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Summary Sheet

There are currently hundreds of millions of space debris fragments orbiting the Earth at speeds of up to several kilometers per second. Action is needed soon to remove the largest pieces of space debris from orbit before the amount of junk destroys massive amounts of critical space infrastructure

Our task is to create an effective model to quantify the costs, risks and benefits of the methods to remove the debris. Our goal is to determine the best alternative or combination of alternatives that a private firm could adopt as a commercial opportunity to address the space debris problem. We compare two typical measures of Active Debris Removal (**ADR**) to one typical measure of Post-Mission Disposal (**PMD**) in the three aspects.

So as to make the estimation of costs, we divide the total costs into two main parts: **launch costs,** and core **technology costs**, then we calculate the rational costs using limited data. Risks in project are generally classified into five categories, including: **technological risks, legal and political risks, economic risks, financial risks, production risks**. We establish Analytic Hierarchy Process (**AHP**) Model to determine the weight of each metric to risks evaluation. For the purpose of overcoming weakness of excess subjective factors in AHP , we establish an improved **probability distribution model** which can quantitatively estimate the risk level probability distribution. As for benefits, we define it as the influence on the increase of orbital debris. We innovatively develop a model of the increasing number of orbital debris, which extremely match the data given by NASA. Sensitivity analysis is performed on this model. In addition, we meticulously analyze how the costs, risks, benefits change as time goes by, then we conclude qualitative estimates of the three aspects. For a comprehensive analysis of costs and risks and benefits, we use AHP model choose a best project.

We test our model by comparing two typical measures of Active Debris Removal (**ADR**) to one typical measure of Post-Mission Disposal (**PMD**) in the three aspects. Our conclusion is that an economically attractive opportunity does not exist under present conditions. We propose a new strategy – **using electron gun which is integrated in an add-on module to the satellites to clean debris when the system detects a collision may occur.**

At last, the strength and weakness of our model are discussed, non-technical explanation is presented and the future work is pointed as well.

Making the Earth More Clean

--Cleaning the Orbital Debris

contents

1 Introduction

The volume of space surrounding the Earth has never been empty. Even before the 1957 launch of Sputnik, a rain of particles of various sizes passed constantly through near-Earth space. Although such naturally occurring meteoroids' hazard to functional spacecraft is low, simple shielding techniques can protect against the vast majority of these predominantly small particles and the chance of a spacecraft colliding with a meteoroid large enough to cause serious damage is remote.

The collision hazard in Earth orbit has steadily increased as the number of artificial objects orbiting the Earth has grown since the beginning of space flight. Since 1957, there are more than 4,500 spacecraft have been launched in to space, nearly 2,200 remain in orbit. It is worth noting that about 450 are still functional, the rest can no longer carry our there missions and are considered debris. However, nonfunctional spacecraft constitute only small fraction of the debris orbiting the Earth.

1.1 What is orbital debris

Orbital debris is "junk" that is circling Earth. It is pieces from spacecraft. Humans have been launching objects into space for more than 50 years. Most of those objects have fallen back to Earth. A piece of debris falls back to Earth about once a day. These objects either land or burn up in the atmosphere. Most objects that return to Earth end up in water, since it makes up 70 percent of Earth's surface. But many of the objects sent into space are still in orbit around Earth. [1]

The various types of debris:

1. Rocket bodies
2. Mission-related debris (exhaust products, objects released in spacecraft deployment and operations, refuse from human missions)
3. Fragmentation debris (breakup fragment, products of deterioration)
4. Nonfunctional spacecraft

The Classification standard of debris is represented in Table 1 [2]

Table 1 **Debris Size Conventions**

Size Category	Approximate Diameter	Approximate Mass
Large	>10 cm	>1 kg
Medium	1 mm-10 cm	1 mg-1 kg
Small	<1 mm	<1 mg

Note: Lines between categories cannot be sharply drawn. For example, how the sizes of objects that are detectable through various means vary depending on sensor capability and the object's altitude, and how damage caused by debris impact depends on the collision velocity and the particular configuration of the spacecraft being struck.

1.2 The creation of orbital debris

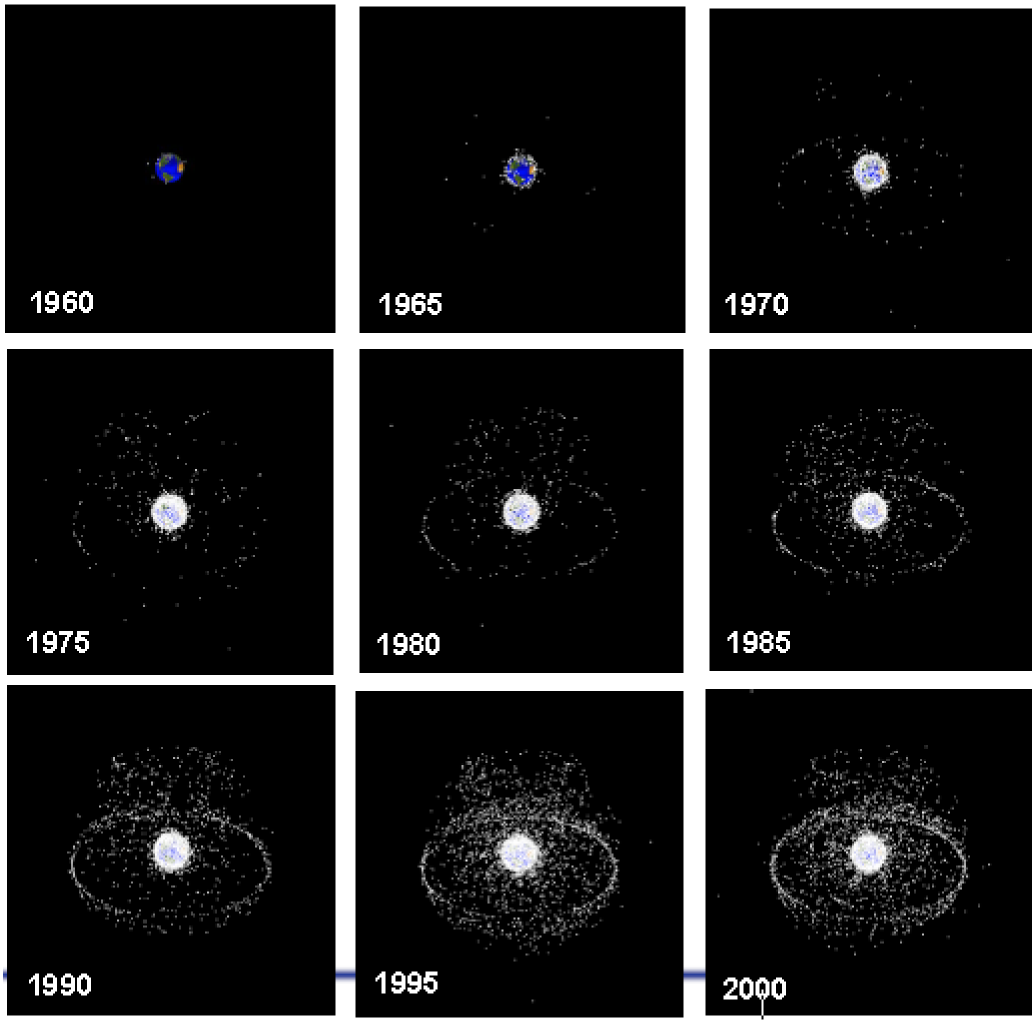
As the number of artificial satellites in earth orbit increases, the probability of collisions between satellites also increases. Satellite collisions would produce orbiting fragments, each of which would increase the probability of further collisions, leading to the growth of a belt of debris around the earth.

