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Implementing Scalable Solutions for Space Debris Mitigation

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Abstract: Collision of space debris present in the LEO (Low Earth Orbit) poses a serious threat to the current operational space missions as well as to the future utilization of the LEO space. These also result in major environmental impairment and significant economic losses due to damage to satellites and space stations. It thus becomes imperative to develop effective strategies and design and build systems which can aid in the removal of both small and large debris. This paper investigates the various existing space debris mitigation models such as ElectroDynamic Debris Eliminator (EDDE), ESA's Space Harpoon, Laser Ablation, and JAXA's Electrodynamic tether. A useful comparison is drawn amongst these different techniques while evaluating their efficiency within the framework of methods for space debris capture and removal. The advantages and drawbacks of these technologies are discussed through examples, previous and ongoing projects. The paper also aims to briefly introduce a novel concept for debris mitigation and to motivate more rigorous research in this area.
Keywords: Space debris, Mitigation, LEO, EDDE, Harpoon, Laser ablation, Hall Effect Thrusters, CMG

I. INTRODUCTION

October 4, 1957 or the launch of Sputnik 1 (the first artificial satellite placed in LEO), while believed to be a magnificent historical feat, is also considered as the main root of the space debris problem that the world currently faces. Space debris is defined as a space object in the Earth orbit that is human made and no longer serves any function. This can include spacecraft whose lifespan has ended, fragments caused by explosions or collisions in space or objects released during missions.

The exponential nature of the space debris collision equation is very hard to control and was first formulated by NASA scientist Donald J. Kessler. Kessler et al. [2] proposed a scenario in which the density of orbital junk in the Low Earth Orbit (LEO) is high enough to give way to collision between any two considerably large pieces of debris. This can trigger a possible cascading effect which in turn has the potential to render space exploration in the lower reaches of the Earth orbit inaccessible to future generations. This also poses a significant threat to billions of dollars worth of existing space infrastructure.

There has been an exponential growth of space debris since the launch of Sputnik 1 in 1957: two catastrophic events in history include the 2007 Chinese anti-satellite (ASAT) test and the 2009 Iridium-Cosmos collision. Consider the example of the 2009 Iridium-Cosmos collision: Cosmos, a defunct Russian satellite collided with the functional Iridium 33 satellite and ended up destroying both. This collision is expected to have created 2201 fragments, out of which at least 1400 are greater than 10 cm in size and still remain in orbit [1]. Any impact of a debris piece greater than or equal to 10 cm with an operational space vehicle can result in complete disintegration of the vehicle. Debris within the range of 1-10 cm in size are classified as the 'lethal population' since it is extremely difficult to track, identify and develop shielding against these debris.

Bonnal and Ruault [3] discussed five major functions associated with Active Debris Removal (ADR) along with potential solutions for the same. Emanuelli et al. [4] then analyzed non-technical challenges in developing an ADR mission by using the scorecard method and CleanSpace's case studies. This was followed by Shan et al. [5] who compared existing technologies for ADR and addressed their advantages and drawbacks. These ideas have contributed significantly to the development of debris mitigation methods such as the European Space Agency's Space Harpoon, JAXA's Electrodynamic Tether and the ElectroDynamic Debris Eliminator.

II. METHODOLOGY

This manuscript aims to assess and review the efficiency of various space debris mitigation models that are either already developed or currently being tested. These include: the ElectroDynamic Debris Eliminator (EDDE), a large, propellantless, maneuverable vehicle for preventing collisions; ESA's Space Harpoon, that targets larger objects for capturing and orbiting; Laser Ablation, or the use of lasers to alter debris path, and JAXA's Electrodynamic tether that utilizes electromagnetic forces to decelerate and deorbit debris.

