# Laser Propulsion of Nanosat from Earth to Low Earth Orbit (LEO)

**A Project Report**

***Submitted by:***


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***in partial fulfillment for the award of the degree***

***of***

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**Ahmedabad, Gujarat**


**MAY 2020**

# DECLARATION

I hereby declare that the project entitled "Laser Propulsion of Nanosat from Earth to Low Earth Orbit (LEO)" submitted for the B. Tech. (ICT) degree is my original work and the project has not formed the basis for the award of any other degree, diploma, fellowship or any other similar titles.

**Signature of the Student**

**Place:** Ahmedabad University, Ahmedabad

**Date:** 3rd May 2020

# CERTIFICATE

This is to certify that the project titled “Laser Propulsion of Nanosat from Earth to Low Earth Orbit (LEO)” is the bona fide work carried out by Sakshi Shrivastava, a student of B Tech (ICT) of School of Engineering and Applied Sciences at Ahmedabad University during the academic year 2019-2020, in partial fulfillment of the requirements for the award of the degree of Bachelor of Technology (Information and Communication Technology) and that the project has not formed the basis for the award previously of any other degree, diploma, fellowship or any other similar title.

**Signature of the Guide**

**Place:** Ahmedabad University, Ahmedabad

**Date:** 3rd May 2020

# ABSTRACT

One of the major limitations of any spacecraft is their weight, which determines the amount of fuel they will have to carry for their journey. It also severely limits the speed achievable by them. Considering the vast expanse of space, the time required to travel those distances, prohibits travel, research and development. Laser propulsion is one of the engine-less ideas of propulsion. By eliminating the need for engine or fuel to be carried aboard, it massively decreases the weight of traditional propulsion systems thereby increasing achievable velocities. This project aims to study the dynamics of a laser propelled spacecraft thereby identifying its control parameters. A simulation environment will be used to do a parameterized study of laser propelled spacecraft and then synthesize guidance and control equations for the system.

# ACKNOWLEDGMENT

Firstly, I would like to thank my advisor, Dr Harshal Oza for giving me the opportunity to work on this project. It couldn’t have been possible without his constant guidance and support.

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# TABLE OF CONTENTS

# INTRODUCTION

It has been nearly 50 years since we landed on the moon. Since then spaceflight has captured the imaginations of billions of people and we have spent the last half a century pushing the boundaries of technological limitations of spaceflight. In 1957, USSR launched the first artificial satellite in space named Sputnik 1 having a speed of 8 km/s. In the historic year of 1969 Apollo 11, having speed 11.27 km/s, escaped earth's gravity to land on the moon. In 1979, Voyager 1 was sent out for a Jupiter flyby at the speed of 17 km/s and after the completion of its mission has continued its journey beyond the solar system. The fastest spacecraft to date is the Parker solar probe, launched in 2018, has achieved a speed of 68.6 km/s. Thus, since 1957 to 2018 we have achieved a 750% improvement in speed. This improvement in speed is remarkable in itself but against the vastness of space is insignificant. Distances in space are measured in light years and compared to the speed of light we have achieved only 0.02% of light speed.

Even if we just hope to explore our neighbourhood i.e the solar system, the limitations are many. Some of which are energy consumption, mass, speed and cost. If we want to explore our solar system in depth, we need sophisticated instruments which leads to increased payload that spacecraft needs to carry for research. The farther we need to go, the more fuel we need to carry. If we want to reduce time taken to reach the destination, we would need to increase speed for which we need more fuel. To increase the amount of energy we get per gram of fuel there have been concepts for different propulsion systems like fission, fusion, nuclear weapon driven, fusion using collected interstellar protons, anti matter as well as laser driven [1, 2, 3, 4, 5]. While many of these concepts work theoretically, in practice they are hard to implement.

