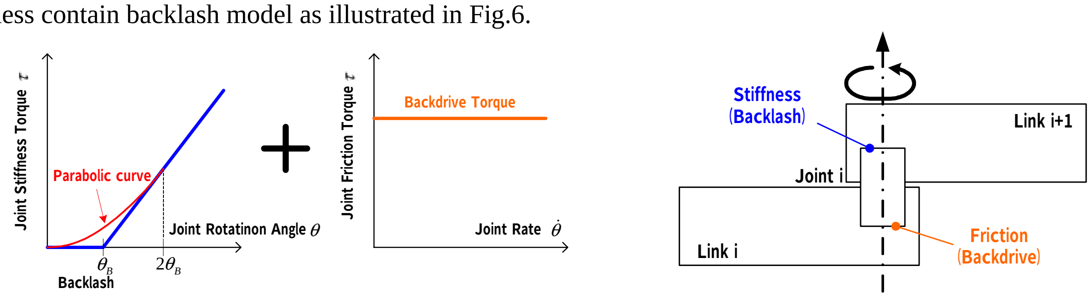


Fig.6 Joint Model

2.3 EE Model

The EE model we applied to the simulation is indicated in Fig.7. A mass property is adopted from the publication as same as the other models, such as RMS and ISS.

We consider that a constraint condition of EE, which is composed with a three-weird mechanism, the EE housing, and a GP pin, can be regarded as the combined model of a ball joint connected to the housing by springs and spring-dumper model attached to a motion constraint virtual parts respectively. Fig.8 shows the EE model we applied. The EE model allows rigidizing operation by pulling a virtual part coupled a spring-ball join model.

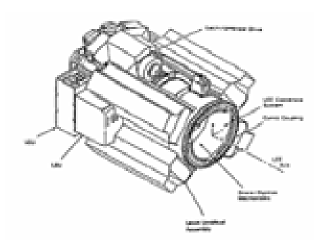


Fig.7 EE Model

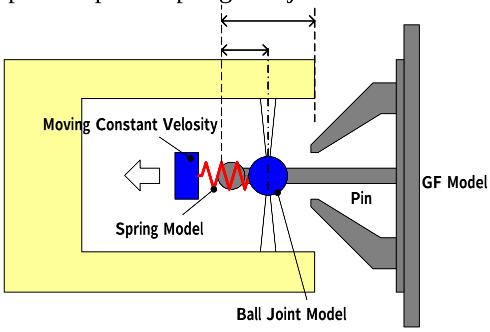


Fig.8 Constraint Model of EE

2.4 Contact Model

We apply simply “spring – dashpot model” as the contact model (Eq.(1))

$$F_n = D_c \dot{\delta} + K_c \delta \qquad (1)$$

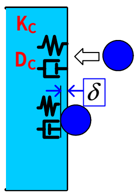


Fig.9 Contact Model

Here,

Fn : normal force,

Kc : stiffness parameter,

Dc : constant damping parameter,

δ : penetration displacement

Conventional friction parameters of surface-lubrication materials, which are based on ground and on-orbit measurements, are used initially. A number of simulations are conducted by widely varying the parameters to predict the worst case analysis as a lower boundary for the problem[8].

3. Simulation Results

First, we verified an effect of contact condition, that is, stiffness and damping parameters. Table 1 shows examples of contact parameter. We verified a various combination of contact parameters and initial condition of RMS posture, relative position and velocity of the RMS tip to the GF. Fig.10 and Fig.11 show the comparison of simulation results in respective contact conditions Table 1. Figures indicate simulation results of position and angular rate profiles after contact of the EE of RMS and the GF of Spacecraft without rigidizing operation, which applying an initial condition indicated in Table 2. The initial conditions are relative motion of the EE to the GF represented in EE coordinate system.

We adopt a condition #02 as contact parameter between the EE and the GF pin based on the simulation results.

