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# Engineering Issues for All Major Modes of In Situ Space Debris Capture

Marshall H. Kaplan, Ph.D.[1], Bradley Boone, Ph.D.[2], Robert Brown[3]
Thomas B. Criss, Ph.D.[4], Edward W. Tunstel, Ph.D.[5]
*Johns Hopkins University/Applied Physics Laboratory, Laurel, Maryland 20723*

**Artificial satellites and launch vehicles have created an ever growing number and variety of orbiting debris objects ranging in size from a few microns to several meters. The urgency of the situation has been exacerbated by the 2007 Chinese anti-satellite test and the 2009 collision of Iridium and Cosmos satellites. Sometime in the next one or two decades a space debris reduction program may be needed to assure continued access to, and use of, space for applications and exploration. Debris removal techniques and programs have been suggested, but none have been implemented. A recently completed investigation of engineering issues associated with the in situ capture of space debris objects spans the spectrum of options for all categories of these derelicts. This work concludes that not all debris can, or should, be removed. Technologies and systems for capturing very small debris do not exist. Only the largest of the objects can be effectively addressed with current technology. However, there remain several complications even for these derelicts. For example, every large debris piece may possess residual angular momentum with associated angular rates that could exceed 30 rpm. These objects are uncooperative and may have to be approached in such a way that angular momentum can be safely removed. Once stabilized, such objects may have to be grappled in order to control them. Then, a device may have to be attached in order to either apply proper removal forces or to store the object for later disposal. This paper attempts to identify and assess technologies and systems associated with in situ capture and control.**

## Nomenclature

| | |
|---|---|
| A | ≡ Average cross-sectional area of a given resident space object |
| APL | ≡ Applied Physics Laboratory of Johns Hopkins University |
| ASAT | ≡ Anti-satellite |
| B | ≡ Ballistic coefficient, defined as the ratio of body mass to the product of drag coefficient and cross-sectional area |
| $C_d$ | ≡ Drag coefficient |
| DARPA | ≡ Defense Advanced Research Projects Agency |
| DIMES | ≡ Descent Imaging Motion Estimation System |
| DOF | ≡ Degrees of freedom |
| DTV | ≡ Debris tender vehicle, a spacecraft dedicated to approaching and capturing Large RSOs. |

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[1]Senior Professional Staff, Space Systems Applications Group, Space Department. AIAA Fellow
[2] Principal Professional Staff Physicist, Defense Applications and Analysis Group. AIAA Senior Member
[3]Principal Professional Staff, Defense Analyses and Applications Group, Space Department.
[4]Principal Professional Staff, Mission Design, Guidance and Control Group, Space Department.
[5]Senior Professional Staff and Robotics Lead, Ground Applications Group, Space Department. AIAA Member

Eotvos ≡ A unit of acceleration divided by distance that was used in conjunction with the older centimeter-gram-second system of units.
ESA ≡ European Space Agency
F ≡ Weighted cross-sectional area of the debris flux.
FPGAs ≡ Field-programmable gate array, an integrated circuit designed to be configured after manufacturing, hence "field-programmable"
FREND ≡ Front-end Robotics Enabling Near-term Demonstration
g ≡ Units conversion constant = 9.8 m/s$^2$
GEO ≡ Geostationary Earth orbit
GNC ≡ Guidance, navigation & control
GOCE ≡ Gravity Field and Steady-State Ocean Circulation Explorer Satellite
GRASP ≡ Grapple, retrieve, and secure payload
$h_0$ ≡ Initial RSO orbit altitude
H ≡ Angular momentum about the spin axis of an RSO
HST ≡ Hubble Space Telescope
HRSDM ≡ Hubble Space Telescope (HST) Robotic Servicing and De-orbit Mission
I ≡ Moment of inertia about the spin axis
$I_{sp}$ ≡ Specific impulse
IOD ≡ Initial Orbit Determination
ISAR ≡ Inverse Synthetic Aperture Radar
ISO ≡ International Standards Organization
JPL ≡ Jet Propulsion Laboratory
L ≡ Thruster moment arm to create torque
LEO ≡ Low Earth orbit
M ≡ RSO mass
$M_p$ ≡ Propellant required to remove angular momentum from an RSO
MEO ≡ Medium Earth oribt
MER ≡ NASA's Mars Exploration Rover Mission
$N_{pix}$ ≡ Number of pixels
NVEOL ≡ Night Vision and Electro-Optics Laboratory
ODR ≡ Orbital debris removal
$P_{hit}$ ≡ Probability of hit, given by the product F·A·T
$r_a$ ≡ Initial RSO orbit radius, $R_{Earth} + h_0$
$r_p$ ≡ Perigee radius
$R_{Earth}$ ≡ Mean radius of the Earth, 6.378 km
RAD6000 ≡ Radiation-hardened single board computer, based on IBM’s RISC Single Chip CPU
RSO ≡ Resident space object
SNR ≡ Signal to noise ratio
SSN ≡ Space Surveillance Network
T ≡ Orbital lifetime or time at a given altitude
TAKO ≡ Target Collaborativize
TRL ≡ Technology readiness level
$\Delta V$ ≡ Change in speed
$\mu$ ≡ Earth’s gravity constant, 398,600 km$^3$/s$^2$
$\omega$ ≡ Angular rate

