Debris Engine: A Potential Thruster for Space Debris Removal

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Abstract: We present a design concept for a space engine that can continuously remove the orbit debris by using the debris as a propellant. Space robotic cleaner is adopted to capture the targeting debris and to transfer them into the engine. Debris with larger size is first disintegrated into small pieces by using a mechanical method. The planetary ball mill is then adopted to grind the pieces into micrometer or smaller powder. The energy needed in this process is get from the nuclear and solar power. By the effect of gamma-ray photoelectric or the behavior of tangently rub of tungsten needles, the debris powered is charged. This behavior can be used to speed up the movement of powder in a tandem electrostatic particle accelerator. By ejecting the high-temperture and high-pressure charged powered from the nozzle of the engine,the continuously thrust is obtained. This thrust can be used to perform orbital maneuver and debris rendezvous for the spacecraft and robotic cleaner. The ejected charged particle will be blown away from the circumterrestrial orbit by the solar wind. By digesting the space debris, we obtain not only the previous thrust but also the clean space. In the near future, start trek will not just a dream, human exploration will extend to deep universe. The analysis shown, the magnitude of the specific impulse for debris engine is determined by the accelerating electrostatic potential and the charge-to-mass ratio of the powder.

Key words: space debris engine, electrostatic particle accelerator, removal, thrust

I. Introduction

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Space debris is the by-product of human activities in the space which includes defunct rockets and satellites, ejection from the rockets and spacecraft, the waste of manned space mission and the products of the collision from other debris[1]. The first artificial satellite were launched in 1957[2]. Now, more and more satellites come into service, but the threat to in-orbit satellites coming from more and more space debris have been grimmer this year. As all knows, the 2009 smash between the Iridium 33 satellite of USA and the Kosmos 2251 satellite of Russia is an extreme case[3]. From the recent research, the collision probability between satellite and debris will find a sharp increase which would causes chain reactions disastrously in the next decade or another decade.

The size of space debris is distributed in seven orders of magnitude between micrometer and meter. They exist in the orbits whose altitude vary from 300km to 36000km, and the quantity reaches its peak in region from 800km to 1100km[4]. These debris run in their own speed from 3km/s to 7km/s.[5] Relative velocity between satellites and debris vary from 0 to 15km/s. Now, the number of debris larger than 10cm is more than 15000. Satellites can avoid crash by maneuvering actively.[6] The number of debris smaller than 1cm is more than one million. Although a great deal of debris are in this size, their kinetic energy is small and satellite can avoid damages by structure protection.[7] The number of debris whose size between 1cm and 10cm is about 100 thousand and it is enough to cause big damage to satellite in this size.[8] So they are supposed to be removed for the safety of artificial satellite.

According to Opiela's research, which is estimated by combining three sources of data: available pre-launch information about satellite materials, ground-based satellite breakup experiments, and chemical compositions of residuals collected from returned remains, 74% (by number) of the breakup debris is from rocket bodies and 26% is from payloads[9]. For spacecraft breakup debris, it has been found that the range of material densities can be simplified into three representative values: high density, medium density, and low density. The typical material of each density group is plastic ($1.4\mathrm{g/cc}$), aluminum ($2.8\mathrm{g/cc}$), and steel($8.0\mathrm{g/cc}$), respectively. The current study develops preliminary distributions for breakup debris: rocket body debris is 90% medium-density and 10% high-density (by number); payload debris is 70% low-density, 27% medium, and 3% high-density. Since the low-density fragments may decay from orbit much more quickly than the high-density fragments. So considering all fragment sizes, from the Satellite Orbital Debris Characterization Impact Test, and excepting the low-density fragments, a reasonable estimate is that about 90% of the breakup debris is of medium density, and about 10% is of high density. High-density fragments includes Fe ($7.9\text{g}/\text{cc}$), Ag ($10.5\text{g}/\text{cc}$), Cu ($8.8\text{g}/\text{cc}$), some solder and circuit ($6.4\text{g}/\text{cc}$). Medium- density fragments includes Al ($2.8\text{g}/\text{cc}$), Ti ($4.5\text{g}/\text{cc}$) and some paint ($2.5\text{g}/\text{cc}$). Generally, most of debris consist of medium-density metal, especially aluminum and titanium. So it aims at aluminum alloy as the model debris firstly in the following research in this paper.

