Development of Commercially-Available Electrothermal Pulsed PlasmaThruster Systems for Micro/Nano-Satellites at Osaka Institute of Technology

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Abstract: In the Project of Osaka Institute of Technology (OIT) Electric-Rocket-Engine onboard Small Space Ship (PROITERES) was started in 2007. In PROITERES, a nano-satellite with electrothermal pulsed plasma thrusters (PPTs) was successfully launched by the Indian PSLV C-21 launcher on September 9th, 2012. Currently, the 2nd PROITERES nano-satellite has been developed since 2010. The 2nd PROITERES nano-satellite with high-power electrothermal pulsed plasma thrusters (PPTs) for orbit changing of 50-100 km in altitude on near-earth orbit was determined to be launched as piggyback payloads (main satellites: GOSAT-2 and Khalifasat) by H-IIA rocket from JAXA Tanegashima Space Center on July in 2018. The PPT system is consisted of Multi-Discharge-Room type PPT (MDR-PPT) head, Power Processing Unit (PPU) and capacitors. The PPT system is going to be marketed for micro/nano-satellites all over the world at OIT. This PPT system is possible to provide a total impulse of 5.0-10^5 Ns according to various main missions by changing the number of PPT single head and charging energy.

I.Introduction

In recent years, number of utilization and plan for micro/nano-satellites of less than 100 kg with small propulsion system have increased year by year. The University of Tokyo developed a small propulsion system named as I-COUPS (Ion Thruster and COld-gas Thruster Unified Propulsion System). This system has integrated an ion thruster

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and cold-gas thrusters by sharing the same gas system, the small deep space explorer PROCYON was equipped the I-COUPS. The PROCYON developed by the University of Tokyo and Japan Aerospace Exploration Agency, was successfully launched on December 3rd, 2014. The mission is to change an orbital altitude (orbital transfer). This mission can be applied collision-prevention by space debris and deep space exploration[1,2].

The 3U CubeSat (STRaND-1) of Surrey Satellite Technology Limited (SSTL) that was equipped eight micro Pulsed Plasma Thrusters (μPPTs) was successfully launched on 2013[3]. The PPT used PTFE (polytetrafluoroethylene: Teflon®) of a solid propellant, and the PPT is a repetitively-pulsed-operation electric thruster. Also, the PPT is consisted of two electrodes, the solid propellant, an ignitor, capacitors and power supply systems for ignition and main discharges. The PPT has some features superior to other electric thruster. It doesn't need to have sealing parts, simple structure and high reliability, which are benefits by using the solid propellant, mainly the PTFE. The PPT systems have advantages of miniaturization and lightweight and low power operation micro/nano-satellites[4-7]. Therefore, the PPT was applied to micro/nano-satellite.

The PPTs have been equipped on over 15 spacecraft and have achievements. The comparison of PPT specification is presented in Table 1[8-10]. The LES 8/9, the EO-1, and the FalconSat-3 are satellites with PPT. The PPTCUP is developing and selling by Mars Space Ltd (MSL), Clyde Space Ltd (CSL), and University of Southampton (UoS). The MPACS is developing and selling by Busek Co. Inc. The representative PPT is an electromagnetic-acceleration-type with electrode geometry of parallel shape because it is boast high specific impulse, as shown in Figure 1. However, as Table 1 indicated thrust cost at 10-20 μNs/W and thrust efficiency at 1-13%. Recent trends of the mission for micro/nano-satellite, plan and space demonstration about a mission of orbital transfer is increasing[1]. Furthermore, small propulsion for high thrust cost and thrust efficiency will be required. An electrothermal-acceleration-type with electrode geometry of coaxial shape can be generated high thrust cost and thrust efficiency, has actively been increasing research[11-14], as shown in Figure 2.

The Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES) was started at Osaka Institute of Technology in 2007. In 1st PROITERES satellite, a nano-satellite with electrothermal-acceleration-type Pulsed Plasma Thrusters (PPTs) was successfully launched in 2012. The main mission is to change an orbital transfer of 1 km as powered-flight by PPT systems[15-17].Currently, the 2nd PROITERES nano-satellite has been developed since 2010[18-21]. The 2nd PROITERES nano-satellite with high-power electrothermal PPTs for orbit changing of 50-100 km in altitude on near-earth orbit was determined to be launched as piggyback payloads (main satellites: GOSAT-2 and Khalifasat) by H-IIA rocket from JAXA Tanegashima Space Center on July in 2018. Succeeding this mission will be able to take measures against space debris using PPT in the future. And it will lead to higher performance of mission in micro/nano-satellites. Therefore, Osaka Institute of Technology will sell PPT for micro/nano-satellite.

