Possible utilization of space debris for laser propulsion

E Y Loktionov and M M Skobelev
Bauman Moscow State Technical University, 2nd Baumanskaya Street 5, Moscow 105005, Russia
E-mail: stcpe@bmstu.ru

Abstract. Laser propulsion perspectives become more realistic with the development of laser systems as well as the necessity to resolve space junk problem and to perform high specific impulse interplanetary flights. Unlike others, laser thrusters can use virtually any type of fuel by turning it into plasma; this provides great abilities for harvesting working medium in space instead of bringing it from the Earth. This and ability to reuse external laser source intensively could save a lot of money and broaden abilities for thrusterless small satellites (nano- and pico-especially) and constellations of those. For the first time, we considered several options to use space debris objects (including out-of-use satellites, rocket stages) as a fuel for spacecraft with laser thruster. We evaluated possible mass consumption, thrust, velocity and energy efficiency performance, as well as optimal laser impact regimes, demanded velocity increment and time scale for different missions. We have shown that sufficient momentum to make 1 ton low Earth orbit object burn in the atmosphere can be produced by ablation of 10 kg only. Our findings appear to be rather realistic in terms of state-of-art launchable lasers, surface scanning systems and cost effect.

1. Introduction
There are about 18 000 artificial objects on Earth orbits, cca 1500 of those are active satellites [1]. About 29 000 space debris objects (SDO) are larger than 10 cm, and cca 1500 of those weigh more than 100 kg. The highest number density of 10 cm and larger SDO (cca $5 \times 10^{-8} \text{ km}^{-3}$) is reached on the orbits of 700–900 km, that is significantly higher than background values due to two major collisions [2]. For 1 mm and larger SDO, concentration reaches $6 \times 10^{-4} \text{ km}^{-3}$. Dangerous space debris size starts from 0.2 mm. Although SDO lifetime on orbits below 400 km is much smaller due to interaction with the residual atmosphere, the greatest danger of collisions with spacecraft is observed on widely used low earth orbits (LEO). The number of SDO on LEO increases annually by 5%. The expected frequency of 10 m$^2$ cross-sectional area satellites collisions with 1 mm SDO in LEO is cca 10 years [3]. Although this is comparable to LEO satellites operation time, every collision would increase probability of subsequent collisions significantly (Kessler syndrome) [1].

Several ways of space debris removal are suggested. In general, those ways imply collection and towing of SDO (using electric thruster or solar sail), external change of trajectory (by jet, magnetic field or light), explosion (leading to a big number of smaller debris). At the moment different towing spacecraft seem to be the most realistic for the disposal of obsolete satellites: pushing the latter to the graveyard orbits or towards the Earth for subsequent combustion in
the atmosphere. Considering numbers of smaller SDO, individual collection or impact does not seem to be an economically reasonable option. Laser space debris removal has been suggested for that long ago [4], but it requires very complicated and expensive terrestrial infrastructure, which could be also considered as an antimissile defense component. More over, multi-MW average power laser and adaptive optics technologies required for that are still being developed.

But more efficient would be not to waste SDO, but to reuse mass, which has been already launched to the space at the price of gold. A significant challenge to SDO recycling is the lack of propulsion systems able to use it as a fuel. Such “omnivore” thrusters could be created using powerful lasers. Focused radiation of sufficient intensity can vaporize almost any substance and turn it into plasma with a mass-average particle speed comparable to the orbital velocity [5]. Although external attachment to SDO is rather complicated, there are already prototypes of such systems. E.g., Minibuilders robot series (Institute for Advanced Architecture of Catalonia) that is capable of travelling on walls and covering those with marble crumb, performing the preparatory and finish work at the same time. Delta-robots and arm manipulators, once established, can scan surfaces of virtually any shape at high speed (up to 10 m/s). The system should also provide processed surface shape analysis, ballistics calculation (considering the thrust vector to be normal to the locally treated surface). One of main laser thrusters features is relatively easy adjustment of thrust to specific impulse ratio in a wide range (more than an order of magnitude) that is not available in other types of engines [6]. This allows, with greater expense of fuel though, faster acceleration of the spacecraft at the initial stage, and upon reaching a certain speed, switching to high specific impulse.

The objective of our work is to evaluate possibilities of using space junk as a source of working medium for laser propulsion system of the spacecraft; increasing technical and economic efficiency of moving SDO from potentially dangerous orbits.