Photon propulsion, first proposed in the early 20th century, still belonged to the realm of fantasy even just a decade ago. In photon propulsion it will be possible to leave the main propulsion system on Earth (ground or orbital) and propel spacecraft by firing at it, thus, providing thrust. When light reflects off a surface, it imparts momentum to the surface leading to radiation pressure. It was recognized in the early 20th century that this effect could be utilized to propel spacecraft with large mirror-like sails harvesting the momentum of incident photons. Since then there have been conceptualization of many different types of sails such as solar sail, laser sail, electric sails, magnetic sails (also known as magsails). Also, there has been work on wafer scale photonics which allows us to create a wafer scale highly integrated spacecraft that include cameras, bi- directional optical communications, power and other sensors that can achieve gram scale systems. All these technological advancements have made photon propulsion possible, though difficult [6, 7].

# LITERATURE SURVEY

It was in the early 20th century that the first serious approaches to application of directed light beams were found in publications. Russian pioneers Fridrikh Tsander [8] and Konstantin Tsiolkovsky [9] and, independently, the German Hermann Oberth [10] in the years 1923 and 1924, mentioned the idea of propulsion by light pressure, leading to the concept of solar sail. But since their work was virtually unknown to the West until the 1930s, rocket technology developed through the independent efforts of Oberth in Germany and Goddard [11] in the United States. There was potential in liquid and solid fuel rocket propulsion for interplanetary space exploration, but the early spaceflight pioneers recognised its limitations for interstellar missions. The need for a propulsion concept of different types (viz. photon rocket), for interstellar missions, was proposed by Eugene Sänger [12] in 1953. As laser had not been developed by that time, , Sänger envisioned photonic propulsion based on the continuum radiation of a hot plasma generated by a fission reactor placed at the focal point of a large reflector. It was hypothesized that the resulting radiation pressure will provide the required momentum to the reflector structure.. He also proposed an antimatter pumped laser, designed to propel a spacecraft up to relativistic velocities, but it is still more science fiction than reality today. Work on laser propulsion is still ongoing at German lab, Deutsche Luft und Raumfahrt Labor (DLR) in Stuttgart, established by Sanger.

Arthur Kantrowitz and Wolfgang Moeckel were also pioneers of laser propulsion and were intimately concerned with the everyday applications of lasers and spacecraft. Arthur Kantrowitz founded AVCO Everett Research Laboratory in Boston, Massachusetts, where some of the leading technologies for high power lasers were developed. The work to scale chemical laser, electrical discharge, and gas dynamic lasers to military or industrial scale from laboratory was done at AVCO, for instance 131 kW average power gas dynamic laser. Kantrowitz trained laser technologists at AVCO, demonstrated the existence of suitable lasers and popularized laser propulsion. Wolfgang Moeckel was chief of the Advanced Propulsion Division at NASA, the U.S. space agency, where he launched the research into electric, ion and plasma propulsion. Moeckel devised the basic equations for non-chemical propulsion and was the first scientist to promote the idea that, while almost unlimited exhaust velocities are possible for laser propulsion, the highest exhaust velocity is not necessarily the best. Most of the energy might go into the plume rather than the spacecraft [13, 14].

In 2002, Nobel Laureate Carlo Rubbia revisited the photonic propulsion scheme using a nuclear-pumped gas laser using a few kilograms of Americium 242 as the energy source for a 3 GW laser [15]. In 2000, at the Laser-Hardened Materials Evaluation Laboratory facility of the Wright-Patterson Air Force Base, an advanced lightsail material was tested with high-power

$CO_2$ lasers [16]. In the same year, at the DLR German Aerospace Center in Braunschweig, a large solar sail was developed [17]. A two year project was awarded to LuxSpace, a Luxembourg company, by ESA in April 2008, to develop solar sail materials.