## I. Introduction

OVER the past 50 years artificial satellites and launch vehicles have created an ever growing number and variety of derelict objects orbiting the Earth. These are often referred to resident space objects (RSOs) ranging in size from a few microns to several meters. For the first 50 years of space flight only a few people expressed concern related to potential collisions between active spacecraft and RSOs. However, in the last three years the probability of such collisions has dramatically increased. This situation has been exacerbated by two significant events. First, the Chinese anti-satellite (ASAT) test in 2007 increased the debris population by as much as 25%. This was followed by the collision of Iridium 33 and Cosmos 2251 in 2009. Experts speculate that sometime in the next one or two decades a space debris reduction program may have to be implemented to assure continued exploration and exploitation of space. Even though several debris mitigation measures have been adopted to minimize the creation of new debris, this will not be sufficient to reduce the danger to active satellites.

Many debris removal techniques and programs have been suggested, but most of these have not been well thought out and many are just not practical. Until recently, no one had carried out a serious engineering assessment of the many suggested approaches. One of the critical issues facing any debris removal program is the challenge of approaching, characterizing and capturing RSOs. A recently completed investigation of such engineering issues has revealed a number of insightful conclusions associated with the in situ capture of space debris. Results of this work are reported here.

The full spectrum of options for all debris categories has been addressed. One key finding is that not all debris can, or should, be removed due to economic and/or technical considerations. It should be noted that political and legal aspects are not addressed here.

While natural orbital decay will eventually result in the elimination of low altitude debris, there are several technology shortfalls preventing the active collection of very small objects. Only a limited number of the largest RSOs may be effectively and economically addressed, but even these present several complications. For example, many of the large debris objects possess some level of residual angular momentum that may have to be controlled before capture and subsequent removal. RSOs may additionally create hazardous and unstable situations when approached. Here, technology and systems engineering issues associated with debris capture and control are the main focus.

## II. Study Methodology and Focus for Large RSOs

Early in the investigation it became clear that RSO size was a key factor in pursuing workable removal techniques. For example, individual removal of small debris objects is simply not practical. Thus, any objects that are less than 10 cm in size will require “macro” methods, i.e., techniques that employ passive collection methods and devices. RSOs that are larger than one meter will require collection techniques in which one large object at a time would be captured and dealt with. Practical techniques for capturing RSOs that are in the 10 cm to one meter size range simply do not exist, even though they represent a continuing serious risk to active satellites.

A thorough discussion of the challenges is presented in the following sections. Begin by considering the approach, capture and removal of large RSOs. Since the exact condition, size or shape of most large RSOs is unknown, each object to be removed must be characterized. Fortunately, a certain level of a priori knowledge is known about many of these RSOs. For example, a recently expired satellite is likely to have maintained its final operational size, shape, mass and other properties. High-powered telescopes and other instruments can help to confirm this. Of course, a complete characterization of each RSO must be verified as a debris tender approaches the object. Thus, a certain level of in situ sensing will also be needed before a final approach and capture can take place. Sensors will facilitate detection, tracking, prescreening, cueing, inspection and characterization.