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This paper aims to evaluate these models on the basis of 4 different parameters: Technical Practicality, Recyclability and Adaptability and Innovation and Economic Efficiency under specified sub criteria as follows:

TABLE I
PARAMETERS FOR EVALUATION

Parameter	Criteria	Sub-Criteria	Maximum Score
Technical Practicality	Effectiveness	Target Debris, Extent of Solution, Energy Efficiency, Timeframe	10
	Practicality	Violation of laws, theoretical practices (not tested yet)	10
Recyclability and Adaptability	Adaptability	Varying operational scenarios/debris sizes, scope of extent of covering debris orbits	10
	Recyclability	Sustainable materials or recycle materials which constitute space debris	10
Innovation	Novel Approach	Novel idea(s), expansion of quality/effectiveness	20
Economic Efficiency	Cost	Cost efficient for intended use/materials/technology	20

Following this review, the paper will introduce a novel concept for space debris mitigation, building on the strengths and addressing the limitations of the existing models. The proposed idea aims to ensure the long term sustainability of space activities by developing a scalable, cost-effective and practical solution. This investigation will further add to the ongoing research on space debris mitigation and promote collaborative efforts toward a cleaner and safer orbital environment.

III. SPACE DEBRIS MITIGATION SYSTEMS

A. *ElectroDynamic Debris Eliminator (EDDE)*

The ElectroDynamic Debris Eliminator (EDDE) is a propellantless, maneuverable 'taxi' that boasts a significantly lower cost than its competitors. It was developed by Star Technology and Research (STAR) and Tether Applications. With a focus on the heavier objects (greater than 2kg in mass), EDDE technology claims to remove approximately 99% of the total mass, collision area and debris-generation potential in LEO [6]. EDDE uses electric current in a long metal tape to react against the Earth's magnetic field. EDDE's thrust comes from the current in the tape crossing geomagnetic field lines. EDDE is capable of climbing and changing its orbit within days to reach other objects, while also cataloging other debris.

Since it is propellantless, it is not restricted by Tsiolkovsky's rocket equation, thus being able to produce hundreds of delta-Vs in its operational lifetime, showing exceptional efficiency in terms of energy generation: practically being able to 'sail' through the Earth's geomagnetic field while being powered by solar arrays. These solar arrays generate current that is driven through the conductor. The magnetic field produces a Lorentz force on the conductor that is proportional to current, length, direction and strength of the magnetic field. Since it is surrounded by ionospheric plasma, the electrons are collected from the plasma near one end of the conductor, and ejected at the other end by an electron emitter [6]. EDDE uses nets through net managers that carry about 100 Spectra fiber nets of 50 grams each to grab the debris and drop it off at a lower orbit so as it de-orbits itself, catering to only larger size debris [6].

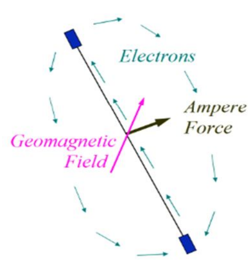

Fig. 1 EDDE Electrodynamic propulsion [6]

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In terms of innovation, the use of nets to capture debris reduces the effectiveness of EDDE. Once the net capture is complete, the EDDE taxis the debris to a lower orbit (a perigee of 200km and below) and cuts the net. At this altitude, the atmospheric drag causes a sharp decline in orbital velocity and the debris de-orbits, and due to this, an opportunity to recycle the materials is lost, reducing its recyclability. In contrast, it shows exceptional adaptability, as its secondary applications include distribution of payloads launched with EDDE and to extend satellite lifetimes, there are concepts for service modules that can refuel satellites or even replace electronic modules.

Another advantage is that it stows very compactly: despite deploying to a length of 10 km, it fits in a 10x24x28” envelope. This lets it be launched in one of the six payload spots on the ESPA (EELV Secondary Payload Adapter) and also as a secondary payload adapter on the Orbital Sciences Pegasus air-launched vehicle, SpaceX Falcon 1 and Falcon 9. In terms of cost, it estimates the cost for removal to be $374 per kg and $84 million annually to the customer [6]. However, it seems to be more efficient than its competitors due to its ability to provide secondary services to the customer, thus generating even more profit.