However, what have been done now is just trying to slow down the increasing course of debris. For example, NASA and a couple of space institutions are appealing to set a regulation together that every space organizations should make their own used rockets depart from the orbits within 25 years from launching. These initiatives just make that more crowded course slower but does not stop it. According to the research of Liou, even though human beings stopped all space activity from December, 2004, debris are still going to increase because of collision and stripping by themselves[10]. More seriously, debris would increase disastrously from 2055 by preliminary estimations. It is extremely urgent for human to take actions or a worse cost in the future.

At present, major space organizations are monitoring debris constantly with space debris environment model like ORDEM system of NASA and MASTER system of ESA.[11][12][13] But the researches in debris elimination still remains a theoretical target. The way of cost and technical feasibility hasn't been found yet, but researchers put forward many suggests by now as follows[14].

1. Using laser to make debris fall into atmosphere is one tentative idea[15][16]. It can be divided into ground-based laser system and space-based laser system[17]. When high energy laser irradiation forcing on the surface of debris, the surface would vaporize fleetingly and transform into steam mixing with many plasma. The hyperthermal and high-pressure steam sprays back in a round-shape, so the debris gets moderating impulse because of momentum exchange and then fall down.[18] These years, many institution carry out research in laser debris cleaning system like ORION of America and CLEANSPACE of EU typically[19]. For the technical limitation of remote sensing and orbital determination,

laser system applies to debris only in ample size. In addition, it is hard to control the potential small pieces created by laser’s incision, and it is involved with attenuation by atmosphere gases and space safety problem waiting to be solved.

2. Sending cleaning robot into space is another tentative idea. When referring to defunct satellites and other big debris, it is an alternative way that space cleaning robots rendezvous with debris automatically, then catch the target debris and return into the atmosphere. Swiss research institute EPFL has made a deep research in this area. They have being building a spacecraft, which called CleanSpace One[20], which could grab orbital debris utilizing a folding conical net and carry it back to towards Earth, burning up in the atmosphere with it on its way down. When it's launched, possibly as early as 2018, CleanSpace One's first target will be the now-defunct SwissCube satellite. Because the $10\times10\times10cm$ object will likely be spinning, swallowing it in a net should be easier than trying to grab it with a claw. Additionally, however, SwissCube's spinning action will make it more difficult to image, as its surfaces will alternately be brilliantly sunlit or hidden in shadow. That's why CleanSpace One's computer vision system will be running algorithms that account for variables such as the angle of the sun, the dimensions of the target, the speed at which that target is moving, and the rate at which CleanSpace One itself is spinning. High dynamic range cameras will also allow it to simultaneously expose for both bright and dark surfaces. Once SwissCube is within range, CleanSpace One will then extend its net around the satellite, subsequently closing that net back down with the target inside. Obviously, it would be very expensive for space cleaner to pursue, rendezvous with target debris and then return into the atmosphere in the method mentioned above. It would cost a large consumption of fuel for cleaning robot to make orbit maneuver especially non-coplanar.

3. At the same time, Japan Aerospace Exploration Agency (JAXA) researchers are developing an electrodynamic tether designed to generate electricity that will slow down space-based debris. To build its debris-catching net, JAXA brought in Nitto Seimo, a company specializing in fishing equipment.[21] The net is composed of a 700-metre-long mesh of aluminum and steel wires that hangs from an uncrewed spacecraft, and the net is equipped with sensors that look for light reflecting from small pieces of debris and

automatically aligns itself so that it can attract the material. The tether changes its orbit thanks to an electrical current flowing through the wires, which creates an electromagnetic field that attracts the debris and pushes the net away from Earth's geomagnetic field. Once the net has grabbed enough debris it is ordered to slow down and de-orbit, allowing the debris, spacecraft and net to burn up as they enter Earth's atmosphere. JAXA thinks the net's main advantage is its simplicity and its lightweight that doesn't require any propellant to move. However, the test will also explore some possible drawbacks. One concern is that the net will work very slowly, taking several months or even a year to de-orbit. Then there is the risk that the net may run into operational satellites. The engineers also worry that the debris they are fighting could fight back. "There is a possibility of the tether being severed by impacts of small debris objects or micrometeoroids," says a JAXA spokesperson.