Once a selection of a particular RSO is made, the debris tender must navigate to the object. This will require guidance, navigation and control (GNC) functions to accomplish orbital transfer, rendezvous and other remediation maneuvers. The next steps involve de-spinning (if required), capture and finally removal or disposal. Since sensor and GNC technologies are well-developed they are considered ready to be integrated into space systems.

Small RSOs, if they are to be removed, will require that each piece of debris find the collecting device and collide with it. Presumably, such collisions will result in capture, or at least loss of energy. In either case, each RSO that encounters a collector will experience a loss of orbital speed, leading to removal. However, there are two key issues with this approach. First, the frequency of collisions must be sufficiently high in order to justify such a program. Second, collisions with collectors should not create more debris.

## III. Technical Problem Areas Addressed

### A. Debris Classification by Size

RSOs exist in a large variety of sizes, shapes, masses, states of angular motion and orbits. Such objects may be categorized in a number of ways, but the most logical first step is to classify debris objects according to size. Other characteristics are addressed in later paragraphs. However, orbital characteristics are not considered important here because rendezvous and capture technologies and operations are largely independent of orbit.

Three size categories[1] have been identified in order to address removal approaches in a meaningful way:

- Category 1 (Small): Up to 0.5 cm
- Category 2 (Medium): 0.5 cm to 10 cm

- Category 3 (Large): 10 cm and larger

These three categories encompass all RSOs of concern while creating a separation of objects in terms of potential hazards and remediation treatment options. As the discussion of debris removal advances, further classification parameters will be introduced where necessary. As a starting point each category represents important implications:

1. Category 1 encompasses debris objects that cannot be individually tracked and can do little or limited damage to operating spacecraft in cases of collisions. Although there is no way to accurately estimate the population of these small objects, it is possible that they number in the tens of millions, and they are pervasive in near-Earth space. Until a removal solution is found that proves to be beneficial at low cost, operational spacecraft will have to employ protective shielding in addition to using operational strategies that might minimize potential damage.
2. Category 2 encompasses debris that can be detected, but are too small and too numerous to be collected individually on a cost-effective basis. Nevertheless, such objects can cause considerable damage or destruction to operating satellites. Thus, Category 2 debris objects represent continuing risks to all satellites. In some cases shielding may be helpful, but such debris hits will likely cause at least some mission degradation. In some cases maneuverable spacecraft can take evasive action if given sufficient advanced notice and precision trajectory knowledge. Unfortunately, current tracking and prediction capabilities are not sufficient to provide this level of information. Furthermore, the difficulties and costs of removing objects in this size range appear to be prohibitive, leaving debris of this size to remain a source of hazard for operating satellites.
3. Category 3 encompasses large debris that will likely cause devastating damage to satellites during collision events. Such objects are likely to be removed by large debris tenders that are dedicated to addressing only the largest and most dangerous objects. Fortunately, such debris objects can be tracked and approached by these tenders using current technology. However, challenges remain regarding their capture and removal.

Removal options for all debris sizes are addressed here, but large objects do require individual attention, present the highest level of hazard for all operating spacecraft and will continue the proliferation of orbital debris. Collisions between satellites and large objects can be assumed catastrophic, and propagation of debris is largely fed by continuing collisions between Category 3 objects and smaller debris. Experts[2] have concluded that if large RSOs are selectively removed the orbital debris population will stabilize as a result of removing as few as five of these each year. Given the magnitude and cost of a complete debris removal program, this approach seems very attractive as a starting point for a comprehensive orbital debris removal (ODR) program.

