# ESTIMATION OF A DYANAMIC BEHAVIOR FOR A CAPTURE MISSION USING FLEXIBLE MECHANISM

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## ABSTRACT

In this paper, real-time estimation method of a dynamic behavior for a capture mission conducted by a free-flying spacecraft which has a capturing mechanism consisted of flexible parts such as wire will be discussed. As a concrete example, HTV capture using ISS's SSRMS is selected as a problem. To estimate dynamic behavior from limited telemetry data in real time, the Real-time Operation-based Dynamics Estimation (RODE) method is introduced. The dynamics model for the HTV and SSRMS with LEE was developed and virtual telemetry generation for a contact force distribution was set. The virtual telemetry is calculated from telemetry data about joint angles of SSRMS. Finally, the proposed estimation system was verified with simulator and ground experiment facility, the results are discussed in this paper. It is concluded that proposed system has a capability to estimate a dynamic behavior with required accuracy and frequency in real-time to use in operation.

## 1 INTRODUCTION

The capture of free flying target is a one of the most necessary and important operation in the orbital servicing mission. The operation enables constructing a large space structures on the orbit, supplying for an existing spacecraft and removal of debris. On the other hand, motions governed by the contact dynamics which has fast time constant and strongly affected by initial conditions will occur during the operation. As a result, the operation including a contact is needed to be conducted carefully to avoid critical incidents, however grasping the behavior of spacecraft has a great number of difficulties. Nakanishi [1], Yoshimitsu [2], Takahashi [3] and many researchers are proposing their methods to make the operation more safety and effectively. For instance, Yoshimitsu et al. are trying to estimate the spacecraft's behavior using a numerical simulator. In the simulator, nonlinear characteristics of a capture arm's joint and flexibility of the manipulator is modeled, and succeeded to obtain matched result in case-study verification. On the other hand, Nakanishi et al. and Takahashi et al. developed a hardware-in-the-loop simulator to avoid a complexity in the modeling of the contact dynamics and improved an estimation accuracy. Based on the researches, what remains as large technological problem is how to apply these technological advances to a space mission in real. Seen from this perspective, there are problems in the conventional ways in how to deal with a sensor data from operated spacecraft and complete the calculation step without losing a real-time performance.

As for an estimation system for an operating spacecraft, there is an approach which is using an online simulator proposed in previous studies [4], [5]. In this presentation, a real-time dynamics estimation method using online simulator is applied to the capture mission in the orbital servicing.

First, constructing dynamics model for a target spacecraft will be explained. Capture mission conducted by latching end effector (LEE) and grapple fixture (GF) is discussed as an example of the mission. These capture tools have been used in real operation and brought successful results from now. However, wire mechanisms in a LEE make it difficult to estimate an operation result because of its flexibility. Add to this, these type of flexible capture mechanisms are also proposing in future advanced capture mechanisms, the limitation of operation estimation should be solved. Then, framework of estimation using an online simulator will be explained.

Second, way of model tuning based on a telemetry data will be explained. The model tuning is consisting of second step; model reduction and parameter identification.

Third, virtual telemetry generation to fill a gap of sensor information will be discussed. Based on the previous studies [6], it is revealed that raw telemetry data is not enough to obtain sufficient simulation result because of the sensor attachment's limitation. Therefore, virtual telemetry which is not obtained by real sensor, but calculation is needed to know the behavior of spacecraft. In this study, conditions of contacts are calculated as virtual telemetry based on the telemetry from sensor data of arm joints.

Finally, a result of verifications will be indicated. The proposed methods are verified using a simulator developed by JAXA and simplified ground experiment facility. For instance, the model tuning methods, change of approximate accuracy and calculation cost are verified.

## 2 MODELING AND ESTIMATION METHOD

HTV capture with ISS's SSRMS is conducted by the LEE and GF capturing method. Figure 1 shows a simple outline image of LEE and GF. LEE is consisted of a wires and drive system for them, and perform a fixture operation with snaring the grapple shaft of GF.

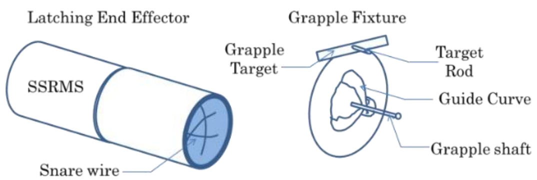



*Figure 1: Image of LEE and GF*

The snare wires themselves have a high flexibility, therefore dynamic movement after contact shows a complex behavior. In this paper, we focused on a first contact time between the wire and the shaft, therefore, the wire's contact force are modeled as shown in the Figure 2 simply.