4. There is also an idea fantastically, when it comes to debris in small sizes, it is one way that make debris crash and adhere to space cleaner in huge size at random just like sand impact plasticine.[22] The cleaner is supposed to be in spherical or caky shape. However, it is the first thing to ensure the cleaner would not fall into fragments and create new debris when suffering from crash. It could be made of high-strength rubber in huge spherical shape as envisaged to face the debris crash from every direction.

These ideas come to a same core problem how to get the momentum for cleaners maneuver and rendezvousing with the debris, and then return to atmosphere. Huge fuel consumption is the biggest inhibitor to space cleaners' lifetime and makes the mission cost increase sharply. Why don't we just obliterate the debris in the space locally and make full use it, so that fuel used to come back to inner atmosphere can be saved for cleaners.

II. Debris Engine

A. Introduction to VASIMR

Just look back to recent research, the NASA Johnson Space Center (JSC) has been developing a new device named Variable Specific Impulse Magnetoplasma Rocket (VASIMR).[23][24][25] VASIMR is an open-ended, RF-heated, magnetic mirror-like plasma device. The system would provide access to very high and variable thrust and exhaust velocities ($3\times10^4 \sim 3\times10^5$) of interest in fast human and robotic interplanetary propulsion as well as efficient, high payload orbit transfer capability. It is important that in its second coupler, known as the Ion Cyclotron Heating (ICH) section, this section further heats the plasma to temperatures upwards of 1,000,000 kelvin—about 173 times the temperature of the sun's surface.

At that temperature, almost all materials could be transformed into plasma. So in this paper, we would like to make debris take the place of neutral gas (such as argon and xenon) as the propellant. If it works, debris would become ions and electrons being forced steadily into lengthening spiral orbits in order to eject from the engine's magnet nozzle parallel and opposite to the direction of motion, propelling the spacecraft forward, at the same time, turning the waste debris into value. Then charged particle will be blown away constantly from circumterrestrial orbits by solar wind finally. So on the one hand, it removes debris from the orbit. On the other hand, spacecraft aren't supposed to carry a lot of propellant which would cut down cost clearly. More important, it provides a new idea for asteroid exploration and interplanetary flight for its sustainable fuel supplement. There is the detailed introduction about debris engine in the following.

B. Design of debris engine

After the cleaner catch target debris using a claw or a net, it would be the next step that decomposing and grind the debris into powder. Currently, there are also several alternative methods for grinding. Laser can make the surface of debris vaporize and transform into steam fleetingly. But it will be hard to ensure that device itself would never be damaged by laser if debris is resolved in a confined space inside the cleaners. Ultrasonic atomization technology is another method for the production of spherical metal powder.[26][27] But before the atomization process, debris are supposed to be transformed into molten fusion firstly with a great deal of energy consumption. In the dark side of space, debris would suffer in cryogenic and vacuum environment. Then metal like aluminum, titanium and iron will become brittle under the circumstance. So pulverizing the debris mechanically may be the direct and practical way since it doesn't care much about powders' roundness or shape, although fineness is important. The size of powders are supposed to be under 1 um at least.

Taking everything into account, ball mill is a classical but feasible way. (Fig. 1) A ball mill is a type of grinder used to grind and blend materials often used in mineral dressing processes, paints, pyrotechnics, ceramics and selective laser sintering.[28][29] A ball mill works on the principle of impact and attrition: size reduction is done by impact as the balls drop from near the top of the shell. A ball mill consists of a hollow cylindrical shell rotating about its axis. It is partially filled with balls. The grinding media is the balls, which may be made of steel(chrome steel), stainless steel or rubber. The inner surface of the cylindrical shell is usually lined with an abrasion-resistant material such as manganese steel or rubber. The length of the mill is approximately equal to its diameter. Ball milling boasts several advantages over other systems: the cost of installation, power and grinding medium is low; it is suitable for both batch and continuous operation, similarly it is suitable for open as well as closed circuit grinding and is applicable for materials of all degrees of hardness.