### B. Debris Identification and Characterization

When an approach is selected for large debris capture it will ultimately dictate many requirements on sensors, actuators, logic and equipment. For example, the use of nets could pose extreme risks for a Debris Tender Vehicle (DTV). Without a certain level of a priori knowledge about a target object's content, makeup, mass and momentum characteristics, the use of a net could lead to a collision or breakup resulting in loss of the mission. In general, it is wise to stand off until these characteristics are determined or use a device or method that does not require the DTV to be physically connected to the device or mechanism used to bring a debris object under control. It follows that in order to maximize mission effectiveness and efficiency it is wise to use all available identification, mass and dynamic properties of a RSO prior to selection of mission operations and debris removal sequencing.

RSOs in the small and medium size ranges are not currently tracked. Future advances in sensor and tracking technologies may lead to better tracking and identification capabilities, but the economic reality of removing such debris through the use of DTVs is not practical. For small debris objects the only seemingly realistic approach might be one that incorporates non-selective or passive collection. Such an approach would not require the identification or characterization of small debris, but the collector must withstand small RSO collisions, transfer energy from the debris and experience enough collision flux density to justify the mission expense.

It is generally thought that medium RSOs possess much greater mass and momentum than small (Category 1) objects and have much lower population densities. Thus, passive collectors do not seem as promising for this category. In fact, of the many suggested removal methods, none seems to be currently economically or technically viable for Category 2 objects. Although it seems that non-selective collection methods would be potentially practical, there are no known workable approaches for this category.

Regarding debris identification, statistical distribution studies of the entire RSO population[3-6] indicate that RSO density is highest ($\geq 10^{-4}$ objects/km$^3$) between the altitudes of 700 km and 1800 km. Densities in GEO are much lower ($\leq 10^{-6}$ objects/km$^3$). Most of the larger debris objects (~ 0.4–6 m diameter) have high enough albedos[7-8] (in the 3-10 range of equivalent stellar magnitudes) to be detectable from the ground. There is, however a large fraction of objects in the range of 0.1–1.5 m, which have equivalent stellar magnitudes in the range of 10-15 which are more difficult to detect from the ground using modest telescope apertures (≤ 1 m).

For mission planning and cost containment purposes it is desirable to detect, track and image major debris objects from the ground in order to obtain an initial orbit determination (IOD) as well as any estimated rigid body dynamics before carrying out proximity operations for a given removal mission. A favorable cost advantage is possible if debris objects can be prescreened[9] to effectively determine which are tumbling, spinning or holding a steady attitude. Even though modest apertures (~ 1 m) will not resolve debris objects very well spatially at ranges much greater than 1,000 km, they should be able to establish time histories of unresolved objects enough for this type of prescreening. A priori information, such as known ephemerides and engineering design drawings should help to interpret results.

The spatial resolution (or number of pixels, $N_{pix}$) and signal-to-noise (SNR) ratio required to support some graded degree of prescreening effectiveness depend strongly on the range and size of the debris.[9] International Standards Organization (ISO) metrics for detection, tracking, and imaging and classic Night Vision and Electro-Optics Laboratory (NVEOL) perceptual task thresholds for detection, orientation estimation, classification and identification of imaged objects can be used to estimate the corresponding ranges at which these particular thresholds occur, which are roughly in agreement with each other and can be used to infer at what ranges prescreening might be successful. These ranges are summarized in Table 1 for various RSO sizes, assuming the use of a 1 m aperture and state-of-the-art focal plane array technology. Motion state estimation should equate to orientation determination and hence be possible at ranges from 500 km (minimum) to 4600 km (maximum). The corresponding SNR at these ranges should be sufficient under favorable solar illumination and viewing conditions. Range values for a given perceptual task and RSO size are elements of the matrix. They represent the ranges at which the given task can be accomplished with a probability of 50%., assuming the sensor has a large aperture, e.g., 1 meter.

