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LARGE ORBITAL OBJECT REMOVAL
- ITS NECESSITY AND TECHNOLOGICAL OPTIONS -

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1. INTRODUCTION

Orbital debris issue is recognized as a potential hazard to tomorrow's space activities. As a result of all very important space debris related activities, the nature of the issue has become fairly clear. However the hazard potential is expected to increase in the future. The space activities itself will result in accumulation of the mass in earth orbit , thus increasing the hazard. The absolute goal of the debris related researches is to insure safe, continuing and expanding space activities in centuries to come. How can safety be sustained under increasing mass environment in earth orbit? There is an obvious solution: if orbiting objects consist only of useful, controllable and known objects, the collision risk will be kept small, perhaps within an acceptable level. This ideal environment can be attained by removal of non-useful objects from the useful orbits. The removal not only maintains the mass accumulation minimum, but also minimizes the chances of small but harmful debris creation by breakups in orbit.

Some objects may be removed through built-in self removal capability. Some will have to be removed through external means. This paper intends to review various removal methods through latter means. It should be noted, however, that removal of small numerous scattered debris will be quite costly and unreliable. The principal philosophy is to eliminate the debris source before it turns into numerous debris.

2. NECESSITY OF REMOVAL

The only source of orbital man-made debris is routinely conducted space launches. In average, 120~130 launches have been made each year before 1990, and the total launches since Sputnik launch in October, 1957 until December 1992 is 3,508. There are 7,120 cataloged space objects, of which 2,096 are payloads both active and derelict. 15,198 objects are known to have re-entered into earth atmosphere after some passage in orbit[1]. Comparing these orbiting object numbers with the launch number, it becomes quite clear that large portion of the objects were created in orbit from larger parent objects which were originally launched from the earth. In fact, 45% of present trackable objects are believed to be debris created by more than 110 breakups of orbiting objets after their useful life[2]. Smaller untrackable debris are not well known, but US sources estimate that there are 3,500,000 debris larger than 1mm in diameter[3].

Causes of breakups are believed to be (1) propulsion related explosions, (2) deliberate destructions and (3) others including collision induced ones. Influences of deliberate destructions will be kept minimum. Various measures have been taken to minimize propulsion related explosions by launching organizations. However, considering that actual procedures of these breakups are not very well known, and that upper stage rockets can explode after long time in orbit, breakup of this kind will continue. Up to now, no report has been made as to a collision between large orbiting objects. But a number of evasive maneuvers were made by active satellites, both manned and unmanned, to avoid possible collision with other orbiting objects. The number growth of large orbiting objects is inevitable in the course of continued space activities, and the possibility of collision will grow. While collisions with large orbiting object is fatal, collisions with smaller untrackable objects will be more serious because of more frequent encounter and difficulty of detection.

To have a numerical idea, debris growth in 1991-1992 period is summarized from Satellite Situation Report data as shown in Fig. 1. There were 88 and 95 launches in each respective years. These launches produced 667 cataloged objects including payloads and large debris, 4 of which experienced breakups creating additional 72 catalogued pieces. There were 7 more breakups caused by objects which were launched before 1991, resulting in more than 200 new cataloged debris. May 1, 1991 event was a fragmentation of Delta 2nd stage (1975-52B) which was launched in 1975 . Titan Transtage of over 20 years old was reported to have broken up in near geostationary orbit. No fragment was cataloged, however. Roughly speaking, nearly 670 objects were put into orbit, and about 400 stayed there at the end of 1992. In addition, nearly 300 debris were created from large launched objects in orbit. Taking account of other decayed objects and newly cataloged objects of earlier launch, the total increment of catalogue number was 332. Almost all of the 300 fragments created in this period seem to be rather long living, and those created in geostationary altitude, although not very well trackable, will remain in that altitude for many centuries.

Kessler[4] and Eichler[5] pointed out that there exists a critical density at which the rate of debris creation by chain reaction equilibrates with natural decay. In their theory, once the orbiting object density exceeds the critical, more debris will be created by hyper-velocity impact of another debris to larger object, and the number will keep growing even under absence of further launches. At higher altitude where atmospheric drag is less effective, the critical density will be smaller. In fact, at the geosynchronous altitude, there is no critical density and the debris number will steadily increase[6].

