Separation Probe System for Self-Inspection in Deep Space

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Abstract

Inspection missions are becoming the focus of attention for inspecting outward appearance of large space structures. For such a demand, nonreusable separation nano-camera probe system released from a spacecraft is proposed. Purpose of the system is to observe dynamics behavior of a small solar sail demonstration spacecraft IKAROS of JAXA after sail deployment. This paper introduces the nano-camera probe system, its separation mechanism and the result of numerical simulation for image acquisition with the nano-camera probe.

1. Introduction

Inspection missions are becoming the focus of attention for inspecting outward appearance of large space structures and spacecrafts. For example, ETS-VIII's antenna deployment [1] was confirmed by two cameras mounted on body. Taken images are shown in Fig. 1. Two cameras are used, but whole of the antenna is not taken. Also, Hayabusa [2] had an unexpected accident (Fig. 2) that it did not behave for half an hour. If it had a probe system for self-inspection, the potential reclamation would become higher.

Fig. 1 Antenna deployment of ETS-VIII(JAXA)

Fig. 2 Image of Hayabusa’s accident (JAXA/Mr. Ikeshita)
Since 2000, the Laboratory for Space Systems (LSS) of the Tokyo Institute of Technology continuously conducts the nano-satellite development project. In the past, LSS has launched three satellites; CUTE-I [3], Cute-1.7 + APD [4] and Cute-1.7 + APD II [5] (Fig. 3). Now it is developing the 4th satellite: TSUBAME. In this project, a technology and knowledge relating to a nano-space system design is built up. Using them, LSS proposes a separation probe system for self-inspection that with a camera probe separated from the spacecraft, which is used to take images the whole spacecraft from a certain distance.
In this paper, a separation probe system for self-inspection and the design method for IKAROS are presented.

2. Separation Probe System for Self-Inspection

2.1 Concept
The proposed separation probe system is illustrated in Fig. 4. This system has two parts; a separated camera probe part and an interface part mounted on spacecrafts. The probe part consists of imager, lens, transmitter, battery and the interface part is composed of separation mechanism for the probe and receiver. Input of this system is system power supply and separation signal and output is data of taken image. A data from the probe is not sent to ground station. Also, it is not received by the communication system of the spacecraft. The proposed system establishes an independent communication link. So it has broad utility. In this system, the probe is unreusable and operates until the battery runs down. But LSS proposes an advance concept of a reusable camera probe which can be caught, charged up and re-separated.

![CUTE-I](Image)
CUTE-I
2003.6 launched

![Cute-1.7 + APD II](Image)
Cute-1.7 + APD II
2008.4 launched

![TSUBAME](Image)
TSUBAME
Under development
Fig. 3 LSS’s nano-Satellites

2.2 Choice of attitude stabilization method
The significant issue of the camera probe is the attitude pointing direction when an image is taken. One of the solutions is that the direction of the optical axis is parallel with the direction of the maximum inertial axis. The method does not require any actuators, which is simple and secure, but not flexible for structural demands. Therefore, LSS proposes 4 solutions.

Table 1 Comparing of attitude stabilization method

<table>
<thead>
<tr>
<th></th>
<th>RW</th>
<th>CMG</th>
<th>THR</th>
<th>SS</th>
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</thead>
<tbody>
<tr>
<td>Size (mm)</td>
<td>φ 50 × H42</td>
<td>φ 50 × H134</td>
<td>about φ 200 × 150</td>
<td>—</td>
</tr>
<tr>
<td>Wight (g)</td>
<td>125</td>
<td>960</td>
<td>450</td>
<td>—</td>
</tr>
<tr>
<td>Power (W)</td>
<td>0.2</td>
<td>6</td>
<td>Low consumption</td>
<td>0</td>
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</table>

First, using Reaction Wheels (RW) and Control Momentum Gyros (CMG), the attitude of the probe is continuous controllable. So it is easy to turn the lens toward an object. But it could need unloading because these devices change angular momentum of wheels for one of the probe.
Second, using Thrusters (THR), the attitude and the orbit of the probe are both controllable. Therefore the reachable regions can be expanded. However, safety demands become harder because it is equipped with a high pressure gas cylinder. Third, using Spin Separation (SS), its attitude becomes spin stabilization. In this way, the camera probe does not need any actuator, and can achieve passive stabilized by the separation mechanism. So it is most simple, but not active controllable. The devices mentioned above are adopted in the nano-satellite developments: CanX-3 (University of Toronto) [6], TSUBAME [7], SNAP-1 (SSTL) [8] and so on. Table 1 refers to these. But a new technology is necessary for spinning and separating a nano-satellite. From characteristics of these, the methods are selected for the demands.