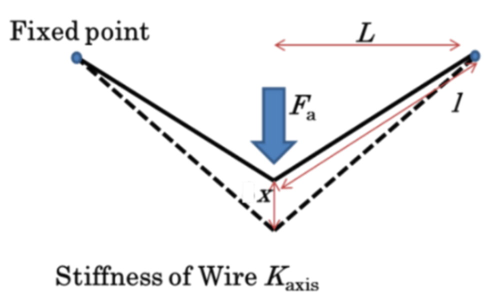



*Figure 2: Modeling of wire's contact force.*

Finally, HTV and SSRMS's model were constructed using the opened data [7]. Table 1, Table 2 show represented data which are used in model.

*Table 1: Referred information of HTV*

| | |
|---|---|
| Total Length | 9.8[m] |
| Radius | 4.4[m] |
| Launching mass (without payload) | 10.5[t] |
| Launching mass (with payload) | 16.5[t] (Max payload: 6[t]) |

*Table 2: Referred information of SSRMS*

| | |
|---|---|
| Mass | 18[t] |
| Length | 17.6 [m] |
| Diameter | 2.2 [m] |
| Degree of Freedom | 7[-] |
| Handling weight | 116[t] |

To estimate a dynamics of contact behavior from telemetry data in real-time, Real-time Operation-based Dynamics Estimation (RODE) method [8] are introduced. The RODE method was developed to estimate dynamic movement of a flexible spacecraft in real-time with limited telemetry. It is consisted of a real-time online dynamics simulator, model tuning step and virtual telemetry generation step. Figure 3 shows an outline of the RODE system and application to the problem discussed in this paper.

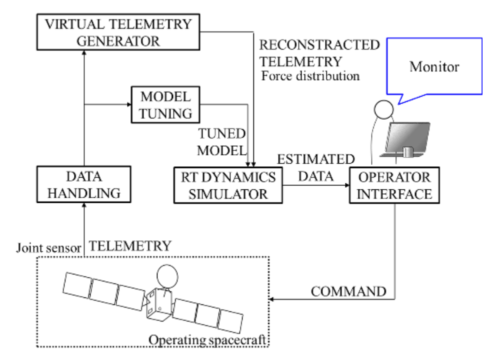



*Figure 3: Framework for real-time dynamics estimation*

## 3 Model tuning

Model tuning was conducted with a HTV capture simulator developed by JAXA [9].

In the tuning, simulations for contact motion were conducted with various dynamic properties and acceleration values at a position of KIBO experiment rack was obtained. Referring the reports made by Ookuma et al [10], an optimal dynamics values were searched. Figure 4 shows a obtained example of acceleration values from the JAXA simulator. And the Table 3 indicates an identified value of the dynamic properties of the SSRMS.

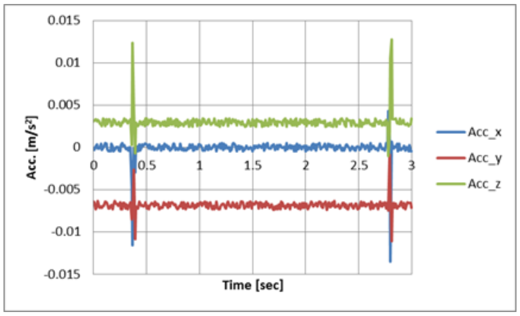



*Figure 4: Simulated reaction acceleration happed by HTV's contact*

*Table 3: Identified parameters of SSRMS*

| | Identified value |
|---|---|
| Joint stiffness [Nm/rad] | $7.1\times 10^5$ |
| Joint damping [%] | 0.09 |

## 4 VIRTUAL TELEMETRY GENERATION

In this section, generation method of the virtual telemetry for the RODE system. With the RODE system, virtual telemetry which is not measured by 'real' sensors are generated to improve a real-time property and cover limitations of sensor data.

When applying the RODE system to the HTV's capture mission, force distribution on the snare wire is selected as target of the virtual telemetry.

First, the relationship between the joint torque $\boldsymbol{\tau}$ and forces happened at the end effector can be written with equation (1) based on the principle of virtual work.

$$\begin{bmatrix}\boldsymbol{F}\\ \boldsymbol{n}\end{bmatrix} = {J^{\omega}}^{\mathrm{T}^{-1}}\boldsymbol{\tau} \tag{1}$$

Where, $\boldsymbol{F}$ and $\boldsymbol{n}$ are the force and torque vector of force at end effector. And $J^{\omega}$ is a Jacobian matrix of the SSRMS.

