A Small Satellite Mission for ISS Debris Collision Avoidance

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Abstract: The increasing population of space debris orbiting the earth justifies the great attention and interest in the protection of spacecraft from collisions. The International Space Station (ISS) is particularly threatened by the collisions with space debris, so that special maneuvers are conducted routinely or when needed to avoid collisions. In this work, a new technology for debris reduction using Spector (Space Debris Collector), a small satellite, is presented. Spector is capable of capturing and storing the debris. This satellite is onboard ISS and ready to be launched when it is needed. This method has some advantages such as avoiding the delay of experiments conducted on the ISS, protecting astronauts, and always being ready for operation in case of emergency. After successfully catching the debris, remaining fuel and a drag sail are used to deorbit the satellite.

1. INTRODUCTION

Space debris has become a growing concern in recent years because collisions at orbital velocities can be highly damaging to operating satellites and also result in more space debris. Collision risks are divided into three categories depending upon size. Debris which are 10 cm or larger are potentially catastrophic for the mission (Table 1). However, conjunction assessments and collision avoidance maneuvers are effective in countering objects which can be tracked by the US Space Surveillance Network (SSN). Debris which are between 1 and 10 cm are usually too small to be tracked and too large to shield against. This kind of debris can cause disruptions to a mission. Debris which are smaller than 1 cm will not harm the spacecraft as long as the spacecraft is shielded, but unshielded portions of satellite subject can lead to mission degradation or loss [1].

<table>
<thead>
<tr>
<th>Size</th>
<th>Threat</th>
<th>Detectability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1 cm</td>
<td>Mission degradation or loss</td>
<td>No SSN</td>
</tr>
<tr>
<td>1-10 cm</td>
<td>Mission disruption</td>
<td>&lt;5 cm no SSN, &gt;5 some SSN</td>
</tr>
<tr>
<td>&gt;10 cm</td>
<td>Catastrophic</td>
<td>Almost complete SSN</td>
</tr>
</tbody>
</table>

Table 1: Collision risk associated with the size of debris

Debris avoidance maneuvers are conducted when the probability of collision from a conjunction reaches specific limits set for the space station flight rules. If the probability of a collision is greater than 1 in 100,000, a maneuver will be conducted if it will not result in significant impact to mission objectives. If it is greater than 1 in 10,000, a maneuver will be conducted unless it will result in additional risk to the crew [1]. Figure 1 shows the situation occurred in October 2012, where Iridium-33...
was predicted to collide with the ISS [2]. This forced the ISS to do a Debris Avoidance Maneuver (DAM) [3]. Figure 2 shows a simulation result of the collision possibility based on the trajectories using AGI’s Satellite Toolkit (STK) software. It is possible that debris is detected too late and there is not enough time to start the DAM. This occurred in 2012 so that the crew retreated to Soyuz module due to insufficient time to plan and perform a maneuver [4]. Fortunately, the object just missed the ISS.

Spector can help the ISS to eliminate the debris when it is too late for a DAM (thruster used for a DAM are on the Zvezda module, Zarya module, Automatic Transfer Vehicle (ATV) or visiting spacecraft [6]). Spector will be deployed from the ISS by using the small satellite deployer provided there, such as the Space Station Integrated Kinetic Launcher for Orbital Payload Systems (SSIKLOPS) aka Cyclops [5], or other potential future satellite deployer.

This paper describes the mission profile and significances of the mission, including the detailed explanation about the mission, and the designed catching and deorbiting mechanism. Then, the satellite specifications including all the subsystems and payloads are carefully explained. Finally, the conclusions of the mission are provided at the end of this paper.

2. SIGNIFICANCES OF THE MISSION

Spector is ready onboard ISS and after being deployed, it can approach and catch the debris larger than 10 cm but limited to the size that can be stored inside the. By collecting threatening debris, Spector can bring some advantages for the ISS such as:

- Redundancy for the ISS DAM in case of emergency: According to the case in [4], DAM could not be done because of inadequate time to do the maneuver. Spector is always ready for operation in the ISS and can fulfil the mission of catching debris rapidly in case of emergency.
- Long term experiments which require special environments in the ISS will not be interrupted: The main purpose of the ISS is to conduct scientific experiments in space. Using small satellites to catch debris will reduce experiment disturbances. Therefore, the less maneuvers have to be done the better.
- The schedule of re-boosting maneuvers will not be disturbed: The ISS is expected to perform re-boosting maneuver to maintain its orbital altitude [7]. Disturbing the schedule means disturbing the experiments conducted in the ISS as well.
- Small amounts of fuel and resources are used: A low cost mission operation can be ensured due to the small weight and size of Spector.
3. DEBRIS COLLISION AVOIDANCE METHODOLOGY

Spector will be launched to the ISS from Earth and will be ready once it is there. Four thrusters are used in order to approach the desired target. Once it is near the target, the satellite will open the door using a gear mechanism and then approach to let the debris in. After a successful catch of the debris, Spector’s door will be closed to store it inside. The captured debris will cause impact force by colliding with the inner wall, but the satellite will not be damaged since it is covered by a special protective material. Then, pictures will be taken for debris analysis and investigation. Afterwards, the satellite will deploy a drag sail to deorbit. The remaining fuel will be used to accelerate the deorbiting process.