The safety of space operations are threatened by both small, untrackable debris and large trackable debris. Considering that both classes of debris can be equally fatal, the more dangerous is the smaller class because of larger population and difficulty in encounter prediction. Therefore, the first idea is to remove those smaller ones. In fact, there are various technologies proposed to decelerate and eliminate dangerous small debris from orbit. Petro[7] described sweeper concept which can be effective for this purpose. The sweeper is a large foam like structure, intended to decelerate the debris velocity when encountered. The concept is straight forward, but a problem expected is collisions with very large objects that might destroy the sweeper itself, and collisions with other useful satellites. Petro summarizes other modifications to avoid this kind of collisions. Intensive laser illumination evaporates small debris. The concept by Schall[8] is to utilize thrust produced by the evaporated gas at the melted portion. With a laser energy which evaporates small portion of the object changes the object orbital velocity to put it into a desired orbit. Very careful execution of the process will be needed so that the altered orbit might not be a harmful one, and that the illumination does not create additional debris.

Although elimination of small debris is desirable, the effectiveness of each proposed method needs careful examination. In general, orbital elements of debris are not observable, and therefore, the elimination cannot be performed on deterministic basis. The most desirable method will be to eliminate possible source of small debris creation. This is attained by removal of large orbiting objects.

Large object removal may be attained either by self disposal or assisted disposal. Self disposal will be more economical in most cases than the other, and will demand less technical challenge. This has been used in geostationary satellite removal from the orbit at end of useful life. Many upper stage boosters have excess energy that can be utilized for this purpose. Drag augmentation by balloons is also proposed. However, most of presently orbiting objects may be removed only by other external assists. Also, not all object will be equipped with self de-orbit capability from one reason to another, and not all those capability may function as originally planned. It is rather clear that a system will be needed in space, taking care of inoperable objects, removing them into earth atmosphere or into more less frequently utilized "graveyard orbit".

3. LARGE OBJECT ROMOVAL SYSTEM

3.1 Requirements

There are technical and economical requirements associated with the selection of the large object removal system structure. In actual operational phase, consideration from legal point of view will become necessary.

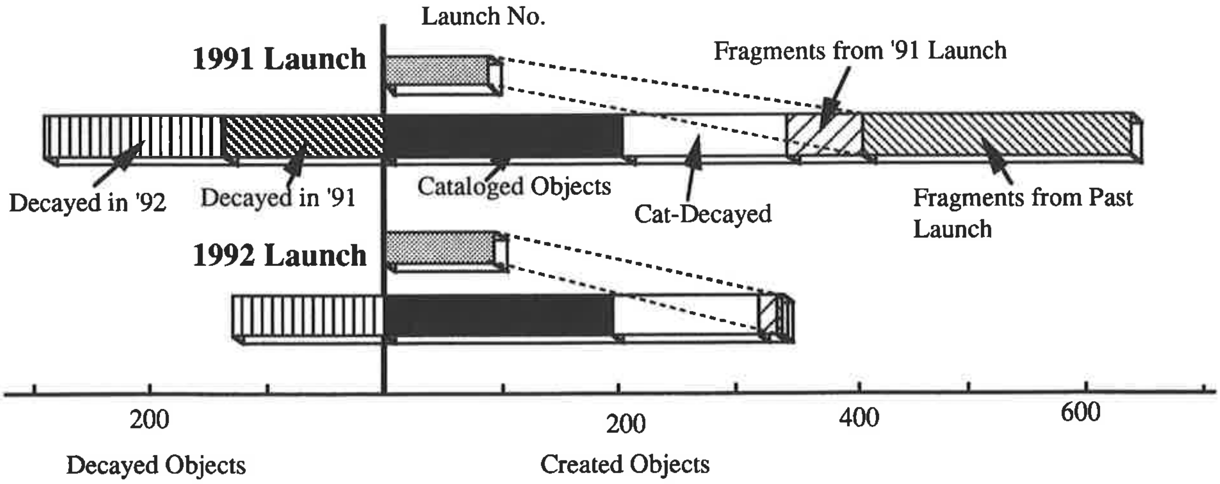

Fig. 1 Large Orbiting Object Growth during 1991-1992

Technical Requirements

Objects in LEO will be best removed by putting it into earth atmosphere entry orbit, while those in GEO into a graveyard orbit which is 300 km or more higher than nominal geostationary orbit of 42,165 km radius. The velocity increments (ΔV) needed in each cases are 100-200 m/s and 10-20 m/s respectively. In general, the objects are non-cooperative. Since no docking mechanism is generally expected, the remover must be equipped with the capability to grasp the objects of arbitrary shape and then to transfer it into another orbit. It is quite questionable that the connection between the object and the remover is rigid enough to keep the original configuration without rotation during subsequent orbit transfer maneuver. The object is most probably rotating around the largest principal axis, no matter whether the object is designed as a spinner or not.