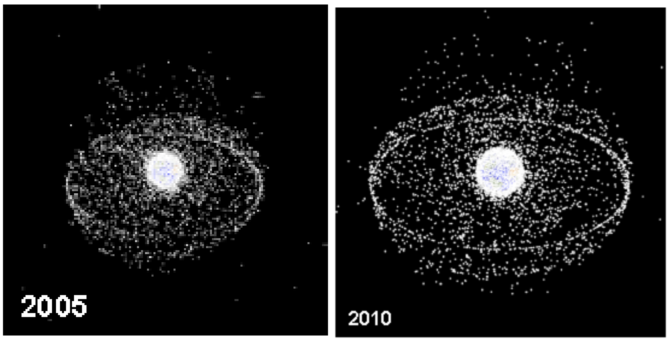
Space debris increase factors:

1. Vehicle and the spacecraft in the transmission and the working process create the fragments;
2. rupture (including explosion and impact)caused the increase in the number of pieces;
3. surface material loss (for example: coating spalling) due to aging;
4. materials (such as nuclear power source of the cooling liquid) to escape.

We can see the numbers of debris are growing faster and faster from Figure 2 and Figure 3.

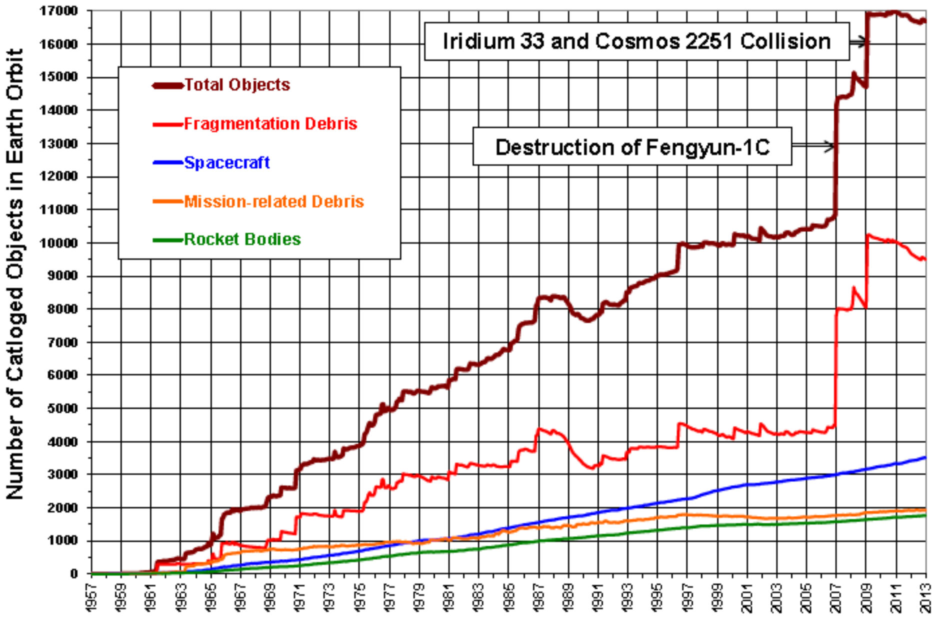
Figure 2. Growth of the satellite population [3]





94% of Tracked Object Population are Debris

Figure 3. [3]Growth of the cataloged satellite population in Earth orbit: numbers of objects



1.3 The necessity of removing orbital debris

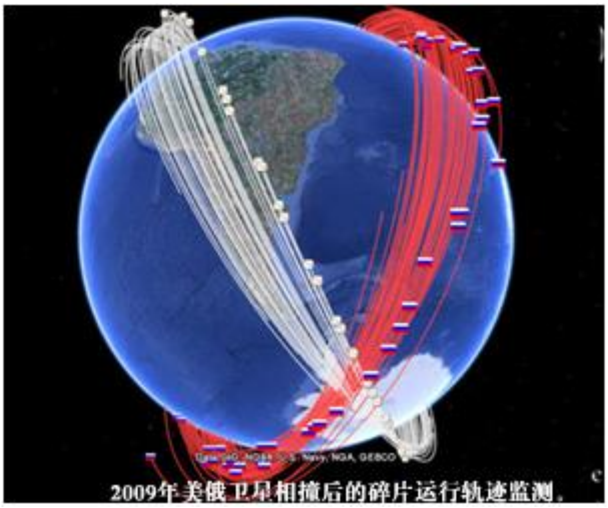
In orbits near the Earth, colliding objects typically will have a relative velocity of more than 10 km/s. At these speeds, collision with objects as small as a centimeter in diameter could damage or prove fatal to most spacecraft, depending on where the impact occurs. Impacts with the much more numerous debris particles that are a millimeter or less in diameter can damage optics, degrade surface coatings, or even crack windows. [2]

Debris is mainly distributed from LEO to GEO, its concentration areas is commonly used spacecraft orbit. It is estimated that within 2000 km of the earth's surface, artificial track the total mass of the object is about 3,000,000 kg.

In 2009, the American Iridium satellite collided with debris from an inactive Russian satellite, producing roughly 2,000 more pieces of debris, some of which went on to destroy a satellite worth $55 million. The more junk accumulates, the more likely collisions between satellites and debris will become, with each collision causing a proliferation of debris.

Figure 4 shows the Debris orbit after the Russian satellite Kosmos-2251 and the USA satellite Iridium-33 collided

Figure4. [4]



According to the size of the debris, the harm is manifested in:

The pieces whose diameter is less than 1cm

1. Because of the large number of tiny debris, they can change the surface of spacecraft seriously
2. Larger debris can damage spacecraft surface material and cause the crater, damage the surface device
3. High speed impact of space debris makes itself and the surface of spacecraft for plasma gasification Cloud, eventually form the spacecraft fault;
4. The impact of debris decrease of the strength of spacecraft surface, even appear crack, damage high pressure vessel bulkhead, the explosion may occur.

