The elements of a small debris mitigation system using spaceborne laser

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Abstract

Despite their small mass, small debris are still fatal when collide and yet have not been discussed in terms of how to avoid collision with them in detail. This paper discusses a scheme for mitigating the collision with and removal of small debris using a spaceborne laser and optics system. Laser pulse specifications for both spotting and shooting the orbital objects have been investigated specifically with small debris in mind. An adaptive digital holographic technique is proposed to realize a beam steering scheme with an order of microradian accuracy. Technical elements to be developed for the system implementation are identified.

1 Introduction

Among the orbital debris problems, small debris have been categorized as “Lethal Non-Trackable (LNT)” debris [1], but not yet given an effective remediation. The purpose of the work is to develop a debris object removal or collision avoidance system using a spaceborne laser system. The targeted size ranges from a millimeter to a few centimeters. The target has been set this way because they are not cataloged at all and yet potentially exert fatal damages to functioning satellites or if collide with defunct satellites, reproduce a tremendous amount of small debris. The fatality of such a small object comes from its hypervelocity nature at the collision[2].

Since the characteristics of this category are small size and a huge number, its remedy needs to be quick and remote operation. A suitable means for the purpose is using light, however, even the short wavelength of light is not short enough to “see” the small debris from the ground. There have been proposed technologies using spaceborne laser systems against LNT[3]. Photon pressure or laser ablation (high-temperature gas jet) on debris surface deorbits it to the earth’s upper atmosphere. However, specific technological details of how to shoot a debris object precisely have not been much discussed nor proposed. A technology, preferably not mechanical, capable of realizing an order of microradian accuracy on laser beam steering is needed.

As an orbital base for the laser system, we assume the International Space Station (ISS) because of its spatial and power capacity and they might be available after the year 2030. Based on this assumption, we will discuss the specifications of the system in detail. In the following sections; a scenario of using laser light for finding and shooting a debris object is introduced in Sec. 2. In Sec. 3, specifications of the laser system such as energy, power, and pulse width of pulses are discussed. Section 4 presents the schemes for spotting and shooting debris objects. Finally, Sec. 5 lists the technical items to be developed to realize the proposed laser system.

2 Scenario of laser operation

2.1 Single encounter with debris object

Given the electrical power available from the ISS paddle and assuming that the ISS will be dedicated to the purpose, about 50-80 kW of electrical power is expected to be shared with the laser system. Then the average optical output would be 10 kW. With this optical power as a probe, small debris can be detected up to 10 km away. Considering the relative velocity of debris against the ISS in the order of 10 km/s, a repetitive probing pulse frequency of 10 Hz would shine the passing-by or colliding debris up to ten times before the removal action. This outline of probing is sufficient for the orbit determination of debris.

The shape of the small debris varies from a simple chunk of aluminum to a paint fragment and to bundle of wires, therefore, their reaction to impulse is unpredictable. One cannot always expect the momentum vector coincides with the mass center of the debris object and should expect to initiate a spinning motion. If a series of multiple pulses hit such an irregular shape of debris, not a linear translational acceleration but a tumbling motion should be expected resulting in a poor operation. Therefore, the momentum transfer should be executed in a single laser shot base.

2.2 Spotting and Shooting

For detecting a debris object passing by the ISS without prior knowledge of its orbit, spherical sheet or shell light waves are utilized as the shape of the probing pulse. The optical power of the probe is distributed uniformly over the sphere. The shell-like light waves are emitted from the transmitting optics on the ISS and illuminate any object entering a sphere region of radius 10 km. A series of 10 Hz probe lights will intercept the object and the reflecting light waves are detected by an image sensor aboard the ISS. Once the trajectory of the object is calculated, the probing pulse is more concentrated on the object to get a clear holographic pattern representing its location. When the object reaches the closest location to the ISS, the hologram is read out by a giant powerful laser pulse that is automatically and optically steered toward the object (the shooting laser pulse).

3 Laser pulse parameters (pulse duration and pulse energy)

3.1 General background of producing high thrust (I_{sp} and C_m)

Producing thrust in space is a problem of choosing the best balance of resources between propellant and energy, or mass and velocity of exhaust. For example, for ground launch systems, chemical propellant is the choice with which the exhaust velocities or specific impulse I_{sp} are basically determined and limited by the specific chemical potential of fuels and do not exceed 1000 seconds with the hydrogen-oxygen thrusters. This situation is characterized by a massive fuel consumption or low payload ratio, only a few percents. The choice is plausible because there is no limit on the amount of propellant loaded to the thruster on the ground. However, once the thruster is up in space, there is a different story, mass is precious and we want to use the mass of propellant as efficiently as possible. In this case, our choice is to use more energy than mass. Fortunately, thanks to the advent of solar panels, we can rely on renewable energies from the sun in space although they are not always as powerful as we would like. This is the reason why all the thrusters used in interplanetary flights adopt electric propulsion systems with much higher I_{sp} or larger exhaust velocities.

