ISS Collision Avoidance System by Debris Reduction in Low Earth Orbit

Spector (Space Debris Collector) Satellite

Vina[1], Alexander Heimann[2], Jesus Sanchez[1], Te-Chuan Huang[1], and Sheng-Hao Wu[1]

[1]*Department of Electrical Engineering, National Cheng Kung University, Taiwan*
[2]*Department of Aeronautics and Astronautics, National Cheng Kung University, Taiwan*

Abstract

The increasing population of space debris orbiting earth justifies the great attention and interest in the spacecraft protection and collision avoidance. The International Space Station (ISS) is particularly threatened by the collisions with space debris, so special maneuvers are conducted every year to avoid the collisions. In this work, a new technology for debris reduction using Spector (Space Debris Collector), a container satellite is presented. Spector has capability to capture and store the debris. Combining these two abilities, this new technology is applicable to support other space debris catcher satellites, satellite recovery and analysis, and the most relevant purpose, to reduce orbital debris. Diverse mechanism including drag-sail will reduce the life-span of the debris. At the end of each mission, Spector will return to the ISS for refueling, replacing its components and debris investigations.

1. Introduction

Space debris has become a growing concern in recent years because collisions at orbital velocities can be highly damaging to functioning satellites and can also result into more space debris. A depiction of this concern is represented in Figure 1. Collision risks are divided into three categories depending upon size of the debris. 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].

Figure 1: Space debris is tracked as it orbits Earth
Image Credit: NASA

Table 1: Collision risk associated with the size of debris

Size	Threat	Detectability
<1 cm	Mission degradation or loss	No SSN
1-10 cm	Mission disruption	<5 cm no >5 some SSN
>10 cm	Catastrophic	Almost complete SSN

Many efforts have been made in order to reduce the space debris. Some technologies which have already been developed are the ground and space based lasers, trash tenders and attachable devices, dual-use orbit transfer vehicles, and space tethers [2]. One particular case for attachable devices is “CleanSpace One”, a microsatellite from Switzerland, whose primary mission is to rendezvous with SwissCube, their previous CubeSat, attach to it using a grabbing system and to perform deorbiting maneuver [3]. Another research about grabbing technique has been developed by JAXA. A flexible robot arm for capturing non-cooperative targets has been designed for this purpose [4].

This paper initially describes the significances of our satellite mission called Spector (Space Debris Collector) to protect the ISS from collisions with debris. Then, our methodology for collecting, storing and deorbiting the debris will be explained. In addition, satellite specifications and key components will be presented as well. Finally, conclusions, originality and social effects of our mission will be summarized at the end of this paper.

2. Aims and Purposes

Due to the overlapping orbits, debris may collide with some operational spacecraft, especially ISS. The ISS is in Low Earth Orbit, and maintains an orbit with an altitude between 330 km and 435 km by means of re-boost using the engines of the Zvezda module or visiting spacecrafts [5]. In this altitude, there is a lot of space debris. Among these debris, large objects may destroy the station, but with the help of organizations from countries which participate in ISS, their orbit can be predicted. Moreover, these debris can be detected by optical and radar instruments while Spector is approaching them. Thus, Spector can keep ISS from collisions with debris larger than 5 cm. By collecting some dangerous debris, Spector can also help ISS to save time and money since ISS does not need to conduct the Debris Avoidance Maneuver (DAM), which uses thrusters to change the orbital altitude. Instead of wasting a huge amount of resources for this maneuver, a good alternative is to use the satellite approach to remove the debris which will consume less fuel and will not interrupt long term experiments which require special environments in ISS.

3. Debris Collection System

3.1 Method for catching debris

There will be two different ways to do the catching procedure. The first one is via a catcher satellite, related to previous research, as JAXA's active space debris removal system using electro-dynamic tethers (EDT) technology; Switzerland's "CleanSpace One" is a 66-pound technology demonstration spacecraft designed to link up with Switzerland's out of commission "SwissCube" and safely deorbit the target. Inspired by these kinds of solutions for space debris problems, Spector will be able to receive the targeted debris being caught by other catcher satellite and then store them in a container. The catcher satellite will need to approach Spector's orbit and release the target. The second way is to use it to catch the debris. Orbital information of the debris can be estimated using the debris database. Several thrusters are used in order to approach the desired target by accurate predictions. So once it is near, the satellite will open the door and then accelerate to let the debris in.