Next, relationship between joint angle and joint torque can be written as below equation when the capture mission is conducting.

$$\tau = K_v(\dot{q}_{\mathrm{ref}} - \dot{q}_{\mathrm{current}}) \tag{2}$$

Here, the 2 dimensions model for one of the snare wire is developed as shown in the Figure 5.

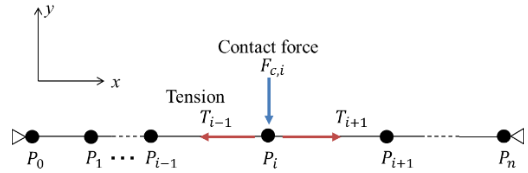



*Figure 5: 2D model of the snare wire*

Based on the model, x direction component of the horizontal tension force caused as contact reaction is like below equation.

$$T_{i-1}^{x} = -\frac{\partial U}{\partial l_{i-1}}\frac{\partial l_{i-1}}{\partial x_i} = \frac{x_i - x_{i-1}}{\cos\theta_l}T_{i-1} = \alpha_x^{i-1}T_{i-1} \tag{3}$$

Otherwise, vertical components can also write as the next equation.

$$F_{c,i}^{x} = -\frac{\partial U}{\partial A_{i-1}}\frac{\partial A_{i-1}}{\partial x_i} = \frac{y_i - y_{i-1}}{2}F_{c,i} = \beta_x^{i-1}F_{c,i} \tag{4}$$

With the equation (3) and (4), load force on each node are like equation (5).

$$F_i = \alpha_x^{i-1}T_{i-1} + \alpha_x^{i+1}T_{i+1} + \beta_x^{i-1}F_{c,i} \tag{5}$$

On the other hand, equation of motion for the nodes can be written as equation (6).

$$m\ddot{x} + kx = F \tag{6}$$

Where, $x$ is a position vector of the node. Also, boundary condition is a rotational freedom at the tip of the wire as shown in equation (7).

$$x_{1,2,3} = 0 \tag{7}$$

Equation of motion for the all system can be written with the collection of the equation (7)

$$\boldsymbol{M}\boldsymbol{x} + \boldsymbol{K}\boldsymbol{x} = \boldsymbol{F} \tag{8}$$

To the equation (8), discretization using Newmark beta method is applied and equation (9) and (10) are obtained.

$$\dot{x}_{i+1} = \dot{x}_i + \frac{1}{2}(\ddot{y}_{i+1} + \ddot{y}_i)\Delta t \tag{9}$$

$$x_{i+1} = x_i + \dot{x}_i\Delta t + \left(\frac{1}{2} - \beta\right)\ddot{x}_i\Delta t^2 + \beta\ddot{x}_{i+1}\Delta t^2 \tag{10}$$

With these equations, equation of finite element is obtained as shown in equation (11).

$$\ddot{x}_{i+1} = (\boldsymbol{M} + \beta\Delta t^2\boldsymbol{K})^{-1}\left\{\boldsymbol{F}_{i+1} - \boldsymbol{K}\left(x_i + \Delta t\dot{x}_i + \left(\frac{1}{2} - \beta\right)\Delta t^2\ddot{x}_i\right)\right\} \tag{11}$$

With the equation, state equation can be written. Based on the state equation, contact force distribution will be able to calculate with Bayesian filtering algorism in the virtual telemetry step.

## 5 VERIFICATION TEST

In this section, verification test for proposed method are explained. The verification is conducted both simulator and ground experiment facility to check an applicability and feasibility.

### 5.1 Simulation

At first, verification using JAXA's HTV capture simulator was conducted.

In this verification, initial properties of the HTV-2 capture mission were referred. Main simulation conditions are indicated in Table 4.

*Table 4: Simulation conditions*

| | |
|---|---|
| Contact stiffness | $1.1 \times 10^{8}$ [N/m] |
| Contact damping | $1.0 \times 10^{4}$ [Ns/m] |
| Penetration depth | $1.0 \times 10^{-4}$ [m] |
| Static friction | 0.3 [-] |
| Dynamics friction | 0.1 [-] |
| Stiction transition velocity | $1.0 \times 10^{-4}$ [m/s] |
| Friction transition velocity | $1.0 \times 10^{-3}$ [m/s] |

Figure 6 shows results of the generated virtual telemetry from simulated telemetry data and correct values directly obtained from the simulator. In the figure, Blue and light blue line indicate a vertical contact force at the node which is in the center position of the wire. And red and yellow ones are position next to center. With the result, contact force on the snare wire is sufficiently estimated as virtual telemetry when they will be used in RODE system.