For producing thrust with limited energy available, the choice is to use more mass and small exhaust velocity. This is in fact the case for giving thrust to small debris by spaceborne laser systems. As far as laser plasma is concerned, large velocity means high temperature requiring high laser intensity where more laser energy is consumed in the kinetic energy with the velocity squared. High temperature does not contribute to the hydrodynamic motion much because of the large ionization and radiation losses that increase with the fourth power of temperature.

Although the laser system on the orbit is provided with energy from sunlight, even the one-shot energy needed for removing a small debris object is rather large compared to the sunlight available. Therefore, our choice for generating the laser thruster is to use the most out of mass, namely, the part of debris itself. The rule of thumb for designing the laser parameters for accelerating debris is to keep the focusing intensity on the debris as low as possible and to use low-temperature gas exhaust as the source of thrust. We call this requirement the “Low Intensity for Large C_m (*LIfLaC*)” condition.

As we will discuss in the following section, the average laser power needed for the spotting and removal even for small debris is rather large; the order of a few tens of kilowatts. Only ISS can currently provide such power using the installed solar paddles. Furthermore, the use of ISS after the year 2030 has not been determined yet, leading to the idea of using it as a demonstration platform for international cooperation projects of spaceborne laser debris remover.

3.2 Laser energy needed for debris removal

Laser pulse energy to deorbit a debris object into the upper atmospheric layer can be evaluated using Δv, a velocity change exerted on the targeted debris object. From Δv, impulses to be generated by laser ablation are calculated as a function of the debris mass.

The momentum coupling coefficients, C_m have been studied by many authors with various laser parameters[4, 5]. C_m depends on laser parameters such as intensity, pulse width and wavelength but, here, C_m is assumed to be constant and thus the impulse generated by the laser is proportional to pulse energy.

To estimate the laser pulse energy needed to be incident onto debris objects, we take Δv value of 50 m/s that is needed for an object on the 500-km altitude to deorbit to re-entry [3], and C_m value of 20 μNs/J, a typical value measured by various authors using Q-switched Nd: YAG laser pulses irradiated on aluminum targets [6]. Then the needed laser pulse energy is proportional to the debris mass, m_{db} like

$$E_{laser} = 2.5\text{x}10^3 \text{x } m_{db} \text{ [Jouls]}, \qquad (1)$$

where m_{db} is in grams. As an example, the removal of a 1-cm^3 aluminum object requires about E_{laser} =7 kJ.

The amount of laser pulse energy giving the same Δv also depends on the angle between the original velocity and the direction of the impulse. A vector algebra shows that the required energy increases significantly when the impulse angle exceeds 60 degrees. Assuming the uniform probability distribution on the angles, the above argument still holds by 66% probability.

The laser system will be designed to have specifications capable of delivering kilojoules of energy in a single encounter event. The pulse shape does not have to be a single “giant” pulse but can be a burst of pulse train or even a CW beam lasting within the single event to carry the total amount of energy needed.

3.3 Spot size limitation for small debris

There is a parameter needing special attention when a small piece of debris object is targeted; the laser spot size, d_{spot} focusing on the object surface is limited to the size of debris. This situation is in contrast to the case when much larger objects are targeted where the spot size can be selected to achieve the desired laser focusing conditions for a good C_m. On the other hand, in the case of small debris, the diffraction of light waves, d_{dfr} needs to be taken into account and is roughly expressed as

$$d_{dfr} \approx \frac{\lambda L}{D_{opt}}, \quad (2)$$

where λ, L and D_{opt} are laser wavelength, laser propagation distance to debris, and the transmitting telescope aperture diameter. The telescope is the focusing output optics of the laser light. For example, taking reasonable values of 1.0 μm, 1 km, and 1 m for these parameters gives d_{difr} =1 mm thus d_{spot} is in the same order as $d_{dfr,}$ and the debris objects size d_{dbr} under consideration. If the debris object has an irregular shape, d_{dbr} needs to be replaced by "facing surface areas (FSA)". FSA changes not only by the shape of the object but also by the attitude of it relative to the laser beam incident direction.

$$d_{dfr} = 1mm \leq d_{spot} \leq d_{FSA} \leq d_{dbr} < 10mm. \quad (3)$$

The pulse energy estimated in the previous section needs to be focused within d_{FSA} while keeping the laser intensity as low as possible but above the plasma onset intensity, I_{th}=10^9 W/cm^2.