Table 1. The comparison of PPT specifications.

	LES 8/9, 1975	EO-1, 2000	PPTCUP/MSL, CSL, UoS	FalconSat-3, 2007 MPACS/Busek Co. Inc.
Electrode geometry	Parallel type	Parallel type	Parallel type	Coaxial type
Capacitor energy, J	20-80	8.5-56	2	1.96
Specific impulse, s	1000-1450	650-1400	600	827
Thrust cost, μNs/W	15-19	10.7-11	20	40.8
Thrust efficiency, %	7-13	3.4-7.6	6	8.4

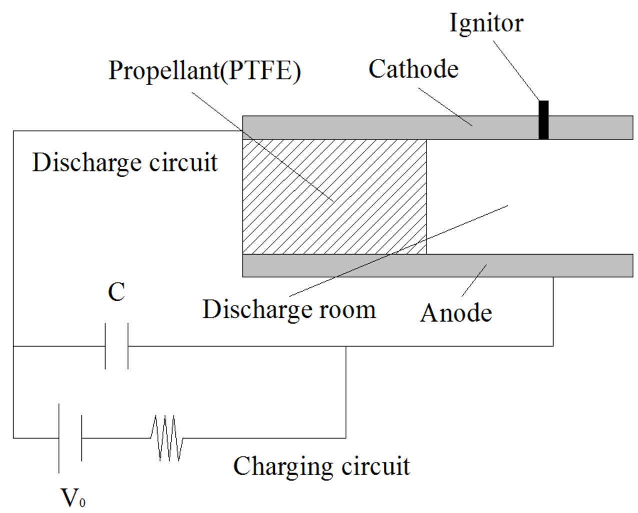


Figure 1. Electromagnetic-acceleration-type pulsed plasma thruster.

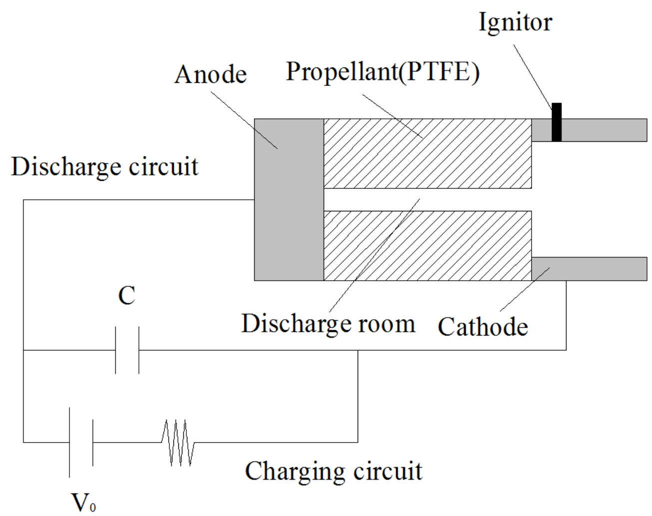


Figure 2. Electrothermal-acceleration-type pulsed plasma thruster.

II.PROITERES

At Osaka Institute of Technology, the PROITERES project started in 2007. The purpose of this project is to develop and produce a small satellite equipped with an electric propulsion device developed at our university, and conduct a demonstration test in outer space.

A. 1st PROITERES

The 1st PROITERES nano-satellite with electrothermal PPT was successfully launched on a Sun-synchronous orbit of 660 km in earth altitude by PSLV C-21 launcher at Satish Dhawa Space Center (SDSC), Indian Space Research Organization (ISRO) on September 9th in 2012. The photograph of the satellite's flight model (FM) is shown in Figure 3. The specification is shown in Table 2. The main mission of the satellite is to achieve orbital powered flight of 1 km in altitude by electrothermal PPTs and to observe Kansai district in Japan with a high-resolution camera.

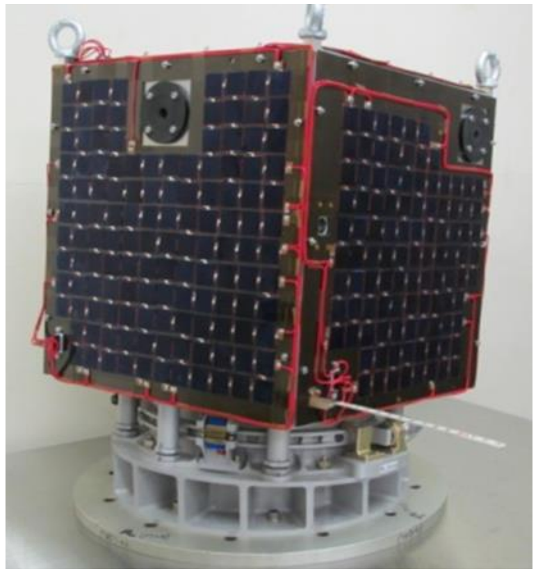


Figure 3. Photo of 1st PROITERES satellite.

