LASER ABLATION BASED SPACE DEBRIS REMOVAL

The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science, with a major in Aerospace Engineering.

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DEDICATION

I would like to dedicate to my advisor, my husband, my mother, my brother, and my family. They have always taken my back and will always appreciate all they have done throughout the process. I would also like to dedicate to my fellow lab mates who have been very supportive during lab presentations.
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ABSTRACT

Space debris are defunct man-made satellites orbiting in the low-earth orbit (LEO) and Geo-synchronous orbit (GEO) orbiting around earth with high velocities posing a serious threat for current and future missions. Controlling the growth of debris is of great importance for sustained space operations. This has led researchers to investigate a wide variety of active debris removal missions basing on their characteristics: contact less, contact, capturing and drag augmentation methods.

This thesis discusses space debris removal using ground based lasers. The effect of laser ablation on de-orbiting process was investigated using Sims-Flanagan model, where change in momentum translates in gradual change in the debris trajectory. A 5 cm spherical shaped debris of mass 0.1 kg was modeled using a series of change in velocities ($\Delta v'$) due to multiple laser engagements to achieve the target orbit of 120 km altitude. The translational dynamics of the debris was determined assuming laser propagation vector non-tangential to its surface under the influence of atmospheric drag. It was observed that the total de-orbit time decreases with the increase in laser coupling coefficient and decrease in laser pulse duration. The model estimated hours to reach the target perigee radius with laser engagement of each 30 seconds, for the coupling coefficient of 6 units, and the correspondingly seconds and engagements for the 6ns laser pulse duration. The model also observed that the atmospheric drag influenced the de-orbit time exponentially accelerating the process as it approaching the earth atmosphere.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. INTRODUCTION</strong></td>
<td>1</td>
</tr>
<tr>
<td>1.1 Motivation</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Literature Review</td>
<td>3</td>
</tr>
<tr>
<td>1.2.1 Ground Based Lasers</td>
<td>3</td>
</tr>
<tr>
<td>1.2.2 Space Based Lasers</td>
<td>4</td>
</tr>
<tr>
<td>1.3 Contribution</td>
<td>5</td>
</tr>
<tr>
<td>1.3.1 Organization of Thesis</td>
<td>6</td>
</tr>
<tr>
<td><strong>2. SPACECRAFT DE-ORBITING TECHNOLOGIES</strong></td>
<td>7</td>
</tr>
<tr>
<td>2.1 Contact less Removal Methods</td>
<td>7</td>
</tr>
<tr>
<td>2.1.1 Space and Ground Based Lasers</td>
<td>7</td>
</tr>
<tr>
<td>2.1.2 Ion Beam Shepherd Method</td>
<td>8</td>
</tr>
<tr>
<td>2.2 Contact Removal Methods</td>
<td>10</td>
</tr>
<tr>
<td>2.2.1 Electrodynmaic Tether Method</td>
<td>10</td>
</tr>
<tr>
<td>2.2.2 TAMU Sweeper with Sling sat 4S Satellite</td>
<td>12</td>
</tr>
<tr>
<td>2.3 Capturing Methods</td>
<td>13</td>
</tr>
<tr>
<td>2.3.1 Capturing using Tentacles</td>
<td>13</td>
</tr>
<tr>
<td>2.3.2 Capturing using Robotic Arm</td>
<td>14</td>
</tr>
<tr>
<td>2.3.3 Capturing using Throw Nets</td>
<td>15</td>
</tr>
<tr>
<td>2.3.4 Capturing using Tether-Gripper Mechanism</td>
<td>16</td>
</tr>
<tr>
<td>2.3.5 Capturing using Harpoon Mechanism</td>
<td>18</td>
</tr>
<tr>
<td>2.4 Drag Augmentation Methods</td>
<td>18</td>
</tr>
<tr>
<td>2.4.1 Foam Method</td>
<td>19</td>
</tr>
<tr>
<td>2.4.2 Inflated Method</td>
<td>20</td>
</tr>
<tr>
<td><strong>3. SPACECRAFT TRANSLATIONAL DYNAMICS</strong></td>
<td>21</td>
</tr>
<tr>
<td>3.1 Two-Body Problem</td>
<td>21</td>
</tr>
<tr>
<td>3.2 Laser Force</td>
<td>22</td>
</tr>
<tr>
<td>3.3 De-Orbit Time</td>
<td>24</td>
</tr>
<tr>
<td>3.3.1 Single Impulse Approximation</td>
<td>25</td>
</tr>
<tr>
<td>3.3.2 Quasi-Circular Approximation</td>
<td>26</td>
</tr>
<tr>
<td>3.3.3 Effect of Coupling Coefficient on De-Orbiting from a Circular Orbit</td>
<td>27</td>
</tr>
<tr>
<td>3.3.4 Effect of Coupling Coefficient on De-Orbiting from a Elliptical Orbit</td>
<td>28</td>
</tr>
<tr>
<td>3.3.5 Comparison of De-Orbit Times between Equivalent Shapes</td>
<td>30</td>
</tr>
</tbody>
</table>
# TABLE OF CONTENTS (continued)

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4 Sims-Flanagan Model</td>
<td>31</td>
</tr>
<tr>
<td>3.5 Laser propagation vector</td>
<td>32</td>
</tr>
<tr>
<td>3.5.1 Change in Perigee radius</td>
<td>34</td>
</tr>
<tr>
<td>3.5.2 Decay due to atmospheric drag</td>
<td>37</td>
</tr>
<tr>
<td>3.5.3 Total de-orbit time</td>
<td>40</td>
</tr>
<tr>
<td>3.5.4 Numerical Simulation</td>
<td>42</td>
</tr>
<tr>
<td>4. Numerical Results</td>
<td>44</td>
</tr>
<tr>
<td>4.1 Accurate Predictions on De-Orbit Times</td>
<td>44</td>
</tr>
<tr>
<td>4.2 Parametric study for Laser propagation vector</td>
<td>45</td>
</tr>
<tr>
<td>4.3 Effect of Coupling Coefficient on De-Orbit Time</td>
<td>46</td>
</tr>
<tr>
<td>4.4 Comparative Study</td>
<td>52</td>
</tr>
<tr>
<td>5. Conclusion</td>
<td>54</td>
</tr>
<tr>
<td>5.1 Thesis Summary</td>
<td>54</td>
</tr>
<tr>
<td>5.2 Future Work</td>
<td>56</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>57</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Net Materials</td>
<td>16</td>
</tr>
<tr>
<td>2.2</td>
<td>Tether Missions</td>
<td>17</td>
</tr>
<tr>
<td>4.1</td>
<td>Number of engagements needed for different $\epsilon$</td>
<td>46</td>
</tr>
<tr>
<td>4.2</td>
<td>De-orbit times with varying $C_m$ for $\epsilon = 30^\circ$</td>
<td>48</td>
</tr>
<tr>
<td>4.3</td>
<td>De-orbit times with varying $\tau$ for $\epsilon = 30^\circ$</td>
<td>49</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Ion beam shepherd method.</td>
</tr>
<tr>
<td>2.2</td>
<td>Electrodynamic Tether Method.</td>
</tr>
<tr>
<td>2.3</td>
<td>Slingsat 4S method.</td>
</tr>
<tr>
<td>2.4</td>
<td>Inflated method.</td>
</tr>
<tr>
<td>2.5</td>
<td>Throw Net method.</td>
</tr>
<tr>
<td>2.6</td>
<td>Tether-Gripper method.</td>
</tr>
<tr>
<td>2.7</td>
<td>Harpoon method.</td>
</tr>
<tr>
<td>2.8</td>
<td>Foam method.</td>
</tr>
<tr>
<td>2.9</td>
<td>Inflated method.</td>
</tr>
<tr>
<td>3.1</td>
<td>Schematic of two-body problem.</td>
</tr>
<tr>
<td>3.2</td>
<td>Schematic of laser ablation of a debris.</td>
</tr>
<tr>
<td>3.3</td>
<td>Hohmann transfer.</td>
</tr>
<tr>
<td>3.4</td>
<td>De-orbit times for altitude changes for 0.1 kg spherical shaped debris in 6600 km radius circular orbit.</td>
</tr>
<tr>
<td>3.5</td>
<td>De-orbit times with varying coupling coefficient in circular orbit.</td>
</tr>
<tr>
<td>3.6</td>
<td>De-orbit trajectory for varying coupling coefficient in elliptical orbit.</td>
</tr>
<tr>
<td>3.7</td>
<td>Comparison of de-orbit times between equivalent shapes.</td>
</tr>
<tr>
<td>3.8</td>
<td>Schematic of debris trajectory over one engagement</td>
</tr>
<tr>
<td>3.9</td>
<td>figure showing the laser propagation vector and spherical coordinates.</td>
</tr>
<tr>
<td>3.10</td>
<td>Variation of scale height with altitude.</td>
</tr>
<tr>
<td>4.1</td>
<td>Effect of change in theta and phi angles on the total de-orbit time of the debris with fixed epsilon angle of 30°.</td>
</tr>
</tbody>
</table>
LIST OF FIGURES (continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>Radius vs time with varying $C_m$</td>
<td>48</td>
</tr>
<tr>
<td>4.3</td>
<td>Radius vs time with varying $\tau$</td>
<td>48</td>
</tr>
<tr>
<td>4.4</td>
<td>Semi-major axis vs time with varying $C_m$</td>
<td>50</td>
</tr>
<tr>
<td>4.5</td>
<td>Semi-major axis vs time with varying $\tau$</td>
<td>50</td>
</tr>
<tr>
<td>4.6</td>
<td>Eccentricity vs time with varying $C_m$</td>
<td>51</td>
</tr>
<tr>
<td>4.7</td>
<td>Eccentricity vs time with varying $\tau$</td>
<td>51</td>
</tr>
<tr>
<td>4.8</td>
<td>Total de-orbit time of 10 kg spherical debris with size 10 cm.</td>
<td>53</td>
</tr>
</tbody>
</table>
NOMENCLATURE

SYMBOLS

\( \beta \)     Scale height, \( 1/\text{m} \)
\( k \)         laser propagation vector
\( n \)        surface normal
\( p \)        perturbing acceleration, \( \text{m}/\text{s}^2 \)
\( \omega_e \)  Earth’s angular velocity, \( \text{rad}/\text{s} \)
\( \phi \)      laser fluence, \( \text{J}/\text{cm}^2 \)
\( \pi \)      mathematical constant
\( \rho \)     atmospheric density, \( \text{kg}/\text{m}^3 \)
\( \tau \)     laser pulse duration or pulse width, \( \text{ns} \)
\( a \)        semi-major axis of an orbit, \( \text{km} \)
\( B \)        Earth’s magnetic field, \( \text{T} \)
\( C_D \)      Coefficient of Drag
\( C_m \)     laser coupling coefficient
\( e \)       eccentricity of an orbit
\( E_{\text{inc}} \) incident laser energy, \( \text{kJ} \)
\( G \)        Newtonian constant of gravitation, \( \text{kgm}^3/\text{s}^2 \)
\( G_m \)     area matrix
\( I \)       laser intensity, \( \text{W}/\text{cm}^2 \)
\( R_{\text{gas}} \) Universal Gas Constant, 8.3145 \( \text{J/mol.K} \)
\( v_r \)     radial velocity of the debris, \( \text{km}/\text{s} \)
\( r_p \)     perigee radius of an orbit, \( \text{km} \)
\( R_E \)     radius of the Earth, \( \text{km} \)
CHAPTER 1
INTRODUCTION

1.1 Motivation

Space debris accumulated in Low Earth Orbit (LEO) can pose serious threat to current and future space missions and extends to about 2000 km from earth’s atmosphere. The low earth orbit comprises of defunct and non-operational satellites, fragmented pieces orbiting at 7.5 km/sec, the geosynchronous orbit constitutes end-of-life telecommunications and meteorological satellites that orbit at 10 km/sec. Currently, there are about 500,000 tracked debris orbiting around the earth. The actual number of debris objects in orbit is believed to be several times the officially tracked objects. However, the greatest danger to operational spacecraft is from objects that in the millimeter-to-centimeter size range. These objects are large in number and have the potential to cause severe damage to the operational spacecraft and may even collapse the space mission. Majority of these debris is accumulated in low-earth orbits, up to an altitude of 800 km. The orbital lifetime of objects in these orbits varies from a few days to few years depending on the atmospheric density variations, and earth’s gravitational field. At higher altitudes, the lifetime of objects is even longer due to very less atmospheric drag. But perturbation forces such as solar wind and radiation pressure, and lunar perturbations eventually bring them down into earth’s atmosphere eventually.