3.2 Method for storage

Instead of deorbiting every small debris directly, many small parts first and make them re-entry altogether. In this way the amount of resources and missions can be decreased. After successful catch of the debris and store it inside the satellite, Spector's door will be closed. Then, when reached a certain closing angle of the door, foam will start to be sprayed to the debris through separate nozzles which are located at the door until the door is fully closed. This foam will slow the debris and make it stick on the wall inside the satellite in order to stabilize the satellite for the next tasks.

3.3 Method for flying back to ISS

To maintain a permanent and low-cost space debris reduction system, a reusable system is recommended. In order to achieve this goal Spector will need to fly back to the ISS to refill its propellant, empty the container and start to a new mission for more collection of debris.

Since debris from higher orbits than the ISS orbit are collected, the following steps are used to get to lower orbit:

1. Change orbit plane to meet inclination of ISS (51.65°) if necessary
2. Bring thruster in opposite flight direction and activate: slow down to lower the perigee
3. When at target point (perigee at ISS altitude) activate again to circularize orbit (lower apogee)
4. Phase change to get close to the ISS

There is no docking maneuver planned. Like the H-II Transfer Vehicle, Spector will fly to a close rendezvous and maintain station-keeping without docking. This allows the ISS Mobile Servicing System (MSS or Canadarm2) to grapple Spector and berth it on the station.

Flying back to the ISS has the following purposes and advantages:

1. Refill fuel to maintain a long-lasting mission lifetime
2. Refill foam in order to keep debris attached to structure to avoid problems with a moving center of mass during orbit change maneuver
3. Refill with container including deorbiting mechanism
4. Inspect debris which is worth of further investigation (e.g. CubeSats)

Spector will include a refill mechanism on its structure. With this, the MSS can push it against a refill station. It will automatically refill foam and fuel when the connection is made as long as the MSS presses it against the station. The container will also be changed by the MSS.

In order to analyze the debris and to reload with container, the access hatch of the ISS will be used. The MSS will help to assist this exchange if needed.

3.5 Method for releasing the debris

Certain threshold will be defined for the maximum mass of the total stored debris. When the total mass of the debris is approaching the threshold, Spector will be alerted to prepare for performing the release mechanism. All of the satellite's actions will be analyzed to ensure that at no time the released container layer intersects with

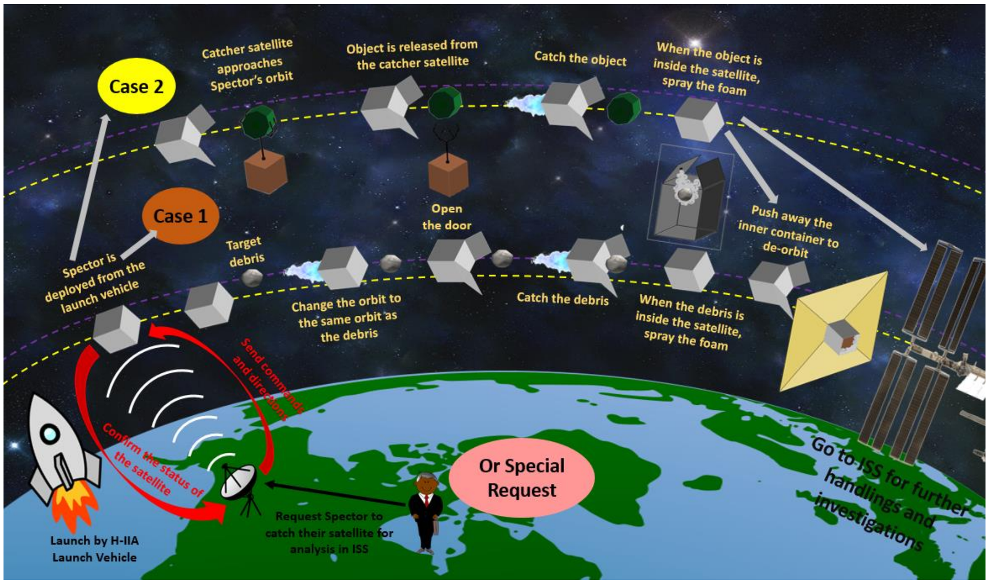

Figure 2: The overall mission concept scenario of Spector showing 2 cases. Case 1 for catching debris independently and case 2 for cooperation with catcher satellites

the ISS orbit. Then, Spector will check its orbit related to the ISS orbit in order to avoid the debris collision with ISS after pushing them out of the container. After all conditions are met, then the most inner layer of the container will be pushed out from the satellite. The pushing mechanism is done by a mechanical spring installed in the bottom of every layer of the containers. Furthermore, a 5x5m^2 sail will be in charge for debris re-entry. A detail explanation about this sail mechanism will be given in section 5.