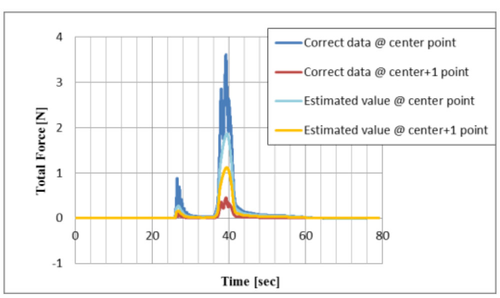



*Figure 6: Calcurated virtual telemetry*

For a reference, sum of the vertical contact force for all wire's node is shown in Figure 7. With the figure, virtual telemetry matched to correct one better than individual results. This is may cause by the lack of the number of the nodes which is limited to real-time calculation condition in current implementation.

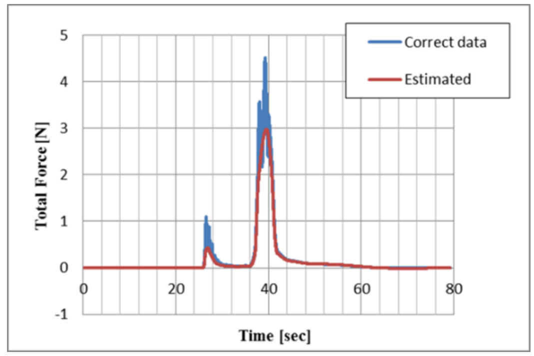
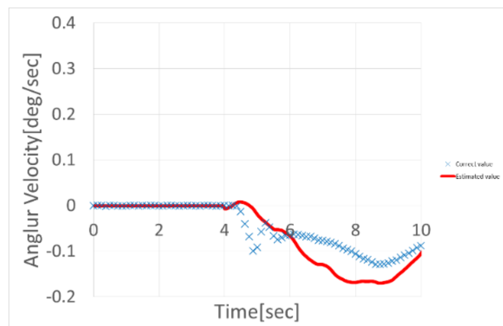
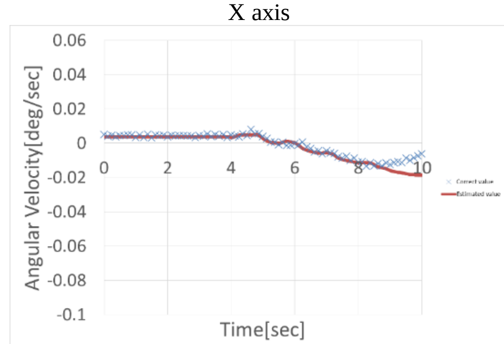



*Figure 7: Calcurated total contact force*

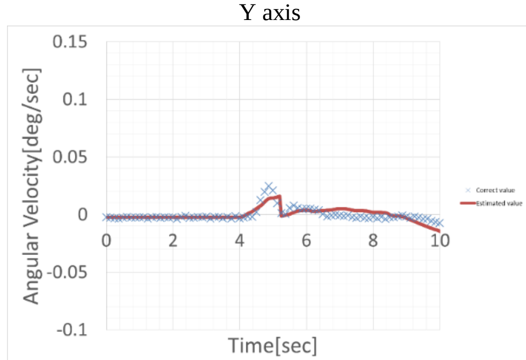
Figure 8 shows an estimated rotation calculated by the RODE system. With the result, proposed method shows a capability to estimate a dynamic behavior based on the telemetry within required accuracy.




X axis




Y axis




Z axis

*Figure 8: Estimated rotation changes of HTV*

### 5.2 Ground experiment

To proof that the proposed estimation method can be applied with a realistic based conditions, a ground experiment facility which model a contact phenomenon between flexible wire and rigid pole in micro gravity environment were developed. The configuration of the facility is shown in the Figure 9. In the experiment, snare wire model is pushed to the target's rod to apply an initial contact force and released at the start of the experiment. Table 5 shows an experiment conditions