On February 10, 2009, a collision between a non-operational Russian satellite Kosmos 2251 and Iridium 33 satellite caused nearly 13,000 debris particles of which only 2,000 were tracked. As the space agency was operating several replacement satellites, the collision created serious interruptions to the services. Currently, space telescopes can track space debris down to about 1 cm in size in low Earth orbit, and about 50 cm in size in geosynchronous orbit. Space debris hitting a spacecraft can potentially cause a continuous chain of reactions, resulting in a cascading effect and increasing the probability of further colli-
sions, thereby creating more debris in the process. The growing concern about the space debris environment in the international space community has initiated many studies in this area, including risk assessment [3], modeling of debris [6], debris removal methods [7, 8], conjunction assessment [9], and optimization of multi-rendezvous debris removal missions [10]. However, the major focus remained on debris mitigation rather than removal. In an attempt to avoid collisions, space agencies have equipped the satellite with high-spectrum cameras to continuously monitor the space environment in that orbit. Every year, the international space station (ISS) performs at least three debris collision avoidance maneuvers.

With increasing number of launches in future years, it has been observed [11] that five debris must be removed every year, starting from 2020, in order to maintain the risks at the current level. Satellites and rocket stages that have enough propellant can drive themselves into decay orbit. However, satellites with little propellant and other space objects such as debris pieces from collision or upper stage parts will rely on atmospheric drag to decay their orbit sufficiently for burning up in the atmosphere. Note that such objects in low-Earth orbit (LEO) experience perturbation due to atmospheric drag, which changes the semi-major axis of the orbit, causing the satellite to eventually crash into the Earth or burn up in the atmosphere.

The natural de-orbiting time of such debris can be on the order of a few years and debris in higher orbits may take hundreds of years to burn up, possibly more. While in orbit, it poses a real threat to spacecraft operators, who must maneuver the satellite to avoid the debris to prevent damage or collision. Hence, active debris removal is essential, and many studies have been performed to investigate the different techniques for on-orbit debris removal.

A well-researched method is the electrodynamic tether that can be attached to the spacecraft and is used to de-orbit at the end of the spacecraft’s lifetime [12, 13, 14, 15, 16]. Another proposed method is the use of a powerful laser to ablate the surface of the debris; the momentum exchange due to the ablation process provides an engine-like thrust to slow the
debris. A similar methodology utilizes an ion beam instead of laser plasma. Another novel solution for performing active debris removal are ultra-thin inflated balloon envelope and foam method with the aim of increasing the atmospheric drag by attaching to the debris, thereby leading to a faster de-orbiting process. Other proposed solutions include tethered nets. This dissertation focuses on laser ablation based removal of space debris.

1.2 Literature Review

Space missions often perform maneuvers to avoid collision with the debris. If collision occurs, to reduce the impact of the damage, a layer of metal foil is used on the outside of the satellite. Although maneuvering and adding an additional layer of metal foil have been proven to be promising, however, these methods have limitations such as adding extra fuel weight to the satellite system to perform collision avoidance maneuvers.

Since 1978, the space debris and its removal has been widely studied. Several removal methods have been proposed and researched extensively to check the feasibility and extent of working. Among all the debris removal methods, laser ablation is the only method that can be used to remove debris of sizes between 1 cm and 10 cm. Although the velocity increment produced by laser ablation is small, upon continuous bombardment of laser pulses to the debris can significantly modify its orbit.

1.2.1 Ground Based Lasers

The feasibility of ground based lasers for debris removal has been studied for several decades. In 1995, a study was initiated by NASA to irradiate the space debris using ground-based lasers. This involved study of five different debris categories: Na/K spheroids, carbon phenolic fragments, multilayered insulation, crumpled aluminum, and steel tank rib supports and their characteristics, the feasibility of three different laser types: pulsed gas lasers, solid state lasers and continuous wave gas lasers, and concluded that Nd:glass laser has the potential to remove debris of size range between 1 cm - 10 cm. They also studied the characteristics of the debris for detection and tracking. One of the major concern about
the ground based laser operation is the laser-atmosphere interaction, they estimated that a fluence of $5\text{ J/cm}^2$ and pulse energy of 20 kJ can provide the necessary momentum change to modify debris orbit. Due to the very small amount of the impulse generated from laser ablation, this method is limited to debris of small sizes, but cleaning the larger defunct satellites is also of greater importance as any collisions may add up thousands of debris. Rezunkov [23] designed a concept called Laser-Orbital Transfer Vehicle (LOTV) to remove debris greater than 10 cm. High power laser propulsion system with a power of 500 kW is used to produce thrust to de-orbit larger debris. Soulard et al. in 2014 [18] presented an idea of using ICAN laser for tracking and de-orbiting fragmented space debris.

Liedahl et al. in 2013 [24] developed an analytical expression to study the dynamic response of the debris due to laser ablation. The linear momentum transfer after laser ablation is then compared between different shapes: cube, sphere, plate, spinning plate, cone cylinder, asymmetric dumbbell and wedge. They observed that the way debris recoil to the ablation is dependent on its shape and orientation. For an idealized shaped debris, the impulse generated due to laser ablation is always a function of orbital parameters but when the debris is irregularly shaped, several external and internal effects must be taken into account to evaluate its response during impulse transfer. The problem with an irregularly shaped debris is when it is hit by a laser, the torque generated results in spinning of the target. Due to this spin, the study of impulse generated between shot to shot is very complex. Liedahl et al. in 2010 [25] studied the impulse effects for an irregularly shaped debris by sampling the mean laser engagements.

1.2.2 Space Based Lasers

Wolfgang O. Schall studied the potential of a pulsed laser space based laser with 100 kW power and wavelength in the 1 - 2 $\mu$m region to de-orbit the debris. The major concern of a space based laser is the selection and placement of the system in the orbit so that the system is not collided by the debris. Schall proposed that with an interception distance of 100km and maximum laser energy of 100 kJ, a 100 gm debris can be de-orbited.
Although modifying the orbit of the debris is the primary goal of any debris removal system, controlling the trajectory debris is also as important as de-orbiting so that the debris won’t collide with any operational satellite in space. Ashish Tewari [26] proposed a deorbiting system using a tug with varying thrust to collect and reduce the velocity of the debris. Using long range laser optics, the tug establishes control over the target debris and docks to it. Through ablation, the tug propels itself and the target to the destination orbit and then release it. Though the propellant consumption is higher for laser tug compared to conventional propulsion system, it can reduced to smaller burns depending on the operation. A more elaborated study on laser tug was performed by Eric S. Smith et al. in 2013 [27]. They studied the performance parameters, propellant requirements and docking risks associated with the tug. The biggest challenge for the laser tug concept is docking with the debris when it’s tumbling. Rubbel Kumar et al. in 2015 [28] developed an algorithm to de-spin the debris by reducing its angular momentum. It’s feasibility was proved by de-tumbling a cylindrical shaped debris using a laser tug with 250 W power in 2.5 days. The comparative studies among laser with 250 W power and 10 kW power proved that with the former the tug can stretch up to 60,000 m but with the latter, the tug would only travel 1800 m.

1.3 Contribution

The contributions of thesis are:

- We modeled the de-orbiting process as a low-thrust transfer under the action of continuous perturbation forces and investigated de-orbit times for debris that has cubic and spherical shapes. The idea is that the laser ablation force slowly changes the orbit of the debris over time. In the literature, the de-orbit times for laser based debris removal are estimated considering the laser action on the debris is impulsive, a Hohmann transfer like orbital transfer. Hohmann orbital transfer is a method of modifying the altitude of the debris by giving two burns on opposite sides of the transfer trajectory. In both cases, the laser force is assumed tangential (opposite to the velocity vector) to the surface of the debris.
• We considered the de-orbiting process under most possible scenario where the laser propagation vector is non-tangential and the trajectory of the debris is modeled as series of $\Delta v$'s due to multiple laser engagements from initial orbit to the resulting orbit using Sims-Flanagan model.

1.3.1 Organization of Thesis

The thesis is organized as follows:

• Chapter 2 discusses contact less removal methods, contact removal methods, capturing methods, and drag augmentation methods for space debris removal along with their advantages and disadvantages.

• Chapter 3 reviews the translational dynamics of the debris assuming two-body problem. Next, the chapter discusses the laser force and laser propagation vector, effect of coupling coefficient on de-orbit times for two cases: Single impulse approximation and quasi-circular approximation. The chapter also introduces Sims-Flanagan model and derives equations for change in perigee radius with a non-tangential laser propagation vector and total de-orbit times under the influence of both laser ablation and atmospheric drag.

• Chapter 4 demonstrates the numerical results with predictions on de-orbit times using Sims-Flanagan model. Next, the chapter presents results for semi-major axis and eccentricity and discusses the effect of coupling coefficient, and pulse duration on the de-orbit times.

• Chapter 5 summarizes the thesis and discusses the future work.
CHAPTER 2

SPACECRAFT DE-ORBITING TECHNOLOGIES

2.1 Contact less Removal Methods

Contactless removal methods does not involve direct contact with the debris. The principle of this method is to lower the altitude of the debris by decreasing its velocity of the debris. Some of the contact less removal methods are: Ground and Space based laser ablation, and Ion beam shepherd method. The advantage of these methods is that this can be operated from long distances and is compatible with different sizes of debris.

