The Excidio System for Space Debris Management

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Abstract: The advancements in technology and research brought about by Human endeavour in space exploration are revolutionary. Orbital debris pose a threat to the same. As a result of 50 years of space operations, the useful orbits around earth are littered with derelict satellites, burn out rocket stages, discarded junk and other debris. Space surveillance catalogues show that its quantity has increased rapidly over the last few decades. When objects in different orbits intersect, they collide at speeds of thousands of kilometres per hour, causing mass destruction. The present work is an attempt to provide a physical insight into a debris management system 'Excidio' by a theoretical approach and to validate it by systematically analysing it. The system encompasses a set of techniques used to effectively monitor the debris in the Low Earth Orbit (LEO). It consists of a satellite system, consisting of a Mother ship, which constantly monitors the debris in close by orbits, and a second class of shepherd satellites equipped with solar lasers, which slow down the debris by reducing their momentum, thereby decelarating them and pushing them to penetrate the earth's atmosphere at re-entry speeds, therefore resulting in their disintegration and permanent elimination. The system concentrates on the reduction of smaller debris of weights less than a kilogram as they are more vulnerable and widespread. The management system thereby aims to address space debris in the region of maximum concentration and high traffic of satellites.

Keywords: Debris, management, laser, LEO, monitoring, atmosphere.

1. INTRODUCTION

Studies state that in space, the estimated population of particles between 1 and 10 cm in diameter is approximately 500,000 in number. In LEO where most of today's satellites are placed, debris orbit around the Earth at speeds of 7 to 8 km/s. Also, its environment is becoming congested with space debris due to the frequency of space launches. This has caused growing concern in recent years, since collisions at orbital velocities can easily be dangerous, and even deadly. Collisions can produce even more space debris in the process, creating a chain reaction leading to Kessler syndrome. The average impact speed of orbital debris with another space object will be approximately 10 km/s [1]. The higher the altitude, the longer the orbital debris will typically remain in Earth orbit. Of 17000 man-made objects in space, just over 7% are operational.1/3rds of these man-made objects are within an altitude 600 km from the earth's surface [2]. This is expected to cause serious threats to space operations in the near feature. The paper proposes a concept for the reduction of space debris with emphasis on a management system functioning with a family of satellites.

2. THE EXCIDIO SYSTEM

In order to make the debris reduction system effective, a continuous monitoring system is essential. A Mother Ship '*Eurybia*' at an altitude of 600 km is utilized for monitoring and to manage a database containing all the essential parameters regarding the various launches from the earth, the specific orbits and the time factor. A simulation and analysis tool, European Space Agency's DELTA is used for prediction as it is capable of tracing any particle larger than 1 mm. Ground based radars can be used for detection purposes in LEO [3]. To support monitoring, simulation using sensors will be effective, using which the shepherd satellite models, '*Perses*' attain data about every encounter of the mother satellite to validate the prediction.

Figure 1.Concept of 'The Excidio' System with the mother ship 'Eurybia' and 'Perses' shepherd satellites (designed and rendered using CATIA)

The data transmitted can be optimized with respect to search regions, observation times and sensor sensitivity, also with reference to the data about the space debris population available at that instant after which, necessary commands are given. Lasers fitted in the satellites are powered by the energy produced from the solar panels. The satellites are fitted with thrusters powered by electric propulsion systems in order to wander in space. Crucial systems in space have an imaginary rectangular control volume enclosure, with respect to earth's frame of reference called as a "*pizza box*" which is of dimensions 1.5 x 1.5 x 50 km [4]. Any object coming within this limit is immediately reported to a ground station. The current space volume setup doesn't give enough reaction time for the satellites to undergo orbit corrections. In order to make it safer, the dimensions are increased to 5 x 5 x 100 km so that the necessary trajectory corrections can be prepared to escape the impact of the debris. Monitoring might be affected due to in-orbit explosions caused due to the ignition of residual fuel left in the various stages of rockets present in space after the end of their lifetime. So they must be drained completely for better monitoring results.

3. OPERATION VALIDITY AND CALCULATIONS

3.1 Scenarios:

Three classes of debris are dealt with during calculation. The classification is on the basis of mass- 10 g, 100 g and 1 kg. Two orbits are chosen: one at an altitude of 600 km and the other at 1200 km.

3.2 Assumptions:

The laser has an output power of 10 kW. There is no loss in energy during the firing of laser onto the target. The shepherd satellite is orbiting at 1250 Km above the surface of earth. For the 600 km orbit, firing will start when the line joining the target and the shepherd subtends an angle of 70 degrees with respect to the horizontal of the target's body-axis system. For the 1200 km orbit, firing will start when the line joining the target and the shepherd subtends an angle of 45 degrees with respect to the horizontal of the target's body-axis system. The average angle subtended by the line joining the target and the shepherd on the horizontal is 80 degrees and 67.5 degrees for the 600 km and 1200 km orbit respectively. Both, the shepherd and the target are moving at the minimum orbital speed of their respective orbits. The curvature of the earth is neglected in the calculation as the distance between the shepherd and the target is very small compared to the earth's radius (6378 km).

