SSC16-X-03

Micropropulsion Systems Enabling Full Active Debris Removal by a small satellite ADRAS-1

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ABSTRACT

In this paper, three types of micropropulsion systems are presented all of which are to be installed on a small satellite ADRAS-1 planned for launch in 2018. The mission target is demonstration of full active debris removal, and a 50 kg target debris will be captured and de-orbited. The satellite consists of a 90 kg carrier satellite, MOTHER, and a 30 kg catcher satellite, BOY. Keys of the mission are three propulsion systems using an ion thruster, monopropellant thrusters, and solid-propellant thrusters. MOTHER is equipped with a miniature and low power, xenon ion thruster for orbit transfer, which has thrust of 350 μN and specific impulse of 1000 s. Additionally, MOTHER is equipped with H_2O_2 monopropellant thrusters for non-cooperative approach to target debris, which have 200 mN and 60 s. BOY, which is finally released from the MOTHER, is equipped with a cluster of 36 laser-ignited solid-thrusters for deorbiting the debris by 7.14 kNs impulse in total.

INTRODUCTION

Japanese universities and institutions have continuously contributed to developing small satellites and their components, since they accomplished the first space operation of a cubesat in 2003 [1]. In 2009, a cubesat, Kiseki (KKS-1), was launched equipped with a laser ignited solid microthrusters developed by Tokyo Metropolitan College of Industrial Technology [2]. Although its in-flight operation could not be executed because of the satellite trouble, the solid thruster showed its capability passing through safety requirements for riding share on a H2A launch vehicle. In 2014, Hodoyoshi series microsatellites [3,4] verified space operations of a H_2O_2 monopropellant microthruster developed by Tokyo Metropolitan University and National Institute of Technology, Oyama College [5] and a miniature ion thruster developed by the University of Tokyo [6-7]. The developments of the two microthrusters were collaborated with NESTRA (Next

Generation Space Technology Research Association) in a five-year's extensive small satellite program. Moreover, advanced version of the ion thruster was developed by the University of Tokyo and it was utilized on the first interplanetary microsatellite, PROCYON [8,9]. In 2018, those three microthrusters (laser-ignited solid thruster, H_2O_2 monopropellant thruster, and xenon ion thruster) are planned to be used to conduct a more advanced mission, active debris removal, on ADRAS-1 microsatellite by ASTROSCALE [10, 11].

ADRAS-1 is a microsatellite demonstrating the capability to remediate mid-to-large orbital debris which mainly consists of abandoned rocket upper stage bodies as well as decommissioned satellites. It has a 120 kg mass in total consisting of a 90 kg main satellite, MOTHER, and a 30kg catcher satellite, BOY (shown in Figure 1). The demonstration mission is planned for launch in 2018 and will present the capability to conduct a successful non-cooperative approach, following by debris attachment and de-orbit phases using three propulsion systems.

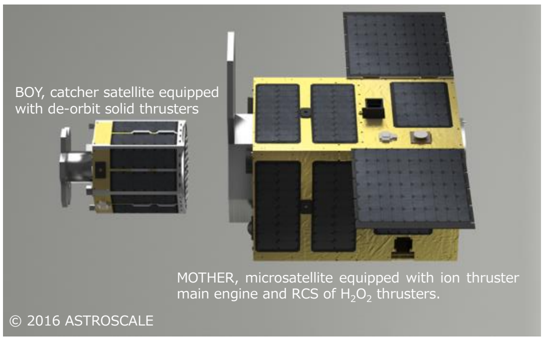


Figure 1: ADRAS-1 images, BOY and MOTHER.

The ADRAS-1 mission consists of sequential and multiple phases shown in Figure 2, which includes several key maneuvers using propulsion systems. First key maneuver is non-cooperative approach to target debris, phase 2. This sequence requires three translational and three rotational controls, and it will be performed twelve monopropellant thrusters. Second key is descending orbit with an ion thruster. It needs higher delta-V than the first maneuver and requires a device with higher specific impulse. Third and final propulsive maneuver is deorbiting the debris from the LEO to burn up upon atmospheric reentry. It requires not only high impulse in a limited time but also low dry mass, because BOY has much more limited mass and volume than MOTHER. Clustered miniature solid thrusters are regarded as the most suitable device for this requirement.