2.1.1 Space and Ground Based Lasers

The laser ablation based debris removal [29] is the process of bombarding laser pulses on the surface of the debris to reduce its orbital speed thereby pulling it into lower earth orbit, where it burns. The force generated due to the ablation process of the debris of mass \( m \) is described using a mechanical coupling coefficient \( C_m \) that converts the incident laser energy \( E_{\text{inc}} \) and the direction of laser impact into an equivalent mechanical force.

\[
m \left( \frac{dv}{dt} \right)_{\text{laser}} = -C_m \frac{dE_{\text{inc}}}{dt} \mathbf{n},
\]  

(2.1)

Researchers have performed feasibility studies on laser ablation method and demonstrated that a ground based laser with 370 kW power and a 25 m laser beam mirror can de-orbit a one-ton object in 3.7 years [29]. For a space-based laser [19], an average power of 100 kW power and 700 kJ laser energy is sufficient to de-orbit the debris. As the distance from the surface of the earth increases, the penetration rate of the laser decreases due to atmospheric interactions with the laser beam. The relationship between change of mass and ablation rate,

\[
\Delta m_e = t_m E
\]  

(2.2)
The blow off velocity can be expressed as

\[ v_e = \frac{C_m}{t_m} \]  

(2.3)

The ablation rate \( t_m \) is defined as the total mass removed from target per laser energy pulse. If the blow velocity \( v_e \) is known, then the minimum mass \( \Delta m \) that has to be ablated and from this the minimum laser for achieving the required velocity can be estimated. As the vapor is ejected from debris, a momentum change occurs that is analogous to impulse delivered by a rocket. This momentum change is usually in the direction of laser’s incoming beam.

A numerical experiment [30], the values of \( C_m \) for Al is \( 2 \times 10^{-5} \) N-s/J. Considering aluminum as debris material, Lenk et al. in 1997 [31] assumed the ablation rate to be \( t_m = 80 \times 10^{-9} kg/J \). The small impulse obtained from the laser ablation of the surface cannot be effective for the space debris of sizes larger than 20 cm. Since the behavior of the debris is shape dependent, Liedahl et al. in 2013 [24] investigated the behaviors of different debris shapes including cube, sphere, cylinder and plate. For the lasers with high power and good beam quality, the optical distraction due to the environment is a limitation and makes this method less efficient for GEO.

2.1.2 Ion Beam Shepherd Method

The Ion beam shepherd (IBS) contact less method was first introduced in 2012 by Claudio Bombardelli et al. in 2011 [20] for asteroid deflection but later extended the study for space debris removal as well. The concept of IBS is to create a force or torque on the debris to modify its orbit by blasting quasi-neutral plasma beam on its surface. The force exerted on the debris is due to the change in momentum of the ions bombarded. The IBS consists of a primary and secondary propulsion system. The primary propulsion system shoots quasi-neutral plasma directed thruster onto debris. The secondary propulsion system produces an equilibrium force so that the IBS does not drift away from the debris.
The most widely tested electric propulsion systems are ion engine and Hall-effect thruster. The ion engine creates a beam by extracting ions from plasma using a set of electrical grids, and the beam is neutralized with electrons. While hall effect thruster accelerates ions of the quasi-neutral plasma through an electric potential. With the assumption that debris orbit is initially circular and undergoes constant tangential acceleration \( F/m \), the time required to transfer the debris from higher altitude \( R \) to lower altitude of radius \( r \) is:

\[
\Delta t = m \frac{\sqrt{\mu}}{F} \frac{\sqrt{R} - \sqrt{r}}{\sqrt{rR}}
\] (2.4)

With an assumption that the ion beam is always pointed in the direction of the IBS velocity vector, Bombardelli and Pelaez \[20\] developed an ion beam interaction simulation package to understand dynamics and control of the IBS system. They also performed design optimization studies to understand how IBS mass and distance between IBS and target can affect the de-orbiting process. By considering the shape of the debris is spherical, Merino et al.

![Figure 2.1: Ion beam shepherd method.](image)

in 2011 \[32\] studied the plasma-target interactions and estimated the momentum transfer efficiency of plasma considering spherically shaped debris. Also, they examined electrically charging phenomena and concluded that the relative charge between IBS and the debris is stable because of the linking high-density plasma beam in space.

Merino et al. in 2013 \[33\] developed Ion Beam Interaction Simulator (IBIS) to examine the IBS model. IBIS is a simulator to study, analyze and understand the feasibility
of IBS concept. IBIS can model ion beam interaction with any rigid object. Also, the IBIS assesses the overall system and optimizes the design parameters and de-orbiting strategies. Kitamura [34] proposed a model of de-orbiting GEO debris by irradiating it with an ion beam. A numerical study was performed by assuming re-orbiter of 1000 kg and ion engines with 40 mN thrust levels and observed that it would take six days to re-orbit debris objects. Ding et al. in 2011 [35] developed a testing platform to validate Ion beam neutralization. Brown et al. in 2007 [36] explored the idea of using a lunar-based ion beam generator as an ion source to accelerate the spacecraft for smaller distances.

The IBS concept has an advantage over laser ablation based debris removal. The momentum generated by accelerating ion beam onto the debris is higher than the momentum transmitted during laser ablation process for equal power cost. As there is no friction to keep the IBS in place after each blast, it pushes itself backwards. To keep IBS steady, it is essential that the secondary propulsion system needs to be designed well that can in turn increase the satellite’s overall size and weight.

2.2 Contact Removal Methods

Contact removal method is an idea of direct interaction between the debris removal system and the space debris.

2.2.1 Electrodynamic Tether Method

Electrodynamic tethers (EDT) work on the principle of utilizing electromagnetic forces generated due to the electric potential across the conductive tether by its motion through earth’s magnetic field [11]. The basic principle of EDT is Lorentz force - a force that a magnetic field exerts on a conductive wire. The idea is to deploy a 2,296 ft tether from a satellite in a way that the tether latches onto the debris. The tether uses the force generated by the electric current and the earth’s magnetic field to pull-down the debris into the atmosphere. The EDT system is composed of two emitter cathodes and a conductive tether. The material for the tether is still questionable as it should survive the extreme space environment. The orientation and vibrations of the tether system can be controlled
by changing and reversing currents [37] in the tether. The force acting on a charge q moving with a velocity v in a magnetic field given as

$$F_{mag} = \int_0^L i \, dL \, B$$  \hspace{1cm} (2.5)

An electric field, E, is observed when the tether moves with velocity v at right angles to earth’s magnetic field B and is given as,

$$E = vB$$ \hspace{1cm} (2.6)

The voltage generated between the opposite ends of the long conducting tether with length, L is

$$V = EL \cos \alpha = vBL \cos \alpha$$ \hspace{1cm} (2.7)

where \( \alpha \) is the angle between length vector of the tether and electric field vector. The positive anode end collects electrons from ambient plasma and expels them from negative charged cathode into outer space. This process generates in Lorentz force that opposes the motion of the tether. The conducting tether with mass \( m_T \) and density d and resistivity \( r \) orbiting through the transverse magnetic field B at a velocity v, will generate electric power P in tether given as:

$$P = \frac{m_T(vB)^2}{2r^2}$$ \hspace{1cm} (2.8)

The time needed to lower a satellite in a circular orbit from radius \( a_2 \) to \( a_1 \), is

$$\Delta t = \int_{a_1}^{a_2} \frac{\mu m}{2r^2P} \, da$$ \hspace{1cm} (2.9)

where m is the satellite mass including tether system and a is the orbital radius.

The continuous flow of current in the conductor moving under the influence of Earths magnetic field exerts a drag force on the tether thereby decelerating it and lowering its orbit.
Because the tether is a long thin cable, electrodynamic forces can cause the tether to drift from vertical position but the gravity gradient pulls the tether to its initial position resulting in pendulum like motion. As the tether orbits the earth, it develops librations due to the varying earth’s magnetic field. The failure of advanced tether experiment that was launched in 1988 proved the significance of controlling librations. The mission was aborted after deploying 22 m of all 6.5 km length tether. Several studies have since then been initiated to develop control strategies to handle these instabilities. Noboru\textsuperscript{[38]} developed a control law using electric switch to control librations of tether system.

Electrodynamic tether have an advantage of not needing a propulsion system to operate and high technology readiness level. Because of the length limitations of the tether, EDT is unavailable in Geostationary orbit and is restricted to LEO.

\subsection{2.2.2 TAMU Sweeper with Sling sat 4S Satellite}

Texas A and M University developed a dual spinning satellite called TAMU sweeper\textsuperscript{[39]} to sweep the debris by capturing and expelling debris. The main components of Sling-sat satellite are the adjustable arms that collect and expel debris. By adjusting the length of the arms, the ejection speed is achieved. With the dynamics of interactions between bodies,
the orbital transfer is achieved by exploiting momentum exchange thereby reducing the need for fuel.

For the sling-sat satellite, it is important to know the effect of ejecting debris on the satellite. Missel and Mortari [40] investigated the effect of satellite-debris interactions on their orbits. They analyzed the effect on satellite and debris after ejecting debris. They performed path optimization for TAMU sweeper by using an algorithm [41] to determine the mass of debris after capturing. By considering the sling-sat as a two-mass system, Missel derived mathematical models using angular momentum conservation. Sling-sat is expected to remove 121 objects in its lifetime and is proven to be low cost and effective debris removal technique.

2.3 Capturing Methods

2.3.1 Capturing using Tentacles

With the aid of clamping mechanism, tentacles embrace a point on debris by robotic arm. The tentacle capturing of debris can be performed with and without robotic arm. By using a robotic arm, tentacles embrace debris with a clamping mechanism after holding a point on the target using robotic arm. Trade-off studies by Forshaw et al. in 2014 [42] show that tentacle capturing mechanism with no robotic arm adds up less mass and volume to the system. Tentacle capturing without robotic arm is a typical phenomenon. Wormnes et al. in 2013 [43] performed simulation of target capturing without robotic arm, but the guidance, navigation and control (GNC) requirements are demanding because of high precision needs.
Figure 2.4: Inflated method.

Tentacles capturing without robotic arm must ideally embrace target debris before making a physical contact to avoid bouncing of satellite. Also, this helps attitude control system to stand by while performing capturing. The clamping mechanism is then locked and the chaser-target debris system turns stiff after capturing. Chiesa and Alberto [44], developed finite element models to simulate and estimate the dynamics during capturing.

2.3.2 Capturing using Robotic Arm

Robotic arm works on the idea of using a service satellite to capture debris using robotic arm. Robotic systems are classified depending on the number of actuator arms. The single arm robotic device has a claw connected at the end of the robotic arm to grapple debris. Technical challenges involved in the design of robotic arm are that the arm must be able to buffer and brake residual motions during operation. Unlike single robotic arm, multi-arm robotic system is equipped with claws to grapple debris using different contact points. DECOM (Debris capture and Orbital Manipulation) mission is proposed for active debris removal to mitigate Kessler syndrome. The DECOM spacecraft uses an European Robotic Arm (ERA) derived robotic arm to capture debris. It is expected to remove 32 debris within first 5-year mission. The overall cost of DECOM mission is 392 million US dollars and estimated to remove 88 metric tons of debris after four missions [45]. Marko Jonkovic [46]. al., studied the feasibility of using AGORA (Active Grabbing and Orbital Removal of Ariane) mission to safely de-orbit Ariane rocket bodies. The Agora mission motive is to
remove rocket bodies using active detumbling device and robotic grabbing mechanism. They performed analysis for a capturing and deploying de-orbiting kit.