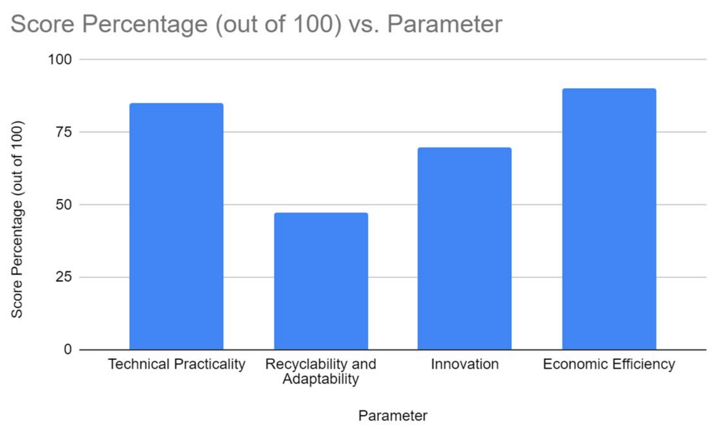

Fig. 2 EDDE Scores

B. ESA Space Harpoon

Development of the harpoon system for capturing space debris was initiated by Jaime Reed and Simon Barraclough. The European Space Agency Harpoon relies on three physical actions to ensure grasping: a high energy impact into the target, piercing the structure and then reeling it in [8]. A chaser satellite can be used to launch a harpoon which would then penetrate into a large debris object. This chaser satellite will then reel the debris in a graveyard orbit, or make it re-orbit [5]. The harpoon targets to eliminate large dysfunctional satellites which contribute to only 2% of the debris population in LEO, with no future plans to expand its reach to smaller debris. The harpoon uses a primitive design: a single unit can be used to target one defunct satellite at a time which significantly increases the required number of missions to achieve the intended objective.

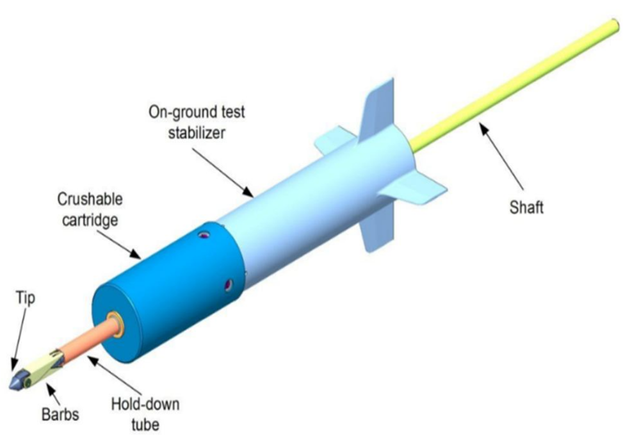

Fig. 3 ESA Space Harpoon [8]

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According to the ESA website [8], 'A prototype harpoon was shot into representative satellite material to assess its penetration, its strength as the target is pulled close and the generation of additional fragments that might threaten the e.DeOrbit satellite.' This clearly portrays a high risk factor and a huge vulnerability of the system to safely and effectively remove the debris. Furthermore, a high energy penetration into the debris piece might create additional debris instead of eliminating debris from orbit, thus posing a greater risk of intensifying the problem. However, according to the results of an experiment, the fragments are assumed to be staying inside the target thus not posing such a huge risk. It is also not capable of treating a target with a high tumbling rate [5].

Some key advantages the harpoon offers include its compatibility with different target types like rocket bodies or satellites, stand-off distance to target, and no required grappling point [5]. In terms of adaptability, the harpoon in its operations finds itself restricted to large satellites which orbit the Earth as debris and therefore cannot adapt to the plethora and size of debris in the LEO. As a part of the e.DeOrbit mission planned by the ESA, the harpoon operates at 800-1000 km, thus capable of covering multiple orbits. It also shows little-to-no recyclability as once the defunct satellite has been rigged to the harpoon, the entire system de-orbits and burns up in the Earth's atmosphere thereby putting recovery of potentially useful materials out of the question.

That being said, it does show innovation by exemplifying an age old concept to introduce a novel technology to the industry. The design incorporates a penetrating tip, crushing cartridge to help embed it in the target satellite structure and barbs to keep it sticking in so the satellite can then be reeled in [8].

In terms of economic efficiency, the costs for carrying out a cleaning operation in orbit using the harpoon are expected to be exorbitantly high with relatively minute profits.