This paper focuses on details and current status of the three propulsion systems installed on ADRAS-1. Details of the satellite and mission itself are shown in the reference and their websites.

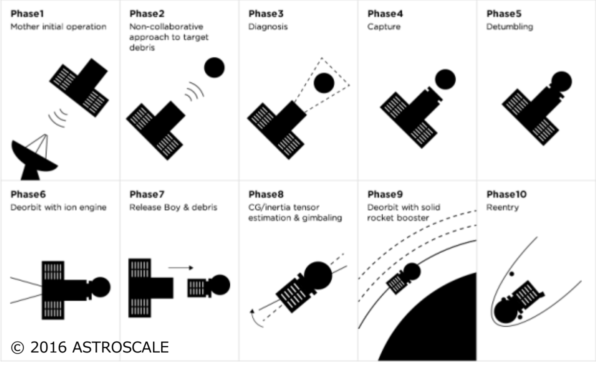


Figure 2: ADRAS-1 planned mission sequences.

MONO-PROPELLANT THRUSTER

Overview

The monopropellant propulsion system utilizes miniature, safe hydrogen peroxide thrusters. The design is based on the policies of safety-first and effective utilizations of COTS (Commercial-Off-The-Shelf). Medium concentration of hydrogen peroxide (60 wt%) is adopted as low toxic, much safer propellant than conventional hydrazine. H_2O_2 is decomposed with a catalyst as follows,

$$2\mathrm{H_2O_2} = 2\mathrm{H_2O} + \mathrm{O_2} + 192\ \mathrm{kJ}. \qquad (1)$$

Prior to 1970, H_2O_2 was researched with high concentration from 70 to 99 wt%. However, usage of the highly concentrated H_2O_2 arises difficulties in its handling ability, availability, transportation and storage. Therefore, medium concentration of hydrogen peroxide (60 wt%) was selected as more suitable propellant for small satellites. Although decomposition heat of 60 wt% H_2O_2 is lower than its heat of vaporization, which means decreasing performance, it has more important advantages of overall costs and risks to handle the system.

Previous version thrusters were demonstrated in space on microsatellites, HODOYOSHI-1 and HODOYOSHI-3. Detailed information of those are shown in references [5]. The thrusters addressed here for ADRAS-1 are upgraded and modified versions based on the lessons learned by the in-space operations. Objectives of Hodoyoshi-1/3, thrusters were verification of their operation in space and each satellite was equipped with a single thruster head. In contrast, ADRAS-1 needs the mono-propellant thruster system to achieve rendezvous with the space-debris, and it need be equipped with twelve thruster heads giving full ability for the translation and rotation.

System Design

The monopropellant propulsion system consists of three components: two propellant tanks, feeding system, and twelve thruster heads. The system diagram of the propulsion system is shown in Figure 3. The each tank contains H_2O_2 surrounded by a bladder and Helium gas, pressurizing the H_2O_2 (blowdown system). Those tanks are originally designed aluminum tanks with maximum expected operating pressure of 2.0 MPa. The feeding system has solenoid valves with series and parallel connections and drain ports filling and discharging the propellant. Each thruster head has a single solenoid valve, atomizer, solid catalyst, rocket nozzle, and temperature and pressure sensing port. Schematic diagram of the thruster head is shown in Figure 4. The catalyst is a platinum metal honeycomb having a sufficient decomposition performance and strength. The atomizer converts the liquid flow to fine droplets without any assistance of outside gas flow. The atomization improved the decomposition efficiency of the H_2O_2 solution with the catalyst. The temperature and pressure port is necessary to check the thruster status and to estimate the thrust and impulse by the operation.

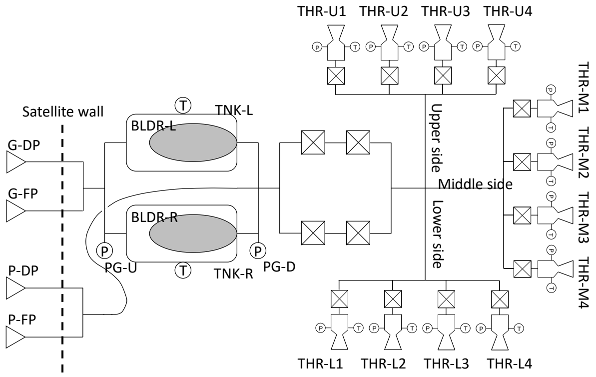


Figure 3: System diagram of the monopropellant thruster system.