Economic Requirements

The removal operation is not going to produce any immediate reward except the orbit environment safety which will be appreciated in far future only. Launching will be always in more immediate need than removals, therefore, the removal operation must be as cost effective as possible. The operation cost is represented by the number of supply flight, which is almost proportional to the amount of propellant that is consumed in rendezvous with target objects and orbit transfer maneuver. In general, the rendezvous procedure consumes far more propellant than the orbit transfer maneuver.

Legal Aspects

It will be mandatory that the registered owner of an object is in agreement with the remover operator prior to disposal. This agreement procedure will be needed even in case of rendezvous trial, which will be accompanied by chances of technical detail disclosures because the remover is expected to have a capability of visual information transmission. Present legal system does not seem to provide any meaningful procedure to deal with objects whose owner is not known.

3.2 Removal Systems by Momentum Exchange

P. Eichler and A. Bade stated in their paper "Strategy for the Economical Removal of Numerous Larger Debris Objects from the Earth Orbit"[9] that conventional strategies will be uneconomical, and they proposed TERESA (TEthered REmover SAtellite) concept. This is a novel concept which realizes removal of numerous objects without any energy consumption, at least in theory. The underlying principle of this concept is momentum exchange between the object and the remover. The momentum, and energy at the same time, of the object is transferred to the remover in the course of tether extension in local vertical direction. After the tether is cut, the object goes into an orbit with smaller semi-major axis, and the remover goes into another with larger one. Tumble Orbit Transfer proposed by the author[10] is based on the same principle. In this case, an extendable arm is used instead of the tether, and the momentum exchange is attained by rotation of the object-remover combined system utilizing a thruster activation (Fig. 2).

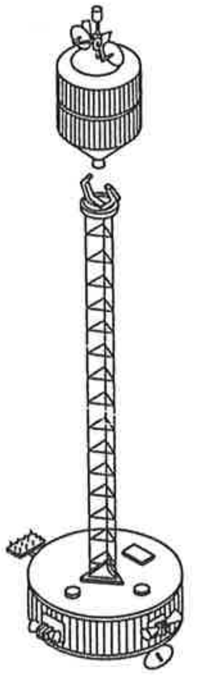

Fig. 2. Remover Vehicle with an Extendable Arm

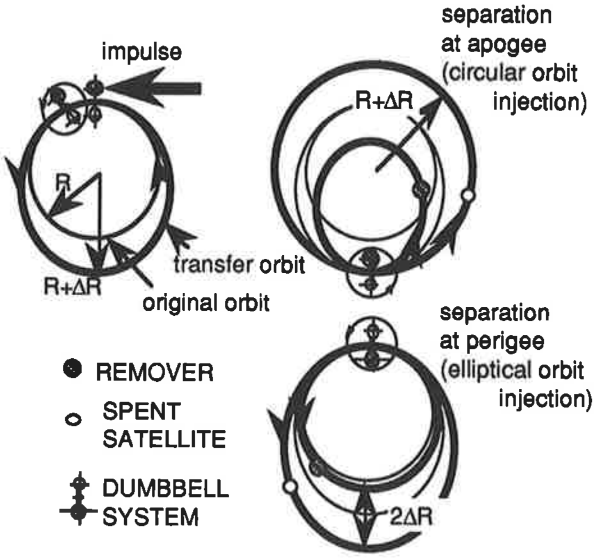

Fig. 3 Tumble Orbit Transfer

Two operational modes of the Tumble Orbit Transfer is shown in Fig. 3. An object is grasped by a mechanism on one end of the extendable arm while it is retracted, and the arm is extended along the local vertical, which is a stable attitude. An impulse applied on the remover in a direction perpendicular to the arm puts the combined system into an intermediate orbit whose perigee (in case of transfer into higher orbit) is the point of the impulse application. The system itself undergoes rotation in the orbital plane around the center of mass. In case of the circular orbit injection, the grasp is released at the apogee of the intermediate orbit which is higher by ΔR than the original altitude, at an instance when the arm is again perpendicular, with the object in upper position. The object is now injected into a circular orbit of elevated altitude by ΔR. In case of the elliptical orbit injection, the separation is made when the system is rotated by 180 degree in the vicinity of the perigee. The apogee height of the discarded object is elevated by $2\Delta R$. The remover generally must come back to the original orbit in order to carry on the next mission. The return maneuver is conducted by two impulse maneuver in case of the circular orbit injection, and one impulse maneuver in case of elliptical. The propellant consumption in term of delta velocity is compared in Fig. 4 with the maneuver using conventional docked rocket transfer method, assuming the application to a geostationary object.