Gravitational constant, $\mu = 398600.4\ km^3/s^2$

3.3 Influence of the laser:

Force exerted by the laser F is given by Power/velocity. In this case, Power is 10 kW and velocity of output $3x10^8$ m/s i.e. velocity of light. Hence, the force F is estimated to be $3.33x10^{-5}$ Nm. The deceleration 'a' due to the laser varies as per mass of debris

In case of debris of 10 g (0.01 kg), a= F/0.01= $3.33x10^{-3}$ N

In case of debris of 100 g (0.1 kg), a= F/0.1= 3.33×10^{-4} N

In case of debris of 1 kg, a= F/1 = 3.33×10^{-5} N

Orbital Speeds:

At 600 km: $u = \sqrt{\frac{\mu}{r}} = \sqrt{\frac{398600.4}{600}}$ (1)

$\approx$ 7.558 km/s

At 1200 km: u$\approx$ 7.253 km/s

At 1250 km: u$\approx$ 7.229 km/s

3.3.1 at 600 km orbit

Debris in this region will be the easiest to eliminate. Very few satellites operate below this region, hence, the risk of collision is less. Debris below this orbit will not survive more than 25 years Considering a piece of debris of mass 10 g, the shepherd fires as soon as the straight line between it and the target is at 70 degrees with respect to the horizontal of the target's body-axis system. The distance covered by both shepherd and target during firing is unknown, hence let the distance traversed by the shepherd during firing be X.

Now, tan 70= 650/X

X= 650 x cot 70 = 236.58 km

Equating the times, the distance traversed by both is found, $\frac{X}{7.229} = \frac{X+236.58}{7.558}$ (2)

X$\approx$ 5198.3 km, hence the time of firing is 719.1 s.

Thus, using plain equations of motion we calculate the decelerated velocity post the firing session

$$v = u + at \quad (3)$$

v = 7.55793 – $3.33 \times 10^{-3} \times 10^{-3} \times 719.1 \times \cos(80)$

= 7.55752 km/s, after the first fire. [an approximate 0.0004 km/s decrease]

After the first fire, the target advances ahead of the shepherd and completes an orbit after which it comes under the shepherd's range of influence once again. The time at which this happens can be found out,

7.55752 x t = 12756 - 236.58 + 7.229 x t (4)

t ~38108.55 s or 10.59 hours.

In addition to that, the time of influence will also change due to the decrease in the target's velocity. Hence, once again equating the times,

$$\frac{X}{7.229} = \frac{X + 236.58}{7.55752}$$

We get X= 5205.88 km. This gives us the new influence time of 720.14 s.

Thus, after 10.59 hours,
$v = 7.55752 – 3.33 \times 10^{-3} \times 10^{-3} \times 720.14 \times \cos(80)$
$= 7.55710$ km/s [an approximate 0.0004 km/s decrease]

Hence, initially every 11 hours, the target loses 0.0004 km/s. This rate increases as days pass on. By the end of a year, the debris will have lost an approximate 0.3 km/s.In case of 100 gram objects, the object loses 0.03 km/s a year. Similarly, for a 1 kg object the approximate loss in velocity is 0.003 km/s for a year.

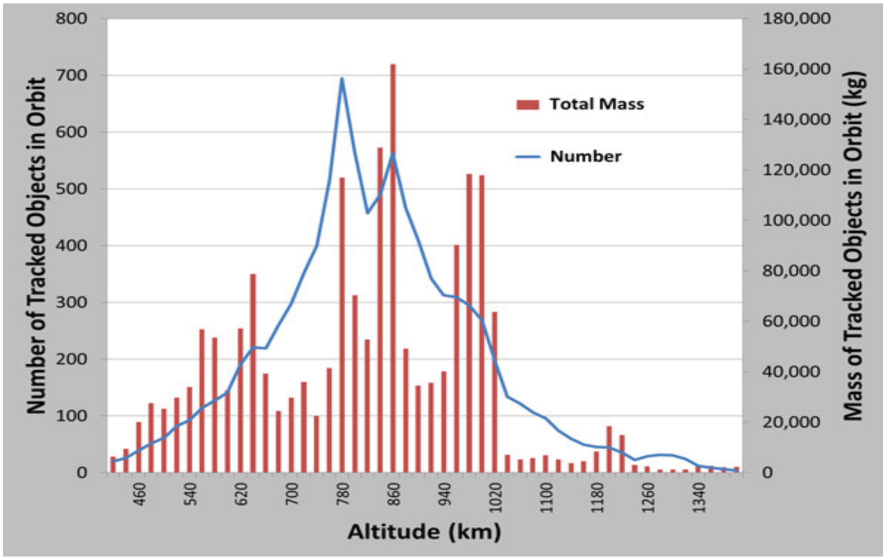

Figure 2.Mass and number of objects traced at different altitudes

3.3.2 at 1200 km orbit

Debris in this region will be the toughest to manage. Objects should be deflected away from the poles as the debris density over this region is the highest. Considering a piece of debris of mass 10 grams, the calculations are done similar to the previous case.