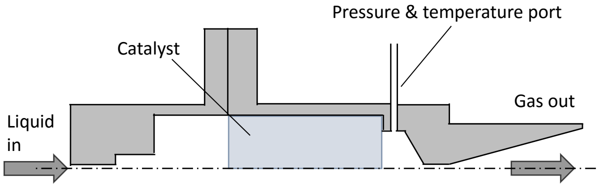


Figure 4: Schematic view of the monopropellant thruster.

Estimated Performance

Bread-board model (BBM) thrusters have been tested prior to the engineering model development. Figure 5 shows the pressure history of the BBM thruster. The thruster head was placed in the atmosphere and the feeding line was connected to 0.40 MPa test tank, which is higher than planned tank pressure in space to compensate the pressure loss on the ground equipment system. Thrust and specific impulse of the BBM thruster were calculated as 275 mN and 75 s in average.

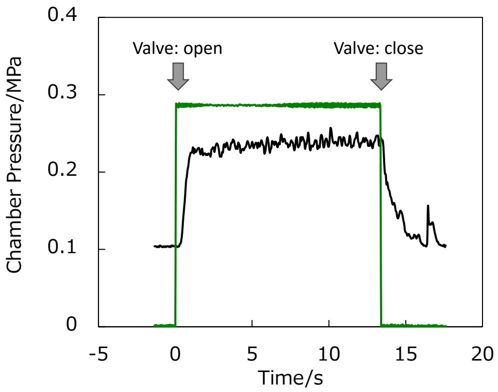


Figure 5: Chamber pressure history at the BBM thruster test.

EM/FM thruster performance is estimated based on the BBM thruster tests as shown in Table 1. Total mass of the monopropellant thruster system is 14.46 kg. Most of the volume and mas of the system is occupied by the propellant tank and feeding system. Figure 6 shows the planned 3D-CAD view of those components. The single tank has dry mass of 2.00 kg and internal volume of 1500 cc. Solenoid valves, pressure sensors, and electric system are located between the two tanks. Power consumption at standby mode is 4 W for pressure and temperature monitoring. Thruster operation needs additional power opening solenoid valves. The number of simultaneous thruster operation is expected as four thrusters in the maximum during the rendezvous sequences. The four thruster operation will need power of 32 W opening the solenoid valves.

Table 1: Estimated specifications of the monopropellant thruster system.

Volume (tank & feeding)	365 × 263 ×120 mm^3
Volume (thruster)	80 × 100 × 120 mm^3
Mass (tank & feeding)	9.66 kg = H_2O_2 1.86 kg + Dry 7.8 kg
Mass (thruster)	4.8 kg = 0.4 kg/head × 12 heads
Power consumption	36 W when 4 thrusters are fired
Thrust	> 200 mN
Specific impulse	> 60 s

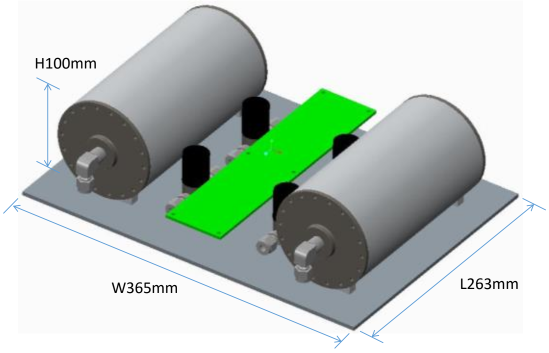


Figure 6: 3D-CAD view of the tank assembly

ION PROPULSION SYSTEM

Overview

The ion propulsion system utilizes Xenon ion thrusters featured by its low power and smallness. They were enabled by microwave discharge plasma and its efficient design. The microwave power injected into a plasma source is as low as 1.0 – 1.5 W to obtain 4 – 6 mA ion or electron current. The thruster head weighs only 160 g, which includes an ion source, a neutralizer, gas isolators, and mounting plate.