3.4 Managing the pulse energy focused into a small spot

This requirement leads to a specific design on the temporal laser pulse shape while high C_m conditions are being taken into account. Having estimated the laser pulse energy and focusing spot size, and with the *LIfLaC* condition, the pulse duration, τ_{lsr} is readily determined,

$$\tau_{lsr} = \frac{E_{laser}}{A_{spot} I_{th}}, \quad (4)$$

where A_{spot} is the laser spot area corresponding to d_{spot}. The detailed specification of each parameter in Eq. 4 depends on the format of the laser pulse(s). As a simple example, when laser energy is delivered in a single long pulse or a burst of pulses to an object of typical size r_{obj}, and considering $E_{laser} \propto r_{obj}^3$ and $A_{spot} \propto r_{obj}^2$, τ_{lsr} scales like r_{obj}. with the typical value of τ_{lsr}=10 μs.

4 Laser debris shooter, phase conjugate waves

4.1 Non-trackable object

The function of a debris finder consists of three steps: spotting, tracking, and wavefront acquisition. Since there is no prior knowledge of the approaching orbits and distribution of the small debris objects, debris objects are spotted only when they come across the vicinity of the laser satellite. The concept of the laser debris spotter is depicted in Fig. 1. It is very similar to the radar system. To realize the function, the laser satellite emits repetitive probing pulses with the shape of spherical power distribution. When a pulse intercepts a debris object, a part of scattered light is detected by an optical image sensor near the telescope. The repetition of the probe pulses is designed so that a single object will be hit by the probe pulse multiple times during its passage through the satellite vicinity.

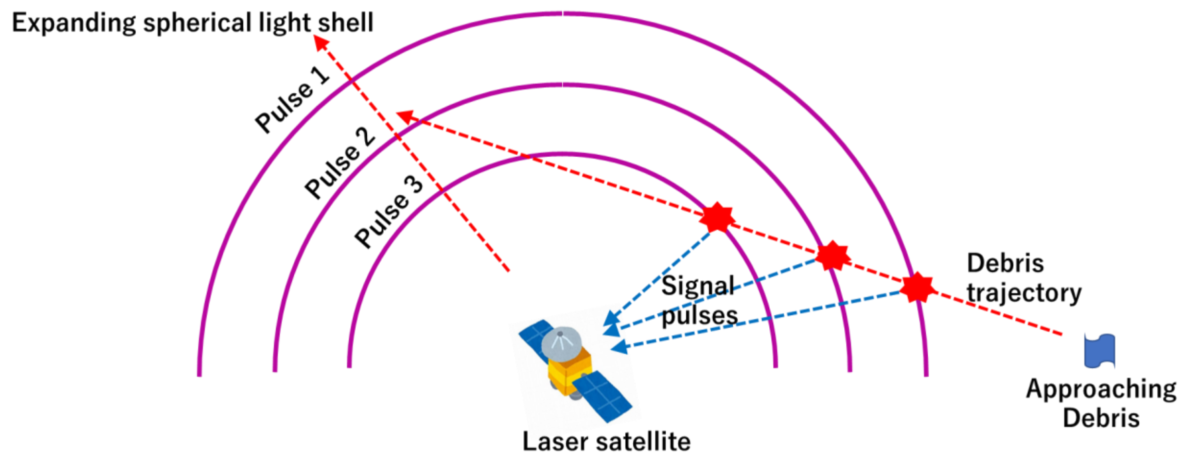

Fig. 1 The concept of debris spotter in its coarse mode. The laser satellite emits spherically shaped laser pulses. When a debris object is hit by the pulse, the scattered lights can be used to identify the trajectory

4.2 How to shoot the debris object in space

Shooting a small distant debris object from an orbit is a challenging task because (1) the distance between the laser and the object is in the order of km, (2) the accuracy of aiming the laser beam is extremely high, close to the diffraction of light wave, (3) tracking the object using mechanical motion of rather large telescope on an orbit is a complex task considering the speed of steering and compensation of angular momentum recoil of the telescope. Therefore, an all-optical scheme of steering and focusing light beam is employed.