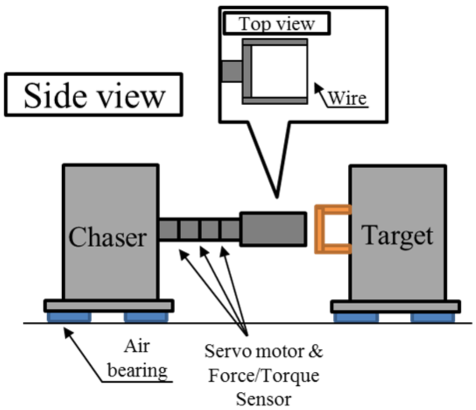



*Figure 9: Ground experiment facility*

*Table 5: Experiment conditions*

| | | | |
|---|---|---|---|
| Chaser | Body | Mass | 6.15 [kg] |
| | | Inertia $I_{zz}$ | 0.033 [kg · m$^2$] |
| | Arm Link1,2 | Mass | 0.33 [kg] |
| | | Dimension | 0.041 [m] |
| | | Inertia $I_{zz}$ | 0.0001 [kg · m$^2$] |
| | End effector | Mass | 0.39 [kg] |
| | | Dimension | 0.075 [m] |
| | | Inertia $I_{zz}$ | 0.0002 [kg · m$^2$] |
| | Wire | Dimension | 0.09 [m] |
| | | Stiffness | $1.1 \times 10^8$ [N/m] |
| | | Initial deform | 0.01 [m] |
| Target | Grapple shaft model | Dimension | 0.15 [m] × ϕ0.02 [m] |

Figure 10 and Figure 11 shows a obtained telemetry data which is input to RODE system.

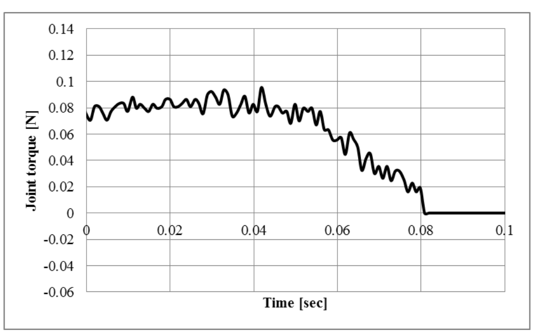



*Figure 10: Obtained telemetry data about joint torque*

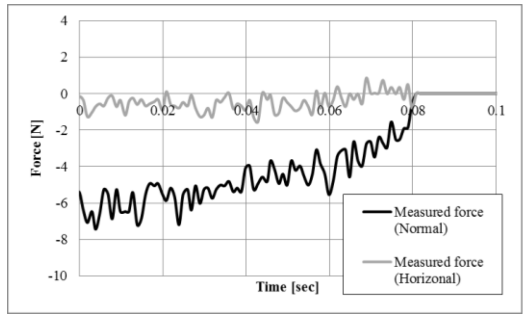



*Figure 11:Obtained telemetry data about tip force*

Figure 12 shows a change of the "chaser" model's positions with time. Blue, Red and Green line indicate positions directly measured by 3D positon sensor. On the other hand, Purple, light-blue and dark green lines indicate estimated position based on the virtual telemetry. As shown in the figure, the result suggest the proposed method can estimate the position after contact within 20[%] error.

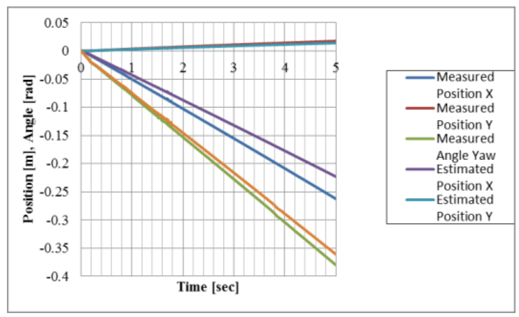



*Figure 12: Change of positions after contact*

## 6 CONCLUSION

In this paper, real-time estimation method of a dynamic behavior for a capture mission conducted by a free-flying spacecraft which has a capturing mechanism consisted of flexible parts such as wire will be discussed.

First, constructing dynamics model for a target spacecraft will be explained. Capture mission conducted by latching end effector (LEE) and grapple fixture (GF) is discussed as an example of the mission. These capture tools have been used in real operation and brought successful results from now. However, wire mechanisms in a LEE make it difficult to estimate an operation result because of its flexibility. Add to this, these type of flexible capture mechanisms are also proposing in future advanced capture mechanisms, the limitation of operation estimation should be solved. Then, framework of estimation using an online simulator will be explained.

Second, way of model tuning based on a telemetry data will be explained. The model tuning is consisting of second step; model reduction and parameter identification. Using a JAXA's HTV capture simulator, dynamic properties of the current SSRMS are estimated.

Third, virtual telemetry generation to fill a gap of sensor information will be discussed. Virtual telemetry which is not obtained by real sensor, but calculation is needed to know the behavior of spacecraft. In this study, conditions of contacts are calculated as virtual telemetry based on the telemetry from sensor data of arm joints.

Finally, a result of verifications will be indicated. The proposed methods are verified using a simulator developed by JAXA and simplified ground experiment facility. For instance, the model tuning methods, change of approximate accuracy and calculation cost are verified.

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