Table 2. Specification of 1st PROITERES satellite.

Mass, kg	14.5
Size, mm	Cube, 290mm on a side
Electrical power, W	10
Altitude, km	660

The PPTs onboard the 1st PROITERES nano-satellite have achieved the total impulse of 5.4 Ns with repetitive 50,000 shots operation at an input energy of 2.43 J/shot and an operational frequency of 1.0 Hz in ground tests, as shown in Figure 4. The FM of the PPT head is shown in Figure 5. The Power Processing Unit (PPU) for the PPT system was specially developed by OIT and High Serve Inc.

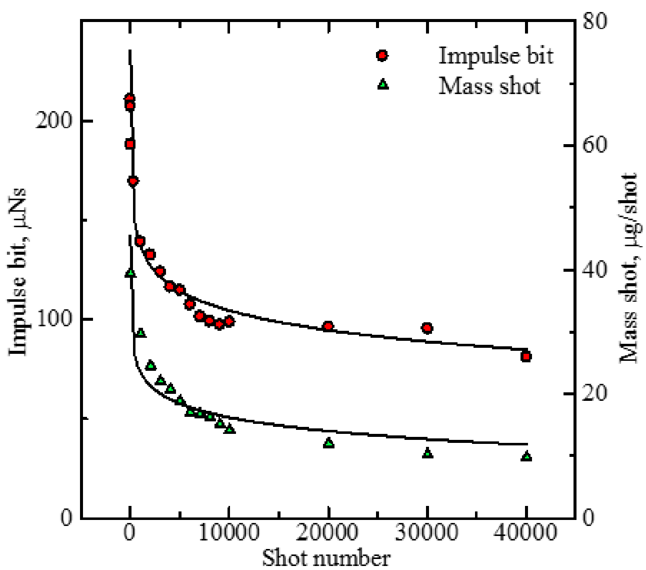
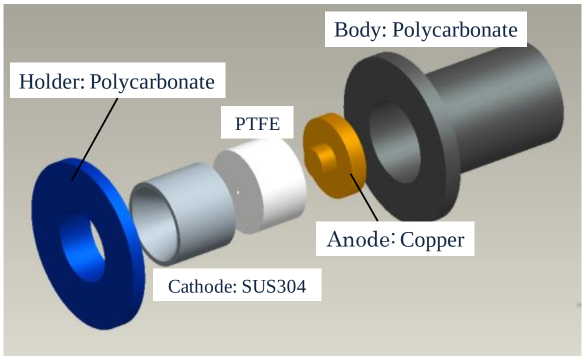
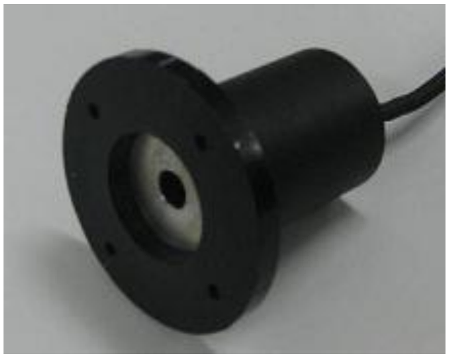


Figure 4. History of impulse bit and mass shot with PPTs onboard 1st PREOITERES nano-satellite.





(a) Structure. **(b) Overview.**

Figure 5. PPT head FM of 1st PROITERES satellite.

B. 2nd PROITERES

The development of the 2nd PROITERES nano-satellite was started in 2010. An illustration and the specification of the satellite is shown in Figure 6 and Table 3. This satellite aims to achieve longer flight than the one of the 1st PROITERES nano-satellite, i.e. changing an orbital altitude from 50 to 100 km propelled by a high-power PPT system and demonstrating a reaction wheel which was developed for micro/nano-satellites. For this mission the PPT system is required to achieve a higher total impulse than the one onboard the 1st PROITERES nano-satellite. To improve thrust performance, the input energy of the PPT system was increased from 2.43 to 31.59 J. Additionally, to achieve the higher total impulse for 2nd PROITERES nano-satellite, the structure of the PPT system was improved to increase the propellant utilization rate.