Table 1. Summary of NVEOL Perceptual Task Threshold Ranges (km).

| Threshold # of pixels vs RSO size | | RSO size [$m^2$] | | |
|---|---|---|---|---|
| Perceptual task ↓ | Req'd # of pixels ↓ | 100 | 10 | 1 |
| Detection | 1 | 13000 | 4600 | 1500 |
| Orientation | 3 | 4600 | 1500 | 500 |
| Recognition | 4 | 3300 | 1100 | 370 |
| Identification | 8 | 1500 | 500 | 150 |

Mass and center of mass properties are of concern in those cases where individual objects are to be removed by a DTV, i.e., for large RSOs. In order to properly dispose of a Category 3 RSO, it may be necessary to first determine its mass properties and center of mass location. Access to this knowledge may be essential prior to establishing physical connections between a DTV and a large RSO. Such requirements may be relaxed in those cases where the DTV does not make direct physical contact with debris. For example, if a fluid is used to change the velocity of an object, impingement on that object should not create a risk for the DTV.

In general, at a minimum it is desirable to have advanced knowledge of an object's mass and momentum properties. For those objects that are, in fact, intact expired satellites, the original builder will very likely have a great deal of knowledge about the satellite's characteristics, mass properties and angular momentum state. For pieces of satellites and rocket bodies, it is possible that there will not be a great deal of information prior to approaching such an object. The U.S Space Surveillance Network (SSN) is able to record radar cross-sections for all large RSOs. Sensors are also capable of measuring some level of an object's attitude motion. However, these data are difficult to access, since there appears to be no established systematic process of recording or archiving.[10] Some physical characteristics of large objects may be found in a variety of open and classified documents, but these usually concentrate on recently launched objects. Once an organized debris removal program starts, it is essential that a central archiving function be established to maintain as complete a database as possible.

On the other hand, operational realities indicate that complete knowledge about the state of any large debris object will not likely be available. Therefore, it is prudent to assume DTVs will carry sensor suites for measuring mass and momentum properties in situ. One instrument of choice might be a gravity gradiometer. The Jet Propulsion Laboratory (JPL) is developing a space-qualified instrument of this type with a sensitivity of 0.001 eotvos with a 10 sec integration time.[11] ESA's Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellite has already flown a gradiometer with a sensitivity of around 0.003 eotvos with a 10 sec integration time.[12-14] Consider a

1,000 kg object at a standoff distance of 10 m. Its signature would be 0.067 eotvos. Assuming the use of the JPL instrument, this would provide a measurement uncertainty of about 15 kg. The background gradient due to Earth is 1,000 eotvos at LEO and 5 eotvos at GEO. The effect of this background could be reduced by orienting one of the axes of the sensor along a null direction of Earth's gravity gradient. By taking a series of measurements at varying standoff distances and fitting the appropriate relationship for the measured gradient as a function of the measured distance to the skin of the object, the object's mass and distance to the center of mass could be obtained with sufficient accuracy for removal operations.[15]

When used in conjunction with other data it may be possible to extract components of the inertia tensor using a gravity gradiometer while the object is rotating. However, this technique is yet to be developed. Since this application is rather specialized, it might be possible to utilize a simple single-axis instrument rather than the normal three-axis configuration.

As noted earlier, large RSOs may possess some level of residual and/or induced angular momentum. For most low Earth orbit (LEO) RSOs the angular rates are thought to be low, because most satellites found in this region of space were originally non-spinning designs. Those spacecraft that used internal momentum devices would have experienced a low level of rotation after loss of power. For expired satellites below about 500 km, these rates tend to dissipate in the presence of gravity gradient and atmospheric drag torques. For such objects above about 500 km, drag has little effect, thus, expired satellites with residual momentum will likely experience slow tumbling motion due to interactions with gravity gradient torques. There may also be some momentum increase due to solar-pressure-induced torques. This situation is quite different in GEO and near-GEO orbits. Of the several hundred large satellites that have expired in this region, well over 100 were originally spin-stabilized at rates of up to 60 rpm. After reaching end-of-life they retained these high levels of angular momentum. It is reasonable to estimate that over 100 large expired satellites are still rotating at several tens of rpm. There are essentially no atmospheric drag effects at GEO altitude. Solar pressure torques have negligible impact on angular momentum. And, gravity gradient torques are quite weak at this altitude. Thus, it is fair to conclude that a large percentage of expired GEOs will retain their angular momentum for a long time. Even expired GEO satellites that employed internal momentum devices will retain some rotational motion, but at much lower rates.