A size required to amount this system is shown in Fig. 7. And the requirement of mass is less than 1kg. A direction of separation is restricted to third negative axis shown in Fig. 7. To meet these requirements, a lens would set to direction of the third positive axis because there is the object to direction of the third negative axis. So the length of third axial direction could be longest of length of other direction. The third axis could become minimum inertial axis. The attitude stabilize is not expected. An attitude stabilize method is chosen base on 2.2. Considering the limitation of size and mass, it is difficult to use CMGs and THR. If the probe uses RWs, RWs would take up about half of the probe’s size, and a vibration of RWs has harmful effects to take images. If the probe uses SSs, SSs would not expect more stability than RWs. But it avoid mechanical vibration because it not use actuator if interface part have spin separation mechanism. Additionally, the mass of the probe becomes lighter, the necessary holding force becomes smaller and the demand for holding mechanism becomes easier. In this case, SSs method offers many advantages. Thus, the SSs method is utilized for attitude stabilization.
3. Spinning separation system

3.1 Overview
The developed camera probe system (FM) is shown Fig. 8. The interface part has holding function [10] and spinning separation function. Here, spinning separation mechanism (Fig. 9) is presented. The push part of separation mechanism pushes the bottom of probe. Two pinplungers (Fig. 10) push two points of wall surface. The forces at two points act as couple of force. The probe gets a torque. The target torque determines 2.0rad/s in consideration of a processing time to take images. However, the target torque is 1.7rad/s on ground because there is assumption that angular velocity is proportional to separation time, based on Euler's equations.

3.2 Adjustment for forces of pinplungers
The pinplungers used commercial-off-the-shelf. Its spring constant is unknown. Therefore, relation torque and pinplunger's plunged displacement are examined.
An experimental setup is shown in Fig. 11. A dummy mass is freed from the spin separation mechanism. Images of its motion are taken by a high-speed camera. Its angular velocity is measured by these images. In this time, the plunged displacement is adjusted at 0.1mm order. The result is shown Table 2. In consequence, the pinplunger's plunged displacement determines 0.9 ~ 1.0mm. Besides, it is found out that little changes of the displacement have great influence on the probe’s angular velocity. But it is difficult to regulate the displacement at 0.01mm. Accordingly, estimating admissible displacement is needed.

<table>
<thead>
<tr>
<th>Length of press</th>
<th>angular velocity</th>
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<tbody>
<tr>
<td>0.80 mm</td>
<td>0.92 rad/s</td>
</tr>
<tr>
<td>0.90 mm</td>
<td>1.64 rad/s</td>
</tr>
<tr>
<td>1.00 mm</td>
<td>1.98 rad/s</td>
</tr>
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</table>
4. Confirmation of image
4.1 Condition for Numerical Simulation
The attitude of separated probe is obtained by numerical simulation with respect to IKAROS fixed coordinates (Fig. 7). During 30s, assumed images taken by the probe are output. The used equations are shown below.

\[ \mathbf{I} \dot{\omega} + \ddot{\omega} = \mathbf{M} \]

This inertia moment is shown below.

\[ \mathbf{I} = \begin{bmatrix} 1.35 & -0.01 & -0.01 \\ -0.01 & 1.39 & -0.1 \\ -0.01 & -0.1 & 1.24 \end{bmatrix} \times 10^{-4} \text{ kg} \cdot \text{m}^2 \]

Initial condition assumes a state shown in Fig. 12. This lean and this displacement between center of gravity and line of action of force is the worst condition. A variable is an initial angular velocity. An evaluation index is a duration taking IKAROS images.

4.2 Results of Numerical Simulation
For example as result, a case of 1.5rad/s is shown below.

Fig. 12 Initial condition

A relation between initial angular velocities and duration is shown in Fig. 15. In addition, a relation between initial angular velocities and chance for taking IKAROS images is shown in Fig. 16.

4.3 Considerations
As shown in Fig. 15 and Fig. 16, it finds out that both duration and chance decrease at 1.5rad/s and stay flat less than 1.0rad/s. As a result, the plunged displacement needs to set more than 0.9mm. Otherwise, this inspection would fail. Besides, in
case of 1.7 rad/s, maximum duration is 4s and chance is fifth.

5. Conclusion
A separation probe system for self-inspection in deep space is proposed. The system is designed for IKAROS’s inspection. Spin separation method is selected as an attitude stabilization method. This specific spin separation mechanism is also introduced. Its performance is confirmed by Numerical Simulation.

References
[10] 稲川慎一, 松永三郎, 澤田弘崇, ”非回収発射型カメラプローブシステムの開発” 第53 回宇宙科学技術連合講演会講演 CD-ROM, 京都, 2009年9月