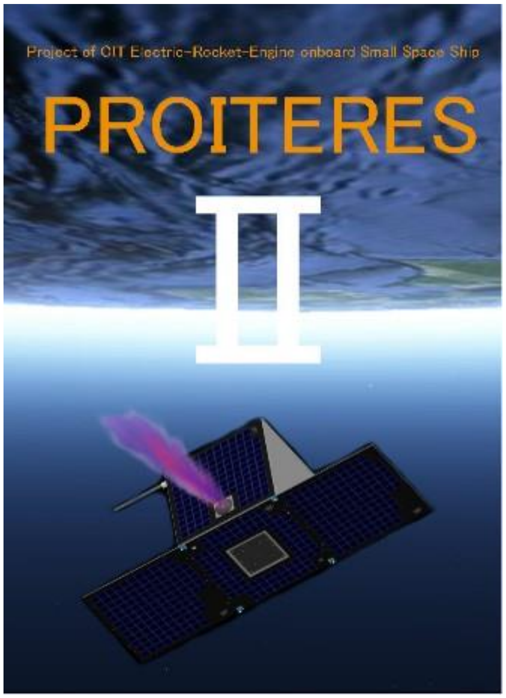


Figure 6. Image of 2nd PROITERES satellite.

Table 3. Specification of 2nd PROITERES satellite.

Mass, kg	45
Size, mm	470 x 470 x 450
Electrical power, W	60
Altitude, km	613

III.PPT system

As a constitution of PPT system, it is necessary to be able to deal with arbitrary satellites and arbitrary missions. For that purpose, we will commercialize PPT system as an independent part and device. The key components of PPT system are PPT head, PPU and capacitors.

A. Capacitors

In the PPT, plasma is generated by using the energy stored in the capacitor, and thrust is generated. It is one of the parameters that depends most on propulsive performance. The mica paper capacitors (CMP92B202155K-02, SOSHIN ELECTRIC Co., LTD.) is shown in the Figure 7. The input energy of the PPT system was enlarged from 2.43 to 31.59 J by connecting 13 sheets of mica paper capacitors having the specifications shown in Table 4 in parallel.

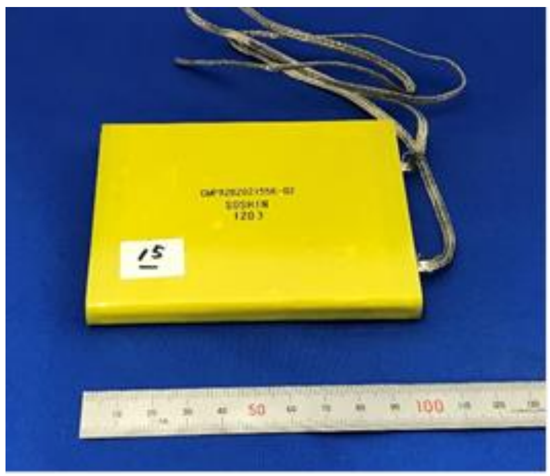


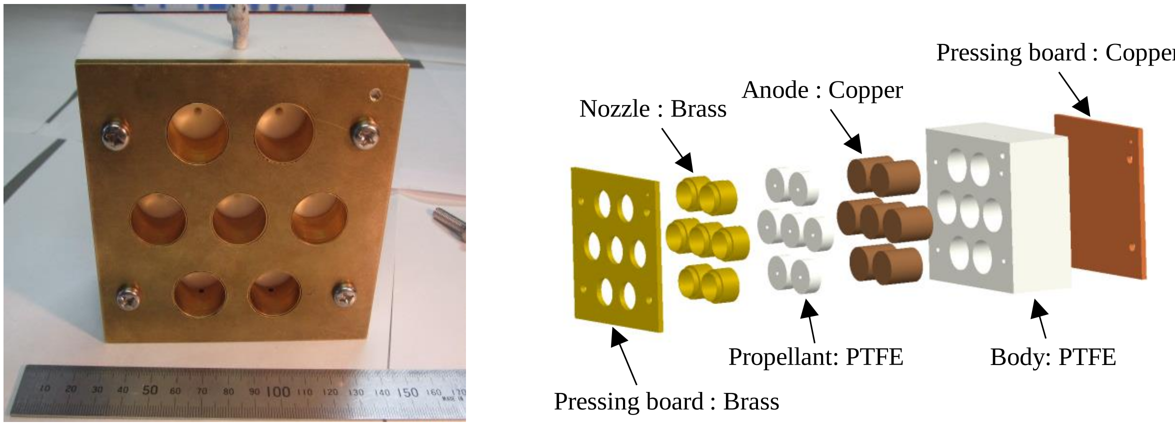
Figure 7. Mica paper capacitor.

Table 4. Specification of capacitor.