The main challenge of the robotic arm concept is to overcome tumbling of debris that occurs due to the residual angular momentum. Nishida and Kawamoto \cite{47}, showed that objects with tumbling rate of $3^\circ$ can be easily captured. Brush contactor is estimated to relive objects from residual angular momentum with smooth contact. Implementing brush contactor produced from PTF, objects tumbling rate between 3 and $30^\circ$ per second can de-tumbled.

Orbit missions involving robotic arm technology are ETS-7 of JAXA, Orbital express of DARPA and many others. It is easier to operate robotic arm in these missions as the targets are cooperative. But operating robotic arm in space is challenging because debris does not provide any information to chaser satellite and the objects are prone to tumbling. DARPA developed robotic arm technology named Front end robotics enabling near term demonstration (FRIEND) to perform unaided capturing \cite{48}.

2.3.3 Capturing using Throw Nets

The net capture system shown in the figure captures the target that could be a defunct satellite or debris. The net is stowed in the net canister, that is placed amidst four flying weights called bullets. These four bullets pull the net open, which is connected to the cover. The cover is connected by a 60m long tether with a controllable reel. The reel is controlled by a tensiometer and an on board computer. The mechanism integrated in two of the four bullets will close the net behind the debris and rolls up the cord connecting four bullets. The mechanism contains a spindle that rotates by a motor.

Several key concerns related to the concept are studied such as using the net and tether to capture and de-orbit debris, whether the net properly entangle the target, the level of force transmitted to target and how the whole system affects the dynamics of pulling phase. The 10 by 16 m net with a mesh size of around 20cm is built from a material with high strength to weight ratio such as Dyneema. With a mass at each corner of the net,
The net reaches its full size few meters away from the impending debris and passively wraps around the debris. Unlike other capturing methods, throw nets can obviate rendezvous and docking by allowing large space between satellite and debris. Cercos et al., worked on an experimental scaled setup to validate net simulator when the motion of net wraps a target mock-up under micro gravity conditions. Golebiowski et al. in 2014 proposed and validated a mathematical model to evaluate the performance of the net during flight, impact and capture.

### Table 2.1: Net Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Stress, $\sigma$ [GPa]</th>
<th>Young Modulus, $E$ [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zylon</td>
<td>5.8</td>
<td>180</td>
</tr>
<tr>
<td>Dyneema</td>
<td>3.7</td>
<td>116</td>
</tr>
</tbody>
</table>

#### 2.3.4 Capturing using Tether-Gripper Mechanism

Since 1960, many space concepts have been implemented using tethered space robots for deep space research. The principle of tether-gripper mechanism is similar to net capturing but is more complicated in operation. The purpose of 3 finger gripper in tether-gripper mechanism is to capture a specific part of debris. To track the debris and identify the right point to take a grip on the debris is complicated as debris move with high velocities. Huang proposed tethered space Robot (TSR) system, which is composed of a platform, a gripper and a space tether. He investigated the tether gripper mechanism for debris removal.
in different areas [53]. He also studied the issue of de-tumbling of tethered robot-target system after capturing target [54]. Before de-orbiting, it is necessary to estimate mass and inertia parameters of debris to ensure controllability. Zhang [55] performed mass estimation during first stage of retrieval and an inertia estimation during middle stage of retrieval.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Sponsor</th>
<th>Year</th>
<th>Length</th>
<th>Orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gemini XI</td>
<td>NASA</td>
<td>1967</td>
<td>50m</td>
<td>LEO</td>
</tr>
<tr>
<td>Gemini XII</td>
<td>NASA</td>
<td>1967</td>
<td>30m</td>
<td>LEO</td>
</tr>
<tr>
<td>CHARGE-2B</td>
<td>NASA</td>
<td>1992</td>
<td>500m</td>
<td>Suborbital</td>
</tr>
<tr>
<td>PICOSAT’s</td>
<td>Aerospace Corporation</td>
<td>2000</td>
<td>30m</td>
<td>LEO</td>
</tr>
<tr>
<td>T-REX</td>
<td>NRO</td>
<td>2013</td>
<td>1km</td>
<td>LEO</td>
</tr>
</tbody>
</table>
2.3.5 Capturing using Harpoon Mechanism

The idea of Harpoon mechanism is to shoot barbs from chaser satellite that penetrates into targeted space debris. Chaser satellite then pulls the debris to re-enter into lower atmosphere where debris burns up. It is an appealing capturing method as the mechanism does not need a grappling point on the debris to shoot barbs. This mechanism can be used to capture debris of any shape. The major concern of this mechanism is when barbs penetrates into debris, there is high risk of generating new debris. To understand the grappling mechanism, Reed [56] conducted tests and experiments on ground. Although trade off studies by European Space Agency (ESA) showed that the net method has better system performance and little physical constraints, harpoon mechanism is still a suggested option because of its easiness to be tested on ground [31]. Since two decades, many techniques for orbital debris removal have been proposed and developed. This paper discusses methods for orbital debris capturing and removal. A comparison between existing technologies is drawn. research areas to be developed such as net deploying, de-tumbling with IBS are prospected.

![Figure 2.7: Harpoon method.]

2.4 Drag Augmentation Methods

The concept of drag augmentation method is to increase the influence of atmospheric drag on the debris by increasing the area-to-mass ratio of the space debris. Unlike capturing and contact based removal methods, drag augmentation method does not require docking with the space debris. The components of this method are a chaser satellite, and a mechanism that carries foam or a inflatable material that can be shot on to the debris.
2.4.1 Foam Method

The chaser satellite with an active debris removal system shoots the foam onto the debris, the foam expands isotropically \[57\] to increase the wet surface of the debris. This process increases the natural drag on the debris and decreases the velocity thereby de-orbiting. Due to the small density and large volume of the foam, the area to mass ratio increases. When compared to the re-entry time of debris under the influence of atmospheric drag, the re-entry time using foam method is less than 20 years. Pergola et al. in 2011 \[58\] proposed and analyzed debris removal using expanding foams.

Assuming the spherical shaped debris with mass \(m\) and the density of the foam ball \(\rho_f\), the area to mass ratio of the foamed debris is,

\[
\frac{A}{m} = \frac{\pi r^2}{\frac{4}{3} \rho_f \pi r^3 + m}
\]  

(2.10)

By assuming constant acceleration, the time needed to perform maneuver\[58\] is

\[
\Delta t = \frac{\Delta V}{a} = \frac{\Delta V}{T} \left( m_0 - \frac{m_f}{2} \right)
\]

(2.11)

Unlike lasers passing through the atmosphere, this method doesn’t pose potential hazards

![Figure 2.8: Foam method.](image)
for ground based systems. A combination of foam and electric propulsion system are studied to remove multiple targets in one mission.

2.4.2 Inflated Method

The principle of inflated method is very similar to foam method. An inflated ball replaces the foam ball in this method. Kerry [59] discusses an inflatable de-orbit system named Gossamer Orbit Lowering Device (GOLD). The idea is to attach a large, lightweight and inflated envelope to the target debris to lower its orbit. The GOLD system can operate successfully in the range of 750 to 900 km. Above 1200 km, propulsive options requires a lower mass fraction of spacecraft than GOLD. The main disadvantage of this method is that when the inflated ball is hit by any space debris the total mission will be collapsed.

Figure 2.9: Inflated method.
CHAPTER 3
SPACECRAFT TRANSLATIONAL DYNAMICS

For any orbital mechanics problem, its necessary that we first understand the dynamics of the spacecraft. This chapter discusses the translational dynamics of the debris within the context of the two-body problem. Newton’s law of gravitation provides a means to study the translational dynamics of a body. The law states that an object attracts the other with a force equal to the product of their masses and inversely proportional to the square of the distance between them. Newton’s law of gravitation combined with Kepler’s laws form the basis to study the orbital motion of the objects. By introducing the approximation that there are only two bodies that are spherically symmetric with uniform density and are point masses form a the two-body problem. These assumptions allow a two-body problem, however, in reality, there could be three bodies and perturbations that can significantly change the orbit of it.

3.1 Two-Body Problem

The space debris orbiting around the Earth, let \( \mathbf{r}_1 \) and \( \mathbf{r}_2 \) represent the position vector of two bodies of mass \( m_1 \) and \( m_2 \) with respect the inertial frame of reference - A reference frame where Newton’s laws of motion are valid. The position vector of \( m_2 \) relative to \( m_1 \) is

\[
\mathbf{r} = \mathbf{r}_2 - \mathbf{r}_1
\]  

(3.1)

Furthermore, let us denote the position vector of the debris with respect to the Earth by \( \mathbf{r} \), and the velocity vector of the debris with respect to the Earth by \( \mathbf{v} \) and by Newton’s law of gravitation, the equation of motion of the debris is

\[
\ddot{\mathbf{r}} = \dot{\mathbf{v}} = -\frac{\mu}{r^3} + \mathbf{p}.
\]  

(3.2)
Figure 3.1: Schematic of two-body problem.

The perturbation in a two-body problem acting on the debris is considered to be the gravitational attraction of the Earth and the force resulting from the laser ablation. To this end, we considered $p$ to be the perturbing acceleration (or deceleration) experienced by the debris due to the laser ablation process.

The perturbation term for the problem under consideration in this paper is given by:

$$p = \left[\frac{dv}{dt}\right]_{laser}. \tag{3.3}$$

### 3.2 Laser Force

The laser ablation process [60] uses a ground-based or a space-based laser shooting laser pulses to produce plasma plumes from the debris, and thus reducing the orbital speed of the debris and pulling it into lower altitudes where it burns up. The laser must provide enough force to alter the trajectory of the debris in reasonable time, so that the debris
eventually loses altitude and burn up in the denser parts of the atmosphere. As the laser pulses continuously bombard the debris, the force resulting from the ablation process induce a momentum change to slowly modify the debris’ orbit. To this end, let us consider a debris of mass $m$ in an orbit of semi-major axis $a$, eccentricity $e$ and inclination $i$. In the literature, the force generated due to the ablation process of the debris is described using a mechanical coupling coefficient that relates the incident laser energy and the direction of laser impact into an equivalent mechanical force. We denote the coupling coefficient by $C_m$ and the laser energy $E$ by

$$m \left[ \frac{dv}{dt} \right]_{laser} = -C_m \frac{dE_{inc}}{dt} \mathbf{n}, \quad (3.4)$$

where $\mathbf{n}$ is the vector normal to the surface of the debris on which the laser is incident. The rate of change of incident laser energy can be related to the laser intensity that we denote by $I$; the intensity being defined as the energy per unit area per unit time. We also define the direction in which the laser is shot onto debris as the laser propagation vector, and denote this direction by $\mathbf{k}$. For all the irradiated surfaces with the surface normal continuously changing, the force equation given in (3.4) can be written as:

$$m \left[ \frac{dv}{dt} \right]_{laser} = C_m I \mathbf{k} G_p, \quad (3.5)$$
where $G_p$ is referred to as the area matrix of the debris, as given in Ref. [24]. The target shape has an impact on the force generated due to laser ablation. Note here, for understanding the translational dynamics of the debris, we will consider a point mass approximation for the debris. The consideration of different shapes for the debris is purely for the purpose of quantifying the force acting on the debris due to the laser ablation process. To this end, we specifically focus on two different simple geometrical shapes of the debris in this paper: (1) solid sphere, and (2) solid cube. In either case, the debris is considered to be a homogeneous solid of density $\rho$. In the first case, the radius of the sphere is denoted by $R$, while in the second case, we denote the length of each side of the debris by $s$.