The scheme is based on an optical phenomenon called optical phase conjugation (OPC). It is the physical principle of generating holographic images. In holography, the shape and structure of wavefronts from an object are recorded on a medium and read out or reproduced onto reference lights which are then detected by, for example, human eyes. The eyes see exactly the same wavefronts as from the object itself and the human brain recognizes as if the object is actually there.

The same principle can be applied to debris shooting with powerful coherent laser light and in this case, the human eyes are replaced by the debris themselves. A debris object is shot by laser light with wavefronts that have been generated by itself.

The technique of generating OPC had been studied for many years using nonlinear optical phenomena (NOP). Nonlinear optical media are sensitive to optical wave modulation and suitable for recording holograms. Recently, for these twenty years, since the advent of electro-optical devices, called special light modulators (SLM), NOP media have been replaced by them as a hologram recording medium. Furthermore, SLM opened a new way of operating OPC, that is, the hologram recorded on SLM can be modified electronically thanks to the same operating principle of SLM as liquid crystals, which is in principle impossible for NOPs. The controllability of SLM makes them an essential element in the debris shooting function[7, 8].

The use of OPC will eliminate the mechanical motion of optical components in the laser steering system. This is a significant advantage in designing a rather massive optical system (including a telescope with a meter class aperture) with a rapid light beam steering capability. A complex angular momentum compensation mechanism would be required without the all-optical beam steering system. A combination of OPC and optical switching techniques covers a wide field of view of the debris shooting system with no mechanical beam path switching as well[9].

4.3 Sending focused probe pulse for wavefront detection

The debris spotter operates in two consecutive modes: coarse mode and precision mode.

In the coarse mode, probing laser pulse energy is distributed uniformly to cover the field of view where colliding debris objects are expected to appear (Fig. 1). The signals from the image sensor are used to calculate the orbit of the object and its characteristics such as size and spinning rate that will be used to determine the shooting laser parameters. Depending on the energy available to the probing pulse, the signal from the object might be at a photon counting level and thus the mode is only for detecting the object's appearance and approximate trajectory with large uncertainty.

Once the orbital information is acquired, the debris spotter goes into the precision mode and tries to obtain as strong a signal as possible from the object to get the most accurate wavefront signal. To accomplish this, the probe pulse energy is moderately focused on the expected position of the debris object more tightly than the coarse mode (Fig. 2). The size of the focus is just to cover the uncertainty of the expected debris position so that the strength of the scattered light signal is strong enough for the hologram generation.

Probe beam in the “precision mode”

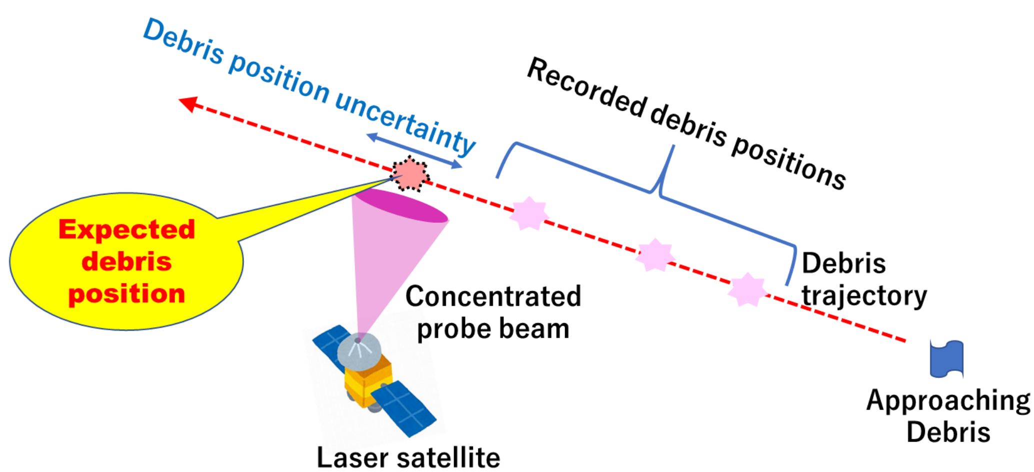

Fig. 2 The concept of debris spotter in its precision mode. The laser satellite emits directed probing pulse to the vicinity of the expected debris position estimated from the previous position measurements during the coarse mode.