In conclusion, most expired LEO satellites and large RSOs can be expected to have at most very low angular rates when approached by debris tenders. All expired GEO satellites are expected to retain some angular motion, and well over 100 will have dangerously high angular rates. Thus, in most cases expected angular rates should be low, but for over 100 GEO objects, they can be as high as roughly 40 rpm. These rates and the angular momentum components, as well as inertia tensor, of each object to be addressed may have to be determined before physical contact can be safely made. Sensors can measure angular rates and software can determine angular momentum properties. This will help to determine the inertia matrix, orientation of the angular momentum vector and center of mass location. These determinations may also require physically perturbing the attitude of the object and watching the reaction.

A good deal of research on the determination of orientation and rotation is available in the literature.[16-20] Most algorithms fall into the category of "structure from motion" and involve using epipolar geometry to determine position and orientation relative to a fixed scene. Other algorithms have been explored to determine orientation using a priori databases of feature points on the object. Both types of algorithms might be effective in determining debris motion. Similar research exists for various lidar configurations including scanning and flash lidar devices, although such systems may require some development before becoming space-rated systems. In summary, algorithms to determine angular orientation of objects are well known. However, there are some engineering challenges that remain to be addressed, including algorithm implementation and transmission of high data rates to the ground for processing.

There are a variety of algorithms for determining relative orientation of objects from optical images. For example, match points in two images can use epipolar geometry to calculate rotation and translation of an object relative to a camera. Lidar techniques are not as advanced, but there are several concepts such as range-Doppler imaging that have been implemented for lidar. Rotation or tumbling presents a special level of complication. Limited research has been done, thus, several engineering challenges remain when approaching objects with significant residual angular momentum.

A limiting factor for using optical and lidar algorithms in space is the lack of hardware needed for implementation in a space environment. For example, JPL implanted a Descent Imaging Motion Estimation System (DIMES) for calculating spacecraft lateral velocity during descent to Martian surface for the MER mission.[21] Their hardware required 3.75 sec to read in each image for a binned image of 256x1024 pixels. The algorithm was allotted 20 sec to process using 40% of a 20 MHz RAD6000 processor and actually required about 14 sec. Their algorithm effectively tracked two features over three images to determine a lateral velocity estimate. Their development work occurred during 2001 (actual mission dates were later), so, space-rated computers are somewhat faster but still in the same ballpark. With these numbers in mind, work should be strongly evaluated on its ability to be implemented in a timely manner. Some considerations are:

- Development/space rating of faster hardware such as graphics cards
- Implementation of algorithms on currently space-rated FPGAs
- Sending images to the ground for processing moves the burden from onboard computation to the telemetry system that transmits images to the ground

Doppler/Inverse Synthetic Aperture Radar (ISAR) offers another ranging option. Single axis Doppler radar or lidar provides relative range rate and possibly range along the boresight. Multiple measurements could be used for rotation calculation. Lidar offers the advantages of finer beams and potential for less mass. However, these devices are not yet ready for space applications.

Since it is likely that only a few large RSOs can be removed on an annual basis due to economic realities, those to be removed should result in the greatest benefit. There appear to be at least two key debris characterization measurements[3] related to collision threat reduction: (1) the probability of hitting a current operational satellite and (2) the probability of creating more debris through a collision between the object and another piece of debris. Both depend on the cross-sectional area of the debris object of interest, its orbital region and the difficulty of removing the object. A simple relationship that governs the probability of hit, $P_{hit}$, is given by the product of the weighted cross-sectional area of the debris flux, F, the average cross-sectional area of a given space system, A, and the orbital lifetime or time at a given altitude, T. Parameter F depends on the time a vehicle spends in different altitudes during its orbital lifetime, given the initial orbit, area-to-mass ratio and original launch date. Paramter A is the spacecraft area averaged over all aspects, accounting for large structures like solar panels. Orbital debris of less than 0.5 cm in diameter are considered insignificant. Orbital debris cross-sectional flux for the size range of 0.5-10 cm diameter is $\sim 10^{-6}/m^2/yr$, and drops linearly down to about $4 \times 10^{-7}/m^2/yr$ for debris sizes of 3 m or more.