\[
\begin{align*}
\left[ \frac{dv}{dt} \right]_{\text{laser}} &= \begin{cases} 
\sqrt{\frac{\pi}{6\rho^2 m}} C_m I_k, & \text{(sphere)}, \\
\sqrt{\frac{1}{m^2}} C_m I_k, & \text{(cube)}.
\end{cases}
\end{align*}
\]

(3.6)

Note that the density can be written as a function of the mass and the dimensions of the debris. We therefore simplify the above-mentioned equation in the following form:

\[
\begin{align*}
\left[ \frac{dv}{dt} \right]_{\text{laser}} &= \begin{cases} 
\frac{3}{96} \sqrt{\frac{\pi R^2}{m^2}} C'_m I_k, & \text{(sphere)}, \\
\frac{s^2}{m} C'_m I_k, & \text{(cube)}.
\end{cases}
\end{align*}
\]

(3.7)

### 3.3 De-Orbit Time

In the literature [24], the de-orbit times for laser based debris removal are estimated considering that the laser action is impulsive, and a Hohmann transfer like orbital transfer is used. In this paper, we propose to model the de-orbiting mechanism as a continuous-thrust transfer, which would be more appropriate representation considering that the de-orbit time could be large, particularly with limited power availability of the laser, or for larger sized debris. The de-orbit times are for both cases are then compared for a spherical shaped debris at 6600 km radius.
3.3.1 Single Impulse Approximation

As the vapor is ejected from debris, a momentum change occurs that is similar to impulse delivered by a chemical thruster. This momentum change is usually in the direction of laser propagation vector. The de-orbit time is computed in the literature by considering the entire de-orbiting process to be an impulsive maneuver [24]. For instance, by considering the Hohmann transfer equation, the velocity change required for a transfer from a circular orbit of radius, \( r \) to an elliptical orbit with perigee radius, \( r_p \) is,

\[
v_1^2 = \frac{GM}{R_c}
\]

\[
v_2^2 = \frac{2GM}{r} - \frac{2GM}{(r + R_p)}
\]

If \( \Delta v = v_2 - v_1 \), then

\[
\frac{\Delta v}{v_1} = \left( \frac{2R_p}{r + R_p} \right)^{1/2} - 1
\]

Figure 3.3: Hohmann transfer:
Considering LEO only and with $\Delta r = R_p - r$, the approximation for the velocity equation

$$\Delta v \approx v_1 \times \frac{\Delta r}{4R_E}$$

(3.11)

### 3.3.2 Quasi-Circular Approximation

The key idea of considering the laser ablation force is that the action of such a force changes the orbit of the debris slowly and over multiple laser engagements. In other words, the orbital elements change slowly over time. In this subsection, we consider that the orbit is approximately a circle. Hence, the semi-major axis of a debris starting from a circular orbit will approximately equal the radial distance of the debris from the center of the Earth. Assuming that the force is tangential (opposite to the velocity vector) and that the deceleration of the debris is constant, we can write down the imparted velocity change and the de-orbit time for the debris:

$$\Delta v = \sqrt{\frac{\mu}{a_0}} - \sqrt{\frac{\mu}{a_f}}$$

(3.12)

Note that the tangential approximation provides the fastest rate to de-orbit, and therefore, the real de-orbit time would be larger in reality. To study the effect of laser ablation on circular orbits, we assumed that the targets are homogeneous bodies, with either a spherical or cube shape. We consider a cube of side 1cm and a sphere of radius 5cm. The significant portion of orbital debris are made of aluminum, so the density of the debris is 2700 $kg/m^3$. With the coupling coefficient 2 dynes/W and laser intensity 50 $W/cm^2$, the magnitude of velocity is found using equation (3.2) and (3.7). The de-orbit time is plotted using equation (3.9) and (3.12) with the change in radial distance of 100 km away from low earth orbit (6600km). The results show that as the radius increases, the rate of increase of the de-orbit time of the debris for quasi-circular transfer is increasing linearly than the Hohmann transfer. For example, spherical debris of mass 1 kg in quasi circular transfer orbit would de-orbit from 6600 km of distance from earth in 300 seconds after the laser is operated onto
debris. Likewise, the debris in Hohmann transfer orbit would take 200 sec to de-orbit. For a debris of cubical shape with a mass of 1kg in quasi-circular transfer orbit would take 120 seconds to de-orbit. Figure(3.3) summarizes the comparison between the de-orbit time for Hohmann-like transfer with the best-case continuous thrust transfer.

![Figure 3.4: De-orbit times for altitude changes for 0.1 kg spherical shaped debris in 6600 km radius circular orbit.](image)

3.3.3 Effect of Coupling Coefficient on De-Orbiting from a Circular orbit

In this subsection, we are interested to understand the effect of mechanical coupling coefficient on the de-orbiting process. Because we found that the de-orbit times are similar, we will only consider the spherical shape in this analysis. To this end, we consider a spherical shaped debris of radius 5 cm and mass 0.1 kg (this mass will mean that the debris has a density close to that of Aluminum). For the laser being applied on the debris, we consider the intensity to remain the same; however, we vary the coupling coefficient from $C_m = 0$ to 5, and propagate the debris trajectory starting from a circular orbit of 6600 km. To improve the effectiveness of numerical computation, the computation of orbit, laser and debris parameters is performed in dimensionless units. The non-dimensionalization used for trajectory purposes is with respect to 1 LU being equal to 6600 km (perigee of the circular orbit), 1 MU equal to 1 kg (mass of the debris) and 1 TU equal to 849.27 secs.
This trajectory propagation allows for a laser operation continuously for 5 TU, with the laser propagation vector being directed opposite to the velocity vector. Based on these considerations, we obtain the fastest rate of de-orbiting for the debris corresponding to the different values of the coupling coefficient $C_m$. Note that for $C_m = 0$, there is no coupling, meaning that the laser action does not yield any change of momentum to the debris. Hence, the radial distance of the debris remains constant over time. As expected, with the increase in coupling coefficient, greater momentum change happens due to the laser action and hence, the debris reaches lower altitudes. In other words, the de-orbit time of the debris decreases. The solid horizontal line on the plot at 0.98 LU (6500 km) indicates the target radial distance. When debris reaches target radius, 120 km, atmospheric drag is significantly pronounced. Considering small size range (1 cm - 10 cm) considered in this study, it is expected that the debris will burn up eventually.

### 3.3.4 Effect of Coupling Coefficient on De-Orbiting from a Elliptical Orbit

In this section, we are going to study the effect of laser ablation on elliptical orbits. The elliptic orbit that we consider has an eccentricity of 0.1: it has its apogee at 8066.3 km and perigee at 6600 km. Similar to the case studied for circular orbits, we consider spherically shaped debris of radius 5 cm and mass 0.1 kg. As before, we vary the mechanical
coupling coefficient to vary from 0 to 5, in increments of 1. The laser propagation vector is still directed to the opposite of the debris velocity vector for 5 hours.

The non-dimensionalization used for trajectory propagation purposes is still with respect to 1 LU being equal to 6600 km (perigee of the elliptic orbit). The comparison is shown in Fig. 3.6, the propagation of the radial distance over time is compared for the corresponding values of $C_m$. Note that $C_m = 0$, unlike the circular orbit, the radial distance still varies owing to the natural motion under the influence of Earth’s gravity; the variations shown in the plot do not reflect any momentum coupling due to laser action. As we increase the value of $C_m$, thereby resulting in a greater change in the linear momentum of the debris, the influence of the greater perturbation forces leads to a rapid de-orbiting to lower altitudes. Note that the dynamics of the debris is influenced by the product of $C_m I$, rather than each of these separately. That was our motivation to consider only a variation of $C_m$ keeping the laser intensity constant. In other words, if we keep the coupling coefficient the same, and vary the laser intensity in a way that the product of these remain same as our studies, then the effect on the de-orbiting of the debris would remain the same. For both circular and elliptical orbit, coupling coefficient plays a crucial role in de-orbiting process. To achieve lower de-orbit times, it is important to chose a higher $C_m$ value. Lower $C_m$ values does
not only require large number of laser-debris engagements to impart significant amount of
impulse to modify debris orbit but also limits the overall operational capabilities.

### 3.3.5 Comparison of De-Orbit Times between Equivalent Shapes

We consider a spherical and cubic shaped debris that are of the same material (meaning same density) and the same mass. For such a case, the volume of the two debris would be the same and the dimensions of the debris and sphere will be related by:

\[
s = \sqrt[3]{\frac{4\pi}{3}} R.
\]

If this relation holds, then we refer to the shapes as equivalent shapes. To compare the de-orbit times between two equivalent target shapes, we consider a sphere of radius 5 cm, resulting in a comparison with a cube of side 8.05996 cm. The laser is operated for an hour. The debris start from 6600 km radius circular orbit, and after one hour decays to a lower orbit (we denote the final radial distance by \( r_f \)). The comparison is depicted in Figure 3.7.

![Figure 3.7](image)

**Figure 3.7**: Comparison of de-orbit times between equivalent shapes.

Figure 3.8. The results show that the de-orbit times are nearly same for both the shapes.
With the varying coupling coefficient $C_m$ from 1 to 10 dyne/W, the final radial distances are computed. These radial distances measured seem to be very much closer to both cube and sphere shaped debris.

### 3.4 Sims-Flanagan Model

In this section, we considered the de-orbiting process under most possible scenario where the laser propagation vector is non-tangential and the trajectory of the debris with multiple laser engagements from initial orbit to the resulting orbit using Sims-Flanagan model. The debris trajectory is modeled as a series of $\Delta v$'s connected by multiple Keplerian arcs. The trajectory is divided into $n$ number of segments, with continuous thrust $\Delta v$ applied at the mid point of each segment. The $\Delta v$ from each segment is used to find the velocity vector of the resulting orbit.

The $\Delta v$ for each segment can be determined as

$$\frac{dv}{dt} = \lim_{\Delta v \to 0} \frac{\Delta v}{\Delta t} \quad (3.14)$$

For infinitesimal change in time, the change in velocity vector with respect to time can be approximated as its first derivative

$$\frac{dv}{dt} \approx \frac{\Delta v}{\Delta t} \quad (3.15)$$

With applying continuous thrust, the $\Delta v$ is applied in the right direction would push the debris out of the orbit reducing the perigee altitude. By substituting $dv/dt$ from equation (16) for a cube, $\Delta v$ for one engagement is given as

$$\Delta v = \begin{cases} \sqrt[3]{\frac{9}{96}} \frac{\pi R^2}{m_s} C_m I k \Delta t & \text{(Sphere)} \\ \frac{s^2}{m_c} C_m I k \Delta t & \text{(Cube)} \end{cases} \quad (3.16)$$

where, $k$ is laser propagation vector, $m_s$ is mass if sphere, $m_c$ is mass of cube and $\Delta t_c$ is laser engagement time.
3.5 Laser propagation vector

In the previous analysis, laser propagation vector is considered non-tangential to the orbital motion of the debris and the de-orbit times were estimated. In this thesis, to study the translational dynamics of the debris the framework is developed based on Newtonian mechanics. A fixed inertial reference frame ($I$) is considered with its origin fixed at the center of Earth. The coordinates are represented as ($x, y, z$) and the unit vectors along this coordinate system are ($i, j, k$). A radial frame at point A is represented as as ($r, \theta, \phi$) and the mutually perpendicular unit vectors along this coordinate system are ($e_r, e_\theta, e_\phi$). The point B is the point from where the laser is shot onto the debris from the surface of the earth.