Capacitance, µF	1.5
Inductance, nH	30
Withstand voltage, V	2,000
Mass, g	180
Size, mm	102 x 81 x 10

B. MDR-PPT head

The MDR-PPT head, as shown in Figure 8, can provide total impulse according to the mission by changing the number of discharge room. Also, there is no mechanical drive to supply the propellant. Integration of the main body and the propellant is advantageous in terms of reliability of the entire system and reduction in size and weight. However, due to the structure, in the discharge room which does not pass through the center of gravity of the satellite, it generates running torque by operation. Therefore, an igniter was attached to each discharge room, and according to the instruction of OBC, it was made possible to alternately jet in the discharge rooms which exist on the diagonal line. By this operation, the generated running torque can be minimized.



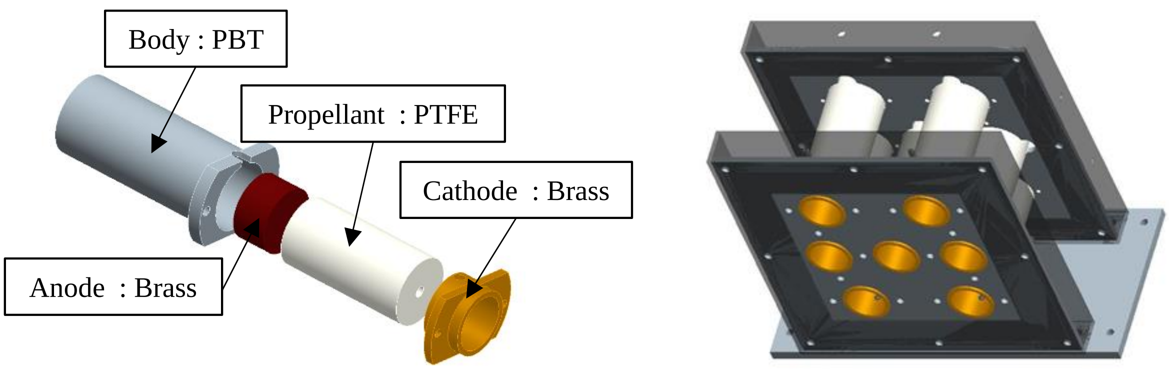
(a) Overview. **(b) Structure.**

Figure 8. MDR-PPT head.

However, there were the following problems in the MDR-PPT head[22,23].

1) The thruster head has lots of part which are not effective as a thruster system due to their high weights.
2) Ignitor configuration for main discharge are non-uniform because of student manufacture in our institute.
3) The attachment of the ignitors in the nozzles with PTFE tape is not reliable.
4) The base plate and the installation jig for the satellite have not been designed.
5) The electric circuit of the MDR-PPT system has two points of groundings, i.e., cathode pressing board and cathode part of capacitors.

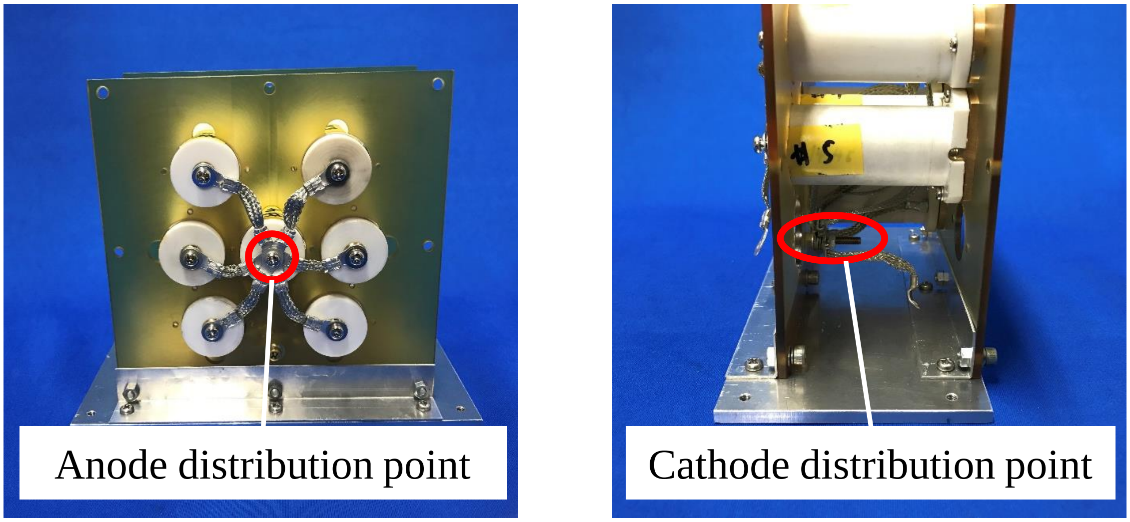
Therefore, the MDR-PPT head was newly designed, as shown in Figure 9, for solving the above problems.