3.5 Mission concept scenario

Spector will have a similar orbit as ISS (current altitude of 420km and inclination of 51.65°). Once it is there, it will first establish contact with a main ground station in order to verify the status of its components and receive the commands, mission and directions to reach certain determined debris. Since the desired orbit is in LEO, the contact time is limited to some minutes in which orbit data and status of mission are interchanged. Once the commands from ground station are received, the satellite will proceed to change its orbit according to regulations (flying permission around certain orbits) and provide measures to ensure avoidance of collisions with other objects. When Spector is in track of a target, it will perform orbital maneuvers to reach it and synchronize with the desired object. It will detect the target and use maneuver procedures to get more proximate to it until it is in proper range and use its capture and store mechanisms while in range. Once the system including the captured target has become stable, it will send confirmation to the ground station to continue with its mission. It will either release it back to earth with sailing mechanisms to increase the drag and go faster to the atmosphere, or either returns back to ISS for further study. After the satellite reaches a threshold of its resources, it will go to ISS for refill of its required components. If the debris is not worth analyzing, the container is full or remaining fuel does not allow any new rendezvous, Spector will get rid of its inner container. Using a spring mechanism, the inner container will be released from the satellite. Additionally, a deployable sail will be used to increase the drag to accelerate the deorbiting process. The overall process of the mission scenario is depicted in Figure 2.

Since the waste is being collected above the ISS altitude, the released and ready-to-reentry container would intersect with the ISS' orbit. To avoid this, the waste is either released when below the ISS or Spector performs a small inclination change, enough to avoid any complications.

4. Satellite Specifications

4.1 Dimension, mass, material

The satellite purpose is to store objects of Cubesat sizes, which are objects in the scale up to 30cm. The estimated size of the satellite including all subsystems, propellant, and tanks storing the liquids to create the foam, is 1.0 x 1.0 x 1.5 m^3. The estimated mass for this satellite is 500 kg.

4.2 Payload

The main payload is a foam mechanism. This payload is critical since the foam that will be spread to the debris will slow it down the rotation and attach the debris to the inner wall of the container in order to complete the storing mechanism.

4.3 Sensors

There are several sensors installed on Spector, including GPS sensor, star tracker, sun sensor, magnetometer, 3-axis angular rate sensor and accelerometer, laser rangefinder and space camera. These sensors collect data for certain purpose. Below are the explanation of the significant function of each sensors:

1. *GPS Sensor*: The GPS sensor receives the latest updated position of the satellite, this ensure accuracy when tracking the target.
2. *Star tracker*: The star tracker is an optical device that measures the position of stars using a photocell or camera. With knowledge of the stars location, it provides attitude determination with high accuracy.
3. *Sun sensor*: This sensor determines the spacecraft angles with respect to the sun. It can also help the satellite for power management while considering eclipse condition.
4. *Magnetometer*: The magnetometer is an instrument that senses magnetic field strength in a 3-axis triad, magnetic field direction. The sensed field strength and direction is compared to a map of the earth's magnetic field stored in the memory of an on-board computer. If satellite position is known then attitude can be inferred.
5. *3-axis angular rate sensor and accelerometer:* These devices will allow the measurement of the angular motion and acceleration.
6. *Laser rangefinder:* The laser rangefinder uses a laser beam to determine the distance to an object. When the Spector approaches the debris, the laser rangefinder determines the distance between them, and checks the direction of the satellite. As the distance to the object decreases, for the aim of better accuracy, space camera is used to confirm the location of target.
7. *Space camera*: Since high accuracy of the debris position is needed, a camera is essential to do this when the satellite and the debris are in a short distance. Once the camera confirms the position of debris, it can go to the next step by catching it. Another function of this camera is to take pictures of the objects to determine if it is worth to be analyzed.