From the figure (3.10), $r$ is the distance from point O to the point A and is also the radius of the earth in this case, $\theta$ is the angle between the z-axis and the position vector of A, $\phi$ is the angle between the x-axis and the projected length of the point A. The laser is shot onto the debris at an angle of $\epsilon$ from the local horizon. The laser propagation vector
Substituting the equation (3.24) in equation (3.12), the force equation can be written as

\[ m \left[ \frac{d\mathbf{v}}{dt} \right]_{laser} = C_m I (\cos \epsilon \mathbf{e}_\theta + \sin \epsilon \mathbf{e}_r) \mathcal{G}, \]  

(3.18)
The matrix transformation from the Cartesian coordinate system to the spherical coordinate system is given as

\[
\begin{bmatrix}
e_r \\
e_\theta \\
e_\phi
\end{bmatrix} =
\begin{bmatrix}
sin\theta \cos\phi & sin\theta \sin\phi & \cos\theta \\
-cos\theta \cos\phi & cos\theta \sin\phi & -\sin\theta \\
-sin\phi & \cos\phi & 0
\end{bmatrix}
\begin{bmatrix}
i \\
j \\
k
\end{bmatrix}
\]  

(3.19)

\[e_r = \sin\theta \cos\phi \hat{i} + \sin\theta \sin\phi \hat{j} + \cos\theta \hat{k}\]  

(3.20)

\[e_\theta = -
\cos\theta \cos\phi \hat{i} + \cos\theta \sin\phi \hat{j} - \sin\theta \hat{k}\]  

(3.21)

\[e_\phi = -\sin\phi \hat{i} + \cos\phi \hat{j}\]  

(3.22)

Substituting the above transformation in the equation (3.24) and equation(3.25) gives,

\[k = \cos\epsilon (-\cos\theta \cos\phi \hat{i} + \cos\theta \sin\phi \hat{j} - \sin\theta \hat{k}) + \sin\epsilon (\sin\theta \cos\phi \hat{i} + \sin\theta \sin\phi \hat{j}) + \cos\theta \hat{k}\]  

(3.23)

\[= (\cos\epsilon \cos\theta \cos\phi - \sin\epsilon \sin\theta) \hat{i} + (\cos\epsilon \cos\theta \sin\phi + \sin\epsilon \cos\theta) \hat{j} - \cos\epsilon \sin\theta \hat{k}\]

3.5.1 Change in Perigee radius

The orbit of the debris is modified due to the force generated by the laser ablation process. The resulting change in velocity leads to a change in the orbit of the debris. The change in debris velocity is achieved by continuous bombardment of the laser pulses onto the debris. The direction of the debris velocity vector depends upon the characteristics of the debris such as it’s mass, size and chemical composition. The orbit of the debris modified as a result of change in the velocity due to laser pulses. An engagement time is a series
of N number of laser pulses shot onto the debris. By substituting $k$ into equation 24, and the laser force in non-tangential direction with an assumption that the angle $\epsilon$ is constant throughout the process, $\Delta \mathbf{v}$ is evaluated for few seconds. For an initial velocity $\mathbf{v}_i$ and final velocity $\mathbf{v}_f$, the change in velocity after laser ablation is

$$\mathbf{v}_f = \mathbf{v}_i + \Delta \mathbf{v} \quad (3.24)$$

Each laser pulse hitting the space debris changes the debris’s orbit in such a way that the perigee radius is decreased. The perigee radius as a function of orbital elements is given by

$$r_p = a(1 - e) \quad (3.25)$$

where $a$ is semi major axis and $e$ is eccentricity. The change in perigee radius with respect to time can be determined by considering the time derivative of the above equation as follows:

$$\frac{dr_p}{dt} = \frac{da}{dt}(1 - e) - a \frac{de}{dt} \quad (3.26)$$

From the radius $r$ and velocity vector $\mathbf{v}$, the orbital elements can be calculated as shown in the further subsections.

**Major Axis**

As the focus of our work is to see the change in perigee radius after the laser ablation. From the equation (3.27), the major axis varies with change in radius of the debris orbit, and its velocity. The change in major axis is estimated using the equation (3.28), with using the first derivative of $a$ with respect to $t$.

$$a = \frac{-\mu}{2} \left( \frac{v^2}{2} - \frac{\mu}{r_p} \right)^{-1} \quad (3.27)$$

$$\frac{da}{dt} = \frac{2}{\mu} a^2 \left[ v \frac{dv}{dt} + \frac{\mu}{r_p^2} \frac{dr_p}{dt} \right] \quad (3.28)$$
Eccentricity

From the radius and velocity, eccentricity of the orbit can be calculated using

\[ e = \frac{1}{\mu} \sqrt{(2\mu - r_p v^2)r_p v_p^2 + (\mu - r_p v^2)^2} \]  

(3.29)

Since point B is the perigee of the orbit, the radial velocity is zero, \( v_r = 0 \), the above equation is further simplified as

\[ e = \frac{1}{\mu} \sqrt{(\mu - r_p v^2)^2} = 1 - \frac{r_p v^2}{\mu} \]  

(3.30)

Applying the first derivative on eccentricity with respect to time,

\[ \frac{de}{dt} = -\frac{1}{\mu} \left[ 2r_p v \frac{dv}{dt} + v^2 \frac{dr_p}{dt} \right] \]  

(3.31)

Substituting \( \frac{da}{dt} \) and \( \frac{de}{dt} \) in equation (3.37) gives

\[ \frac{dr_p}{dt} = \frac{da}{dt}(1 - e) + a \left( -\frac{de}{dt} \right) \]

\[ = \frac{2}{\mu} a^2 (1 - e) \left[ \frac{dv}{dt} + \frac{\mu}{r_p^2} \frac{dr_p}{dt} \right] + a \left[ \frac{2r_p v}{\mu} \frac{dv}{dt} + v^2 \frac{dr_p}{dt} \right] \]

\[ = \frac{dv}{dt} \left[ \frac{2va^2(1 - e)}{\mu} + \frac{2ar_p v}{\mu} \right] + \frac{dr_p}{dt} \left[ \frac{2a^2 \mu (1 - e)}{\mu r_p^2} + \frac{av^2}{\mu} \right] \]  

(3.32)

Re-arranging \( \frac{dr_p}{dt} \) and \( \frac{dv}{dt} \),

\[ \frac{dr_p}{dt} \left[ 1 - \frac{2a^2 \mu (1 - e)}{\mu r_p^2} - \frac{av^2}{\mu} \right] = \frac{dv}{dt} \left[ \frac{2va^2 (1 - e)}{\mu} + \frac{2ar_p v}{\mu} \right] \]  

(3.33)

\[ \frac{dr_p}{dt} = \left[ \frac{2va^2 (1 - e)}{\mu} + \frac{2ar_p v}{\mu} \right] \frac{dv}{dt} \left[ 1 - \frac{2a^2 \mu (1 - e)}{\mu r_p^2} - \frac{av^2}{\mu} \right] \]  

(3.34)
Substituting \( r_p = a(1 - e) \) in equation (3.45), the equation deduces to

\[
\frac{dr_p}{dt} = \left[ \frac{4avr_p}{\mu \left( 1 - \frac{2a}{r_p} \right) - av^2} \right] \frac{dv}{dt}
\] (3.35)

\[
\frac{\Delta r_p}{\Delta t} = \frac{dr_p}{dt}
\] (3.36)

Substituting \( \frac{dr_p}{dt} \) and equation

\[
\frac{\Delta r_p}{\Delta t_e} = \left[ \frac{4avr_p}{\mu \left( 1 - \frac{2a}{r_p} \right) - av^2} \right] \frac{dv}{dt}
\] (3.37)

\[
\Delta r_p = \left[ \frac{4avr_p}{\mu \left( 1 - \frac{2a}{r_p} \right) - av^2} \right] \frac{dv}{dt} \Delta t_e
\] (3.38)

The de-orbit times due to laser ablation can be determined using the below equations for sphere:

\[
\Delta r_p = \sqrt[3]{\frac{9}{96}} \frac{\pi R^2}{m_s} \frac{\Phi}{\tau} \frac{k}{C_m} \left[ \frac{4avr_p}{\mu \left( 1 - \frac{2a}{r_p} \right) - av^2} \right] \Delta t_e
\] (3.39)

### 3.5.2 Decay due to atmospheric drag

In this section, the effect of atmospheric drag on the space debris in the low-Earth orbit is investigated. The debris’s orbital motion around earth is assumed as a Keplerian orbit: Earth is oblate with mass greater than the space debris and the only force acting on the debris is gravitational force. The satellites in the orbit are also subjected to various perturbation forces including rapid fluctuations in density, variations in geomagnetic activity, and solar activity. At low altitudes until 75 km, the rate of orbital decay is more evident. The density of the air is significantly higher such that it forms a continuum over the satellite’s body thereby pulling into atmosphere. Above the aforementioned altitudes, satellites
experience frictional drag due to the intense solar winds, heating up the upper stratosphere. These winds produce drag that works against the velocity of the debris affecting its orbital lifetime and thus lowering its altitude and eventually burning up in the Earth’s atmosphere. The time it takes to fall into the earth’s atmosphere under the influence of drag is called orbital lifetime. For this reason, the satellites are often launched in orbits above the earth’s atmosphere where there is no frictional drag to reduce its velocity.

\[
D = \frac{1}{2} \rho V^2 f^2 S C_D \frac{S}{m} 
\]  \hspace{1cm} (3.40)

where \( C_D \) is the drag coefficient, \( \rho \) is the atmospheric density, \( f \) is the latitude correction, and \( S \) is the surface area of debris with mass, \( m \).