3.3 Comparison of Two Methods

Delta Velocity Capability

TERESA has an unlimited capability as far as theoretical delta velocity capability is concerned. This is a function of the tether length only. Practical limit will be encountered perhaps by the time required to handle the long tether manipulation in extending and extracting, and the risk of collision of other debris to the tether. On the other hand, Tumble Orbit Transfer (TOT) has a limitation from the magnitude of force which acts at the grapple point and the rotational speed which must be slow enough within timing capability of thrustering and separation. This limitation is shown in Fig. 5. Assuming maximum of 10 G equivalent force and 10 rpm, the delta velocity attainable is 100 m/s with the arm length of 100 m.

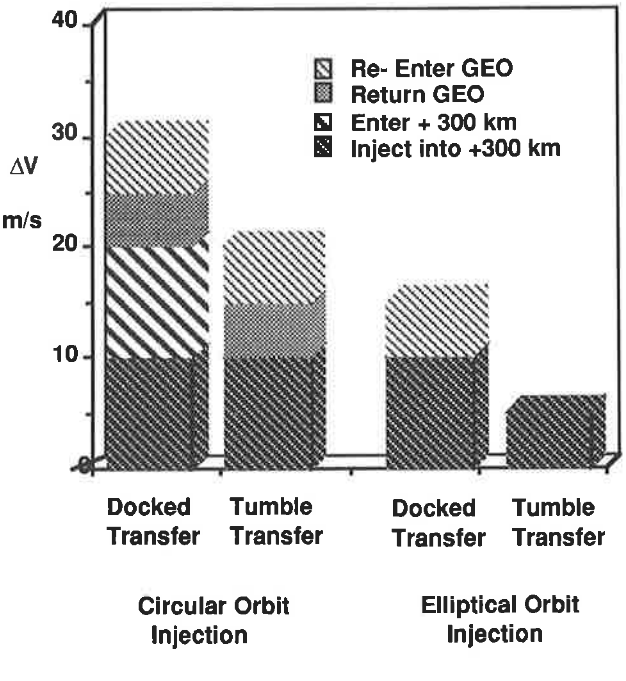

Fig. 4. Propellant Requirement in Terms of ΔV

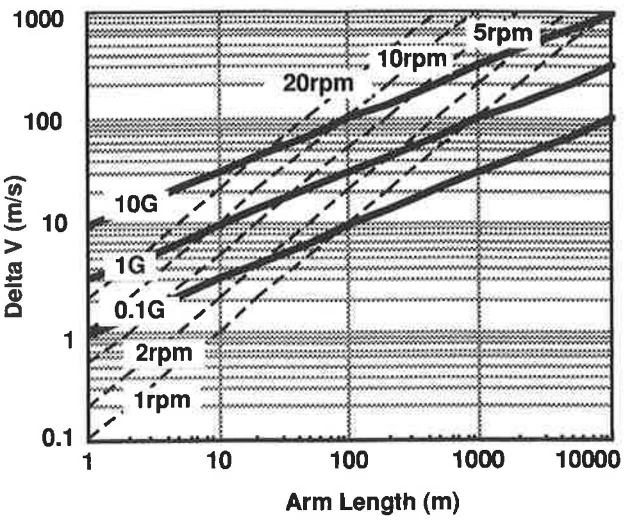

Fig. 5. Delta Velocity Capability in TOT

Non-Cooperative Object Disposal Capability

Objects without rigid docking mechanism can be handles by both methods, as long as a hard point for grapple is available. It is quite evident that the rigidity at the grapple point is not necessary in case of TERESA. In TOT, the centrifugal force by the rotation stabilizes the system as shown in Fig. 6, which shows that the angle variation at the grapple point during maneuver is kept below 30 degrees under the absence of rigidity.