2. Theoretical basis
Most of SDO consist of metal. Nanosecond and shorter laser radiation pulses are rather effective for impact on metals. Higher pulse energy values can be reached in nanosecond range, while heat dissipation losses are relatively small. Pulse energies achieved nowadays in a compact diode-pumped solid-state (DPSS) lasers are in 1–100 mJ range (in disk and slab lasers pulse energy of 100 J is reached [7], but such systems are not compact). The characteristic size of a focal spot arising from the focal plane positioning precision, and based on laser technology experience should be assumed as 30–100 µm. Thus, laser fluence 10 to 10³ J/cm² can be achieved at target surface. These values exceed nanosecond laser ablation and plasma thresholds even for refractory metals (up to 4 J/cm² [8]). Typical specific mass consumption at nanosecond laser ablation for metals in vacuum is cca $3 \times 10^{-5}$ g/J [9], or $3 \times 10^{-8}$ to $3 \times 10^{-6}$ g/pulse in our case. At pulse repetition rate of 1 kHz, the same numerical values in kg/s are obtained. Thus, ablation of 1 kg would take 4 days at 100 mJ.

In the above mentioned range of fluences, momentum coupling coefficient for metals is about $3 \times 10^{-5}$ N/W [10], giving an average thrust $3 \times 10^{-5}$ to $3 \times 10^{-3}$ N. The recoil momentum imparted due to ablation of 1 kg of matter will be cca $10^9$ Ns, which corresponds to a specific impulse of cca 100 s. By the exposure parameters optimization, possibility of 1000 s specific impulse was shown for metals [11]. On the one hand, there is no need to save working medium using space debris. But on the other, it makes sense to maximize the use of the scanned surface to minimize system reinstallation to access new surfaces with working medium and to reduce its dimensions. For the impact mode discussed, laser generation thrust energy efficiency is 1.5% only. Which represents the lower bound of the expected range, since values reached at nanosecond impact on massive metals in vacuum are 10–30 times higher [12]. The general dependence of thrust generation and energy efficiency parameters on laser fluence are as follows [13]: specific impulse increases logarithmically; momentum coupling coefficient has an
Figure 1. Dependence of thrust generation efficiency on the laser fluence to ablation threshold ratio: 1—momentum coupling coefficient $C_m$; 2—specific mass consumption $\Delta m/E$; 3 and 4—$C_m$ for SS304 steel nanosecond irradiation with 1064 nm and 532 nm [15]; 5—energy efficiency $\eta$; 6—mass averaged velocity $\langle v \rangle$; 7—$\langle v \rangle$ for titanium [16]. Lines result from our modeling for titanium according to relations from [13].

Optimum at ablation threshold exceeded by cca 4.5 times [14] (nearly matches plasma threshold); for energy efficiency, optimum excess is cca 7.5. These dependencies represented by figure 1 show that laser ablation threshold should be exceeded by cca 10 times to obtain optimum thrusters performance.

Velocity augmentation sufficient for SDO pushing from LEO is of several tens to few hundreds of m/s. According to jet propulsion principle, the ablated to SDO mass ratio should be equal to required velocity increment to the ablation flow mass averaged speed ratio (specific impulse multiplied by gravitational acceleration). Thus, at $\Delta v \approx 100$ m/s and specific impulse of about 1000 s, only about 1% of SDO+spacecraft mass is to be removed. Spacecraft structure elements usually comprise about 20% of its dry mass. Since there is no need in strong construction after launch, it could be used, at proper design for being laser ablated, for orbital manoeuvres. However, it should be borne in mind that continuous scanning of construction, high pressures reached at impact zone [17, 18], and microscopic phenomena [19, 20] can lead to undesirable separation in small fragments. Considering use of SDO for interplanetary flights, e.g., to the moon, according to Tsiolkovsky relation, the final mass of the propelled object should be about $1/55$ of the initial one. For meteoroids composed of iron primarily, this ratio can in principle be achieved.

3. Possible implementation

To resolve the space junk problem we propose a method of SDO moving by using its mass gradually as a working medium for laser thruster, while the towing spacecraft is rigidly fixed on the surface of SDO. Using the scanning system SDO surface mapping is to be performed. A program of surface scanning should be created as a result of map analysis to ensure the maximum value of the recoil momentum projection on a given axis. Laser impact parameters—
pulse energy and focusing spot size—are selected according to the chemical composition of the specific SDO. Those could be selected experimentally by plasma threshold evaluation or using the data from spacecraft attitude control system, or chosen from presets, based on the chemical composition of space debris, as defined, e.g., according to atomic emission spectroscopy of the ablation plume. Ablative plume is oriented by the local normal to the irradiated surface [21], and has a full divergence angle in vacuum of cca 15° [16]. This zone of plume propagation should be free of any constructions in general, or presence of those should be taken into account. To increase pulse energy and reliability of the system, multiple laser sources should be used for the impact on the same or different regions of the scanned surface.