Table 1 Contact Condition of Simulation

No.	01	02	03	04
Normal Force	Impact	Impact	Impact	Impact
Stiffness [N/m]	1.00E+08	1.00E+14	1.00E+14	1.00E+14
ForceExponent	2.2	2.2	2.2	2.2
Damping [N sec/m]	1.00E+04	1.00E+12	1.00E+08	1.00E+04
Penetration Depth [m]	1.00E-04	1.00E-04	1.00E-04	1.00E-04
Friction Force	None	None	None	None

Table 2 Initial condition of Relative Motion

Initial Velocity [m/s]	X	0.0028
	Y	-0.009
	Z	-0.025
Initial Rate [deg/s]	Yaw	0
	Pitch	0
	Roll	0.025

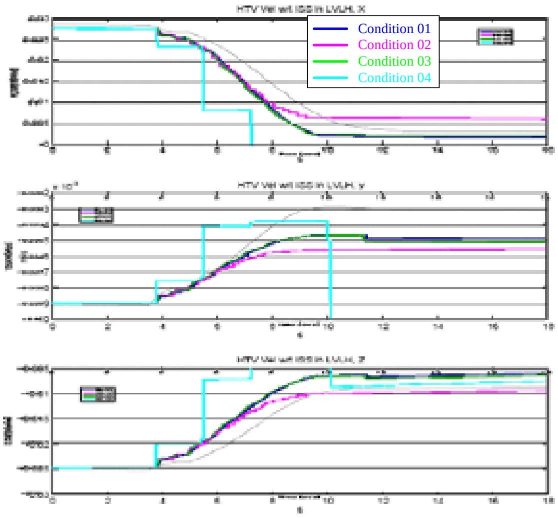


Fig.10 Velocity of Spacecraft

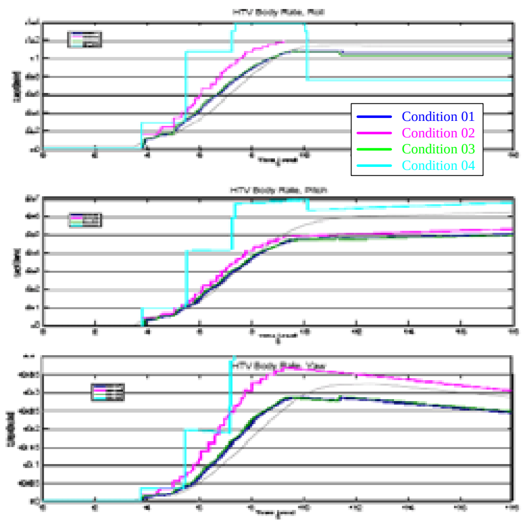


Fig.11 Angular Rate of Spacecraft

Then, we conduct dynamics simulation of rigidizing operation. The initial condition of the case is listed in Table 3. The simulation sequence is as follows.

1)Assume that the GF pin of target spacecraft is completely snared by three-wires of the EE, and it is constrained as a ball joint that has rotation stiffness and dumping.
2)The target Spacecraft has residual velocity and miss alignment to the EE.
3)The EE pulls the GF pin in 2 seconds at 5s from a simulation start, then the GF is regidized while GF contacts to a surface of EE housing.
4)After rigidizing GF, the spacecraft motion is restrained by joints stiffness and friction of the RMS.

Fig.12 shows an example of simulation result. In this case, the spacecraft collides with the EE inner surface during regidizing about 7 seconds from the start. We can find that the collision causes an over load of rigidizing force from the result of the simulation case.

We will improve the simulation model applying data of experimental results mentioned in section 4, and practically use for capturing analysis of spacecraft /space structure, or safety analysis, for example, collision of ISS and THV, over load of EE/joint, and so on.