Spinning Object Disposal Capability

It will be difficult for TERESA to handle spinning objects. Capture will be possible by approaching along the spin axis and grappling the spin center portion. Then spin must be damped

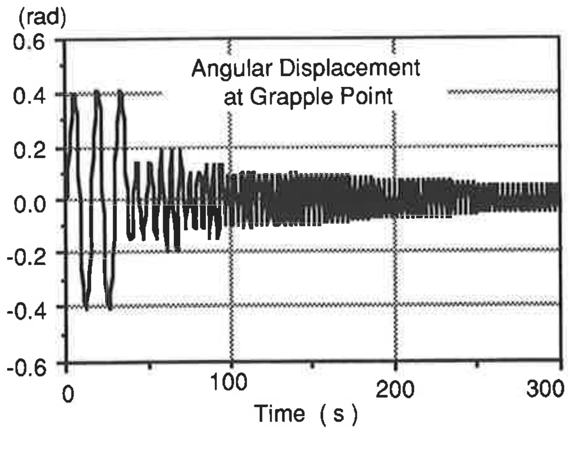

Fig. 6. Stability of Remover-Object Combination with Free Joint under Thruster Maneuver

out before tether extension. Otherwise there will be a risk of tangling because of difficulty in spin axis re-orientation along the tether line. On the other hand, TOT can utilize the spin angular momentum by converting it into orbital momentum. Capture at the spin center with the remover adjusting the spin rate will result in a slender body spinning along the axis of minimum moment of inertia. This will soon result in a flat spin. The orbit normal component of the flat spin contributes to the momentum in addition to the momentum to be gained by thruster maneuver[11).

Propellant Requirement

TERESA requires very small amount of propellant throughout its operational life. TOT needs much greater amount, which, however is smaller by two-third to half compared to conventional docked method. Table 1 taken from Ref. 12 shows a comparison among various methods applied to geostationary object disposal. The largest portion of propellant will be consumed not in the orbit transfer maneuver itself, but in rendezvous with next object. Both methods based on momentum exchange have an advantage over other conventional methods that the orbit of the remover after separation of the object can be adjusted by slightly altering the final orbit of the object. This becomes possible from the fact that the desired disposal orbit lies in a finite band within which one can choose arbitrarily. The variation of the disposal orbit is reflected into a variation of the remover orbit after separation, and the remover orbit can be chosen within a finite band. Carefully choosing the next target which is within the allowable band, large portion of the rendezvous propellant can be saved.

4. CONCLUSIONS AND NECESSARY ACTIONS

It has been pointed out that removal of large orbiting objects will be necessary, and if the action is delayed, there is a possibility of creating great many small debris which might grow uncontrollable. Debris removal will be an important program which will be vital for continued space activities in the next century and further. Among various removal options, removal of larger objects is considered superior over removal of smaller fragments, the fragments left after breakups of larger objects. Self de-orbiting of those objects utilizing build-in capability will be most economical and efficient. However, an infrastructure to remove inoperative large objects left in orbit becomes indispensable sooner or later. Considering many requirements in technology and economy, momentum exchange methods are best recommended for this purpose. Two known methods, tether application and tumble orbit transfer are compared somewhat in detail.

Removal plan should be considered to establish two different facilities: one to deorbit objects from LEO into earth atmosphere, the other to put objects into higher graveyard orbits from GEO. Collected storages in orbit will be considered as the next step. The most important actions needed now is to establish a development program for an efficient systems to accomplish these two purposes. This will be best conducted by a group of representatives from major space developing powers. The program will first specify the best system configurations, perhaps from those already proposed, elaborate on needed technical requirements, identify specific contributors and finally to blue-print actual execution organization.

Finally, a legal issue must be pointed out as an important step to removal execution. The status of space debris, including the exact definition of "debris", is still unclear among the international legal group. What is thought of as universal is that an orbiting object, no matter whether it is active or not, may not be removed or handled by those organizations that do not possesses the asset. A clear understanding must be established as to the

Table 1. Comparison of Disposal Systems
GEO Satellite Disposal into 300 km Higher Orbit

Operational Phase	Rocket	Tumble Orbit Transfer	Tether Disposal	
			Hanging	Swinging
		Delta Velocity		
Transfer to GEO+300km	10 m/s	10 m/s	0 m/s	0 m/s
Enter GEO+300	10	0	0	0
Return to GEO	5	5	0	0
Re-Enter GEO	5	5	0.8	0
Rendezvous with Next	0	0	5.7	4.8
Total	30	20	6.5	4.8
		mass		
Propellant per Disposal	23 kg	15.3 kg	4.8 kg	3.7 kg
Tether System Mass	0	0	200 kg	200 kg

terms of agreement between the executing organization and the possible or known owner of the object to be removed.

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