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Technical Notes

Laser Ablation Propulsion Tractor Beam System

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Introduction

REALIZATION of a space tractor beam system would constitute a paradigm shift in the use of space and space systems. Here, a tractor beam is intended to mean a beam of energy that imparts an impulse to a remote object of interest to enable remote control. Potential applications include orbital debris removal, spacecraft rendezvous, satellite attitude and orbital adjustment, redundant systems for space rescue, etc. Assuming development is possible, what propulsion system is best? Field propulsion systems (such as laser tweezers [1]) typically operate on micrometer- and nanometer-scale targets. Concepts such as magnetic tractor beams [2] are severely limited in range. Power beaming [3] with conventional propulsion systems can produce tractor-beam-like effects, but categorization as a tractor beam is questionable because the beam itself does not produce a significant impulse.

Laser Ablation Propulsion

Laser ablation propulsion, proposed in 1972 by Arthur Kantrowitz [4], is a viable alternative to the aforementioned options. Research on laser propulsion has been conducted worldwide in atmospheric and simulated space environment conditions. Many technical challenges, such as beam riding, target tracking, and choice of target materials have already been overcome. Challenges associated with using a high-energy space-based laser source have been addressed elsewhere [3]. Despite these efforts, with current technology, laser propulsion is uneconomical when applied to traditional propulsion applications. Ground launch is more feasible using rockets, and electric propulsion is well suited for most space missions [5]. Therefore, applications for laser propulsion should be sought that emphasize its many strengths, which include a finely adjustable impulse bit (nNs to Ns), an adjustable specific impulse (I_{sp}) (200–3600 s has been demonstrated [6]), and remote operation (in laser propulsion, the power source can be separated from the propellant, enabling operation from a remote location, which is impossible with conventional thruster concepts). Of special interest for this paper is the remote control of a target using laser ablation propulsion, to date only tentatively explored by a few groups.

Previous Laser Ablation Propulsion Tractor Beam Research

One study of remote control by laser ablation propulsion was conducted by the Yabe group [7,8], which researched a bulk liquid propellant laser propulsion thruster, the metal-free water cannon. Remote torque production and tractor-beam-like propulsion of a free-floating water-born target were demonstrated using a water propellant. Laser propulsion studies that used liquid propellant, such as [7,8], often exhibited a low specific impulse; however, at least one study [9] already demonstrated operation in a vacuum with exhaust velocities of $\sim 5\ \mathrm{km/s}$ by exhaust confinement and preheating of the propellant.

Phipps et al. [6,10,11] pioneered the use of multilayer laser ablation propellants and developed a laser microthruster capable of generating tractor-beam-like thrust. Initially, low-fluence laser light is focused through a transparent substrate layer to generate confined ablation of a second layer, producing tractor-beam-like propulsion. The microthruster can operate bidirectionally (e.g., see [12]), but such operation impairs the optics by depositing ablated exhaust during the driving mode operation. Because the laser and the necessary optics are onboard, the system is not a tractor beam.

In Russia, the laser jet engine (LJE) [13,14] has been demonstrated in both repetitive pulse and continuous wave modes. Experiments used impulse from CO_2 laser ablation and exhaust combustion to drive wire-guided LJE craft toward the laser beam, a distance of some meters, using polymer or liquid propellants and operating in atmospheric or vacuum conditions. The LJE is a tractor beam vehicle concept; in fact, it is an example of a class of tractor beam targets, discussed next.

Laser Ablation Propulsion Tractor Beam Target Concepts

The concept of cooperative tractor beam targets is introduced here (i.e., targets of special structure, composition, or geometry that enable selection of either reverse or forward thrust and throttle control in real time at the whim of a remote laser operator, merely by changing laser beam parameters). It is instructive to classify cooperative targets as indirect or direct, as explained next.

Indirect Targets

Indirect cooperative targets redirect the laser beam (e.g., with lenses, mirrors, or fiber optics) to the rear of the target to produce tractor beam propulsion but without allowing the beam to pass directly through the target material itself. Some examples are shown in Fig. 1. Figure 1a shows a target with a central concentrator and a peripheral ablator; Fig. 1b shows a peripheral concentrator and a central ablator, and Fig. 1c shows an asymmetric system. Black arrows denote the path of the laser light (the remote source is not shown), circled areas denote ablation, and gray arrows denote the exhausted propellant. The concept in Fig. 1b is similar to the Russian LJE [13,14]. The target shown in Fig. 1c is asymmetric, and it could be used to impart torque to an object. Alternatively, several targets mounted around a single object could be ablated in sequence to produce a net linear thrust, somewhat akin to the operation of a kayak

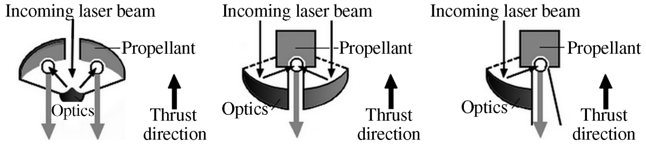

Fig. 1 Conceptual diagrams, in cross section, of indirect laser propulsion tractor beam targets (gray arrows indicate direction of ablation exhaust).