(a) Structure of single head for 3rd MDR-PPT. **(b) Overview of assembly.**

Figure 9. 3D model of new MDR-PPT head.

In the structure of MDR-PPT head so far, a number of discharge rooms are provided in the body of one PPT head. In contrast, the new MDR-PPT head consists of seven single-PPT heads equipped with cathodes, anodes and propellants. And it is a structure to fix with front and rear panels. The anodes have male screws shape and is screwed into female screws portion provided in the bodies. Thereby, even if there are no front and rear panels, it can be autonomous as one PPT head. That is, it is possible to fix the positional relationship of each part and to make the airtightness of the discharge room uniform, thereby improving the reliability. Furthermore, an aluminum frame was attached to ensure strength. The single-PPTs can be operated as a single unit by connecting electric wires. The front panel and the rear panel were changed from conductive materials to poly-Ether-Imide (PEI). PEI is excellent in heat resistance (continuous use temperature 170 °C) and excellent in radiation resistance. The front and rear panels are structures for fixing the PPT heads, not the electric paths. Electric wires are used to secure electrical paths. The wiring of the new MDR-PPT head is shown in the Figure 10.



(a) On the anode side. **(b) On the cathode side.**

Figure 10. Wiring of the new MDR-PPT head.

The front and rear panels were attached to an aluminum base plate. This base plate is fixed to the structure of the satellites. Although not attached to the photograph in the Figure 10, a copper cylinder will be attached to the body of each PPT head as electromagnetic interference (EMI) filters. Therefore, EMI generated by the main discharge during PPT operation is reduced. In addition, the structure of the new igniters is covered with a stainless steel pipe screwing the core electrode rod and the insulator. This structure made it possible to screw connection the cathode of the PPT head and the igniter.

C. PPU

To work and control the MDR-PPT of the 2nd PROITERES nano-satellite in space, a compact and lightweight power supply device is necessary. Also, since the PPU is linked with the MDR-PPT head, the discharge rooms must be selectable separately. Therefore, a PPU was designed at OIT and High Serve Inc. The PPU and its' specifications are shown in Figure 11 and Table 5. The PPU is controlled by an On Board Computer (OBC) in space.

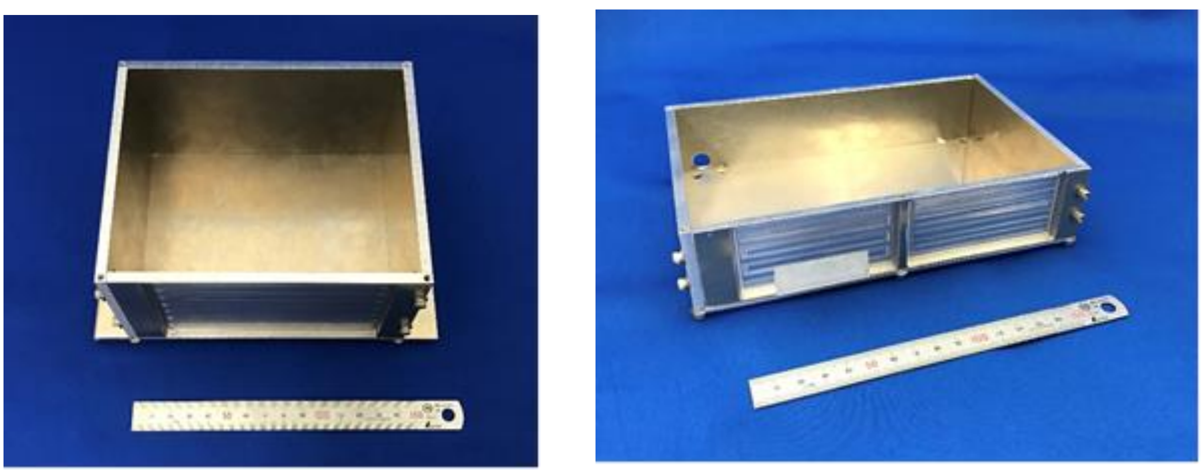
Figure 11. PPU for MDR-PPT system.

Table 5. Specification of PPU for MDR-PPT system.