That miniature ion propulsion system, referred as to MIPS-A, is a successor model of MIPS and I-COUPS, both of which demonstrated the in-flight operation in 2014-2015. MIPS, the original system, was the first miniature ion thruster operated in microsatellite in space. I-COUPS is its advanced model with extension of cold-gas thrusters sharing the xenon propellant with the ion thruster. An interplanetary micro-space probe, PROCYON, was equipped with I-COUPS and accomplished 223 hours ion thruster operation in deep space in spite of several thruster troubles. MIPS-A implements significant improvements, two ion thrusters and two flow lines for redundancy and flexible operation based on lessons learned obtained in that operation. Technology maturation and 3D-printing technology realized those under the same weight and size limitation as MIPS.

System Design

First improvement of MIPS-A from MIPS and I-COUPS is independent flow supplies to the ion source and the neutralizer. MIPS and I-COUPS had one controlled flow line and it were passively separated to the ion source and neutralizer using a difference of orifice gas conductance. It means that increasing the flow rate to the neutralizer is always accompanied with increasing the flow rate to the ion source, and vice versa. In the 223-hours in-flight operation of I-COUPS, problem arising at the neutralizer was fixed by increasing the flow rate to much higher level than the nominal value. However, that high flow rate finally led to a fatal anomaly of the ion source and it limited the operating time to 223 hours. Mass and volume increase by the independent flow control was almost compensated by introducing 3D-printing technology to the low pressure tank where pressure was regulated around 10 kPa.

Second improvement was to install another identical ion thruster for redundancy. The mass of the ion thruster was 2% of the total system mass, and installation of additional thruster has low impact to the system. In contrast to the thruster, adding power supplies had non-negligible impact to the system. Two high-voltage switches and two microwave switches are introduced to preserve the power supply configuration, which means that only one thruster can be operated at a time.

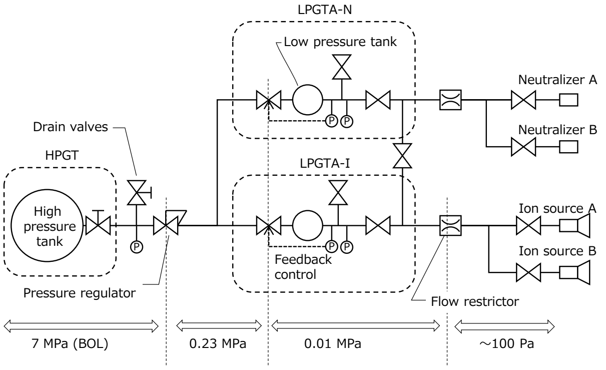


Figure 7: System diagram of xenon feeding system.

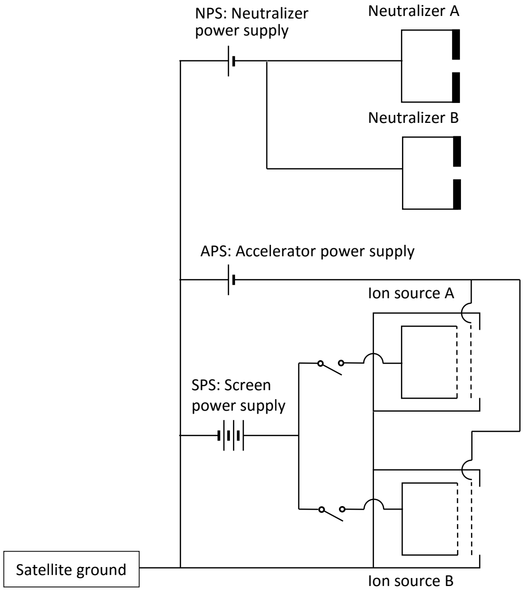


Figure 8: Electrical connections and switching of high voltages.

Figure 7 shows the gas feeding system and Figure 8 shows the high voltage connections. This feeding system and two set thrusters enable twelve types of operation in total, which are summarized in Table 2. Operation of #1 – 4 uses nominal gas feeding and difference is the combination of the ion source and neutralizer. It will be used when trouble occurs at one of the ion sources and neutralizers. Operations of #5 – 12 are for flow control anomaly where only one side LPGT is used and the flow is split by using the ladder valve. The system has much higher flexibility by the two improvements than the MIPS and I-COUPS.