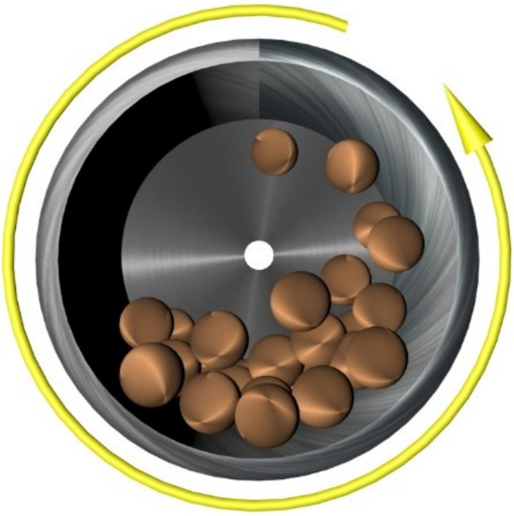

Fig. 1 Common ball mill

Aside from common ball mills there is a second type of ball mill called a planetary ball mill.[30][31] (Fig. 2) Planetary ball mills are smaller than common ball mills and mainly used in laboratories for grinding sample material down to very small sizes. A planetary ball mill consists of at least one grinding jar which is arranged eccentrically on a so-called sun wheel. The direction of movement of the sun wheel is opposite to that of the grinding jars (ratio: 1:2 or 1:1 or else). The grinding balls in the grinding jars are subjected to superimposed rotational movements, the so-called Coriolis forces. The difference in speeds between the balls and grinding jars produces an interaction between frictional and impact forces, which releases high dynamic energies. The interplay between these forces produces the high and very effective degree of size reduction of the planetary ball mill. In the space, there is no acceleration of gravity to improve the grinding. So it will be the effective way to use rapid rotational centrifuge and planetary ball mill to ensure the process. It is worth noting that violent oxidation are supposed to be avoided in the ball mill process.

At the first stage of the project, it will be experimentalized that using debris powder as propellant directly. Powder will get charged taking advantage of gamma-ray photoelectric effect or getting charged tangently by tungsten needles. Then the charged powder would speed up in an electrostatic particle accelerator and ejected from thrust nozzle of engine. A electrostatic particle accelerator is a device that uses electrostatic fields to propel charged particles to high speeds by static high voltage potential.[32] The static high voltage method is contrasted with the dynamic fields used in oscillating field particle accelerators. Owing to their simpler design, historically these accelerators were developed earlier. These machines are operated at lower energy than some larger oscillating field accelerators, and to the extent that the energy regime scales with the cost of these machines, in broad terms these machines are less expensive than higher energy machines, and as such they are much more common.

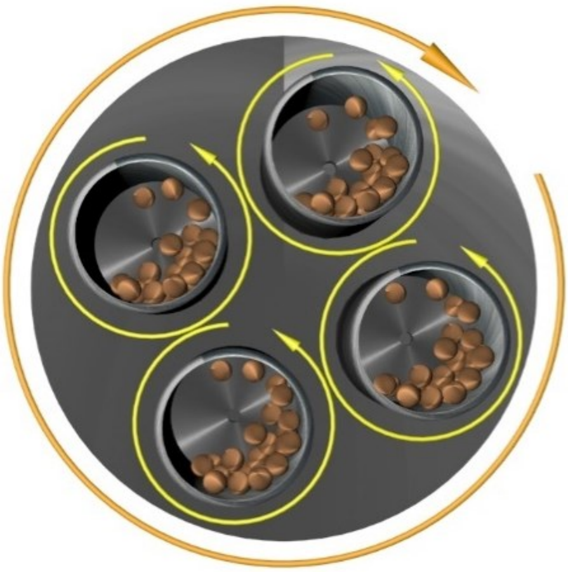

Fig. 2 Planetary ball mill

It is a whole designation of debris engine in Fig. 3. It is mainly composed of preliminary debris disintegrator, ball mill, charging system, tandem electrostatic accelerator. The preliminary disintegrator disintegrates the big space debris into fragments in suitable size.

Then, planetary ball mill grinds the fragments into powder. The powder get charged in the charging system. Then, the charged powder are being accelerated in the tandem electrostatic accelerator and get a high speed. Finally, the charged powder are ejected from thrust nozzle of engine, so the spacecraft get the thrust to move forward to catch next debris and the charged powder are being blown away constantly from circumterrestrial orbits by solar wind. Electrons are released into space near the nozzle so that the spacecraft can remain electric equilibrium.