4.4 Actuators

Actuators are responsible for moving and controlling a mechanism or system. Since Spector comprises altitude and attitude control, some actuators such as reaction wheels and magnetorquers are essential. Below are the explanations of the significant function of each actuators:

1. Reaction wheels: The reaction wheel is a type of flywheel used primarily for attitude control. It is particularly useful when the spacecraft must be rotated.
2. *Magnetorquers*: The magnetorquer will develop a magnetic field which interfaces with earth magnetic field; so that the counter-forces produced provide useful torque for stabilization and attitude control and to desaturate the reaction wheels.
3. *Thruster:* Spector will use thrusters only for orbit control. There will be a more detail explanation in section 5.

4.5 Satellite subsystems

There are seven subsystems in Spector which will be briefly introduced here:

1. Structure and Mechanisms Subsystem (SMS)

The SMS design is to fulfil the configuration, mass and center of gravity requirements. The configuration of Spector will be dealt with CAD engine software, considering center of gravity, moment of inertia, and weight. The structure analysis will be conducted to make sure Spector can survive during the launch and fit the environment of the space.

2. Thermal Control Subsystem (TCS)

The thermal control on Spector is passive except for its payload. The locations of the different subsystems are taken into account in the design in order to keep all of them in proper temperature range.

3. Attitude and Orbit Control Subsystem (AOCS)

The AOCS is responsible for determining the attitude of satellite at different condition, detumbling for the satellite after deployment, pointing the satellite in a favorable attitude, and recovering it from any spin ups during the mission.

4. Electrical Power Subsystem (EPS)

The EPS has to generate power with solar cells and store the energy into batteries, as well as regulate voltage for distributing power to each subsystem.

5. Telemetry, Tracking and Command Subsystem (TT&C)

The TT&C is a bridge between ground station and satellite itself. It will give C&DH subsystem the telecommands sent from ground station and return the telemetry requested.

6. Command and Data Handling Subsystem (C&DH)

The C&DH plays an important role in the whole satellite. It is in charge of command validation and execution, data reception, data storage and the health information of the satellite. It is also the interface for the communication between each subsystem.

7. Spacecraft Propulsion Subsystem (SPS)

The SPS consists of 4 thrusters which are essential to the mission requirement of Spector: provide a sufficient propulsion subsystem to obtain station keeping and orbit changes with a high efficiency and high thrust by low propellant consumption. For the purpose of efficiency a high specific impulse is needed to keep low the propellant consumption and the storage volume and weight.

4.7 Communication procedure

The communication time with the satellite is limited to some minutes because of its orbit. The required transfer data are the current status of locations and changes of orbits. Uplink commands will include the required information to determine the change of orbital parameters. Downlink telemetry will received data which consists of transfer orbit achievement, detection and track of the object, capture of the object and its release if needed. Additional information is also related to the status of the satellites components, including the container, catching mechanisms, solar panels and subsystems. This means the data exchange requirements do not need to be a lot. Baudrate of at least 9600bps can be the minimum for these basic requirements. Higher requirements like detail track of object, information about transfer and images can increase the baudrate up to 100kbps range. Thus, S-band communication link will be an appropriate range of frequencies to transmit both basic and complementary data. The antenna will be a patch antenna allocated on a side of the satellite pointing towards earth.

5. Key Components

5.1 Thruster

5.1.1 Introduction

Main priority has the security of the ISS rather than just removing trash from the LEO. Therefore Spector has to fly to a potentially threat, eliminate the threat and return to its other missions in a certain safety time-frame to, in case of a failure, still give the crew members enough time to perform an evasive maneuver. The procedure looks as follows:

1. Detecting the threat
2. Connect with Spector: exists enough fuel/space to fly to debris and collect it?
3. Activate security mode of Spector (other mode is normal mode/trash collecting mode)
4. Fly to the threat: rendezvous and station keeping. If first attempt fails, try as long as possible (depending on propellent) to catch the debris
5. Send signal to ISS to warn them or to give the all-clear
6. Return to the normal mode