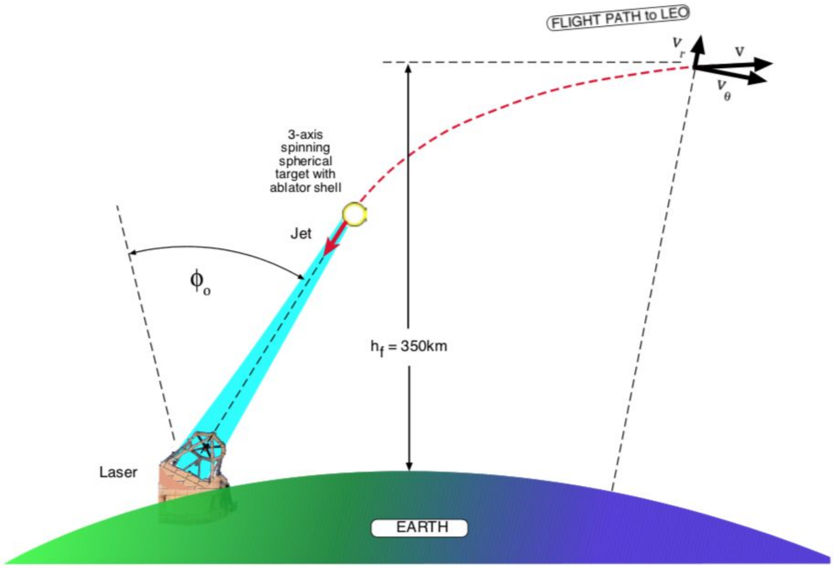
In 1966, Georgii Marx, the head of Physics at the Roland Eotvos University in Budapest, arrived at a surprising conclusion in his paper, that though the instantaneous and total efficiencies of laser energy transfer start at zero, they reach around 42 and 67%, respectively, at half the speed of light and reach 100% at the speed of light itself [18]. Marx's paper was followed a year later by J. L. Redding, who gave highly critical analysis of his work in the same journal [19]. Redding claimed that Marx's [18] efficiency calculations do not take into account the laser energy stored in the space between the laser station and the spacecraft, therefore, a correction factor must be included that would reduce the Marxian efficiencies by half at $c = 2$ and to zero at the speed of light itself. A quarter-century passed before Marx's [18] was justified by Simmons and McInnes, in the American Journal of Physics [20]. They pointed out that if one considers retarded time (i.e., spacecraft time) instead of terrestrial time, the Redding correction drops away. Simmons and McInnes rederived one of Marx's most valuable equations. The relativistic velocity attained depends on the Marxian energy quotient $Pt = Mc^2$, which is the ratio of laser output energy to the spacecraft mass expressed as $Mc^2$.

# LASER PROPULSION THEORY

To get payloads from Earth to LEO, using pure photonic propulsion is extremely difficult because the laser sail will face a significant drag of the atmosphere in reaching altitudes above dense atmosphere. To cut through Earth's atmosphere, instead of just laser propulsion, laser ablative propulsion (LAP) is used. The basis of this project follows that of C. R. Phipps et al [22]. Energy consumption to transfer a payload to LEO is given using 'Rocket Equation' for payload ratio: $\zeta = \frac{M}{m} = exp[(\upsilon_F + gt_F)/\upsilon_E]$ where $M$ is the launch pad mass and $m$ is that which reaches LEO. $\upsilon_E$ and $\upsilon_F$ are the exhaust and final velocities, respectively, $t_F$ is the time to orbit in seconds and $g$ is the gravitational acceleration.

If $\zeta = 30$ and payload mass is 27 tons, liftoff mass would become 850 tons, not counting the 600 ton solid booster rockets. $\upsilon_F \approx 8$ km/s near LEO, and $\upsilon_E$ is between 2 and 4 km/s for various chemical fuels. All this makes chemical propulsion quite prohibitive.

There are many parameters in LAP, essential of which are specific impulse, defined as $Isp = \upsilon_E/g$ in seconds and $Cm$ is the momentum coupling coefficient. Expressed in N-s/J or N/W, it is the ratio of surface pressure to incident intensity or the ratio of momentum delivered to a target by an ablation jet to the incident beam energy W for a laser pulse. Thrust delivered by pure photon reflecting of a polished surface is miniscule $Cm$ = 2/c = 6.7 nN/W. Even a 10 kW laser would produce a thrust of only 67 $\mu$N. The coupling coefficient due to laser assisted ablation of common materials can yield $Cm$ 100 N/MW to 10 kN/MW, which is four to six times than pure photonic propulsion. Therefore, ablative propulsion is the only applicable solution to achieving useful thrust from photons until gigawatt lasers are developed.