tan 45= 50/X

X= 50 x cot 45 = 50 km

X≈ 15060.417 km, hence the time of firing is 2083.3 s

v = 7.25033 km/s after first fire. [an approximate 0.003 km/s decrease]

t ~ 521642.5 s or 144.9 hours.

Hence, initially every 145.5 hours, the target loses 0.003 km/s. This rate increases as days pass on. By the end of a year, the debris will have lost an approximate 0.15 km/s. In case of 100 g objects, the object loses 0.015 km/s a year. Similarly, for a 1 kg object the approximate loss in velocity is 0.0015 km/s for a year.

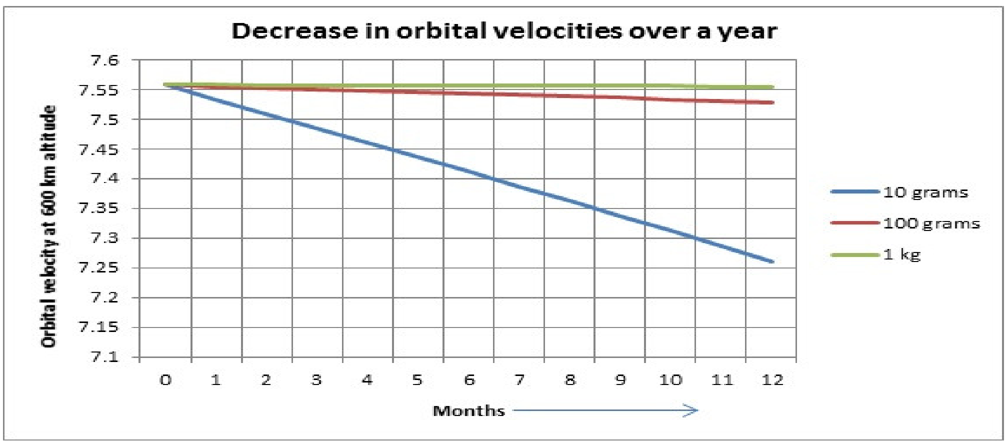

Figure 3. ***Graph demonstrating decline in orbital velocities of debris present at 600 km altitude***

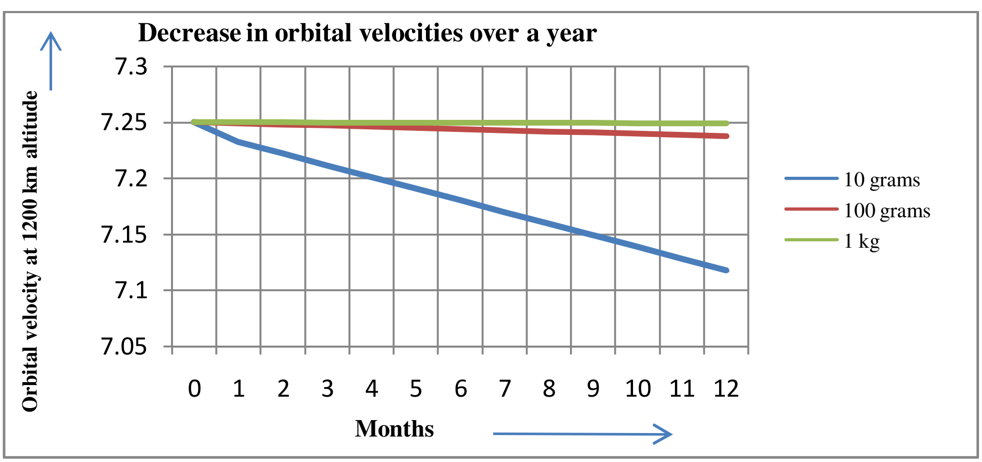

Figure 4***: Graph demonstrating decline in orbital velocities of debris present at 1200 km altitude***

4. CONCLUSION

Space debris, being a global problem, requires international cooperation, as in the case of the International Space Station. The proposed management system is expected to completely monitor the hazardous space debris in the Low Earth Orbit. As mentioned earlier, the smaller the size of the debris, the more efficient and timely is the process of de orbiting them back to the earth. The development of powerful lasers and target systems are crucial for the efficient functioning of the shepherd satellites. This will enhance their de-orbiting capabilities, enabling them to tackle heavier debris. This can be a boon for mitigating space debris and a great opportunity to widen the human horizon in space exploration and research.

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