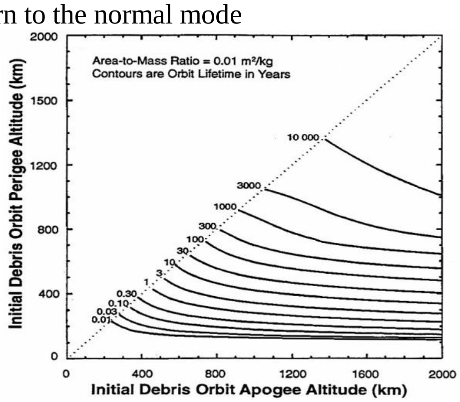

Figure 3: Orbit lifetimes for debris released in low altitude, low eccentricity orbits

Figure 3 shows the orbital lifetime in years for objects with an area-to-mass ratio of 0.01m²/kg. The ISS has a current altitude of 420km. Objects at around 15km above that would intersect and force the ISS to avoid collision within one month. Therefore the propulsion system has to be capable to reach objects early enough.

5.1.2 Types of thrusters

There are several types of thruster available. Nitrogen is the most commonly used propellant for cold gas thruster. The advantages are its storage density, performance and safety due to a minimum of contamination concerns [6]. Other options are hydrogen or helium but due to their low atomic weight they utilize a huge storage volume and cause a heavy system weight. An alternative could be Carbon Dioxide, its disadvantage is toxicity but it has a high atomic weight leading to a smaller system size and weight.

Exhaled air consists to 4% of Carbon Dioxide. As mentioned above it is highly toxic so it is removed from the air with the help of the Environmental Control and Life Support System (ISS-ECLSS), with a Russian system called Vozdukh. The advantage of using Carbon Dioxide is that no propellant is needed to be brought to the ISS but is produced by the ISS instead and more precisely by the humans on board the ISS.

Other options are electrical propulsion systems such as ion or plasma thruster. Electrical propulsion system produce a much lower thrust but consume less propellant. Table 2 shows the comparison of some thruster types.

5.1.3 System Components and Weight

For the mission purpose the µ10 IES (Ion Engine System) of the Hayabusa asteroid explorer have the best performance (Table 3: Specifications of IES on Hayabusa [6]) and will be used on Spector. The propulsion system will consist of 4 thruster, each with a pointing mechanism for small thrust adjustments during operation to maximize the thrust during operation. Also the 51 liter Titanium alloy pressure tank will be used since it showed trustworthy with the success of Hayabusa. The system, as it is the same as in Hayabusa, will have a dry mass of 59kg including gimbal and propellant tank plus 73kg Xe maximum.

Table 3: Specifications of IES on Hayabusa [6]

Ion ThrusteRs (ITR)	Four µ10s, cathode-less ECR microwave discharge plasma generation carbon-carbon composite 3-grid electro-static acceleration 10 cm effective diameter, 8 mN nominal thrust
Microwave Power Amplifiers (MPA)	Traveling Wave Tubes, 4.2 GHz, four units A single MPA driving both an ion generator and a neutralizer simultaneously 32 W for an ion generator, 8 W for a neutralizer, 110 W total power consumption
IES Power Processing Units (IPPU)	Three units distributed to four ITRs via relay switches 1.5 kV to screen grid, –330 V to acceleration grid 240 W total power consumption
Propellant Management System (PMU)	Titanium alloy pressure tank, 51 liters in volume, 73 kg maximum Xe loading Two propellant flow controllers for redundancy Blow down via flow restrictors
IES Pointing Mechanism (IPM)	Two axis gimbal, +/-5 deg

Table 2: Propellant Performance

Type	Propellant	Density [g/cm³ STP]	Specific Impulse [s]	Advantage	Disadvantage
Cold Gas	Nitrogen	0.808	73	Low energy consumption	Low Isp
	Carbon Dioxide	0.77	61		Low Isp, Toxic
cathode-less electron cyclotron resonance ion	Xenon	2.942	3000	Very high Isp	High energy consumption

5.1.4 Case Study

Case one:

The ISS weights currently approximately 450,000 kg. To lift the ISS just a few hundred meters in order to avoid a collision, it consumes a huge amount of propellant. A light weight satellite such as Spector just needs a few kg.

The initial altitude of Spector will be 420km (current ISS' altitude). The threatening debris to the ISS is approximately 15km higher and has an inclination difference of 2°. The time to collision is 30 days.