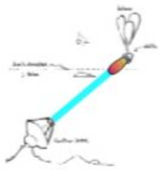

There are many variables that need to be taken into account for a successful laser launch. Some of them are momentum coupling coefficient,  delivered mass fraction, insertion altitude, laser range, final elevation angle, aser power, flight time, minimum altitude and laser propagation range. Balancing the various factors can be more art than science. Even with a 5-15 MW power laser it can be easy for the target to be lost over the horizon before insertion while having an undesirable amount of radial velocity. Best performance is obtained in the range of $Cm$ = 120 - 150 N/MW.

| Case | $C_m/\eta_{AB}$ (N/MW) | Chord (km) | $T$ (s) | $T_{\text{pk drag}}$ | $\phi_o$(°) | $\phi_f$(°) | $a_{max}$ (m/s$^2$) | $v_{rf}$ (km/s) | $m_f/M$ (%) | $h_o$(km) | $h_p$(km) | $h_a$(km) | $s_f$(km) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 150 | 1.5 | 344 | 60 | 57 | 84 | 73 | 2.87 | 23 | 1 | -1570 | 4080 | 1270 |
| 5 | 130 | 61 | 429 | 55 | 60 | 90 | 47 | 1.47 | 28 | 35 | 112 | 10000 | 1680 |
| 3A | 150 | 1.5 | 402 | 60 | 56 | 84 | 173 | 0.25 | 38 | 1 | 96 | 842 | 1030 |
| 11B | 120 | 1 | 496 | 10 | 45.5 | 90 | 216 | 0.39 | 54 | 1 | 104 | 41700 | 873 |

In Table 3, "Chord" is the horizontal distance from the laser station to the point beneath the satellite at launch. $T$ is flight duration. $T_{\text{pkdrag}}$ is the time at which drag is maximized. $\phi_o$ and $\phi_f$ are initial and final zenith angles, $h_o$, $h_p$ and $h_a$ initial, perigee and apogee altitudes, $v_{rf}$ final radial velocity and $s_f$ final laser range to the spacecraft, $a_{max}$ is maximum acceleration, $m$ is mass delivered to orbit and $M$ is mass on the ground.

Considering a single phase flight in case 3 and 5, the delivered mass ratio is low due to a significant amount of loss to drag. Even a 35 km launch altitude to LEO is not able to compensate for drag due to poor elevation angle, which leads to an excessive radial velocity. Case 3 also suffers from negative perigee making it an unsuccessful single phase test flight. Of course then there is a dilemma of how to reach the altitude of 35 km.

**Table 2.** Ways to achieve initial target altitude above denser part of atmosphere

| Method | | Problems | Additional Est. Cost |
|---|---|---|---|
|  | Balloon to 35km | • Uncontrolled target position at laser turnon<br>• To launch 6 targets, 9,900 $m^3$ volume<br>• \$45k helium cost<br>• Helium is a precious resource | \$300/kg |
|  | Very large gun | • 1000 G's Acceleration<br>• Need 1km/s muzzle velocity<br>• Facility cost dominant<br>• Noise, gov't opposition | \$200/kg |
|  | Loitering jet plane | • \$3k/hr cost<br>• 12km max altitude<br>• 4 hrs/fuel load<br>• 8-target load at 50/day | \$60/kg to 12km |
|  | Black Brant Rocket | • One flight per target<br>• \$600k/launch | \$2,400/kg |
|  | 8km tower | • Uncertain development cost<br>• Uncertain stability<br>• 8km not enough to help much | Uncertain |
|  | Laser | • Combusting target in atmosphere<br>• Penalty on laser energy at lower launch altitude | Zero additional cost |

In three phase flights, Case 3A and 11B, despite laser launch from just 1 km altitude, they perform better than single phase flight by delivering a better m/M ratio. Minimal energy is wasted in drag, even though we are starting from the ground. The amount of drag faced can also be lowered by choosing an appropriate initial elevation angle.