A large number of space debris are accumulated in low-earth orbits, 800 -1200 km. The rate of decay of these objects due to atmospheric drag depends on its area-to-mass ratio \( \frac{A}{m} \), orbit parameters, and atmospheric density. The objects with low area-to-mass ratios within the altitude range of 500 km takes a few days to enter into the upper part of the earth’s atmosphere, while objects with high area-to-mass ratios takes months. Ballistic coefficient is the measure of the ability of the debris to overcome drag and various for different object shapes. For an object of mass \( m \), surface area \( S \), and drag coefficient \( C_D \), ballistic coefficient \( b_c \) is

\[
b_c = \frac{S C_D}{m} \hspace{1cm} (3.41)
\]

In the earth’s atmosphere, several number of thermodynamic, and chemical reactions takes place that effect the air properties. Due to the Sun’s heat, the temperature at the surface of the earth is higher and decreases as the altitude increases. Scale height, \( 1/\beta \) is the measure of the distance from earth’s surface at which the atmospheric density decreases by \( 1/e \), and the density increases exponentially with decrease in altitude and increase in temperature.
\[ \beta = \frac{g}{R_{\text{gas}}} + \frac{dT}{dr} \]  
\[ \rho = \rho_0 \exp \left[ -\frac{g(h - h_1)}{R_{\text{gas}}T} \right] \]

where \( R_{\text{gas}} \) is the universal gas constant, \( g \) is the gravitational acceleration and \( T \) is the temperature. Scale height depends on earth’s gravitational field, temperature and the mass of atoms in the atmosphere. For altitudes below 120 km in analyzing aerodynamic drag, scale height can be considered a constant mean value of 7.1 km. As we go beyond 120 km, atmospheric density varies exponentially with altitude, and the scale height could be in the order of tens of kilometers. The orbital lifetime of the debris depends on the density of the atmosphere with altitude. At an altitude above 50 km, the temperature \( T \) is related to altitude as where \( T \) is the temperature in \( ^\circ \text{F} \) and \( h \) is the altitude in meters. Atmospheric

![Graph showing variation of scale height with altitude.](image)

**Figure 3.10:** Variation of scale height with altitude.

drag effects keplerian orbital elements, semi-major axis and the eccentricity of the orbit, in non-dimensional form the decay of semi-major axis \[ \frac{a}{a_0} = 1 + \epsilon h_1(\alpha) + \epsilon^2 h_2(\alpha) + \epsilon^3 h_3(\alpha) + \ldots \ldots \]  

(3.44)

39
The decay in the semi major axis is used to estimate other changes in other orbital parameters. The change in perigee radius can be found from

\[
\frac{r_p}{r_{p_0}} = \frac{(1 - \epsilon_0)(a/a_0)}{(1 - e_0)}
\]

\[
\left(\frac{e}{e_0}\right)^2 = 1 - \frac{T_d}{T_L}
\]

Non-dimensional orbital lifetime \(T_L\) is expressed as

\[
T_L = \left[1 - \frac{(9\beta^2a_0^2e_0^2/20 - 1)\epsilon}{2}\right] \frac{e_0^2}{2\epsilon^2}
\]

The non dimensional time in terms of orbit parameters is expressed as

\[
T_d = B \frac{t_{AD}}{\tau_0}
\]

where \(B\) is

\[
B = 2\pi b_c \rho_0 f^2 \beta^2 a_0^3 \epsilon_0 I_1(\beta a_0 e_0) \exp(-\beta a_0 e_0)
\]

The parameter \(f\) \[52\] is expressed as

\[
f = \left[1 - \left(\frac{\omega_e r_o}{V_o}\right) \cos i\right]
\]

where \(i\) is the orbital inclination, \(\omega_e\) is the earth’s angular velocity and \(V_o\) is the velocity in the initial orbit.

**3.5.3 Total de-orbit time**

The total de-orbit time of the debris from initial orbit to target radius can be estimated by considering the influence of both laser ablation and atmospheric drag. From equations (3.40) and (3.50),
Total number of engagements, $\Delta t_e$

$$\Delta r_p = \sqrt{\frac{9}{96}} \frac{\pi R^2}{m_s} C_m \frac{\Phi k}{\tau} \left( \frac{4avr_p}{\mu \left( 1 - \frac{2a}{r_p} \right) - av^2} \right) \Delta t_e$$

Decay due to drag, $t_{AD}$

$$T_d = B \frac{t_{AD}}{\tau_0}$$

The total de-orbit time is

$$t = \sum_{i=1}^{n} (\Delta t_{ei} + t_{ADi}) \quad (3.51)$$
3.5.4 Numerical Simulation

As discussed earlier, the total de-orbit time of debris due to laser force and atmospheric drag force are simulated with varying intensity, by changing the coupling coefficient, $C_m$ from 0 to 6 units. Spherical debris of mass 100 gm and size 5 cm at an altitude of 220 km is initially subjected to laser force for 30 seconds. Debris de-orbit due to atmospheric drag force was examined by estimating the orbit to reach a target eccentricity. The target eccentricity is assumed to a 5 percent drop of its value resulted from the laser force. The initial specification of the debris and the orbital parameters are as follows:

1. Spherical debris with weight 100 grams and radius 5 cm
2. Initial orbital radius, 6600 km
3. Orbital velocity of the debris in the 6600 km orbit, 7.14 km/s
4. Assuming mean solar activity region, the air density of $1.66 \times 10^{-10}$ kg/m$^3$ was considered

The de-orbit time due to atmospheric drag, resulting from the change in air density by using equations [62]. With the fixed target eccentricity, the major axis of the resultant orbital was estimated using the semi-major axis decay equation (3.46), and the resulting orbital radius was estimated using the equation (3.47). It is observed in the equation (3.48), in the present case, that de-orbit time is linearly varied to the square of the target eccentricity. With decreasing the target eccentricity, relative to the value resulted from the laser ablation, will increase the de-orbit time.

The objective of the laser ablation is to accelerate debris de-orbit, however, the presence of atmospheric drag influences the total de-orbit time and is strongly related to the target eccentricity value. For a value of dis proportionality low, the atmospheric drag is likely to influence the total de-orbit phenomena in a favorable way as it does not require for
the laser to track the debris once it reaches an altitude where the drag force is significant to de-orbit in a considerable time without laser further influence.
CHAPTER 4
NUMERICAL RESULTS

4.1 Accurate Predictions on De-Orbit Times

The de-orbit times in the previous sections were estimated considering the laser propagation vector is tangential to the velocity of the debris, and the change in velocity due to laser action is instantaneous, resulted in the fastest rate to de-orbit. However, in reality, the orbit of the debris is gradually modified with laser ablation that indicate the de-orbit times could be larger.

In this section, we consider Sims-Flanagan model in which the debris trajectory is modeled as a low thrust transfer with series of continuous $\Delta v$’s applied using laser force. The laser propagation vector is considered non-tangential to the velocity of the debris and is shot at an angle of $\epsilon$. The angle $\epsilon$ is considered constant throughout the ablation process. It is important to chose a position and direction of the laser to engage with the debris to ensure that the $\Delta v$ does not raise its perigee.

Engaging the debris with the laser when it is rising above the horizon gives the best result. Shooting a debris when it is rising above the horizon results in a momentum vector component opposite to the debris motion resulting in perigee reduction. Throughout the analysis, the laser is continuously engaged with the debris for an estimated 30 secs until it reaches the next orbit. Once the debris orbit is changed, the laser is shot again when the debris is rising above the horizon that is closest to the perigee radius. The best case is the debris guided to the field of view, i.e. horizon, by laser ablation and the shooting process continuous until it reaches the target orbit. But in reality, several factors such as atmospheric drag can affect the motion and orbit of debris. In the present work, the de-orbit times are estimated by considering collective effect of laser ablation and atmospheric drag on the debris. In the low-earth orbit, below 2000 km, the orbital lifetime of a satellite is a
few days, under the influence of laser ablation the lifetime can be reduced even further to a few hours depending on the size and mass of the debris.

4.2 Parametric study for Laser propagation vector

Laser ablation effectiveness is dependent on the field-of-view (FOV). The change in velocity, due to laser ablation is applied in an direction so that it does not raise the orbit of the debris. Horizon as the field of view, the laser is bombarded for 30 seconds, at an non-tangential direction such that the propagation vector incident onto the debris at an angle of $\epsilon$ above the horizon. When the laser engage with its surface, the debris has a momentum vector component opposite to its motion. To maintain laser above the horizon the $\epsilon$ angle was set at minimum $30^\circ$. As the angle above the horizon increases, the air density decreases, reducing the atmospheric effects on the laser pulse and also increases the visibility of the target. It is also essential to choose the right field-of-view (FOV) to reduce atmospheric interactions that effects the tracking capabilities (track debris before and after laser engagement).

The angles for the laser propagation vectors are estimated with fixed $\epsilon$ at $30^\circ$, and varying $\theta$ and $\phi$ angles from $0^\circ$ to $60^\circ$, to obtain the lowest total de-orbit time. The total de-orbit time due to laser ablation and atmospheric drag was estimated. The results of the simulation is shown in figure 4.1, with varying coupling coefficient between 1 and 6 dyne/W. The angle $\theta$ was considered between $30^\circ$ and $60^\circ$ while $\epsilon$ was set at $30^\circ$ respectively, for all the coupling coefficients. However, the angle $\phi$ is varied between $10^\circ$ and $50^\circ$. The angle $\epsilon$ was estimated with varying its value from $30^\circ$ and $60^\circ$, while setting the $\theta$ and $\phi$ angles at $60^\circ$ and $30^\circ$ to observe the lowest number of engagements necessary for debris to reach the target radius of 6498 km and the value was estimated at $60^\circ$. The angles $\epsilon$, $\theta$, and $\phi$ of $30^\circ$, $30^\circ$, and $30^\circ$ respectively, are used for the rest of the total de-orbit time analysis.
Figure 4.1: Effect of change in theta and phi angles on the total de-orbit time of the debris with fixed epsilon angle of 30°

Table 4.1: Number of engagements needed for different $\epsilon$

<table>
<thead>
<tr>
<th>$C_m$</th>
<th>$\epsilon=30^\circ$</th>
<th>$\epsilon=45^\circ$</th>
<th>$\epsilon=60^\circ$</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>17</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
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</tr>
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</tr>
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</tr>
<tr>
<td>6</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

4.3 Effect of Coupling Coefficient on De-Orbit Time

In the orbital space, debris moves with high velocities around 7.77 km/second. Tackling and bombarding the laser onto the debris continuously is challenging. Using industrial lasers with high intensity and a pulse duration in nanoseconds is necessary to significantly modify the debris orbit within a fewer laser engagements. Laser coupling coefficient is defined as the amount of momentum generated due to the applied laser energy. The relationship
between laser incident energy, $E$, its intensity $I$, and pulse duration $\tau$ is given below

$$E = \Phi \ast A = I\tau A$$  \hspace{1cm} (4.1)

where $A$ is the area of laser beam.

In the section 3.3, the de-orbit times were estimated by considering laser force alone with the laser propagation vector tangential to the surface of the debris. In this section, the de-orbit times were estimated with the laser propagation vector non-tangential to the velocity of the debris by varying coupling coefficient under the influence of both laser force and atmospheric drag. In the absence of laser force, the debris will still reach lower altitudes due to frictional drag but takes a few months to a years depending on the shape to mass of the debris and atmospheric density. It was estimated that an object of mass 10 gm, may take a few days to enter into the atmosphere, while a mass 100 kg takes few months.

A spherical shaped debris with radius 5 cm and mass 100 gm was considered. The laser intensity is $50 \text{ W/cm}^2$ and 120 kJ laser energy were considered. The ground based laser system is equipped with surveillance cameras to track debris. When the debris reaches the field of view, i.e rising above horizon, the laser pulses are bombarded onto the surface of the debris. The laser pulses ablates a layer of surface of the debris imparting a momentum change to modify its orbit. With varying the coupling coefficient from $C_m = 0$ to 6 and laser pulse duration from 0 and 8 nanoseconds, the trajectory of the debris is propagated from a circular orbit of radius 6600 km with a constant engagement time of 30 secs using equation (3.51), (3.52) and (3.31).