Spector has 4 thruster with 8mN nominal thrust and 3,000 sec Isp each, leading to a total thrust of 24mN.

The time needed to reach the objects altitude can be calculated with the following equation:

$$t = \frac{m_0 g_0 I_{sp}}{T}[1 - e^{\frac{1}{I_{sp} g_0}\left[\sqrt{\left(\frac{\mu}{r_0}\right)} - \sqrt{\left(\frac{\mu}{r_1}\right)}\right]}] * 1.35 \qquad (1)$$

where m_0 is the initial mass, T is the thrust in kN, r_0 is the initial altitude r_1 is the target altitude, μ is the gravitational parameter and the factor 1.35 is due to the fact that 35% of the time the satellite will be in eclipse and therefore during that time doesn't have enough power. This is causing the maneuver to take 35% longer.

For the 15km, Spector, with an initial weight of 500kg including propellant needs 2 days and 18hours. The amount of propellant used for the maneuver can be calculated with (pure burning time; without the factor 1.35):

$$m_p = \dot{m}_e t = \frac{T}{I_{sp} g_0} t \qquad (2)$$

Which is in this case only 0.144kg.

After reaching the target orbit an inclination change might occur. The Δv_i for a circular orbit inclination change is:

$$\Delta v_i = 2v \sin\left(\frac{\Delta i}{2}\right) \qquad (3)$$

For an inclination change of 5°, an additional Δv of 10% of the circular orbit velocity has to be produced.

The $\sqrt{\left(\frac{\mu}{r_0}\right)} - \sqrt{\left(\frac{\mu}{r_1}\right)}$ part in Eq.(1) represents the Δv of two circular orbits, exchanging by Δv_i for the inclination change, the time needed can be calculated. The time needed to change the inclination by just 0.1° would be 187days leading to an additional fuel consumption of 13.2 kg. The time needed is unacceptable and caused by the low thrust. A propulsion system with a higher thrust, i.e. 300s Isp an 10kN thrust, would only need 44s but consumes 149kg propellant. Therefore an inclination change cannot be performed and an alternative solution has to be found for future work.

Considering the worst case scenario where the object is in the same orbit but currently on the other side of the earth, we need to perform a phase change maneuver. The time needed for this maneuver is 28 days and 4.5 hours and it consumes 1.47101 kg of propellant (including 30 revolutions for the rendezvous and factor 1.35 for the time). The all in all time and propellant used for this safety maneuver can be seen in Table 4.

Table 4: Result of the safety-maneuver case study

Maneuver	Δv [km/s]	Propellant used [kg]	Δt
Altitude change	0.2168	0.14336	2d, 18h
Inclination change	-	-	-
Phasing	0.08643	1.47101	28d, 4.5h
Total	0.30330	1.61437	30d, 22.5h

Case two:

Considering that every object is 15km apart from each other by altitude and we need 30 revolution for phasing where the object is on the other side of the earth and finally flying back to the ISS to reload propellant and foam, we can accumulate around 27 objects. It has been considered 40% propellant for margin.

5.2 Foam

The foam is very critical in this mission. It will slow the debris rotation when it is inside the container. The foam also has to be flexible and can stick on the inner wall, so the object inside cannot go outside of the container during the re-entry. Another intended purpose is to keep the center of mass (CoM) fixed. For these purposes, polyurethane foam is chosen. This foam has rigid and rubbery properties. This foam is a suitable option for this mission considering its highly reasonably expansion factor and easy production process.

The polyurethane foam is generated by the reaction of two liquid components, polymeric diol and polyisocyanate. The reaction starts after the two components are mixed together. Upon mixing, a polymerization reaction occurs in three directions, leading to a large molecule that is rigidly held into a three dimensional structure. CO_2 will be released during this reaction which causes the foaming. The blowing agent, a low boiling liquid, is vaporized by the heat of the reaction and along with CO_2 creates gas bubbles into the viscous mixture as the foam sets into a rigid mass [7].

The foam-forming process by components mixing starts when debris is getting near to the container since the mixing process also needs certain time to finish. Two separated tanks with proper temperature control are used to store the liquids and connected to a mixing chamber. Then, the chamber is connected with pipes located in the side parts of the container to bring the foam to the nozzles located in the door. Overall configuration of the foam payload (half cut of the satellite) can be seen in Figure 4.