# THE CONTROL PROBLEM

For this project, we focused on studying the control problem to stabilize the trajectory of spacecraft with minimum deviations in its path. The equation of motion in this case is very simple:

$$d^2s/dt^2 = P\,Cm\,/m$$

where $P$ is power, $Cm$ is the momentum coupling coefficient and m is mass. Double integrating the equation will give us the position of the spacecraft. Here acceleration is the controlled variable and power the control signal.

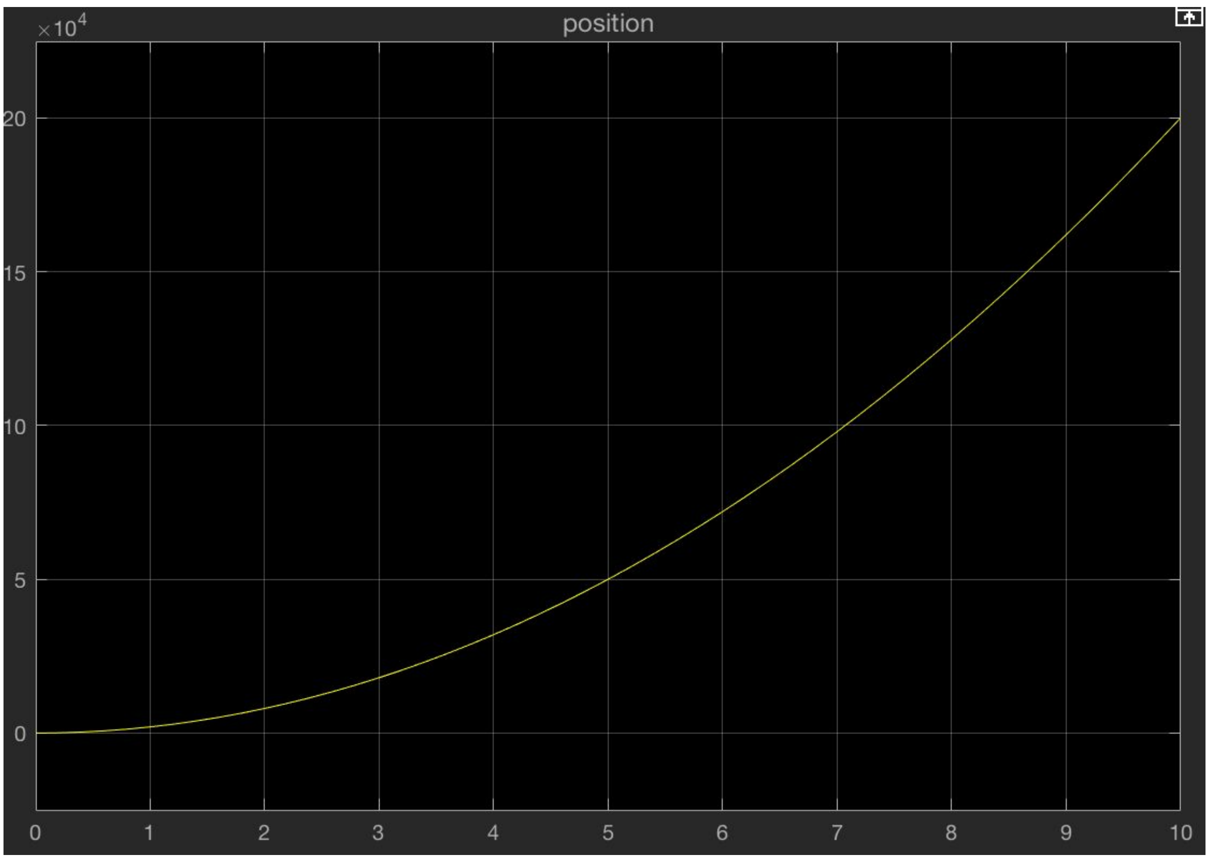



**Fig 1.** No feedback error signal. Unstable system.

In Fig 1, without a feedback loop for reference, given constant power, the spacecraft will spiral out of its trajectory. Therefore this is an unstable system. Even choosing a step signal as control signal does not yield any dissimilar results.