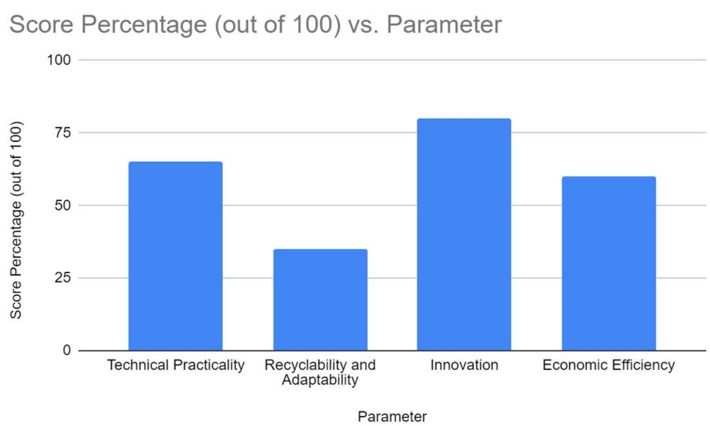

Fig. 4 ESA Harpoon Scores

C. Laser Ablation

Laser ablation is a contactless method of removal of space debris. Laser Orbit Debris Removal (LODR) is one of the most effective means to address the issue of collision of small and large debris. It was developed as an application of the LISP (Laser Impulse Space Propulsion) Principle [9].

The space debris problem can be addressed by causing an ablation jet to occur on the side of the debris facing the Earth using high power impulse causing its perigee to fall sufficiently, resulting in re-entry. The LODR produces a high quality beam through repetitive pulses which is directed towards the surface of the debris which is then propelled due to the reaction force generated by the ablation jet. As laser ablation occurs on the surface of the target, it causes it to recoil and depletes its orbital angular momentum, which further accelerates its atmospheric re-entry. However, both magnitude and direction of recoil is shape dependent.

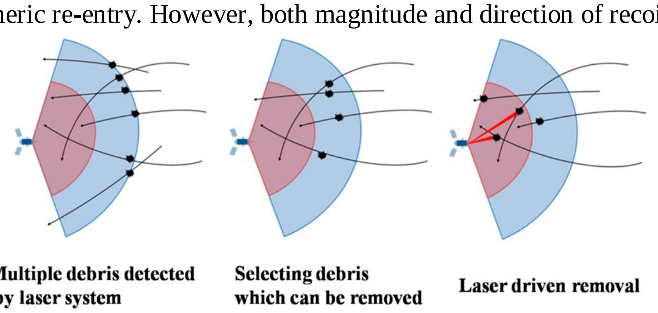

Fig. 5 Task flow of space-based laser removal of space debris [10]

Several physicists have contributed to the development of the laser system over the past few decades. It was C.R.Phipps who in 1996 proposed for the first time, a laser system called Orion consisting of a high resolution detection system and a laser beam of 20kW which could clear the near earth space debris larger than 1 cm but weighing less than 100 kg in 4 years and all debris within size range 1-20 cm in 2 years if operated continuously [11].

Illumination provided by a repeatedly pulsed laser to the debris object generates a laser ablation jet which results in de-orbiting the object due to its strong impulse. He even suggested a suitable location for the Orion base near the equator at high altitude to achieve maximum success. Phipps [12] proposed an updated and more efficient system, LODR, for removal of both large and small debris. Liedahl et al. [13] also contributed to the study by investigating the response of objects of various shape orientations to ablation jets. The determination and accurate prediction of debris orbits is essential to avoid collisions and valuable laser operation time. Bennett et al. [14] through their research, helped improve the accuracy for debris maneuver.

It was found that it is extremely versatile as it is compatible with debris of different sizes (both large and small) and can work on multi-ton objects. It is economical as it causes the space debris to re-enter and burn in the atmosphere but that also means it does not offer any recyclability.

Some of the drawbacks of this system are that it is unavailable in GEO (Geostationary Orbit). The system also runs the risk of generating new debris. Another drawback of the LODR is the shape dependency between the debris piece and the target area of interaction. Also, various atmospheric processes such as air breakdown, atmospheric turbulence, diffraction and atmospheric absorption can lead to beam degradation. However, the effect of these processes on beam quality can be diminished by adjusting the device parameters. Yet, it seems to be more efficient than mechanical removal methods as it can steer falling objects with greater ease.