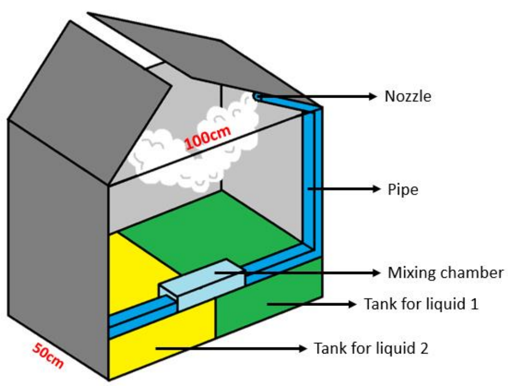

Figure 4: Foam payload configuration

5.3 Drag sail and ISS security during debris re-entry

The mechanism which pushes the container out consists of a spring system, triggered by the ground station or the ISS and includes a drag-sail and a deployment system. According to SSC' (Surrey Space Center) CubeSail satellite deorbiter [8], the mechanism can be stored in a double CubeSat sized box and reaches up to 5 x 5m² when deployed and weights less than 3 kg. The drag-sail will increase the area such that the container and its debris will deorbit within a few weeks.

5.4 Center of mass detection

In order to change the orbit, Spector needs to be accelerated. This can only be done if the line of action of the thrust vector passes through the center of mass (CoM). Otherwise, it would start to rotate rather than change its velocity. Since Spector accumulates mass by collecting debris and due to the fact that the mass will not be equally distributed inside, measurements of the new center of mass are needed before any orbit maneuver. Because Spector has a symmetrical shape, acceleration sensors will also be placed symmetrically. To measure the CoM, Spector will perform a roll, initiated by the reaction wheels. In an appropriate reference frame, the precession (1^{st} Euler angle), nutation (2^{nd} Euler angle) and rotation (3^{rd} Euler angle) can be determined. In case that the CoM is not within the geometrical center, the accelerations will differ from one another and the new CoM can be resolved by processing accelerometer measurements. This will be done separately around each of Spector's axis.

Consequently, the thrusters can be adjusted in a way that it keeps the line of action through the CoM during the maneuver.

6. Conclusions

The debris which are the main concern of the mission are known to be threats to ISS and operating satellites. In this paper, a new method of space debris removal in Low Earth Orbit using a container satellite which is capable of catching and storing debris has been presented. Special thruster has been designed to perform the required maneuvers and foam-based storing method has been proposed to collect debris. Returning to ISS at the end of each mission enables the satellite to perform long mission operation by further treatments in ISS such as refueling and components replacement needs. As a results of these activities, the realization of the international cooperation for space debris removal is becoming more feasible. Moreover, the proposed technology of cooperation with ISS can increase the mission lifetime of the future satellite missions as well as helping further development of the satellite missions. As a consequences, the number of debris in LEO will also be significantly reduced.

References

[1] NASA, The Threat of Orbital Debris and Protecting NASA Space Assets from Satellite Collisions, 2009.

[2] M. Kaplan, Survey of Space Debris Reduction Methods, in: Proceedings of the AIAA SPACE Conference and Exposition, Pasadena, California, 2009.

[3] M. Richard, L. Kronig, F. Belloni, S. Rossi, V. Gass, Uncooperative Rendezvous and Docking for MicroSats, in: Proceedings of the International Conference on Recent Advances in Space Technologies, Istanbul, Turkey, 2013.

[4] S. Nishida, S. Kawamoto, Y. Okawa, F. Terui, S. Kitamura, Space debris removal system using a small satellite, Acta Astonautica 65 (2009) 95-102.

[5] NASA, Current ISS Tracking Data, Retrieved 28 January 2009, http://spaceflight.nasa.gov/realdata/tracking/index.html

[6] Assad Anis, Cold Gas Propulsion System – An Ideal Choice for Remote Sensing Small Satellites, NED University of Engineering and Technology, Pakistan.

[7] M. Andrenucci, P. Pergola, A. Ruggiero, Expanding foam application for active debris removal, ESA Final Report, 2011.

[8] A mission to clear dangerous debris from space, 2010, http://www2.surrey.ac.uk/mediacentre/press/2010/26099_a_mission_to_clear_dangerous_debris_from_space.htm