Reliability issues of 3D-printers and solutions for many of those are currently well known (this is a question of price mainly—in special cases lifetime exceeds 10 000 h). Traditional laser technology systems and 3D-printers scanners with orthogonal slides have relatively low reliability and scanning velocity (0.1 m/s). Arm manipulators, widely used in laser welding technology (processing speed up to 0.25 m/s, relocation—usually about 1 m/s, and up to 10 m/s in some specimens), are rather expensive and complicated (question of reliability). However, those are matching well speed and scanned area size requirements, and robo-arms were tested at the ISS external surface. In authors’ opinion, the in terms of reliability and performance delta-robots should be used for small (less than spacecraft size), robo-arms for medium and galvo-scanners—for large (more than 10 spacecraft size) scale SDO (figure 2). There are also some less popular alternatives: electro-optical 3D-scanning system [22] (limited lateral size, high-voltage); the gimbal (consumes a relatively large amount of energy); Risley prism (not sensitive to vibrations). In our case, scanning system should be highly resistant to vibration (at launch) and thermal stresses.

We used Thorlabs GVS312(/M) as a sample of galvo-scanner. Maximum deflection of beam is ±20° (±0.35 rad), positioning accuracy 15 µrad, and scanning speed in high precision mode 200 °/s. Problem of this system is the need for dynamic focusing of radiation, which reduces reliability and is rather complicated. This problem could be reduced with long focal range focusing system having an elongated waist, with restricted operation radius though. Precise surface mapping with galvo-scanner is also hard in implementation. Use of the F-theta lens
in this case is impossible due to large scan areas and need to impact normally to the surface. Another disadvantage of galvo-scanner is dead zone near the mirror: divergence angle 15° of the ablative plume restricts about one third of the radius (or 11% of treated surface).

Delta-robot is somewhat analogous to the robo-arm but has fewer servos and allows easier redundancy of those. For robotic arms, backup of the whole system is possible (some arms working simultaneously on the same surface, which would significantly increase reliability and performance). As a model of delta-robot, we used a 3D-printer kit HE3D K200. The scanned surface area is 314 cm² and depth is 30 cm. An SDO of several tens kg mass or 5 kg satellite can fit in this volume. Both surface scanning and laser impact modules could be easily fixed on the operating device.

We used a compact passively Q-switched end-DPSS Nd:YAG laser with pulse energy of 2.7 mJ and duration of 1.5 ns at fundamental frequency [23]. The delivery of pump radiation via optical fiber significantly reduces the size of the structure fixed on the scanning head, and heat sink for diode pumping can be organized easier. To test the implementation of the proposed solutions we developed Delta-scan software, designed for laser evaporation of materials from the surface random shaped solid objects in automatic mode. Delta-scan detects surface with 25 µm lateral and 50 µm axial precision. Local orientation of the elementary surface relative to the main axis of the delta-robot is evaluated. Impact and surface probing lasers focusing areas are collocated. Imparted recoil momentum is predicted. The system calculates and senses available surface at any point and time. The laser demonstrated ability to work in harsh temperature and vibration environment for dozens of minutes. Delta-robot was also able to work for hours, its mechanisms can be fixed automatically to persist high dynamic loads. We expect robotic arm would provide same performance.

4. Conclusions
Space junk, out of use satellites, and meteoroids can provide tons of working medium for laser thrusters. Unlike other spacecraft engines, which, in most cases, are fed with a highly specific substance in a specific way, laser impact can be performed on virtually any material leading to reactive plasma jet generation. Laser thruster performance can be relatively simply adjusted by radiation focal spot size and pulse repetition rate. Irradiation regimes should be adjusted to avoid destruction of a target and emergence of small-sized debris. The process of external source mass utilization is actually opposite to additive technology, so it is reasonable to use experience gained in this field. The experience of space operation of 3D-scanning systems, DPSS lasers, and object capturing devices ensures technical possibility of such propulsion systems.

For SDO, towing to graveyard orbits or towards the atmosphere for subsequent combustion, only cca 1% of mass should be removed. Physical and chemical properties of SDO are not so critical since laser ablation thresholds for most expected materials are within 1 order of magnitude. Optimum laser fluence is suggested to match laser ablation threshold multiplied by 5 to 10, which in most cases results in 2 to 20 J/cm² for nanosecond pulses. It is obvious that for greater average density objects (for spacecraft it is cca 500 kg/m³ only) removed material volume is smaller, and so, scanning system is smaller and lighter. For spatially homogeneous objects with relatively high density (e.g., iron meteoroids), velocity augmentation enough to reach the moon becomes possible, that requires the initial to final mass ratio of at least 55. Unlike other ways of active space debris removal, we suggest recycling, which could save a lot of money due to towing system reuse and to no need in propellant brought from the Earth.

Acknowledgments
This work was performed at the research facilities cluster “Beam-M”, supported by the Russian Ministry of Education and Science under the Federal Target Program 1.2 “Research and
development in priority directions of science and technology in Russia 2014–2020”—contract No. 14.574.21.0146 (RFMEFI57417X0146).

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