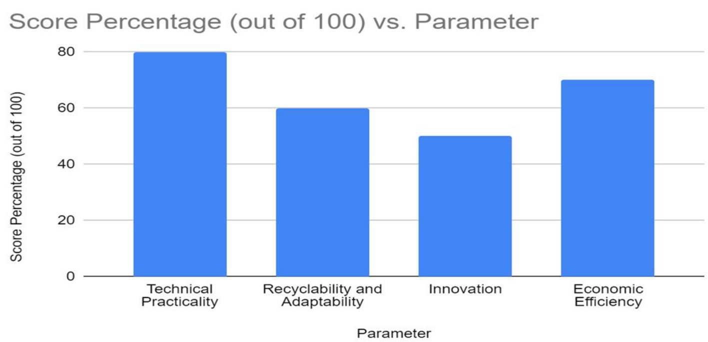

Fig. 6 LODR Scores

D. JAXA's Electrodynamic Tether

The electrodynamic tether, designed by the Japanese Aerospace Exploration Agency is a 700m long, knotless and conductive metal mesh. It is a method originally used in orbit transfer and orbit maneuvering [19]. Developed by Nitto Seimo, Japan's largest maker of fishing nets, the tether generates an electromagnetic force or the Lorentz force which is used to propel it. Hence, this offers a significant advantage as no propulsion system is needed. However, even though the concept of using Lorentz force for propulsion seems feasible, its practicality is yet to be tested. A space robot is required for capturing the target and it does so by using a robotic arm and installing an extendable electrodynamic tether on it [5]. It consists of two emitter array cathodes and a bare conductive tether. One cathode collects electrons and the other emits them in the way current is generated [18].

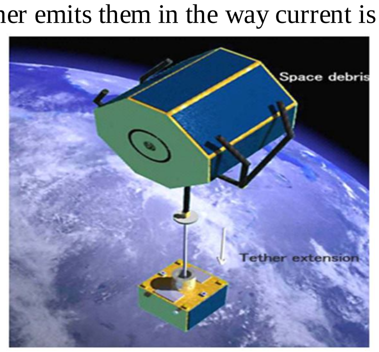

Fig. 7 JAXA's EDT [18]

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However, JAXA's proposal of using a 700m long tether to carry out a debris cleaning operation might give rise to new problems such as: spinning shrapnel might cut through the tether resulting in the system becoming space debris itself thus negating the usefulness of the mission, and the possibility of the tether inadvertently snagging an operational satellite. This makes its technical practicality less ideal.

It displays decent adaptability as it can be used to snag up small as well as large pieces of debris. With the tether being 700m long and with plans to extend its length, the Electrodynamic tether can cover multiple orbits. However, as of its current design, it cannot treat targets beyond LEO due to insufficient magnetic intensity [20]. It also doesn't show any recyclability as once the tether has collected a significant amount of debris, it is released into the atmosphere where it burns up along with the debris on re-entry. Another disadvantage is that when current is low, the thrust is not large enough to realize orbit transferring as the Lorentz force depends largely on the current flowing through the conductor [20]. However, the use of the cathodes and tether collectively portray an innovative solution.

Kawamoto et al. [15] performed numerical simulations to explore deployment dynamics and other factors such as tether stability. It was found that the EDT is prone to libration instability due to the complex space environment. Based on delayed feedback control, Kojima et al. [16] studied the in-plane libration instability in elliptical orbit experimentally.