Table 2: Combinations of the ion thruster operation.

#	Ion source	Ion flow cont.	Neutralizer	Neut. flow cont.
1	Ion-A	LPGT-I	Nuet.-A	LPGT-N
2	Ion-A	LPGT-I	Nuet.-B	LPGT-N
3	Ion-B	LPGT-I	Nuet.-A	LPGT-N
4	Ion-B	LPGT-I	Nuet.-B	LPGT-N
5	Ion-A	LPGT-I	Nuet.-A	LPGT-I
6	Ion-A	LPGT-I	Nuet.-B	LPGT-I
7	Ion-B	LPGT-I	Nuet.-A	LPGT-I
8	Ion-B	LPGT-I	Nuet.-B	LPGT-I
9	Ion-A	LPGT-N	Nuet.-A	LPGT-N
10	Ion-A	LPGT-N	Nuet.-B	LPGT-N
11	Ion-B	LPGT-N	Nuet.-A	LPGT-N
12	Ion-B	LPGT-N	Nuet.-B	LPGT-N

Estimated Performance and Schedule

There is no modification at the ion thruster, and expected performance of the ion propulsion system is similar with the MIPS and I-COUPS. Slight difference is caused by the microwave power setting and Xenon loading pressure. The estimated specifications are shown in

Table 3: Estimated specifications of the miniature ion propulsion system.

Volume (thruster)	$37 \times 26 \times 16$ mm^3
Mass (tank & feeding)	9 kg (TBD) including Xe 1.25 kg
Power consumption	35 W (TBD)
Thrust	> 300 μN
Specific impulse	> 900 s

LASER IGNITED SOLID THRUSTER

Overview

The catcher satellite Boy will be equipped with thirty solid microthrusters. Those thruster will be to decelerate BOY and the space debris at the final phase of ADRAS-1 mission. This maneuver requires short time and high thrust using simple and compact structure applicable to the BOY. The single solid thruster has 421 g wet mass and contains 125 g solid propellant with specific impulse of 195 s. As a result, expected total impulse is 7.14 kNs by total 12.6 kg propulsion system. The each thruster will be sequentially ignited, one by one, for precise and secured de-orbit control. The ignition is performed by laser ignition system installed on each thruster.

Key features of the solid microthruster are laser ignition and stack of small propellants. Laser beam ignition enables a safety system blocking the laser beam by a mechanical shutter made of thin film. Light weight and compactness of the thin film can drastically miniaturize the safety system compared with conventional system which inserts mechanical cut of ignition heater line. Actually, light-weight and compact laser ignition system has been already developed and used for a cubesat, Kiseki, where the ignition system weights just a few grams. Hence, this laser ignition system had heritage to be installed and launched, although the Kiseki cubesat had fatal error as to its OBC software on orbit and could not verify the ignition system in space. Additionally, laser ignition realize short-time, high-probability ignition due to its high power intensity.

Another feature of the thruster is to stack and cluster tiny propellant pellets. This method enables to adjust the thruster impulse without fabricating a new design/size propellant, which is suitable for small satellites, since, in general, fabrication of a new propellant needs a lot of legal efforts and production cost. The pellet used in this thruster is boron potassium nitrate (B/KNO_3) with diameter of 10 mm, height of 6.3 mm, and mass of 920 mg. In ADRAS-1 mission, the number of pellets are 140 by 20 stacking and 7 clustering.