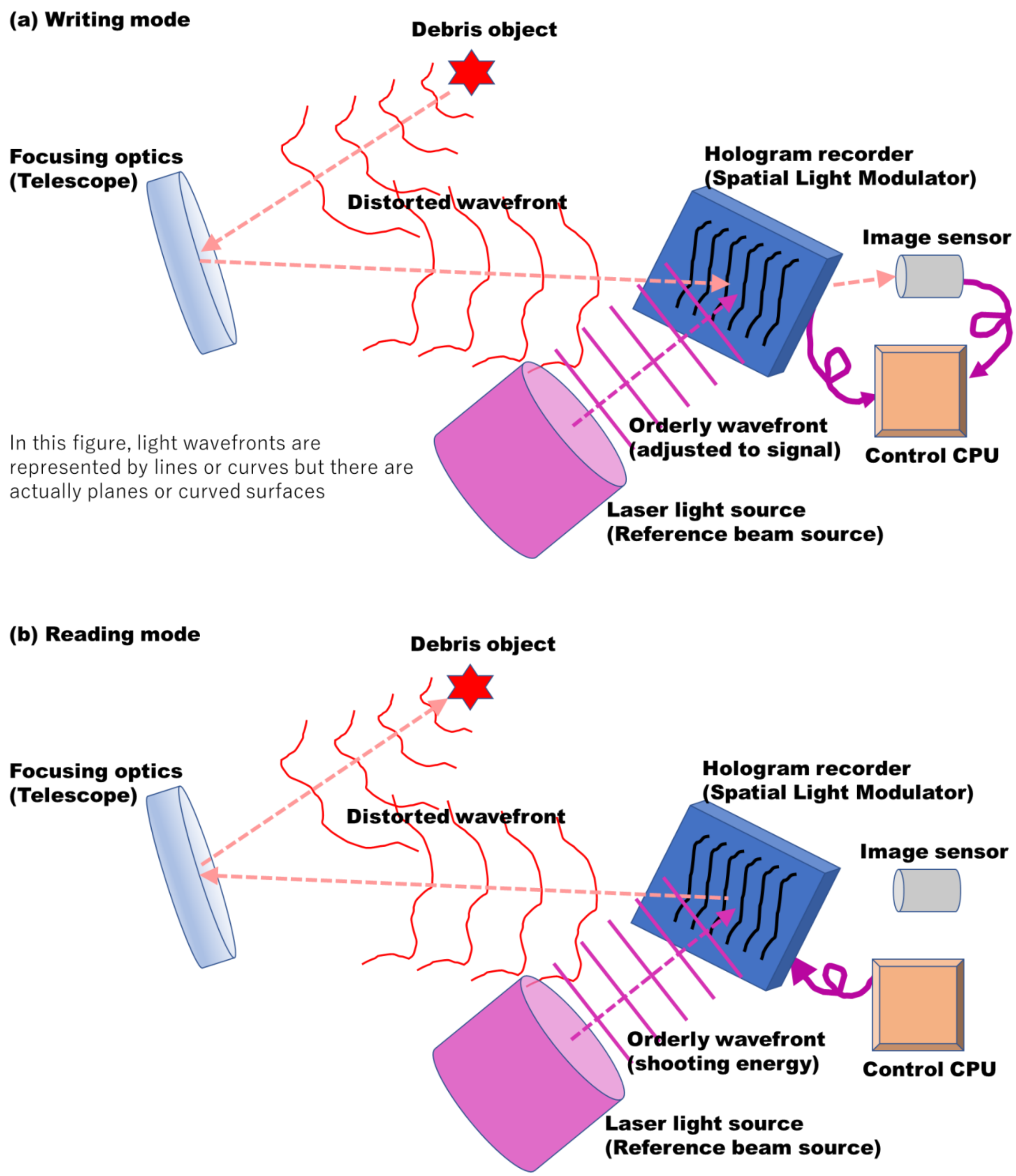

Fig 3 Basic operational concept of optical phase conjugation: "Writing" step (a) and "Reading" step (b). Note that the differences between the two modes are the directions of the light waves and the electronic signals of the hologram reverse.

4.4 Hologram generation and reading out

The basic operational concept of the OPC is depicted in Fig. 3. The operation is divided into two consecutive steps: the hologram writing step and the reading-out step. In the writing step, a part of the probe beam scattered by the debris object is collected by the telescope as a signal light and leads to a hologram recorder where the interference(hologram) pattern is generated through interference with the orderly waves(reference light) from the laser source. Since the wavefront of the signal light carries the information of the debris shape and instantaneous position, the recorded hologram also reflects the information. In the reading-out step, a powerful energetic pulse light with an orderly wavefront reads out the hologram pattern and thus the resulting wavefront carries the information of the debris object. The reflected(diffracted) light wavefront possesses the same wavefront as the signal light but with only the propagation direction reverse. The read-out light beam propagates back to the debris object as if time reverses and focuses exactly on the position where the original signal waves are generated.