The pieces whose diameter is greater than 1cm have stronger lethality. It is estimated that when 1.3cm-diameter small aluminum particles runs at a rate of 10km/s, its kinetic energy is equivalent to a domestic sports car runs at a rate of 50km/s. Its destructive cans be imagined.

Summarized as follows

1. When big high-speed debris crash to spacecraft, it pass huge kinetic energy to the spacecraft, change navigation days of attitude, even change the spacecraft's orbit
2. When the energy of the space debris is large enough, will penetrate the surface of spacecraft, and damage the inside of the spacecraft control system or payload
3. Big space debris impact spacecraft truss structure, the entire structure is likely to break up

The pieces whose diameter is greater than 10cm can cause devastating blow to the spacecraft.

French electronic reconnaissance satellite is fragments slam a long 6cm on the satellite on July 24, 1996, gravity gradient stabilizer bar was broken off, later determined that the impact of the satellite fragments is a launch Ariane rocket debris launched in 1986, the relative speed of collision fragments is 14km/s, which is confirmed for the first time human caused by space debris collision events.

In addition to presenting a collision hazard to space operations, orbital debris can also have **other detrimental effects**. For example, debris can affect astronomical observations by leaving light trails on long-exposure photographs with wide fields of view. In addition, debris reentering the atmosphere can potentially harm people and property on the ground. In the past, this has been a minor hazard, since most reentering debris objects burn up completely in the atmosphere. However, there have been some exceptions (e.g., Kosmos 954, Skylab, and Salyut-7/Kosmos 1686), and the exact number of objects surviving reentry is unknown. [2]

Claude Nicollier, an astronaut and EPFL professor, compared the space junk problem with global warming. "In a way, there’s some similarity between the two problems," he said. "If we don't do anything, we’ll have big problems in the future." [5]

Scientists warn that if you don't solve the problem of debris, humans may lose geosynchronous satellite orbit over the next 20 years, also can't issue any satellite, it is because if launch a rocket then it will be crashed by space junk. Mason said. "Collisions like this were predicted by Kessler in 1978, and he predicted that if the number of debris in certain orbits got high enough then there would be a cascading series of collisions that might eventually render whole orbits unusable."

1.4 Examples of Heavily Used Orbital Regions

Low Earth Orbit (LEO) [2]**:** A majority of the world's spacecraft operate in LEO because these orbits have characteristics that are advantageous for a wide array of missions. First, less energy (and thus a smaller launch vehicle) is required to launch a spacecraft into LEO than to put it into any higher orbit. Second, proximity to Earth allows remote sensing missions to receive higher resolution images. Finally, the Earth's magnetic field protects spacecraft in some LEOs from cosmic radiation and solar flares; this is of particular importance for human operations in space.

Sun-Synchronous Orbit [2]**:** These LEOs precess in such a way that they do not experience changes in Sun angle due to the movement of the Earth around the Sun. This means that the lighting conditions for points on the Earth as the spacecraft passes overhead do not change over the course of a year—a useful feature for some remote sensing missions. Sun-synchronous orbits have inclinations greater than 90 degrees (the exact inclination varies with altitude). Although spacecraft can occupy Sun-synchronous orbits at most altitudes, for a number of reasons the altitudes near 900 and 1,500 km are the most widely used.

Geosynchronous Earth Orbit (GEO) [2]**:** GEOs are circular with orbital periods of approximately 1,436 minutes (about 24 hours), so spacecraft in them remain above roughly the same longitude on the Earth throughout their orbit. A special type of GEO is the geostationary Earth orbit, which has an inclination close to zero degrees. From the surface of the Earth, spacecraft in geostationary Earth orbits appear to be fixed in the sky. Communications with the spacecraft are thus simplified—both because the spacecraft is in view at all times and because ground antennas do not have to follow the spacecraft's movement. Inclined GEOs are also useful for some missions, although they require ground stations that are able to track a spacecraft's north-south as well as its apparent east-west movement.

2 Assumptions

1. When we calculate the number of debris, we suppose that **the movement of the space**

debris obey the motion law of ideal gas molecules. It means space debris in the study area can move to any direction freely and randomly, unless they contact with another debris.

That is, the calculation of hit probability is a complex academic technical problems. First of all, the hit probability depends on the space debris environment, namely the fragment size, quality, space position (density) and the three-dimensional distribution of velocity. So far, in addition to the size is more than 10 cm near-earth orbit, and geostationary orbit is greater than 1 m of large fragments, can be observed and recorded the catalog on the ground (currently about nearly 9000), the rest of the millions of medium and small pieces whose size shorter than 10cm, and the tiny pieces' distribution density is only according to a handful of recycled spacecraft measurement and the established model, carries on the statistical analysis and calculation. The measurement data is mainly from the United States " Long Duration Exposure Facility (LDEF)" and space shuttles, EURECA recoverable satellite, namely through analysis on the spacecraft and parts' indentation and dent caused by the impact of the space debris.

Second, the hit probability is associated with the physical properties and orbit of satellite. Most obviously, the hit probability is proportional to the cross-sectional area of the satellite and in-orbit running time. And the hit probability is related to the orbit of the dip angle, semi major axis and eccentricity ratio.

Experts in the United States, Russia, ESA in order to analyze hit probability calculation and collision risk, have established their own space debris environment uncertainty or half analytical stochastic model, there are five model that NASA is using are as follow: ORDEM96,BUMPER Ⅱ,EVOLV E,CHAIN and DAS. They are not only difficult to understand but also take a lot of time. So in order to simplify the model, we use bold assumption, ignore the orbit of debris, we suppose that they can move freely in the study area.

3 Model

3.1 Costs

It is hard to estimate the cost of orbital debris, so we calculate the sum of main costs to estimate the total costs per year.

3.1.1 Launch costs P_1

The definition of a standard satellite is determined by its rough estimate size, which is based on its subsystem the quality models. The subsystem level cost model parameter was chosen from Wong (1991), quote some parameters of the Koelle's(1991) model to evaluate cost of AKM. These models can be used to determine the improvement and production cost. All factors can be expressed by parameter, this means that the launch of the past data can be used in the future. Depending on a parameter estimation has its own advantages, it is based on historical data and include all kinds of influence factors, such as transmitting delay, error, design etc. Therefore, cost estimate model also takes into consideration the factors such as the satellite system of subdivision directory allows the use of parameter formula to express satellite operations, quality and cost. The deficiency of the process is it doesn't have a standard subsystem expression. Because of lack of proper operating cost model, here have adopted a more simplified method. Assuming that satellite is a constant, only years running costs related to the satellite complexity. This concept is realized by associating the annual operation cost with satellite hardware costs. Through adjusting this relationship, we found that the cost of operation per year is about 3% of the cost of hardware. Average costs is acquired by studying some satellite launch data (from Isakowitz et al., 1999). [9]

3.1.2 The costs of core technology P_2

The core technology is one of the most important aspects of each method, is also most expensive aspects, so we consider in this costs.