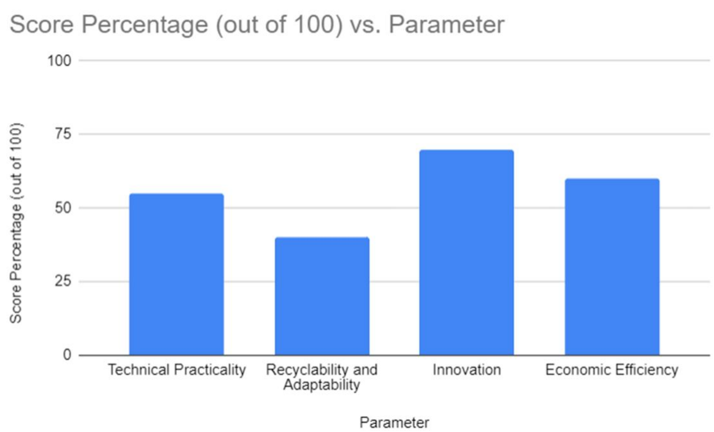

Fig. 8 EDT Scores

IV. PROPOSED IDEA

A space debris elimination device (which targets <10cm size debris - that contribute to 98% of the debris population in LEO) that works on the basis of location, tracking, collection, elimination of debris from their orbits and recycling of these is proposed. The device would first be launched by a launch vehicle and it would then classify debris according to existing databases and catalogs. Once it identifies its target debris using various sensors such as Hyperspectral Image sensors, LIDAR proximity sensors, radar transmitters and receivers etc., the orbit of the device is aligned with the orbit of the debris using thrust vectoring from Solar Powered Hall Effect thrusters. This orientation can be efficiently achieved through the usage of CMGs (Control Moment Gyroscopes). The concept of Solar Powered Hall Effect Thrusters was first used by the European Space Agency to power its SMART-1 satellite in 2003 [17]. The thrusters operate by their channel or anode being charged to a high positive potential by their power supply (solar energy), while a hollow cathode located on the downstream perimeter of the thruster generates electrons. As the electrons move towards the channel, they encounter a magnetic field generated by the thruster's powerful electromagnets. This magnetic field traps the electrons, causing them to form a circular ring, known as the Hall current. A propellant (typically Xenon) is injected into the thrusters channel. The thrusters ionize propellant atoms through electron bombardment, where high energy electrons collide with propellant atoms to release a second electron. The propellant ions which have been generated experience the electric field produced by the positive channel, and the negative ring of electrons accelerate out of the thruster, creating an ion beam. The force which the ions impart to the electron cloud generates the thrust required.

The CMG would form the non-propulsive altitude control system for the device which works in correspondence with the Hall Effect thrusters. Using a concept known as momentum management for their functioning, CMGs act as momentum storing devices that exchange momentum with the device through induced torques, the changing angular momentum further causes a gyroscopic torque that rotates the device [21]. This can be used in a cost-effective way to make fine adjustments to the orbital altitude of the device.

A sealed system or airlock incorporated in the device that 'stores' the debris at relative rest can be pressurized using compressed N_2 gas. Automated flow-control valves can be used to maintain a check on the pressure balance in the device. Solar power used to operate the motors can be connected to a set of fans so as the blades of the fan turn, they create a pressure difference by creating a partial vacuum on one side. The difference in pressure propels the particles of nitrogen gas from the debris containing airlock towards the fan which consequently creates a suction within its pressurized environment. The debris piece can then be pulled further in where another suction pull maneuvers the piece of debris into 'storage containers'. The walls of the container are coated with a layer of Elastosil, an adhesive which is highly resistant to extreme temperatures. This can make the debris piece stick to the walls of the container, and can thus be transported to any said station for recycling purposes. This can be achieved by constructing an 'arm' of the device of sorts that can dock with other stations, which in turn could collect the debris and transfer it back to Earth for recycling.

This device can prove to be relatively energy efficient and offer recyclability to a great extent, while exemplifying innovation. However, this system poses certain limitations. Even though there has been testing of the above mentioned technologies, they have not been used in conjunction yet to corroborate the technical practicality of such a device. Due to highly elliptical orbits and high velocity motion, sudden and sharp fluctuations in the rotation rates of debris particles have been observed. At these rates, the spinning of the debris particles can put the device's internal components at risk. However, this may be avoided by the usage of Magnetic Damping embedded in the walls of the airlocks. Furthermore, this device can be expected to give rise to high operational costs.

V. CONCLUSIONS

The rise of space debris in the Low Earth Orbit (LEO) is an obstacle to future space missions, necessitating the development of effective mitigation strategies. This research paper assesses various existing solutions including the ElectroDynamic Debris Eliminator (EDDE), ESA's Space Harpoon, Laser Ablation, and JAXA's Electrodynamic Tether on the basis of specific parameters. Each of the models are reviewed and their advantages and disadvantages have been discussed. Building on these insights, this paper briefly introduces a novel concept for debris mitigation that aims to target smaller debris by leveraging advanced technologies. Ongoing innovation and teamwork between international space agencies and private companies are essential for tackling the increasing problem of space debris and ensuring the future success of space exploration and use.