4.5 Digital hologram generator

The conventional OPC returns the light waves only where the signal waves are generated. In the case of shooting a debris object, it is not enough since the moving object with hypervelocity would shift to a different position when the phase conjugated light waves come back. One solution for compensating for the shift of the object is to calculate the point-a-head angle and steer the optics accordingly. Since the solution causes the angular momentum recoil compensation problem to the base satellite as described above, we make the best use of the full advantages of SLM.

The hologram recorded on the SLM is transformed into electronic signals and stored and further modified by the CPU. During the coarse mode, the trajectory of the targeted object is determined, and thus its new position at the time of the shooting pulse arrival at the object can be calculated. These data are then used to calculate the modification of the hologram pattern that includes the point-a-head angle adjustments. This scheme of actively controlling the hologram is called “Digital Holography (DH)” and recently its application to high-power laser systems has become prominent [10].

DH can also be used to control the spot size at the focus to d_{spot}. Without DH, the focused spot size on a debris object is fixed to its d_{FSA} and the laser intensity could be below the plasma threshold I_{th}. This is the case, especially for larger d_{FSA}.

It is also important to point out that the shooting laser pulse is rather long and OPC using NOP might not support hologram pattern for such an extended period. In the case of digital holograms, that is not the problem since the electronic hologram can be rewritten many times as long as it is needed.

5 Elemental developments

5.1 Mirror for spherical light waves

Spherical light shell pulses are generated by using a spherical reflecting mirror. Considering that any debris objects colliding with you take a side-on approach, a simple calculation gives the colliding angles ranging from 45 to 90 degrees from your proceeding direction. Therefore, the spherical mirror and the incident laser radiation are to be designed together so that only these spaces will be covered by the probe pulse. Actually, the shape of the mirror would be only a part of a sphere.

It is very important to have a uniform power distribution over the “light shell”. Any non-uniform phase distribution of the electromagnetic components across the laser beam cross-section might cause “intensity holes” across the light shell and result in “missing debris”. To “patch” the holes, the mirror surface needs to be deformed subtly according to the actual characteristics of the light source. The resulting optical surface should be asymmetry and irregular one. Manufacturing such an optical surface has become possible due to the recent progress of precision 3D printing technology [11].

5.2 Algorism of modifying phase conjugation

The hologram recorded on the SLM using the reflecting light from the object represents the exact location of the object. However, as described in section 4.5, modification on the hologram is inevitable to compensate for the position shift of the object during the round trip of the laser pulse.

The modification corresponds to the beam steering (transverse direction) and focusing position (longitudinal direction). The algorithm is based on the treatment of the raw hologram signal and information on the trajectory and size of the object.

5.3 High power long pulse laser

The laser pulse specifications depend on the mode of operation, spotting and shooting.

For spotting mode, as discussed in section 2.2, the most important function of the mode is to measure the location and the size of the object, and it depends on the pulse width, τ_{laser} of the probing light. The criterion for the pulse width is that the motion of the object during its passage through the pulse should be smaller than the object itself, d_{dbr},

$$\tau_{laser} v_{obj} < d_{dbr} \tag{5}$$

Taking typical values for v_{obj}=10 km/s and d_{dbr}, =1mm, τ_{laser} should be less than 100 ns.

For shooting mode, Eq.4 requires shooting pulse widths to be 10 μs. This could be done by coherently adding the Q-switched pulses consecutively in the oscillator [12].

For a simple configuration of the laser system, both spotting pulses and shooting pulses are preferably generated in a single laser system and by changing its operation mode.

6 Conclusions

A group of technologies that make the remediation of small debris a practical scheme has been presented. Pulsed laser parameters are described to realize the maximum C_m. It is shown that the digital hologram technique plays essential roles in shooting, not limited to, small debris object.

Considering the requirements on laser, optics and optoelectronic devices, it appears that the proposed system can be implemented with a reasonable extension of the current level of technologies.

Besides the demonstration of debris removal technology, the system could be used to monitor the mid-sized orbital debris as well. Monitoring this category is also important because of its number and lacks of distribution information.

It would be a unique opportunity for the ISS to be shut down in the year 2030, leaving behind valuable power generation assets, which is more than a suitable platform for a high-power spaceborne laser system and for a symbolic cooperative project of humankind.

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