Feeding back the output signal to acceleration, to calculate error, enables the spacecraft to correct its trajectory (Fig 2). However, the resulting trajectory oscillates wildly in its path. Therefore the system is still very unstable.

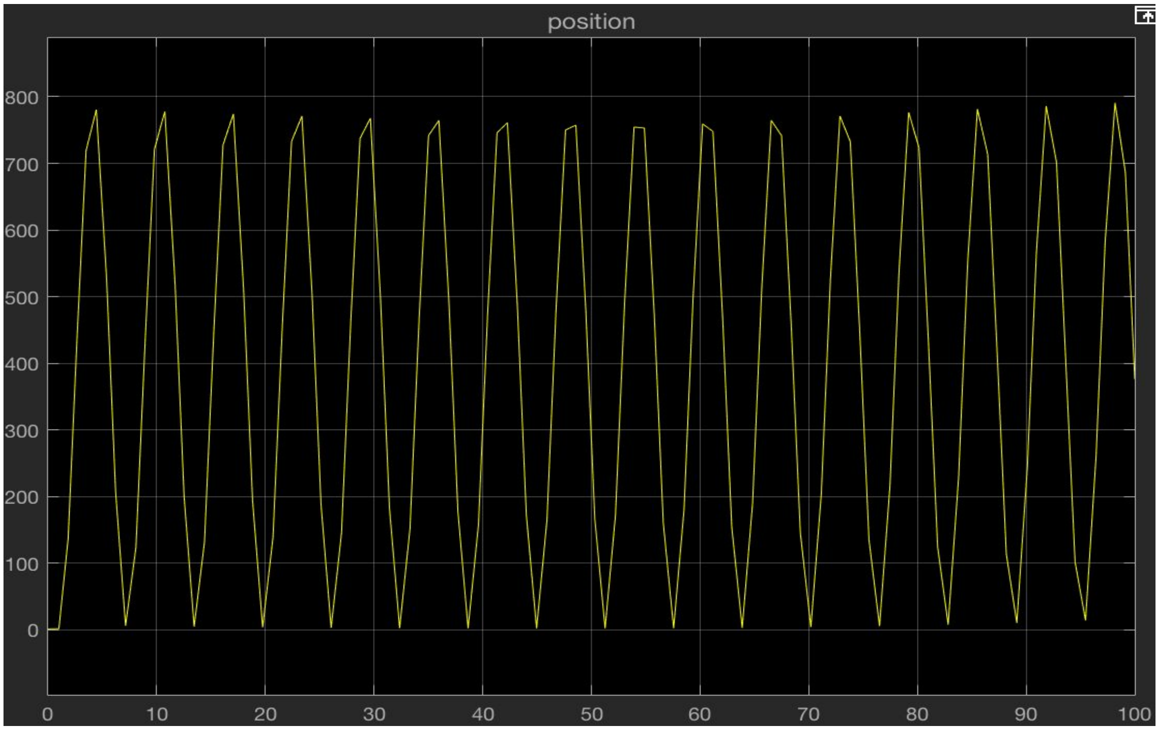



**Fig 2.** Feedback signal. Unstable oscillatory system.

We added a PID controller to help stabilize the spacecraft trajectory. This time it took longer for the spacecraft to start oscillating in its path. Since the controller gains of the PID controller are not tuned, it destabilizes soon enough (Fig 3).