Mass, g		500
Size, mm		120 x 185 x 40
Power consumption, W		30
Input voltage, V		DC 28
Charge time, s		< 1.5
Output voltage, kV	to CAP	1.8
	to Ignitor	3.0

D. MDR-PPT System

The PPT system is consisted of MDR-PPT head, PPU and capacitors. Therefore, a housing of PPU and capacitors are required[24]. The housing was designed newly as shown in Figure 12. The PPT system is shown in the figure, and the size of the PPT system is shown in the table. An aluminum plate (A5052) is used for the housing, and the wall surface is thin so as to reduce the weight. The capacitor and the MDR-PPT head were placed as close as possible to reduce energy loss due to the resistance of the circuit cable. The placement of each device was determined taking into account the position of the center of gravity of the satellite when it was mounted on the satellite main body. The MDR-PPT system is shown in the Figure 13 and the size of each device is shown in the Table 6. The single-PPT can operate over 100,000 shots. However, the carbon contained in the propellant adheres to the discharge room surface, short-circuits the electrodes, and spontaneously starts or stops operation. Each single-PPT of MDR-PPT head is gathered with the same electrode by a cable. Therefore, there is a possibility that operation stops if single-PPT is short-circuited with even one. Therefore, single-PPT of MDR-PPT system at the 2nd PROITERES nano-satellite is stopped by operation of maximum 80,000 shots and operated so as not to short circuit. Total impulse at 80,000 shots is about 81 Ns, as shown in Figure 14. That is, when MDR-PPT with seven discharge rooms is used, a total impulse of about 567 Ns can be expected. And the PPT system can achieve a powered flight of approximately 23 km, if a 50 kg nano-satellite is equipped with the PPT system. In the future we will be able to fire single-PPT to the maximum and we will consider a mechanism to switch the discharge rooms so as not to short - circuit.



(a) Capacitor box. **(b) PPU box.**

Figure 12. Overview of Housing.

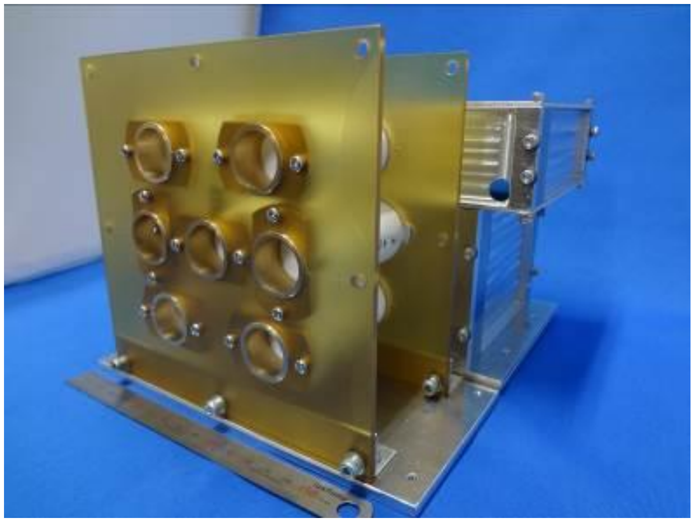


Figure 13. MDR-PPT system.

Table 6. Specification of capacitor.

PPT system, mm	244 x 235 x 153
MDR-PPT head, mm	244 x 93 x 153
PPU-BOX, mm	244 x 142 x 46
Capacitor-BOX, mm	202 x 142 x 89