3.1.3 Durable years t_{use}

If we find durable years of each machine, we can annual cost.

A number of methods to remove the debris have been proposed. Here are some of them [13]:

1. Knock debris down with a net.
2. Huffing and Puffing.
3. Solar sail.
4. A space debris slingshot.
5. Using the power of electricity.
6. Pushing debris out of space.
7. Snagging and moving space junk.

   Etc.

There are so many methods, we only select two methods analysis as follow.

3.1.4 The ElectroDynamic Debris Eliminator (EDDE)

EDDE [10] is a vehicle of a new class that was unveiled at the NASA/DARPA International Conference on Debris Removal in December 2009. It is a propellantless roving space vehicle for LEO that "sails" in the magnetic field. EDDE is solar-powered. It uses electric current in a long conductor to thrust against the Earth's magnetic field. Electrons are collected from the plasma near one end by an electron collector, and are ejected at the other end by an electron emitter. The current loop is closed through the plasma. Operating without propellant, EDDE can repeatedly change its altitude by hundreds of kilometers per day and its orbital plane by several degrees per day, providing enormous delta-Vs of hundreds of km/sec over its operational lifetime. It can be described as several nanosats "taped" together with long conductor segments.

3.1.4.1 The costs of EDDE

Launch costs

EDDE weighs only about 100 kg, but it can move multiton payloads throughout LEO. [10]

$P_1 = 100 \times 12 = 120$ FY02$

The costs of core technology

It cost under $400 per kg [11]. According to de NASA's data, we can get the average mass of debris, it is about 353kg. So:

$P_2 = 400 \times 353 = 141,200$

Durable years

Two EDDE vehicles can be launched every year and retired after 5 years of service. [10]

$t_{use} = 5$

Average cost

$$P = \frac{P_1 + P_2}{t_{use}} = \frac{120,000,000 + 141200}{5} = 24,028,240 \ \$$$

3.1.5 Lasers

It is a method to remove the debris remaining on the ground and zapping it with lasers. [11] Light can exert a push on matter, a fact that scientists have used to develop solar sails that can fly through space on sunlight. The researchers suggest that a medium-power commercially available laser with a 5-to-10-kilowatt beam constantly focused on a piece of debris could work, located someplace such as the Plateau Observatory in Antarctica.

3.1.5.1 The costs of Lasers

Launch costs

Because it is a method that emission lasers on the ground. So the launch costs is 0.

$P_1 = 0$

The costs of core technology

The 5-kilowatt laser would cost about $800,000, and a single device could probably engage about 10 objects a day. [11]

However, the scientists do note that the actual cost of an operating system, including telescope, would likely be tens of millions of dollars. [11]

$P_2 = 800,000 + 10,000,000 = 10,800,000$

Durable years

According to search references, we get that $t_{use} = 1$.

Average cost

$$P = \frac{P_1 + P_2}{t_{use}} = \frac{0+10800000}{1} = 10{,}800{,}000 \ \$$$

There are also many method to prevent new debris. [9]

1. Passivation
2. Mooring
3. Grave track
4. Repeated use
5. Recovery
6. Derailment

   Etc.

Now we analysis one typical method.

3.1.6 Geostationary orbit (GEO) transfer

Geo-stationary orbit (GEO) transfer [9] is a method that remove retired satellite from orbit. Transfer of motor is residual fuel, it will reduce the life of the satellite. The growth rate per year for posture keeping is $\Delta \mathrm{v}_i$, fixing initial orbit error is $\Delta \mathrm{v}_0$, according to the former's fuel, we can finally calculate the initial mass(BOL) by final mass(EOL). So:

$$\frac{m_{BOL}}{m_{EOL}} = \exp(\frac{\Delta v_0 + n_y \Delta v_i}{w})$$

In the equation, n_y is durable years. w is the speed of the spacecraft when the fuel runs out.

Calculating the estimate reducing life needs to know the quantity of fuel for posture keeping each year. In order to estimate the quantity, we collected several satellite BOL and EOL data of the amount of fuel. Results show that in order to correct the initial error and position satellites again need $\Delta v_0 = 214m/s$ on average, annual operation need $\Delta v_i = 37.9m/s$ .Supposing that Δv_i includes orbit maneuver increment, the reducing life of the orbits $n_{y,red}$ can be calculated as follow:

$$n_{y,red} = \frac{n_y \Delta v_i - \Delta v_{re-orbit}}{\Delta v_i}$$

Contact satellite cost and the orbit life reduction of translating hardware cost , can get a easy to understand mobile cost estimate. The satellite that evaluated from geostationary orbit to 300 km will reduce 2.5 months of life. According to evaluate, we get that a satellite costs 9.0 FY02 $M on average. But this shall be the minimum consumption cost calculation, some other factors such as the calculation of the uncertainty of the residual fuel, extra EOL mobile operating expenses, the reliability of the subsystem extra and eventually complexity, etc. Should also be taken into consideration.

So we can get the consequence as follow:

Table 2

methods	The ElectroDynamic Debris Eliminator (EDDE)	Lasers	Geostationary orbit (GEO) transfer
costs	24,028,240$	10,800,000$	9,000,000$

And as time goes by, more and more developed science and technology changing in plants could also reduce the cost. The gap between then will be smaller and smaller.

3.2 RISK ASSESSMENT

A risk is any factor that may potentially interfere with successful completion of the project .A risk is not a problem -- a problem has already occurred; a risk is the recognition that a problem might occur. By recognizing potential problems, the project manager can attempt to avoid a problem through proper actions. It is particularly important in the planning stage to document risks and identify reserves that have been applied to the risks. [15]

According the definition above, risks in project can be generally classified into five categories, including：

Technological risk. It refers to the threats to people's life and production arising from the rapid development and of science and technology and the change of production mode. There are various areas that can affect the technical risk, including the lack of advanced technologies, the research and development of new technologies and security links, as well as other important factors. Active De-orbiting of debris requires 5 functions: F1: Far range rendezvous between chaser and debris; F2: Short rang rendezvous, up to contact; F3: Mechanical interfacing between chaser and debris; F4: Control, De-tumbling and orientation of the debris. F5: De-orbitation. The degree of difficulty of varies among different alternatives and their combination. [16]Although the technology for active debris removal and on-orbit satellite servicing may be ready, the relevant operational procedures are lagging behind.[3]

Legal and political risk. Current international and national laws and policies play important roles in limiting the creation of new orbital debris and in establishing liability for collisions. By their very nature as well as their dual use attributes, the active space debris removal technologies come with very significant strategic and military implications. They can be used for Anti-Satellite Tests (ASAT). What matters the most in this connection is the capability of the technology, not the intent behind it. All of these capabilities are important from a strategic and military perspective. [16]

Economic risk. In most cases, it refers to unexpected risks of potential losses resulting from the change of the stock market prices, interest rates, exchange rates . Economic risks can be manifested in lower incomes or higher expenditures than expected. The causes can be many, for instance, the hike in the price for raw materials, the lapsing of deadlines for construction of a new operating facility, disruptions in a production process, emergence of a serious competitor on the market, the loss of key personnel, the change of a political regime, or natural disasters. [17]

Financial risk. Financial risk is due to the unexpected change in the balance of payments of enterprises that creates enterprise financial difficulties.