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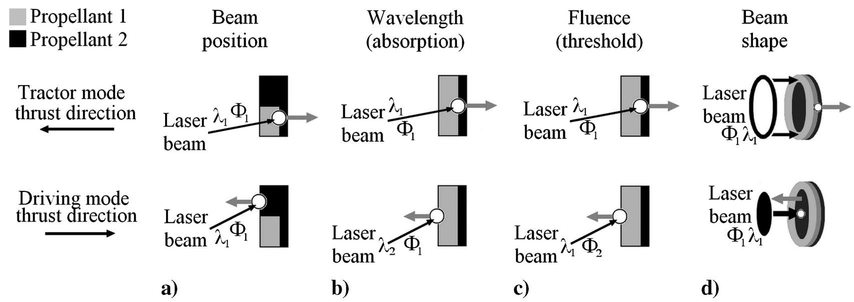

Fig. 2 Control parameters for direct targets (gray arrows indicate direction of ablation exhaust).

or canoe; however, efficiency would be reduced because significant energy would be directed into adjustment of the angular momentum at each shot.

By modifying the laser profile or selecting between irradiation of the center and edges of the targets, each of the previously mentioned systems could be switched between driving and tractor beam propulsion at the whim of a remote operator. As an additional benefit, indirect systems focus laser light after it arrives at the craft, enabling operation at low incident power levels. This is an appealing feature, because it reduces the likelihood of damage to any space systems that are accidentally illuminated by the laser beam, and it might assuage fears of use of the laser source as a weapon.

Direct Targets

Direct targets transmit the laser beam through a transparent target material to facilitate absorption and confined ablation at a second material for tractor beam propulsion. Direct targets are not purely confined systems, because in driving mode, they operate by ablation at the front surface of the target. In some concepts proposed here, an unfocused laser beam would be used for both the tractor beam and driving modes, but other concepts [11] rely on focusing the beam for one or both modes.

For direct systems, thrust parity (i.e., toward or away from the laser source), as well as thrust vectoring, can be controlled in several ways. At the target, the propellant or propellant geometry can be varied, but these parameters are fixed during a mission. At the laser source, the wavelength, fluence (pulse energy/spot area), beam position on the target, and beam spatial profile can be modified in real time. Because of the abundance of control parameters, many types of direct targets are possible, including single-layer and multilayer targets. Some examples of two-layer targets are provided in Fig. 2 in terms of wavelengths λ_1 and λ_2 and fluences Φ_1 and Φ_2.

Figure 2a shows thrust parity selection based on the laser beam position on a spatially patterned target, enabling tractor beam (top) or driving (bottom) propulsion. Torque can also be imparted, facilitating attitude control. Targeting and beam divergence become crucial as the distance from the laser source increases.

Figure 2b shows thrust parity selection by laser wavelength for tractor beam (top) or driving (bottom) propulsion. This concept uses at least two laser wavelengths: λ_1 and λ_2. At a minimum, the first propellant should be transparent at λ_1 and strongly absorbing at λ_2. In principle, the second propellant need only be strongly absorbing at λ_1, but if it were also transparent at λ_2, the target could be remotely controlled from two directions (e.g., enabling guided target transfer between two laser stations).

Figure 2c shows thrust parity selection by fluence. At low fluence (top), the laser beam passes through the first material with a high ablation threshold and impinges on a second material with a low ablation threshold. Confined ablation of the second layer produces tractor beam propulsion. At high fluence (bottom), the laser beam exceeds the first ablation threshold, generating driving propulsion.

Figure 2d shows a structured target similar to Fig. 2a, but in this case, the laser beam remains centered, and it is merely switched between operational modes to generate different beam profiles. For instance, a CO_2 laser could be switched between stable oscillator (quasi TEM_{00}) and unstable oscillator (washer) modes to select tractor beam (top) or driving propulsion (bottom). An asymmetric laser beam profile incident on this target could generate torque for attitude control.

Conclusions

Essential concepts for laser ablation propulsion tractor beams were introduced. Direct and indirect cooperative targets were proposed, including control pathways. For direct targets, target parameters include material and geometry; adjustable control parameters at the laser source include beam position at the target, fluence, wavelength, and laser beam spatial profile. Application of thrust and torque to remote targets is possible in real time, facilitating novel space applications.

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