Table 3 Initial Condition of Rigidizing Simulation

Initial Miss-Alignment (RMS Cordinates System) [m] , [deg]	X	-0.12	Initial Velocity [m/s]	X	0.024
	Y	0		Y	0.024
	Z	0		Z	0.024
	Yaw	0	Initial Rate [deg/s]	Yaw	-0.08
	Pitch	-7		Pitch	0
	Row	0		Roll	0

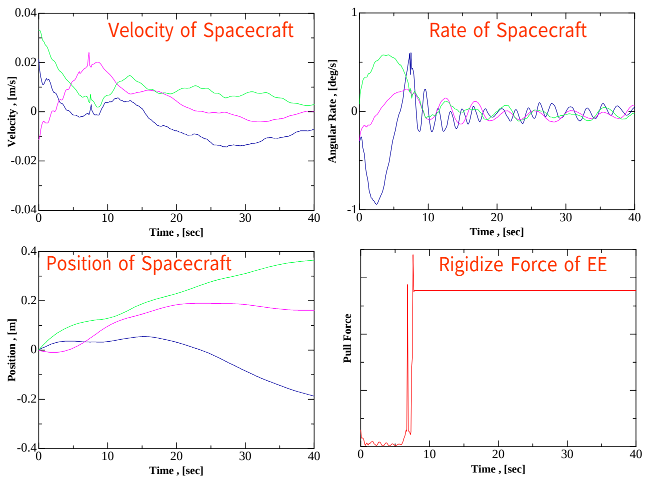


Fig.12 Simulation Result of Rigidizing Operation

4. Ground Experiments

In this section, we introduce experimental system and results conducted for detecting a constraint condition and contact parameters of EE.

4.1 Experimental Setup

We setup a capturing operation dynamics simulator composed of a large RMS mockup and a spacecraft dynamics simulator using an industrial 6-DOF manipulator and a force/torque sensor. The RMS mockup has 1-DOF and allows observation of passive dynamics of a large RMS. The three-wired EE mockup is attached to a tip of RMS as shown in Fig.13.

The spacecraft dynamics simulator can realize a virtual 3-dimensional motion feeding-back values of 6-axis force/torque (FT) sensor and solving an equation of motion of assumed spacecraft inertia properties.

4.2 Three-wired EE Mechanism Mockup

We developed a three-wired EE mechanism model that is approximately 1/2 scale of Latching End-Effector (LEE) of SSRMS. Fig.14 shows overview of EE mechanism model and GF pin model that is also 1/2 scale. The mechanism can be driven manually using worm-gear, as shown in Fig.15, and can snares a GF pin, although it does not have rigidize function.

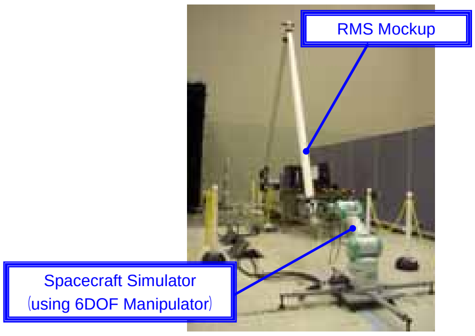
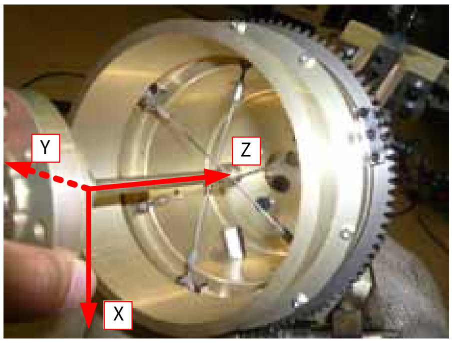


Fig.13 Ground Experimental SystemFig.



14 Three-Wired EE Mechanism Model

Fig.15 Snaring Function

4.3 Experimental Results

The experiment of constraint condition measuring is conducted so that we can apply the results to simulation model of the EE and the GF pin. It is assume that the GF pin is snared at the center of EE, then, we measure a constrain force and torque by moving the GF pin model, that is integrated on the FT sensor, +-3mm to x,y-direction, +-10mm to z-direction respectively. Fig.16 to 18 show experimental results of the constraint condition measuring experiment.