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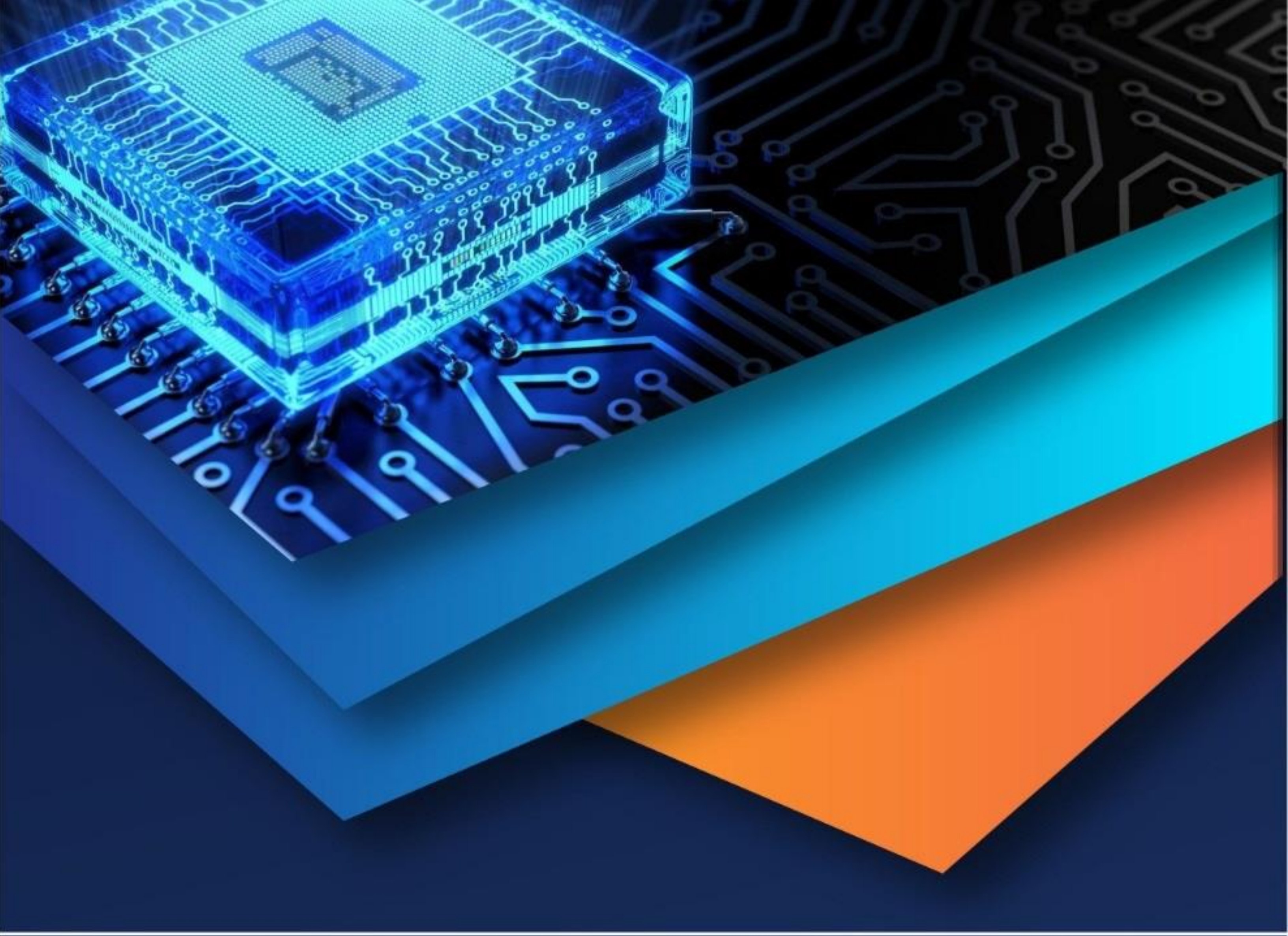

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