Production Risk. It is mainly about that the production plan can not be completed at a predetermined cost. There are two main factors causing such risks, including unexpected interruption of production process and production planning errors, which resulting in the production process disorders.

In order to quantify the risk of active debris removal (ADR) and post-mission disposal (PMD),we choose five metrics as the evaluation standard, where U1 is technological risk, U2 is legal and political risk, U3 is Economic risk, U4 is financial risk, U5 is Production Risk.

When we try to obtain the weight of mainly five aspects as the first class index and the weight of several second class index, subjective judgment is ill-considered. So we choose the Analytic Hierarchy Process (AHP) as the way to conform the weighting coefficient of all the indicators in the evaluation system.

Table 3. The three hierarchy structure which contains criteria level and alternatives level is shown in following table.

Goal	Criterion	Alternatives
The risk of investment	Technological risk	Passivation
	Legal and political risk	Laser
	Economic risk	EDDE
	Financial risk	
	Production risk	

Determine the judging matrix

We use the pairwise comparison method and one-nine method to construct judging matrix $A=(a_{ij})$

$$a_{ik} * a_{kj} = a_{ij}$$

Where a_{ij} is set according to the one-nine method.

Judging matrix:

$$A=\begin{pmatrix} 1 & 2 & 3 & 5 & 5 \\ 1/2 & 1 & 2 & 4 & 5 \\ 1/3 & 1/2 & 1 & 2 & 3 \\ 1/5 & 1/4 & 1/2 & 1 & 2 \\ 1/5 & 1/5 & 1/3 & 1/2 & 1 \end{pmatrix}$$

Weight vector of criteria level:

$CW = (0.4243, 0.2805, 0.1529, 0.0849,0.0574)$

For this level, CI=0.0201, CR=0.0179 satisfying $\frac{CI}{RI} < 0.1$.

In order to get the quantitative estimate of the risk, we establish an improved probability distribution model based on the AHP.

Based on the above analysis, we set the stage 1 to 5 according to the level of risk index value, which are described in table 4

Table 4.Risk classification evaluation standard

Level	Risk	Acceptance criterion
1	0≤R≤0.2	ignorable
2	0.2<R≤0.4	admissible
3	0.4<R≤0.6	acceptable
4	0.6<R≤0.8	unacceptable
5	0.8<R≤∞	reject

Since we have the weights of investment risk factors, we can obtain the probability distribution of investment risk factors, as shown in the tables blow.

Table 5 Investment risk factors of probability distribution of passivation

Factors	Risk level				
	5	4	3	2	1
U1	0.009	0.037	0.105	0.352	0.497
U2	0.005	0.021	0.097	0.346	0.531

U3	0.041	0.075	0.146	0.431	0.307
U4	0.007	0.067	0.142	0.475	0.3.9
U5	0.029	0.050	0.114	0.329	0.478

Table 6.The total investment risk probability distribution of passivation

Risk level	**Probability distribution**
5	0.013
4	0.030
3	0.125
2	0.380
1	0.451

Table 7.Investment risk factors of probability distribution of laser

Factors	Risk level				
	5	4	3	2	1
U1	0.025	0.088	0.403	0.306	0.178
U2	0.027	0.123	0.541	0.256	0.053
U3	0.041	0.075	0.146	0.431	0.307
U4	0.01	0.057	0.492	0.361	0.040
U5	0.007	0.105	0.462	0.312	0.114

Table 8.The total investment risk probability distribution oflaser

Risk level	**Probability distribution**
5	0.020
4	0.048
3	0.427
2	0.392
1	0.113

Table 9. Investment risk factors of probability distribution of EDDT

Factors	Risk level				
	5	4	3	2	1
U1	0.050	0.053	0.107	0.476	0.314
U2	0.090	0.011	0.577	0.138	0.085
U3	0.041	0.075	0.146	0.431	0.307
U4	0.009	0.091	0.143	0.531	0.226
U5	0.023	0.094	0.154	0.397	0.332

Table 10.The total investment risk probability distribution oflaser

Risk level	Probability distribution
5	0.970
4	0.041
3	0.275
2	0.405
1	0.362

Analysis of tables above, we can conclude the following points:

The risk of passivation is most likely ranked in the 1st level, with the probability of 45.1%.

The risk of laser is most likely ranked in the 3rd level, with the probability of 42.7%.

The risk of EDDT is most likely ranked in the 2nd level, with the probability of 40.5%.

3.3 Modelling an analyzing of debris environment in low Earth orbit

We now study the increase in the number of debris. Modeling of debris is a difficult theory analysis. It should use a lot of history observation data as the foundation, consider various factors of space debris increase and decrease, through physical analysis, mathematical equations, finally compiled algorithm of solving equations.

We use PIB model and the theory of gas molecular kinetics, a differential equation for the population of space debris in low earth orbit (LEO) is established. [6]

Considering the factors are as follow:

Space debris source—increase

1. orbit of space object

2. the explosion and fracture of the space objects in orbit
3. the collision between space debris

Space debris sink—decrease

1. the atmospheric drag make debris fall
2. space objects are regularly recycled
3. space debris removed from orbit by dedicated collectors

Annual variable rate in debris ***N***

Set in low earth orbit area at any time *t* (in years) the total number of space debris is *M*, the annual variable rate in debris

$$N = \frac{dM}{dt}$$

The contribution to the variation of the fragments of orbit of space object $\boldsymbol{N_1}$

If $\boldsymbol{n_L}$ is annual space launch times, $\boldsymbol{n_0}$ is the number of satellite launch each time. Then,

$$N_1 = n_0 \bullet n_L$$

The contribution to the variation of the fragments of the explosion and fracture of the space objects in orbit $\boldsymbol{N_2}$

The contribution to the variation of the fragments of the explosion and fracture of the space objects in orbit $\boldsymbol{N_3}$

According to the theory of collision, the collision fragments generated number is proportional to the square of the total number of pieces, so $N_3 \propto N^2$. Set the collision frequency between the pieces to ***H***, then

$$N_3 = \beta \bullet H \bullet N^2$$

In the equation, $\boldsymbol{\beta}$ is collision fragments generated factor. According to PIB model, β is a constant. We have supposed that debris movement obey the theory of gas molecular kinetics, so the collision frequency between the pieces *H* can be represented as:

$$H = F \bullet \left[\frac{\sqrt{2} v_c D^2}{(3/4)\left(R_T^2 - R_B^2\right)} \right] \bullet \left[\frac{1-(1/N)}{2} \right]$$

In the equation, ***F*** is non-completely mixed fragment coefficient, $F \le 1.0$; $\boldsymbol{v_c}$ is debris speed; ***D*** is debris average diameter; $\boldsymbol{R_T}$ is the radius of up spherical shell; $\boldsymbol{R_B}$ is the radius of down spherical shell.

