デブリ軌道変換用の推進系取付技術について
Mounting Technology of the Propulsion System for De-orbiting Debris

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人類が将来に亘り宇宙開発・利用を持続させていくためにデブリ除去は不可欠なテーマと考えられている。
その実施に不可欠な要素技術の一つにデブリをデオービットするための推進系をデブリに取付ける推進系
取付け技術が挙げられる。推進系の取付けについては、各種の方式が検討されているが、デブリのタイプとデ
オービットの方式により適否が決まるので、これらの条件を定めて、方式を選定する必要がある。ここでは、持
続的の宇宙開発・利用に効果的に寄与することを想定して、一回の衝突で多数のデブリを発生させる低軌
道周回軌道上のロケット上段部等の大型デブリを、低コストで除去できる方式として、導電性テザー方式を想
定して検討している。この方式に対する推進系取付け技術として、ブーム伸展方式、パンチャ打ち込み方式
などが候補として挙げられるので、その実現性に向けた課題などの検討を進めている。本プレゼンテーション
では、これらのトレードオフを要約すると共に、その実現性に向けた仕様・課題などにつき講演する。

The removal of the debris is considered to be the inevitable item for the sustainable space development and
utilization activities of the mankind. To realize this item, the technology for mounting the propulsion system
on the debris to be orbiting it is thought indispensable. Various kind of concept on the mounting method are
studied today and the selection from them must be made based upon the type of the debris and the method to
de-orbit. We are thinking that the most effective targets to be decayed are the large scale debris, such as upper
stage of the launching vehicle which had been used to putting the payload satellites on to the orbit, because
they may create huge number of small debris at the single collision with other space flying object. We are now
studying the Electrodynamics Tether(EDT) method for the deorbit of the above described large scale debris
taking into account its feature of low cost and the simpleness. So we are now picking up the various mounting
technologies to suit to EDT, such as the boom expanding method and puncher injecting method to study the
trade-off and feasibility, items subject to be solved and so on. In this presentation, current status of the above
study and subject to be solved are to be summarized.
Mounting Technology of the Propulsion System for De-orbiting Debris

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Introduction

- The mounting technology of the propulsion system on the debris is one of the indispensable item for the debris removal.
- The selection of the mounting technology depends strongly on the type of the debris and the method to deorbit.
- Debris of many small size may be the candidates to damage operating satellites, it’s not cost effective to deorbit them, because there are so many of small debris.

On the hand, large debris, such as upper stage of launch vehicle or non-operating large satellites, are candidate to generate a lot of small debris at a single collision.

⇒ It is cost effective to de-orbit the large debris to suppress the increase of debris, especially upper stage, and also to progress the standardization of the debris removal because many rockets used PAF.

(e.g. H-Ⅱ A, Ariane, Delta, Atlas, Soyuz, Proton and others.)

[Image: NASA The Orbital Debris Quarterly News 18-1 (2014, Jan.)]
Requirements on Mounting of the Propulsion System

Mount the propulsion system on debris with:

- approach to the non-cooperative debris,
- existence of the uncertainty of the attitude and position of the debris
- possibly tumbling at the rate of about few degree per second.

Transfer large total momentum to debris:

- with the uncertainty of position of CG.
- $\Delta V$: a few of 100m/sec to the several tons of debris

Cost effective & simple debris removal is needed

$\Rightarrow$ Robustness with cost-effective and simple method is strongly desired.

Mounting Technology of Propulsion System(1/2)

<table>
<thead>
<tr>
<th>Items</th>
<th>Concept to Capture</th>
<th>Method</th>
<th>Merit</th>
<th>De-merit</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extendable Boom Hooking</td>
<td>Boom are extended into PAF of debris to hook it.</td>
<td>Easy to test. Need not precise position and attitude information.</td>
<td>Applicable only to PAF.</td>
<td>Upper stage of many rocket using PAF.</td>
<td></td>
</tr>
<tr>
<td>Harpoon/Puncher Penetrating</td>
<td>Harpoon/Puncher is lodged in the body of debris to capture it</td>
<td>Easy to test. Need not precise position and attitude information.</td>
<td>Risk of generation of small paticles.</td>
<td>Reduction of reaction force at fire of harpoon/puncher is needed.</td>
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</tbody>
</table>
## Mounting Technology of Propulsion System (2/2)