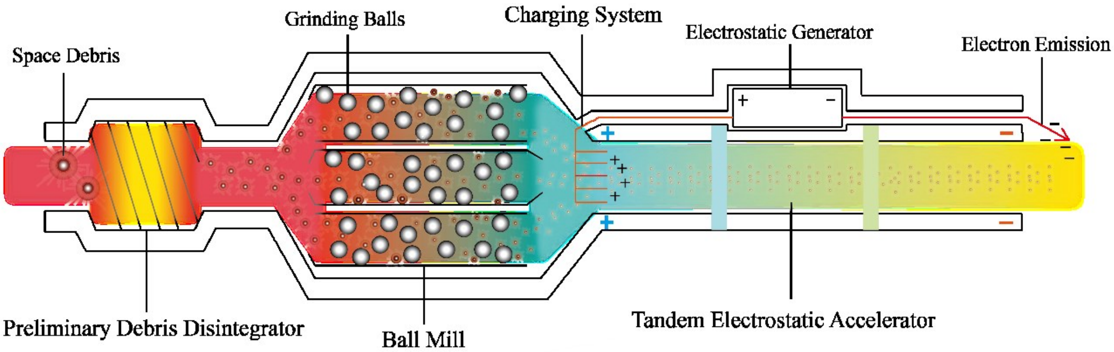

Fig. 3 Debris engine

Powders can get a high speed by tandem electrostatic accelerator with whole electrostatic potential more than 2 million volt. Taking the aluminum into research and assuming that all aluminum alloy powders are tiny metal sphere with a diameter of 1 um. We can get powder's relative velocity away from the spacecraft:

$$v_r = \sqrt{\frac{2qU}{m}} \tag{1}$$

where v_r is the relative velocity away from the nozzle, namely, the jet velocity, and U is the electrostatic potential, $\frac{q}{m}$ means the charge-to-mass ratio. Then:

$$I_{sp} = \frac{v_r}{g_0} = \sqrt{\frac{2qU}{mg_0^2}} \tag{2}$$

where I_{sp} is the specific impulse. As shown in Fig. 4, from the numerical simulation, we get the result:

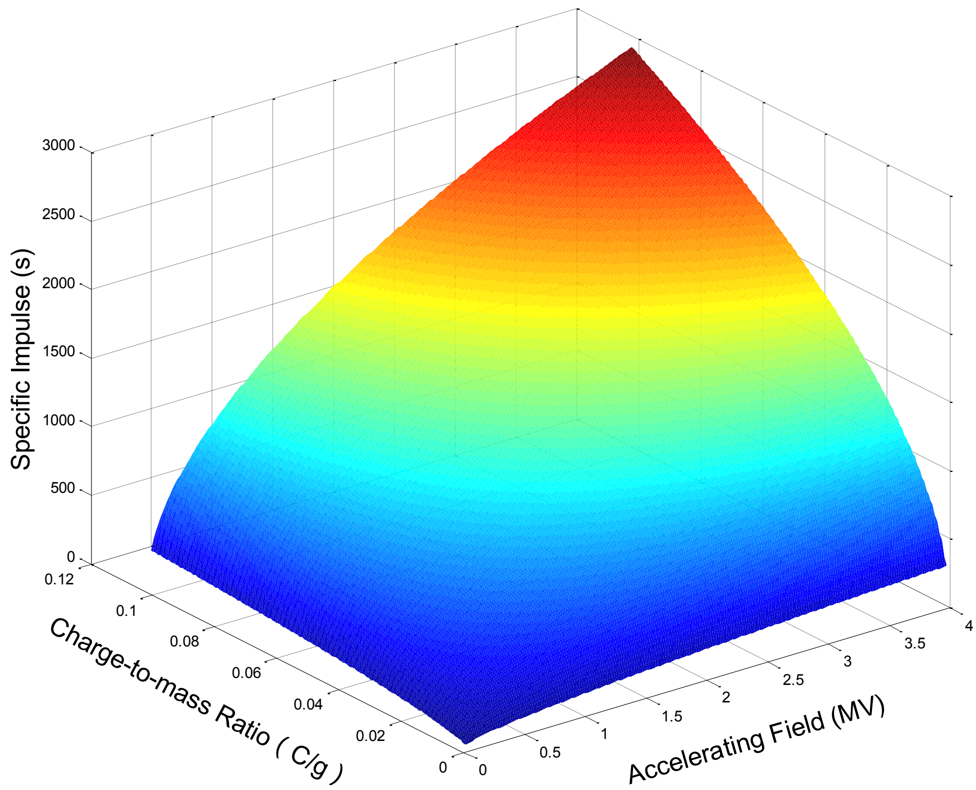

Fig. 4 Specific impulse is relative to charge-to-mass ratio and accelerating field