The contribution to the variation of the fragments of the atmospheric drag $\boldsymbol{N_4}$

From theoretical analysis we can know that the number of debris that the atmospheric drag produce (the actual is to eliminate) is proportional to the total debris *N*

$$N_4 = B_1 \bullet N$$

In the equation, B_1 is atmospheric damping factor, it in directly proportional to the debris area-mass ratio. So it is inversely proportional to the average diameter of debris ***D***.

The contribution to the variation of the fragments of orbit of regularly recycle N_5

N_5 is a constant and have nothing to do with *N*.

The contribution to the variation of the fragments of orbit of dedicated collectors N_6

N_6 in directly proportional to *N*, $N_6 = B_2 \bullet N$ (B_2 is collection coefficient, it is a negative constant).

So

$$N = N_1 + N_2 + N_3 + N_4 + N_5 + N_6$$

At first, we now calculate the number of debris when we do not use dedicated collectors. So we let

$$N_5 = N_6 = 0$$

So

$$N = AN^2 + BN + C \qquad (0.1)$$

In the equation,

$$A = \beta \bullet H \quad B = B_1 \quad C = n_0 \bullet n_L + N_2$$

Calculating (0.2) need a number of known statistical data and the initial conditions. We find some data in NASA [7] [8].

a. About coefficient A. We can find that $\beta = 200$, $F = 0.55$, $v_c = 7.3 km/s$, $R_B = 6728 km$, $R_T = 8178 km$.

b. About coefficient B. According to a large number of operations to the data, we get that $B_1 = 0.01$.

c. About coefficient C. $n_0 = 4$, $n_L = 120$, $N_2 = 720$.

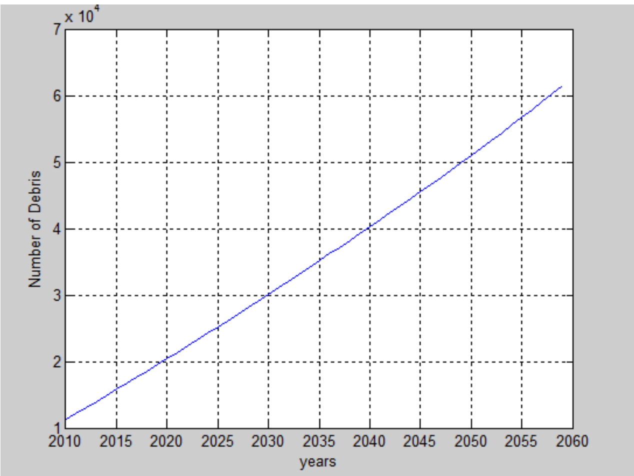
In 2010, the initial total number of pieces is

$N = 15000 * 75\% = 11250$ (the 75% of total number of debris in 2010)

The computation result

Set from 2010 to 2060, annual space launch times n_L increase with the rate of 2%, then we get the population between 2010 and 2060. We draw a picture to show the tendency of the number of debris as figure 5.

Figure 5． The tendency of the number of debris



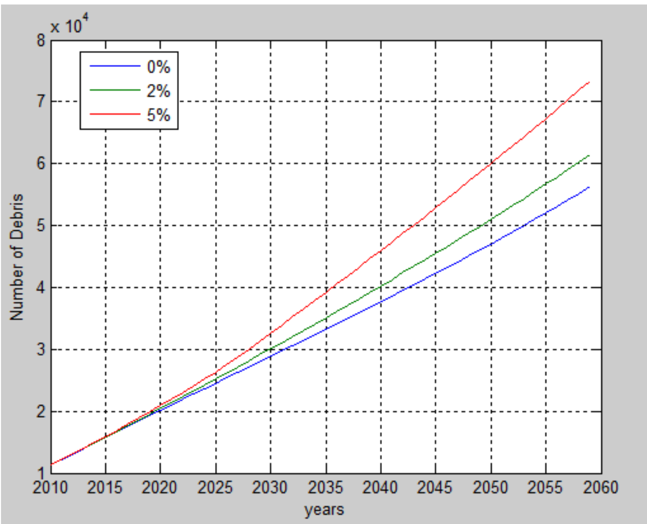
From the picture 5, we can see the number of debris grows very fast. There will be approximately 6.3×10^4 debris in 2060. It's no wonder that scientists say that if we don't solve the problem of debris, humans may lose geosynchronous satellite orbit over the next 20 years. The space is too crowed to launch a satellite!

3.3.1 Sensitivity analysis

3.3.1.1 The change of N_1

If the annual space launch times n_L increase with the rate of 0% and 5%, we can get the forecast as figure 6.

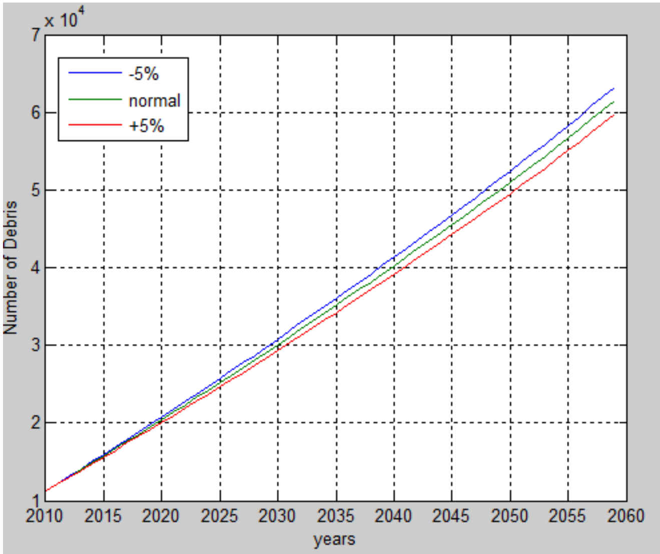
Figure 6



3.3.1.2 The change of N_2

If the number of the explosion and fracture of the space objects in orbit N_2 change into 5% , we can get the forecast as figure 7.