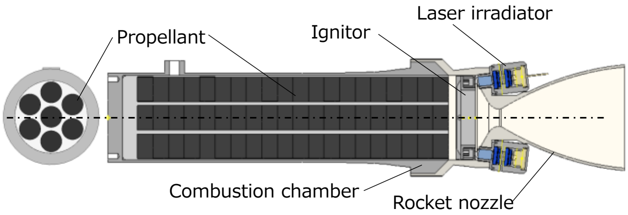
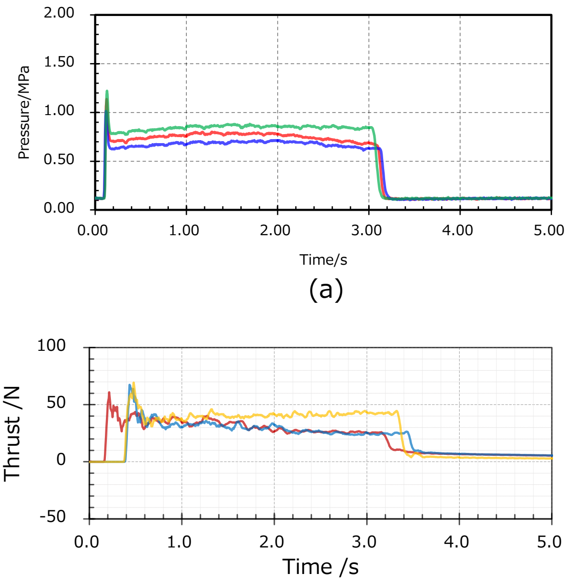


Figure 9: schematic of the laser ignited solid microthruster

System Design

The solid thruster consists of combustion chamber, rocket nozzle, main propellant, ignition cartridge, and two laser ignition devices. Figure 9 shows the schematic of the solid thruster. The combustion chamber and rocket nozzle were made of stainless steel in BBM tests, and it will be changed to titanium in the EM and FM. The main propellant is stacking of 140 pellets in 20 layers and 7 rods as shown in Figure 9. Gap between 7 rods and the chamber was filled by silicone resin, called as filler. The filler also has a function of an ablator to guard the combustion chamber. On the other hand, the rocket nozzle has no cooling system, and metal wall is eroded during the combustion. The ignition cartridge contains smaller pellets of 30 mg each, which were originally installed in the Kiseki cubesat. Those 30 mg pellets are directly irradiated by laser beam and ignited prior to the main propellant. Its combustion gas ignites the main propellant. Each thruster has two sets of laser ignition devices for redundancy on the rocket nozzle. Details of the laser ignition system is shown in the reference [2].



(a)

(b)

Figure 10: Results of the BBM thrusters loading 98 pellets at three different tests; (a) pressure of the combustion chamber and (b) thrust measured by a load cell.

Estimated performance

The development began from combustion tests of BBM thrusters in which the number of stacking pellets can be changed. All the combustion test were carried in a vacuum chamber with inner diameter of 30 cm and length of 200 cm. Background pressure was 50 Pa before the combustion test and it monotonically increased during the combustion (all vacuum valves are closed). Figure 10 (a) shows time histories of the combustion chamber loading 98 pellets at three different tests. The pressure was maintained around the designed 0.6 – 0.7 MPa. In this tests, thrusts were simultaneously measured by using a load cell on which the thruster was attached. Time histories of the measured thrusts are shown in Figure 10 (b). Thrusts measured in this ground tests are affected by change of the background pressure which will not occur in space operation. This effect becomes difficult when flow separation occurred about 0.5 s after ignition. Therefore we obtained actual thrust coefficient from the initial data of pressure and thrust histories in combustion and estimated the thruster performance in space by using the pressure histories and the coefficient.

Table 4: Estimated specifications of the laser ignited solid microthruster.

30-thrusters cluster		
	Total impulse	7.14 kNs *
	Total weight	12.63 kg
Single thruster		
	Volume	∅4.7 cm × 20.9 cm
	Wet mass	421 g
	Power consumption	6 W for laser ignition
	Impulse	238 Ns *
	Specific impulse	195 s *
	Averaged thrust	61.9 N *
	Combustion time	3.8 s *

* based on BBM results

Performance of an EM/FM solid thruster is estimated based on the BBM thruster tests as shown in Table 4. Total mass of the solid thruster is 400 g including the two sets of laser ignition devices which includes diode lasers, focusing lenses, and SADs. Most of the dry mas of the system is occupied by the combustion chambers and rocket nozzles as 208 g. Dry mas fraction of the solid propulsion system is the lowest among the other three propulsion systems, although it is still higher than standard-sized propulsion system. The system needs 6 W power for the laser ignition by 5 V and 1.2 A. The combustion typically starts 0.1 s after the laser beam irradiation. The mass shown in Table 4 does not include the power processing and switching unit for this laser power.

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