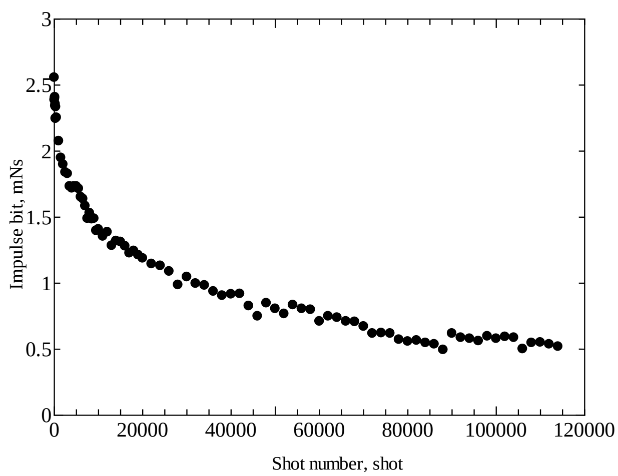


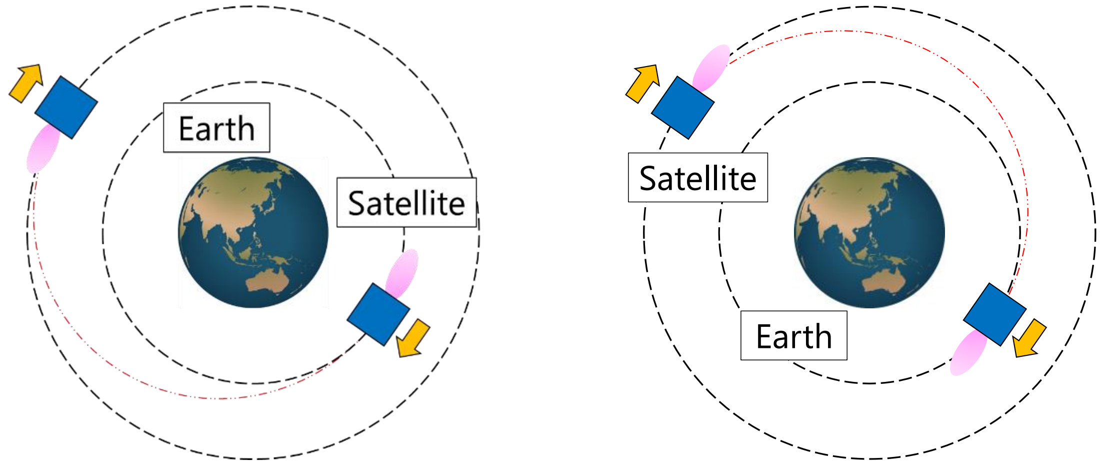
Figure 14. Impulse bit vs. shot number characteristics.

The MDR-PPT head, PPU, and capacitor are self-supporting, respectively. By further reducing these size and weight in the future, the range of satellites that can be equipped will be expanded. The PPT system can change the number of single-PPT heads and charging energy. It is possible to provide a total impulse of 5 to 10^5 Ns according to various missions.

IV.Operation method by MDR-PPT system

We propose future MDR-PPT system operation method.

Micro/nano-satellites often become piggyback payloads. Therefore, the satellite's orbit and orbital altitude is limited by the main satellite. By using MDR - PPT, the satellite gains velocity increment. The micro/nano-satellites can change the orbit altitude, as shown in Figure 15. Also, by firing MDR-PPT in the direction of movement of the satellite, it also helps to lower the speed and altitude and prevent the satellite itself from becoming space debris. By using MDR-PPT like this, micro/nano-satellites can fly freely in outer space like drone.



(a) Orbit ascent. **(b) Orbit descent.**

Figure 15. Image of change the orbit altitude.

In recent years, researchers are taken interest in micro/nano-satellites by cutting launching cost and shortening development period. Therefore, micro/nano-satellites around the earth have increased year by year. However, there is a problem which is often causing collisions among living satellites and space debris. Therefore, we propose deorbiting space debris. The principle of deorbiting space debris, as shown in Figure 16, is exposure of thruster plume to space debris by the MDR-PPT. That is, reaction impulse is given to debris, and after that debris decreases velocity and deorbits. Accordingly, by using MDR-PPT system, micro/nano-satellites can deorbit space debris with safety without contacting to space debris. It is thought that a very meaningful mission can be established in the future nanosatellite. This MDR-PPT system is going to be marketed at Osaka Institute of Technology.

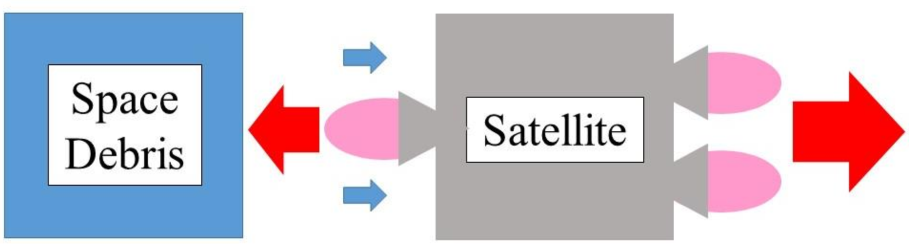


Figure 16. Image of deorbiting space debris.

V.Conclusion

The Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES) was started at Osaka Institute of Technology in 2007.

1) The 1st PROITERES nano-satellite with electrothermal PPT was successfully launched on September 9th in 2012.
2) The 2nd PROITERES nano-satellite with high-power electrothermal PPTs for orbit changing of 50-100 km in altitude on near-earth orbit was determined to be launched as piggyback payloads (main satellites: GOSAT-2 and Khalifasat) by H-IIA rocket from JAXA Tanegashima Space Center on July in 2018.
3) To achieve a longer lifetime, the MDR-PPT system was designed at OIT. The MDR-PPT system is consisted of MDR-PPT head, PPU and capacitors. The MDR-PPT has seven Single-PPTs and the Single-PPTs are fixed to two PEI board. The MDR-PPT design is compact and lightweight.
4) A capacitor and a PPU box were developed to load the capacitors and the PPU into the nano-satellite.

5) The MDR-PPT system can change the number of single-PPT heads and charging energy. It is possible to provide a total impulse of 5 to 10^3 Ns according to various missions.

The PPT system is going to be marketed for micro/nano-satellites all over the world at OIT. This PPT system is possible to provide a total impulse of 5.0-10^5 Ns according to various main missions by changing the number of PPT single head and charging energy.

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