When coupling coefficient $C_m = 0$ and pulse duration multiplier was set at 0 units, that implies no momentum change due to laser ablation process. The de-orbit of the debris is resulted from the atmospheric drag alone. The debris reaches the target radius of 6498 km in 5 days (550 TU). The relationship between the total number of engagements and the corresponding de-orbit times are linearly related the laser pulse duration, and inversely
related to the coupling coefficient. The total de-orbit times and the corresponding number of laser engagements with varying coupling coefficient and the laser pulse duration are shown in the tables 4.2 and 4.3, respectively.

In the range of low laser energies, where the coupling coefficient is low and the pulse duration is low, the total de-orbit times were high, and it is largely because of low momentum change, resulting significantly low change in altitude. When the laser energy is high, it results in higher momentum change leading to lower de-orbit times. In the range where coupling coefficient is above 3 dyne/W and pulse duration lower than 4 nanoseconds resulting lower number of engagements and the corresponding de-orbit times.

Table 4.2: De-orbit times with varying $C_m$ for $\epsilon = 30^\circ$

<table>
<thead>
<tr>
<th>$C_m$</th>
<th>Engagements</th>
<th>Total de-orbit time (TU)</th>
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<tbody>
<tr>
<td>-</td>
<td>-</td>
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Table 4.3: De-orbit times with varying $\tau$ for $\epsilon = 30^\circ$

<table>
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<th>$\tau$ (ns)</th>
<th>Engagements</th>
<th>Total de-orbit time (TU)</th>
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</thead>
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</tr>
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</tbody>
</table>

For $C_m = 1$, there is less momentum change due to laser ablation and requires multiple engagements to reach the surface of the earth. The debris needs 18 engagements and takes almost 9 hours to reach the Earth’s atmosphere, 120 km from the surface of the Earth. When $C_m = 2$, the debris needs 13 engagements and takes few hours to reach the surface of the earth due to laser ablation. Due to very low-intensity, the orbit of the debris is modified largely because of atmospheric drag. Debris takes longer time to reach lower altitudes and requires significant number of engagements to speed up the de-orbiting process.

For $C_m = 3$, the number of engagements needed decreases and the debris reaches the earth’s surface in 7 hours. From $C_m = 4$ to $C_m = 6$, there is a significant change in momentum due to laser ablation with the debris reaching the earth’s atmosphere (6498 km) in less than 5 hours with only a few laser engagements. This is because as the coupling coefficient is increased, a greater momentum change is imparted to the debris leading to faster de-orbit time. From the literature review, the maximum value for $C_m$ for aluminum is considered as 10 dyne/W that means if the coupling coefficient is increased till 10, the de-orbit time could decrease.

To estimate de-orbit times with varying pulse duration, from equation (4.1), as the pulse duration increases, more laser energy reaches the target resulting in higher momentum change. From figure (4.3), when $\tau = 0$ ns, there is no laser energy and the de-orbiting is due
to atmospheric drag. As we increase pulse duration from 1 ns to 8 ns, the de-orbit times largely decreases. When $\tau = 1$ ns, debris reaches the earth’s atmosphere in 30 days whereas for $\tau = 8$ ns, debris takes less than a day to enter earth’s atmosphere. The de-orbit times also depends on area-to-mass ratio of the debris, in this work we have considered debris with mass 0.1 kg at 220 km altitude. If the debris mass is 100 kg and is at the same altitude with no laser force, it could take a few days to re-enter atmosphere due to density variations. As discussed earlier, due to laser bombardment onto the surface of the debris, its altitude decreases with changing its orbit from circular to elliptical orbit.

The effect of laser parameters, coupling coefficient and pulse duration on the orbital parameters such as the semi-major axis and eccentricity is shown in the figure 4.4 to 4.8. The trend in variation in the orbital parameters, particularly the semi-major axis, is similar to that of the trend observed for the perigee radius. As the laser energy increases, it was observed that the eccentricity of the orbit increases to as high as 0.014 and semi-major axis to 0.964 LU or 6396 km. Although, the semi-major axis is significantly lower than that of the target altitude of 6498 km and near earth radius of 6378 km, the value is theoretically possible as the change in debris mass due to ionization and vaporization are not considered. The resultant eccentricity values in the near circular orbit ($e < 0.02$), and the study with

![Figure 4.4: Semi-major axis vs time with varying $C_m$](image)

![Figure 4.5: Semi-major axis vs time with varying $\tau$](image)
assuming circular orbit approximation can be considered in the future. To estimate the effects of atmospheric drag, the target eccentricity was set to 95 percent of the value resulted from a laser ablation.

The effect of laser ablation on de-orbit the debris to clean the lower earth orbit was studied with varying its parameters, primarily varying its incident energy onto the surface of the debris. It was observed that in the absence of laser energy, the debris reaches 6498 km in around 15 hours, and in its presence the de-orbit time significantly reduced to as low as 5 hours. These values may vary significantly for different combination of the debris area to mass ratio. The implication of the atmospheric drag was rather encouraging particularly of its comparable values to that of laser engagement. In the best use case, it can be observed that the role of laser engagement is to accelerate the de-orbiting process to a relatively higher air density region where atmospheric drag influence is prominent.
4.4 Comparative Study

In 2016, Nazzoli and Burger [63] studied the applications of space and ground based lasers in cleaning up the space debris in low-Earth orbits. A debris of mass 10 kg with area to mass ratio of 0.1 was considered to investigate the total de-orbit time from the initial orbit altitude of 800 km to reach the target altitude of 200 km using Hohmann-like transfer. To understand the influence of atmospheric drag force, they modeled atmospheric density using Jacchia-Bowman 2008 density model. In this thesis, the scale height and atmospheric density are estimated using the model results shown in figure (3.10). The Jacchia-Bowman 2008 was not considered because it is beyond the scope of the current research as it requires to investigate the affects of barometric and diffusion phenomena.

By considering the model we developed in this thesis, we estimated the de-orbit times of the debris for the same debris and laser parameters considered in the literature [63]. For a spherical shaped debris with mass 10 kg, size 10 cm and the laser engagement time of 10 minutes, the de-orbit times were estimated with varying coupling coefficients between 1 and 6 units, and the results are shown in the figure (4.8), and the corresponding total de-orbit times. The results were as low as 5 times higher than that of the estimated by Nazzoli et. al.

Researchers estimated that debris took only 5 days to enter into earth’s atmosphere for a combined 1 hour laser operation at regular intervals assuming a constant change in momentum of 3 Ns. Using Sims-Flanagan model developed in this thesis, debris took more than 10 days to reach earth’s atmosphere with and the de-orbit times are even longer as we decrease the laser intensity. From figure(4.8), it was observed that for low laser intensities, $C_m$ is between 1 and 3, the de-orbit times are between 70 and 207 days and is largely due to atmospheric drag than laser energy. As we increase the $C_m$, higher laser energy passes to the surface of the debris leading to lower de-orbiting time, 17 days. As we have considered a more realistic case in which the laser propagation is non-tangential to the debris surface and the de-orbiting process is not Hohmann-like transfer but with a series of laser
Figure 4.8: Total de-orbit time of 10 kg spherical debris with size 10 cm.

engagements guiding the debris till it reaches the earth’s atmosphere, the higher de-orbit times are justifiable.
CHAPTER 5
CONCLUSION

5.1 Thesis Summary

Space debris are non-operational man-made satellites orbiting in the low-earth. These objects are classified into different sizes ranging between 1 - 10 cm to objects greater than 10 cm. These objects are orbiting around earth at high velocities posing a serious threat to current and future space missions. Several scientific researches have been initiated to develop space debris removal methods to clean up space environment for future space exploration technologies.

In this work, space debris removal methods including contact less and contact based removal methods, capturing methods and drag augmentation methods were studied. With primary focus on ground based laser-ablation debris removal, the effect of laser ablation on the dynamics of the debris and de-orbiting process was studied. The idea of laser based removal is to accelerate the de-orbiting process of objects in LEO by shooting high intensity laser pulses onto the surface of the debris that provides necessary amount of momentum change to slowly modify its orbit. Majority of debris in LEO are of sizes ranging between 1 cm and 10 cm. Due to their extremely small sizes, laser based removal method is estimated to be effective among other removal methods in cleaning up debris of this range.

In the literature, the de-orbit times of the debris were estimated by considering the laser action as impulsive, where a single $\Delta v$ given to debris in one orbit puts it into another orbit of lesser altitude. In this work, we modeled the de-orbiting process due to laser ablation as continuous-thrust quasi circular transfer, where pulses are continuously bombarded onto the surface of the debris gradually increasing its velocity, $\Delta v$ and modifying its orbit until it reaches the desired altitude.

In the quasi-circular model, the total de-orbit time for a debris to reach 6478 km from the initial altitude of 6600 km were estimated for circular and elliptical orbits with varying
$C_m$. Assuming two-body approximation, debris with homogeneous body for both spherical and cube shapes, and the laser propagation vector tangential to the velocity of the debris, the total de-orbit times to reach the target orbit were estimated. It was observed that the tangential approximation results with lowest de-orbit time. It was observed that the total de-orbit times decreases with increase in couple coefficient. However it is challenging for a laser to incident the pulses tangential to the motion of the debris, and evidently results in longer de-orbit times.

To investigate the de-orbiting process under most possible scenario, the laser propagation vector was considered in non-tangential direction to the orbital motion of the debris. The low-thrust debris trajectory was modeled as a series of $\Delta v$’s connected by keplerian arcs using Sims Flanagan model. Unlike in the quasi-circular model, the laser was engaged onto the debris from above the horizon at an angle $\epsilon$ of 30 degrees for fixed 30 seconds, while considering the effects of atmospheric drag. The number of such laser engagements required and the corresponding total de-orbit time for the debris to reach lower altitude decreases with increasing in coupling coefficient and decreasing in the pulse duration.

In the case where atmospheric drag was alone considered, in the absence of laser engagement, the total de-orbit time was estimated 5 days. The implication of the atmospheric drag was rather encouraging particularly of its comparable values to that of laser engagement. In the best use case, it can be observed that the role of laser engagement is to accelerate the de-orbiting process to a relatively higher air density region where atmospheric drag influence is prominent. However, the total de-orbit times are expected to be higher, but the laser engagement will be minimum and consequently the debris tracking is not essential.

Researchers considered several methods to make a cleaner space in the lower earth orbit to avoid catastrophic effects on active space missions and satellites. All the methods have advantages and disadvantages, similarly laser ablation has a advantage of de-orbiting the debris with a laser engagement as observed in the present simulation study. However, the challenges are predominately related to operational including tracking and engaging debris
for an proposed 30 seconds, which is relatively long for an object moving at 7.14 km/second velocity.

5.2 Future Work

In the future, we recommend to perform a parametric study various combination of debris specifications and laser parameters including laser operational specifications such as transmission losses. It was also recommended to incorporate ionization affect on the debris results in mass loss. We recommend to investigate the deorbit with considering Jacchi Bowman model that provides better model to estimate atmospheric density.
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REFERENCES (continued)


REFERENCES (continued)


REFERENCES (continued)


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