![Figure 3: The Overall Mission Concept Scenario](image)

4. SATELLITE SPECIFICATIONS AND KEY COMPONENTS

4.1 Dimension, mass, and structure design

The dimension of Spector is $1 \times 1 \times 1.5 \text{ m}^3$ and it weighs approximately 100 kg.

The configuration of Spector is shown in Figure 4 (left). The door is opened and closed by using a gear mechanism which is made of plastics [8]. The suitable motor drive for the gear is the space qualified motor manufactured by Maxon [9].

A camera is located on the inside of the door in order to take photos for two main purposes: 1. While the debris is still outside and near Spector, the door will be opened and the camera will be heading towards outside. In this case, the camera is used to
help for estimating the accurate position of the debris. Besides, it is also used to take the pictures of the debris for analysis and investigations. These can be useful to identify the source of the debris, if it is an artificial, a human made, or a natural debris. 2. While the debris is inside, the door will be closed and the photos are taken again. Thus, the collected pictures will provide information about the debris. The inner walls as well as the subsystems are covered by the special materials (yellow layers in Figure 4) to protect them from colliding with the debris.

Spector’s subsystems are located below the satellite’s storage area. They consist of several major subsystems including Altitude and Attitude Determination and Control Subsystem (AADCS), Thermal Control Subsystem (TCS), Command and Data Handling Subsystem (C&DH), Telemetry Tracking and Command Subsystem (TT&C), and Electrical Power Subsystem (EPS). Solar cells located on the side panel of the satellite are also needed to gather the energy from the sun to give sufficient power for the satellite during the whole mission.

The component below the subsystems is the drag sail for the deorbiting process. And finally, the propulsion systems are located at the lowermost part of the satellite. Four tanks and four nozzles are chosen for this mission because of symmetry reasons. It will be easier for the satellite to be balanced, as well for redundancy reasons. The specifications of the thruster and a case study are provided in section 4.2 below.

4.2 Thruster

Considering a 100 kg satellite with the size of 1 x 1 x 1.5 m³, a good thruster for this mission could be a S400/2 thruster from Daimler-Benz (Table 2, Figure 5) including propellant tank, propellant and subsystems because of its light-weight and good performance.

<table>
<thead>
<tr>
<th>Thrust</th>
<th>400N</th>
</tr>
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<tbody>
<tr>
<td>Power (kW/HP)</td>
<td>625/850</td>
</tr>
<tr>
<td>Propellant</td>
<td>MON/MMH</td>
</tr>
<tr>
<td>Isp</td>
<td>3120 m/s</td>
</tr>
<tr>
<td>Chamber Pressure</td>
<td>10 bar</td>
</tr>
<tr>
<td>Weight</td>
<td>3.4 kg</td>
</tr>
<tr>
<td>Length</td>
<td>531 mm</td>
</tr>
<tr>
<td>Nozzle Diameter</td>
<td>248 mm</td>
</tr>
</tbody>
</table>

Table 2: Thruster specifications [10]

Figure 5: Thruster S400/2 from Daimler-Benz [10]

Electrical propulsion systems have high Isp (>2000) but low thrust. That means that they use longer to perform the same operation compared to a chemical propulsion system but consume less propellant. Depending on the case, two different options could be possible, either a chemical propulsion system for emergency cases where time is important or an electrical propulsion system to catch the debris earlier, without time constraints but with a higher possibility due to more time to catch the debris. Table 3 shows different cases where one can see that the chemical propulsion system is, due to its higher thrust, always
faster but the electrical propulsion uses significantly less fuel and therefore can operate in a wider range if time is not a constraint.

| Table 3: Comparison between chemical and electrical propulsion systems |
|-----------------|-------------|-------------|-------------|-----------------|-----------------|-----------------|
| S400/2          | 400         | 303         | 10             | 6               | 31.0            | 17              |
| Electr.         | 2.55e-5     | 2000        | 10             | 6               | 7.5             | 24              |
| S400/2          | 400         | 303         | 10             | 13              | 50.0            | 17              |
| Electr.         | 2.55e-5     | 2000        | 10             | 13              | 14.5            | 32              |

For the calculations, some simple assumptions were made. The electrical propulsion system has a specific impulse \( (Isp) \) of 2000 s and a power consumption of 50 W. The power \( P \) per unit thrust \( F \) can be derived from the following equation:

\[
P = \frac{1}{2} g_0 * Isp\]

(1)

where \( g_0 \) is the gravitational parameter.