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<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Net Wrapping</td>
<td>Net thrown to debris wrapping the debris.</td>
<td>Large-scale craw mounted on satellite grasps the debris to capture</td>
<td>Adaptable for tumbling and nutating small debris.</td>
<td>Not easy to analyze and test performance</td>
<td>Not easy to capture large debris (upper stage of rocket or large sat.)</td>
</tr>
<tr>
<td></td>
<td>Large-Scale Craw Grasping</td>
<td>Satellite</td>
<td>Debris</td>
<td>Effective for small debris</td>
<td>Needs large craw mechanism</td>
<td>Not easy to capture large debris (upper stage of rocket or large sat.)</td>
</tr>
<tr>
<td></td>
<td>Mother sat. pulling in</td>
<td>Large-scale craw mounted on satellite grasps the debris to capture</td>
<td>Mother sat. pulling in debris thru the mouth</td>
<td>Small debris may be easy to be pulled in.</td>
<td>Large debris cannot be pulled in.</td>
<td>Not easy to capture large debris (upper stage of rocket or large sat.)</td>
</tr>
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## Robustness of Propulsion Mounting System

<table>
<thead>
<tr>
<th>Type</th>
<th>I. Extendable Boom</th>
<th>II. Puncher</th>
<th>III. Robotics Arm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robustness</td>
<td>Transverse Robustness</td>
<td>Horizontal &amp; Vertical Margin</td>
<td>Transverse Adjustable Range</td>
</tr>
<tr>
<td></td>
<td>Rotational Robustness</td>
<td>Angular Margin</td>
<td>Rotational Adjustable Range</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Angular Margin</td>
</tr>
</tbody>
</table>
**Extendable Boom Capturing (1/2)**

### Debris Capturing Concept

1. Estimate the relative attitude and position of debris analyzing the pictures of PAF.
2. **-1** Extend the base-side extendable boom to the center of PAF at the position of 1.5m away from PAF.
   -2 Extend the 4 tip-side extendable booms radially toward circle of PAF.
3. Making sure of the completion of extension of booms to be fixed at hem of PAF, the satellite escape extending the tether.

![Concept of Extendable Boom on Satellite](image)

**Extendable Boom Capturing (2/2)**

### Capturing Feasibility

- Preliminary feasibility of extendable boom capturing of debris was evaluated as follows by the conceptual study:
  - Alignment requirement of position: ±100 mm along X-axis (long axis of debris) ±200 mm across X-axis attitude: no limitation around X-axis ±5 deg. around Y & Z-axis
  - Approaching velocity of debris: 0 ~ 100 mm/sec. along X-axis
  - Angular velocity of debris: ±1 deg./sec. around all-axis
- Preproduction sample of boom and extension mechanism was manufactured and evaluated to be:
  - Basic feasibility of the extendable boom for debris capturing was evaluated.
  - Some characteristics of boom were find to be improved:
    - review the extension method of tip side boom to reduce the stress on base-side boom
    - review the manufacturing process to improve the quality
    - Increase the stiffness of boom for future mission
Harpoon/Puncher Penetrating (1/2)

Debris Capturing Concept

I. Concept of debris capturing (Arm + Puncher Method)

1. Identification of debris motion
2. Puncher arming
3. Capture and penetration of the debris wall
4. Make sure of fixed and then escape

II. Reduction of reaction force on satellite at fire

- Puncher is carried by arm, then injected. (Firing by booster is not needed.)
- The reaction force is reduced by absorber in arm (Arm + Puncher method)

<Candidate>

- Arm+Puncher
- Soft release + Puncher
- Improved Harpoon

Harpoon/Puncher Penetrating (2/2)

Affirmation of the Penetration thru. the Debris Wall

The penetration of the Harpoon/Puncher through the debris wall was evaluated preliminarily:

- Collision model study
  Possibility of penetration at collision of harpoon/puncher to debris wall was studied to be evaluated in order-level validity.

- Preliminary experimental feasibility study
  Feasibility was studied by preliminary experiment to be evaluated the penetration of harpoon/puncher to be able to penetrate the outer wall of debris.

- Further studies are to be carried out to evaluate more precise modeling to make sure of the penetration.
Further to be Studied

Following task are going to be carried out:

<Extendable boom>
Characteristics of boom are to be improved:
• to improve the quality of extension and holding.
• to increase the stiffness for future mission.

<Harpoon/Puncher>
Further studies and tests to evaluate more precise model of penetration to make sure of penetration.

<Debris Removal System>
Further studies are to be carried out on:
• countermeasure for the electric discharge at the contact of satellite with debris of different charge level.
• ensure of communication link at flyaround and capturing.
  electric power
  thermal balance
  and other system budget