As it implies, specific impulse is determined by the whole accelerating electrostatic potential and charge-to-mass ratio. Trying to improve specific impulse (Fig. 5), on the one hand, it is supposed to improve electrostatic potential which can be realized by increasing the voltage of every stage of electrostatic accelerator or increasing the stages of electrostatic accelerator; On the other hand, it is supposed to improve the powder's charge-to-mass ratio by improving fineness of powder which can be realized by improving the mill ability and efficiency, or improving the efficiency that powder get charged. In addition, the thrust of engine is relative to mass-flow rate of powder:

$$F = \dot{m}v_r \quad (p_{-} - p_3) A_2 \tag{3}$$

Where F is the thrust of engine; $\dot{m}$ is the mass flow-rate of charged powder at the nozzle of engine; p_2 is the pressure at the nozzle of engine; p_3 is the pressure of outer space. Assuming $p_2 - p_3$ is small and negligible for space engine, so we can get the thrust:

$$F = \dot{m}v_r \tag{4}$$

As it implies, the thrust of engine is depended largely on the mass flow-rate of charged powder at the nozzle of engine and the relative velocity away from the nozzle. If the input power is constant, specific impulse is in inverse proportion of thrust. According to the different requirement of mission, various combination of specific impulse and thrust can be chosen. Spacecraft can get a high acceleration with a low specific impulse and high thrust combination. On the contrary, powder can be saved with a high specific impulse and low thrust. With the optimal regulation of specific impulse and thrust, spacecraft can run in an optimal trajectory.

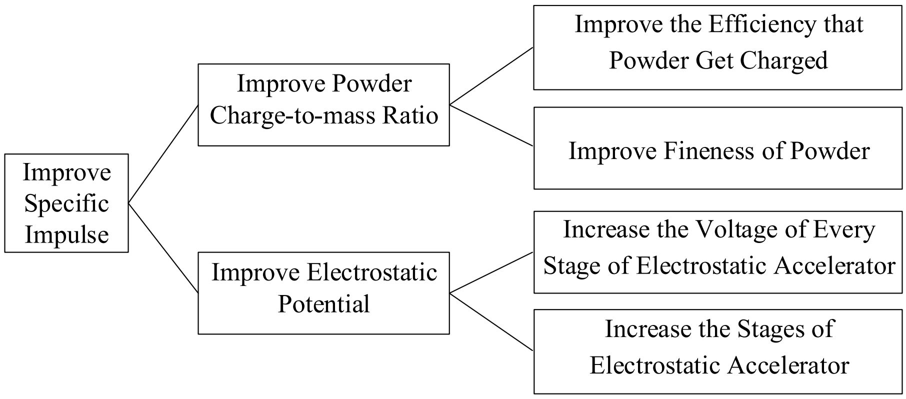

Fig. 5 How to improve specific impulse

III. Conclusion

Space debris cause a great potential threat to active satellite especially some high-value spaceships. By now, major space organizations are monitoring debris constantly with space debris environment model. At the same time, researchers propose a series of methods to remove the debris such as using claw, net or gecko adhesive tool to grapple the debris, deploying the ground-based or space-based laser to deorbit the debris. Nevertheless, it will consume large amounts of fuel for spacecraft to chase and rendezvous with the debris. So the debris engine we propose in this paper is a potential thruster for spacecraft to remove the debris and transform the debris into propellant constantly. As it implies a reasonable estimate is that about 90% of the breakup debris is of medium density. Especially, alloy occupy a large portion of the medium-density. So in the numerical simulation, it takes aluminum alloy as model material of debris and tests the thrust produced by aluminum alloy powder firstly. According to the analysis, it is the key way for greater specific impulse to improve electrostatic potential and powders' charge-to-mass ratio. In addition, the thrust of engine is depended largely on the mass flow-rate of charged powder at the nozzle of engine and the relative velocity away from the nozzle. With the optimal regulation of specific impulse and thrust, spacecraft can run in an optimal trajectory. Obviously, on the one hand, using debris engine as the thruster of space cleaning spacecraft is an effective way to remove debris from the orbit. On the other hand, spacecraft get propellant and maneuver for next action. More important, it provides a new idea for asteroid exploration and interplanetary flight for its sustainable fuel supplement.

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