For the chemical propulsion, the Hohmann transfer, which is a two-impulse maneuver was chosen. It is not the fastest orbit change maneuver, but the most energy efficient one. The time was sufficient enough, so that in this case study, the requirements of time and weight can be fulfilled at the same time.

The inclination change is most effectively done when in perigee (to decrease the necessary \( \Delta V \)). For the electrical propulsion with a permanent thrust, the \( \Delta V \) can be calculated with a combination of altitude and inclination change as follows:

\[
\Delta V_{elec} = V_0 \cos (\beta_0) - \frac{V_0 \sin (\beta_0)}{\tan \left( \frac{\pi}{2} \Delta i + \beta_0 \right)}
\]

(2)

where the initial 'out-of-plane' thrust angle is defined by:

\[
\tan (\beta_0) = \frac{\sin \left( \frac{\pi}{2} \Delta i \right)}{\frac{V_0}{V_f} - \cos \left( \frac{\pi}{2} \Delta i \right)}
\]

(3)

\( \beta_0 \) is initial thrust vector yaw angle, \( \Delta i \) is the inclination change angle, \( V_0 \) and \( V_f \) are the velocities of the initial orbit and final orbit as \( V = \sqrt{\mu/r} \), where \( r \) is the radius of the initial orbit or the final orbit.
When Spector is in the same orbit (-plane) as the target debris, it still needs to catch it. In this case study, it is assumed that the worst case is when the debris is exactly on the other side of the earth. Then, it is also assumed that flying for 10 rounds around the earth (10 revolutions) is needed to catch it.

This is called 'phasing maneuver'. The orbit altitude has to be changed in order to change the period. For example: lowering Spector's altitude causes the period to decrease, therefore one orbit needs less time than one orbit of the debris in a slightly higher orbit as if Spector would start to overtake. A couple of orbits later, Spector will be close enough to get into the higher orbit again to catch the debris. The phasing orbit period $T_{phase}$ must be equal to the time it takes for the debris to cast around the earth and is equal to the period of the final orbit minus the flight time of Spector from one side of the earth to the other side of the earth (assume that the true anomaly is $180^\circ$) divided by the number $n$ of revolutions:

$$T_{phase} = T_{final} - T_{(180^\circ)} / n$$

(4)

The time was added so that the complete time needed from releasing Spector at the ISS until it catches the debris inside can be obtained and it is also shown in Table 3.

4.2 Drag sail mechanism

According to SSC' (Surrey Space Center) CubeSail satellite deorbiter [11], the drag sail mechanism can be stored in a double CubeSat sized box and reaches up to 5 x 5 m² when deployed and weighs less than 3 kg. The drag-sail will increase the area such that the satellite and the debris will deorbit within a few weeks. The drag-sail is stored inside Spector and will be deployed as soon as the debris is successfully captured.

4.3 Camera

Taking pictures of the debris is very significant for debris research and investigation. After it is successfully captured by Spector, photos will be taken by the space camera installed in Spector’s door. The camera used in Spector utilize the Micron Technology's MT9V011 image sensor and VIMicro's VC0706 digital video processor. Both are commonly used in camera modules for industrial and outdoor security applications [12]. The image sensor and digital video processor have been proven to be used in satellite, such as in SkyCube’s mission (Figure 5). Also, with the advantages of low power and cost, it is a suitable camera for this mission to capture the image of the debris stored in the Spector.

4.4 Satellite protection
After capturing the target inside the satellite, the debris will cause impact force by colliding with the satellite’s inner wall. In order to avoid this destruction, the inner wall will be covered by a layer of special material. The potential material for this purpose is Kevlar, which is usually used in chainsaw protection pants and bulletproof vest. Kevlar is also used in various space applications, such as spacesuit and also in the space shuttle, to bring protection against the impact from orbital debris. It is also strong enough to survive the extreme forces and temperature fluctuations, so it is suitable to protect satellite’s inner wall for this mission [14].

5 CONCLUSIONS AND FUTURE WORK

In this paper, a new small satellite mission for the ISS space debris collision avoidance has been presented. As a result of this proposed mission design, the threatening debris can be caught by Spector in case that the ISS debris avoidance maneuver cannot be performed. Moreover, the proposed technology will not bring disruption of the scientific experiments conducted in the ISS. As a consequences, the fatal accident caused by the debris collision will also be significantly reduced.

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7 REFERENCES