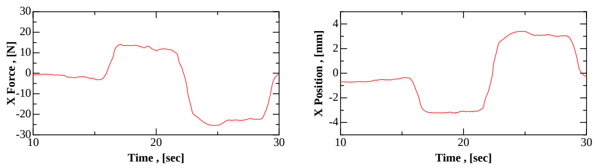


Fig.16 X-direction Translation Experiment Result

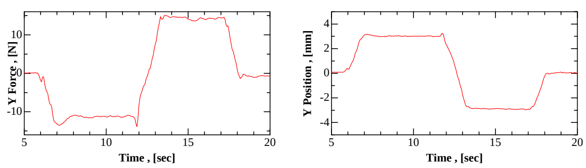


Fig.17 Y-direction Translation Experiment Result

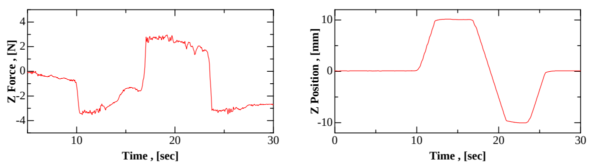


Fig.18 Z-direction Translation Experiment Result

It can be regarded that stiffness of x-direction and y-direction is liner to deflection. The results of Deflection-Force curve of each axis is shown in Fig.19. Although a slight hysteresis is observed, a relationship of deflection and stiffness force is liner as above. On the other side, the deflection-force curve of z-direction is not liner, which indicates constant friction and a hysteresis is not negligible because the z direction is outer-plane direction of the plane formed by three wired. We can verify the characteristics of stiffness in those experiments.

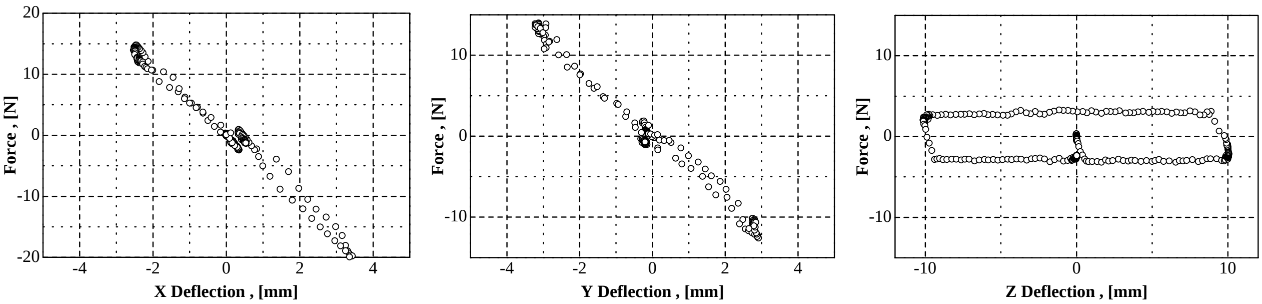


Fig.19 Results of Deflection-Force Curve

5. Conclusion Remarks

We setup the contact dynamics simulation tool and the ground experimental system of a spacecraft capturing by a space robotic manipulator with a specific end-effector. The simulation tool is an efficient one applying a spiting-dumper contact model to interfaces of contact point. In addition, we improved the simulation model, which can realize snaring and rigidizing operation applying spring-constrained ball joint and pulling virtual parts connected to the ball joint with certain spring stiffness. We conducted contact dynamics analysis of the spacecraft capturing by the end-effector of space robotic manipulator on various initial conditions, and we make it clear that the dynamics of target spacecraft during capturing, rigidizing, and after rigidized completely, which applying joints elastic and friction of the manipulator. We verify the overload of pulling force of EE mechanism occurs in some cases of initial conditions.

However, the result of simulation is much predominated by initial conditions and contact conditions. Therefore, we need more detail data of contact characteristics of contact interface, especially three-wired mechanism and GF pin. Thus, we develop three-wired mechanism model for ground experiment, that is 1/2 scale of that of SSRMS' LEE, and conduct a constraint condition and contact characteristics measuring experiments. It is made clear that the characteristics of deflection-force of GF pin load in the condition that the pin is restricted in position by three snared wires. The experimental data is analyzed, and we will apply them to the simulation model so that we can improve the model and conduct more precision analysis.

6. Reference

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