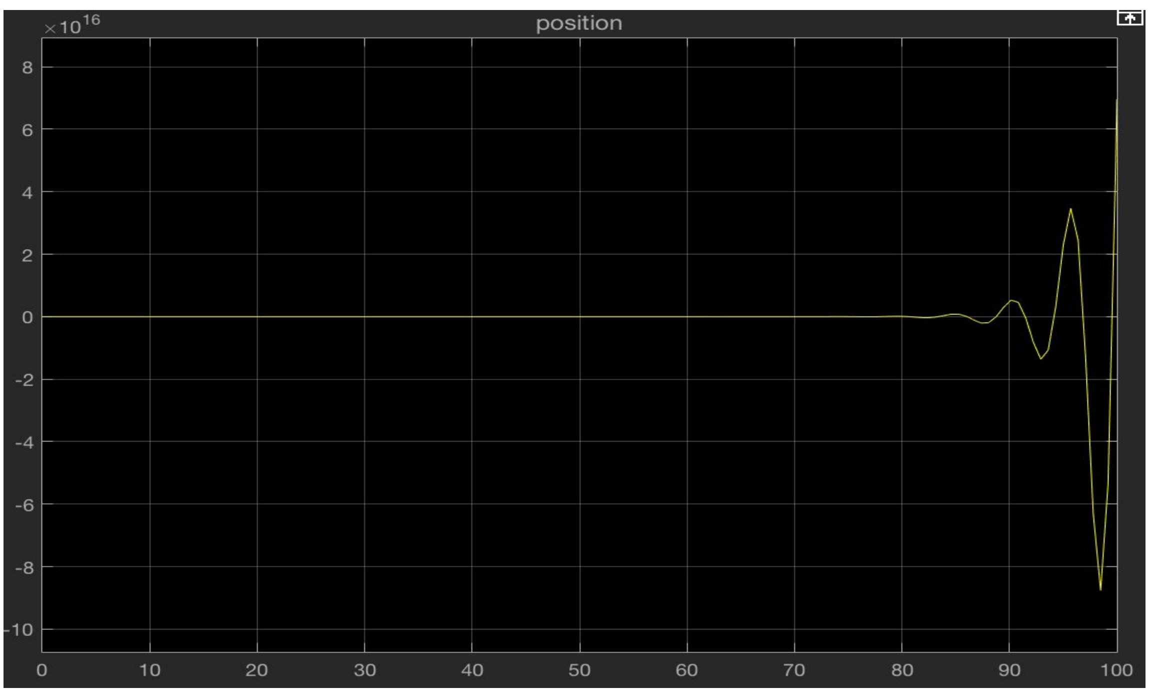



**Fig 3.** Untuned PID controller added, stabilizes the system partially.

A tuned PID controller gives a better response over all and stabilizes the system (Fig 4).