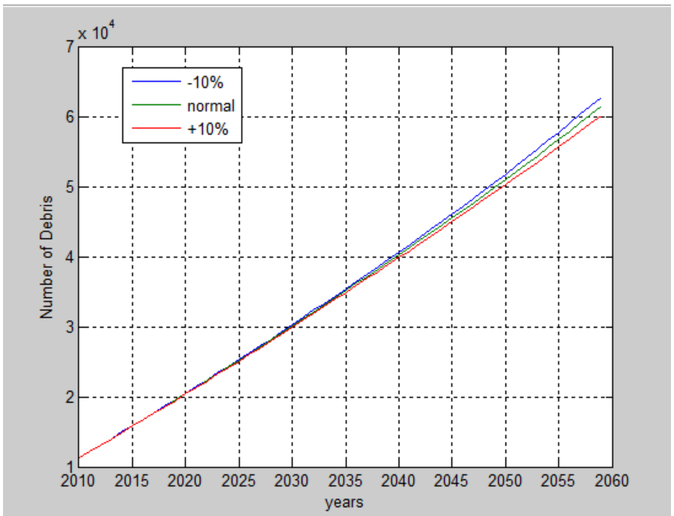
Figure 7



3.3.1.3 The change of N_3

If the collision number change into 10% , we can get the forecast as figure 8.

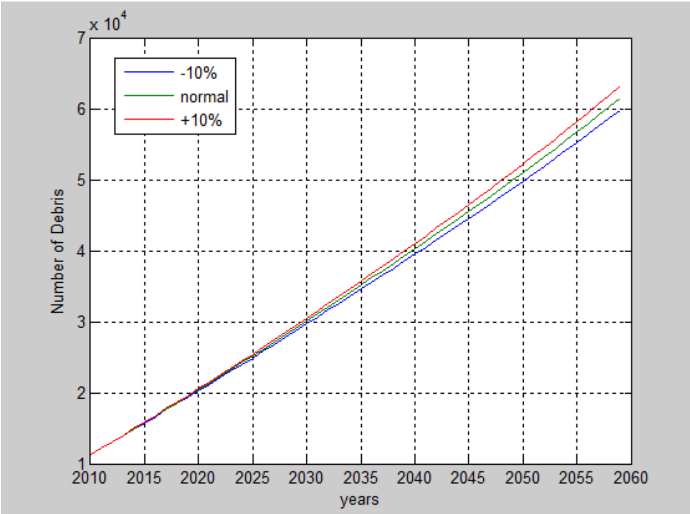
Figure 4



3.3.1.4 The change of N_4

If atmospheric damping factor B_I change into 10%, we can get the forecast as figure 9.

Figure 9



In brief, if N_1, N_2, N_3, N_4 change within a certain range, it will affect the total numbers of debris. But the influence is limited. The annual space launch times has great influence in 50 years. It is the main factor that leads to an increase of debris. However, with the development of science and technology and people's demand for space exploration, the times of launching will increase. If we reduce the times of launching in order to decrease the debris, it is not wise. So for cut down the number of debris, we should mainly put our hands to reducing the number of the explosion and fracture of the space objects in orbit and clean the debris on our own initiative.

3.4 Benefits

3.4.1 Passivation

Passivation is the act of removing any internal energy from a satellite or rocket body at the end of its life to avoid accidental explosions. A research from NASA shows that nearly 50% of the causes of known satellite breakups are propulsion and battery (see Figure 9). There is a reasonable estimate base on it. Since 2016, all satellites we launch would take steps of passivation at the end of their lives. Therefore, the number of satellite breakups would reduce to 50% in 2026. After calculating, we get the estimation of orbital debris 50 years later. (see figure 10)

Figure 10 [14]

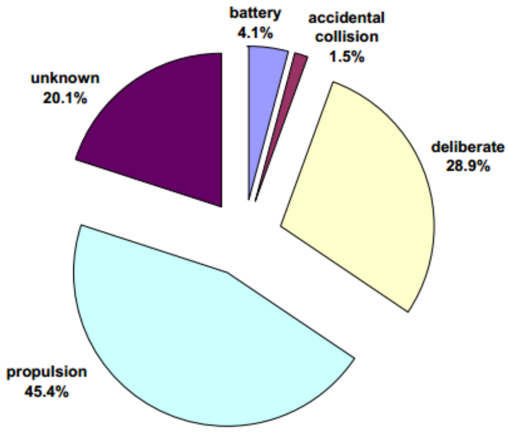
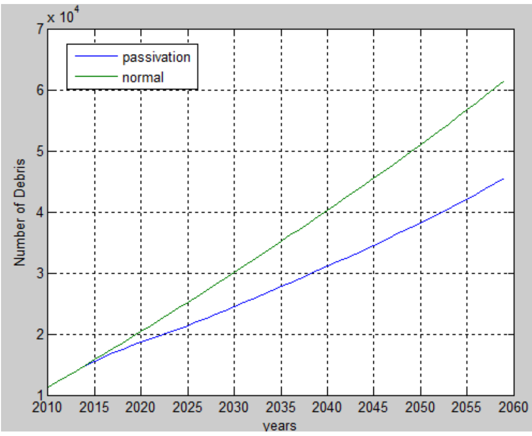


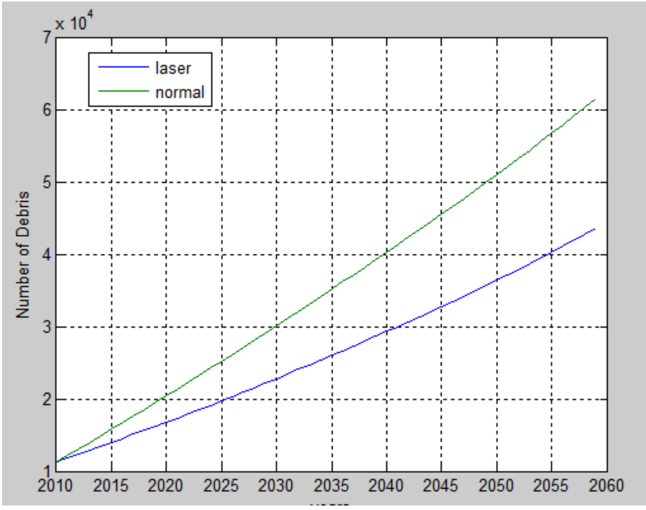
Figure 11



3.4.2 Earth-base Lasers

From Charles Q. Choi's article, we know that a single earth-based laser could engage about 10 objects a day at most. [11]However, consider that it would be limited by weather, the objects' orbit, and many other factors, we assume that it can engage about 1 object a day on average, which means it can engage 365 objects per year. Set N5=-365, the result is in (see figure 12)。

Figure 12



3.4.3 The Electro-Dynamic Debris Eliminator (EDDE)

A dozen EDDE vehicles can remove all large debris from LEO in less than 7 years. [13] Base on the description of EDDE's debris cleaning ability from Jerome Pearson, we can estimate that an EDDE can collect nearly 187 debris in a year. Set N5= -187, the result is in (see figure 13).