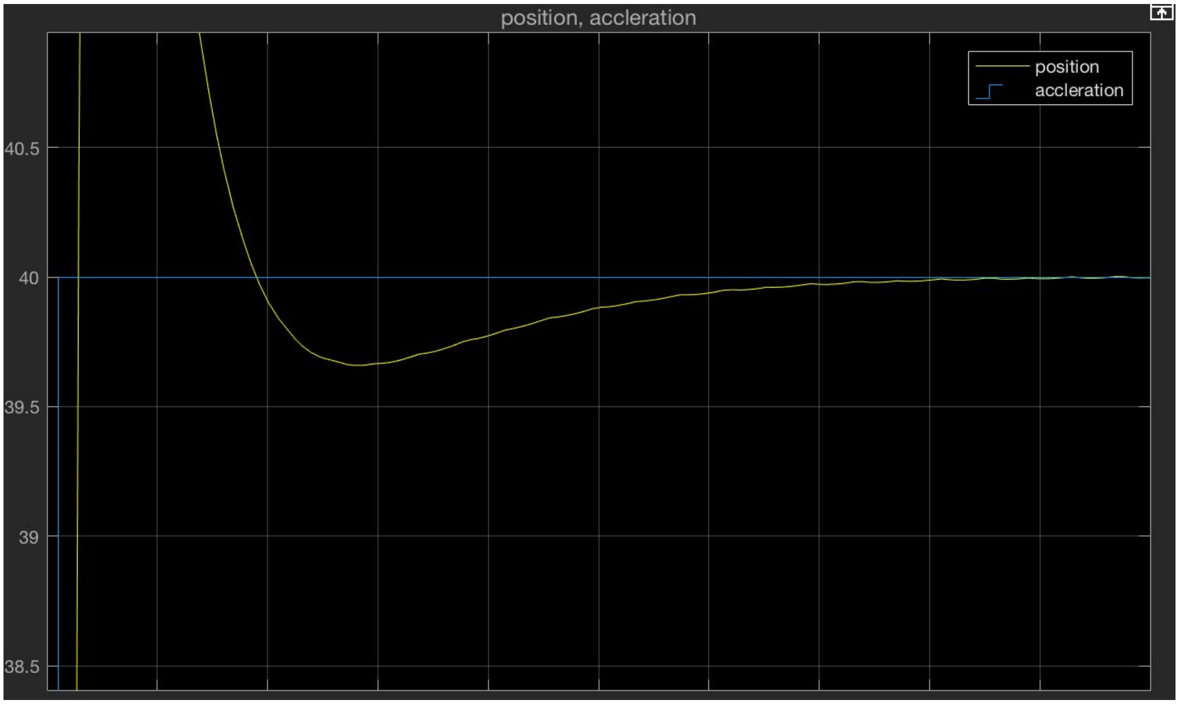



**Fig 4.** Tuned PID controller stabilizes spacecraft trajectory.

Even when making mass a variable using formula $dm/dt = \frac{1}{2} P C m^2$, the system remains stable (Fig 5).

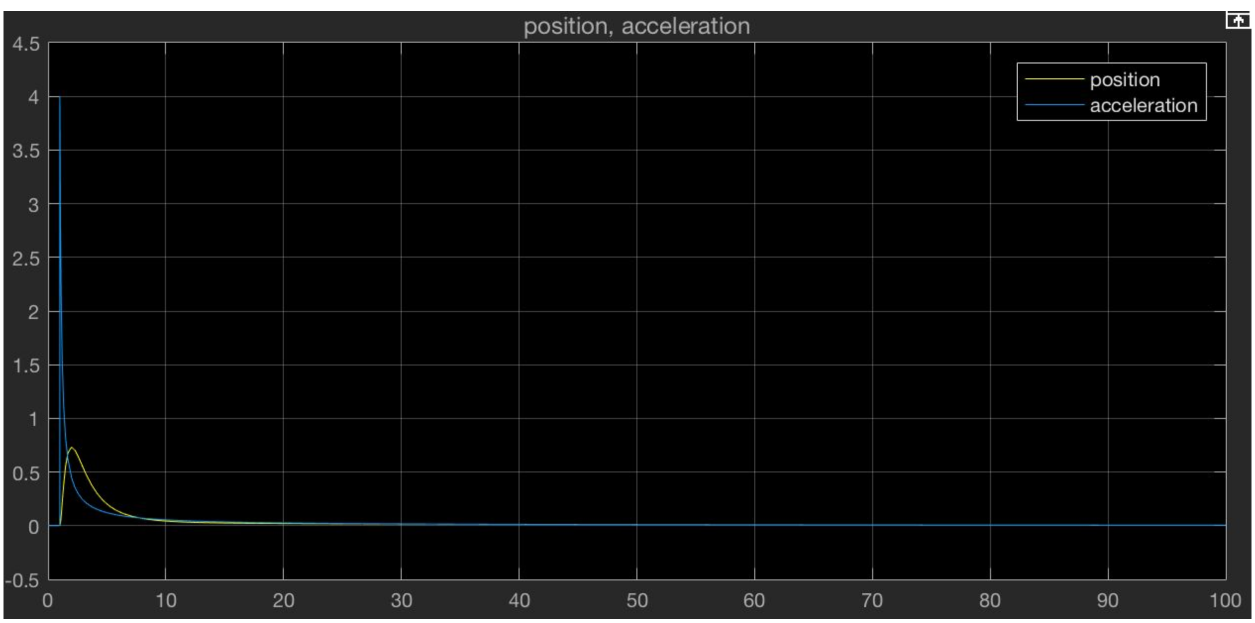



**Fig 5.** Even with variable spacecraft mass, system remains stable.

# CONCLUSIONS

In this project we conclude that laser propulsion is a major technological advancement in space exploration, maybe presenting a paradigm shift in space transportation. Our work was to model motion equations so that control parameters could be identified. Then using MATLAB software we synthesised control variables to be able to control the trajectory of the spacecraft. Moreover, we aimed to stabilize the spacecraft's trajectory using a PID controller. In future, we plan to work on trajectory planning of spacecraft.

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