Figure 13

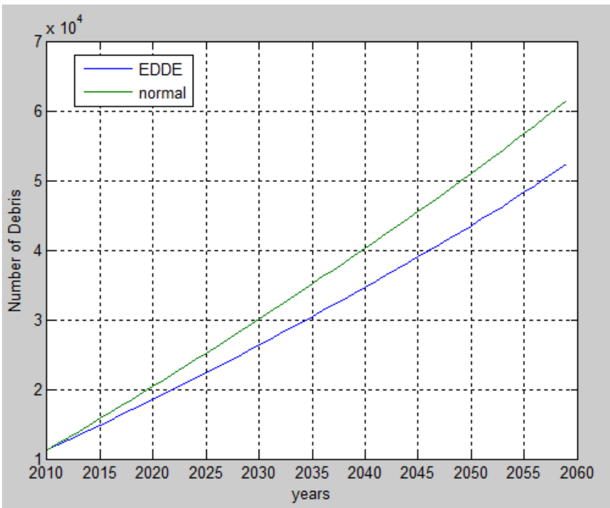


Figure 14

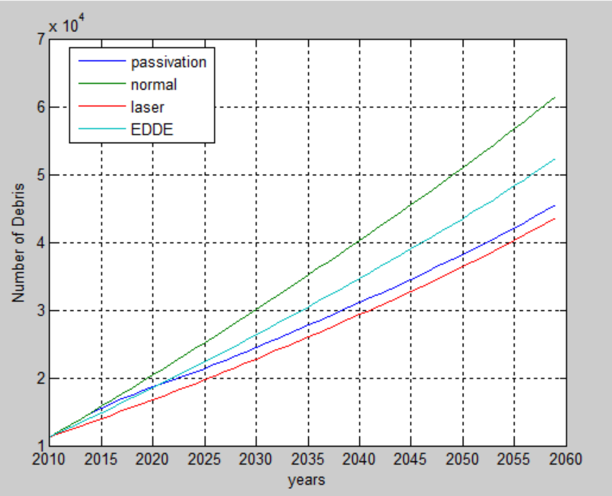


Figure 14 shows each method's contribution on mitigating orbital debris problem in the future. We can easily find out that the Earth-base Laser is the most effective method. Base on the figure 14 , we grade each method from 1 to 5(see table 11).

Table 11

Method	Passivation	Laser	EDDE
Grade	3	5	1

4. Conclusion

Based on the above analysis, this is not a suitable opportunity at present but will be a promising project in the future.

5. Advantages and disadvantages

5.1 Advantages:

1. The sensitivity analyses are made for experimental results, making the results more accurate and scientific

5.2 Disadvantages:

1. When we calculate the number of debris, we suppose that the movement of the space debris obey the motion law of ideal gas molecules. Although this will simplify the calculation, but this will increase the error.
2. We only consider the number of debris, but do not consider the size of debris.
3. AHP include more subjective factors.

4. When we are evaluating the costs, because of the lack of date, so only analyze two factors.

6. An innovative alternative

Now we provide an innovative alternative method for avoiding collisions.

The cost of designing, developing, testing and launching such a spacecraft, with sufficient fuel onboard to repeatedly intercept multiple debris fragments at different speeds, orbits and altitudes, does not seem to be economically viable. In summary, the cost/benefit ratio of the above solutions appears to be the main reason none has been implemented to date to proactively mitigate the most dangerous debris.

There are some of the essential prerequisites for the conduct of active debris removal and on-orbit satellite servicing:

•A "cost effective" technique;

•A proper legal and policy framework to protect the parties involved;

•Available and willing target for removal or customer for servicing;

•Someone to pay;

•Capability to locate, approach, connect deorbit/servicing device, control orientation and to move the target object to desired destination; and

•Safety of the public on ground, at sea and traveling by air. [15]

Since many of the above conditions is not possible now and the space environment is so harsh, we must struggle for innovative alternatives for avoiding collision. Here we propose a new strategy – **using electron gun which is integrated in an add-on module to the satellites to clean debris when the system detects a collision may occur.** This electron gun device is mounted on the satellite early in the design stage and launched into along with satellites. It can clean low and medium Earth orbits of small- to medium-sized orbital debris. This solution would be more easily adopted by the international space community, since it does not have the capability to damage or destroy a spacecraft. This solution would be more easily adopted by the international space community, since it does not have the capability to damage or destroy a spacecraft

This approach would use the principle of deflecting an electrically charged, moving object in a magnetic field. The old television tube is probably the most common example of this principle, where electrical charges (electrons) are deflected by the magnetic fields generated by the tube deflection coils.

The benefits include:

Cost: Lower cost is the major advantage of electromagnetic deflection.

Feasibility: There is no new or speculative technology to develop. Used in particle accelerators and in millions of old-style television tubes, the electron gun technology is very mature. The energy used to generate the electron beam is orders of magnitude lower than high-power lasers.

Risk: It would reduce the probability of creating additional debris by avoiding any physical contact. [16]

This can be a more affordable approach for cleaning low and medium Earth orbits of small- to medium-sized orbital debris. We are optimistic that in the near future, this technology will be implemented.

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Executive Summary

Dear:

As we know, satellites are used for broadcasting radio, television, data communications, telephone and other communication signal, GPS positioning, taking photos etc. They are closely related to our life. Space junk caught people's attention recently. Space junk also called orbital debris. They are all man-made objects in orbit about the Earth which no longer serve a useful purpose, such as derelict spacecraft and upper stages of launch vehicles, carriers for multiple payloads, debris intentionally released during spacecraft separation from its launch vehicle or during mission operations, debris created as a result of spacecraft or upper stage explosions or collisions。They circle the Earth at high speed, consequently, collisions with even a small piece of debris will involve considerable energy. What's more, the number of debris are increasing. Some scientist even forecast that humans may lose geosynchronous satellite orbit over the next 20 years. So, cleaning debris seems like a big business opportunity. We build a model and analyze this problem, the consequence is that **it's not the time of the investment, but will be a promising project in the future.**

Our model include quantitative and/or qualitative estimates of costs, risks, benefits. In the aspect of economy, The ElectroDynamic Debris Eliminator (EDDE) uses electric current in a long conductor to thrust against the Earth's magnetic field. Electrons are collected from the plasma near one end by an electron collector, and are ejected at the other end by an electron emitter. It use net to catch the debris. It will cost 24,028,240$ per year. The second one is lasers. It is a method to remove the debris remaining on the ground and zapping it with lasers. Its estimated cost is 10,800,000$. The third one is Geostationary orbit (GEO) transfer. It will spend about 9,000,000$ to realize that.

By estimate the number of debris 50 years after, Earthbase laser is the most effective method t o mitigate orbital debris problem.

Risks in project are generally classified into five categories, including: technological risks, legal and political risks, economic risks, financial risks, production risks. We establish Analytic

Hierarchy Process (AHP) Model to determine the weight of each metric to risks evaluation. For the purpose of overcoming weakness of excess subjective factors in AHP , we establish an improved probability distribution model which can quantitatively estimate the risk level probability distribution.

Yours