A number of debris characterization issues have been identified that inform approaches to determining the best sensors and algorithms to be used for extracting pertinent information about RSOs, particularly at standoff distances prior to launching a remediation mission or deploying a vehicle to apprehend a selected RSO or debris object. High resolution images derived from large aperture ground optical telescopes should be able to remotely determine the motion state of large RSOs if sufficient clear line-of-sight records can be acquired in which the imagery is collected contiguously from frame-to-frame for several minutes in duration. Additionally, these data as well as radar tracks from the ground should be used to maintain tracks on objects of interest prior to in-situ rendezvous and proximity operations. By necessity, such objects must be contiguously tracked and updated to keep the uncertainty ellipse small enough to allow rendezvous while minimizing the possibility of collision, which would only add more debris to the orbital environment. The extent to which the rigid-body motion state of such objects can be determined from standoff measurements will determine if such objects can be screened-out of proximity operations, thus reducing total system costs. Costs can be reduced by allocating reserve $\Delta V$ capacity only to those RSO engagements selected for rendezvous based on RSO motion and possibly some albedo variations or anomalies. If the selected RSOs are domestic, a priori information, e.g., engineering drawings, mass properties, and ephemeris will significantly help prescreening and proximity operations. When only partially resolved or unresolved imagery is available, motion state can still be estimated using such a priori information, but there should be sufficient SNR under solar illumination conditions to support detection, tracking and subsequently prescreening and mission planning for proximity engagements. Detailed characterization requires closer range inspection to support more precise motion state and mass properties estimation or proximity navigation and hazard avoidance. The most viable sensor options for standoff operations are likely to be adjunct modes (not necessarily imaging-based) to add to a baseline imaging capability. For proximity operations sensor modes such as passive stereo, structured light, and lidar can be used with increasing fidelity but with increasing cost per mission.

### C. Precision Tracking, Rendezvous and Standoff

Precision tracking, rendezvous, maneuvering and station-keeping are required for large debris removal. In order to maneuver to the debris and maintain a stand-off position, the orbital and inertial parameters of the object will need to be precisely known. Current tracking techniques have accuracies that appear to be sufficient to steer a DTV to within several hundred meters of a RSOs of interest. Once within a prescribed distance and position relative to the RSO, the DTV will have to take direct ranging and position measurements for the final rendezvous maneuvers. At some prescribed position relative to the debris object, the DTV will assume a proximity station-keeping mode to achieve actual physical contact with the RSO for grappling or towing.

There are several stages to this approach:

1. Acquiring the debris object. This will occur at a prescribed distance from the object, depending on the uncertainty ellipsoid bounded by observations from ground sensors networked for global coverage. Initial estimates place the size of such an ellipsoid at roughly 500 m, if observations can be executed in a timely fashion.
2. Once the DTV has established a standoff position and distance sufficient to avoid any inadvertent contact with the debris object or any of its appendages, it can commence its local (proximity) observations. This mode should enable high-resolution imaging using either passive sensing or active lidar sensors to investigate the size, shape and rigid-body motion-state of the object.
3. During the gathering of image data it may be necessary to execute one or more fly-around maneuvers or circumnavigation to acquire multiple views or perspectives.
4. Analyze the collected data to determine the best course of action. This function may be accomplished by ground station personnel or by in situ astronauts operating in-the-loop between local imaging and guidance, navigation and control protocols. It could be done automatically, but this task is already challenging enough by human-in-the loop means.
5. Maneuver into a position, which allows execution of disposal operations. The exact maneuver will depend on the techniques and devices used to capture the object. For example, if the object is simply spinning about its major moment of inertia axis, the best approach trajectory might be along the spin axis such that a grappling device can synchronize itself with and capture the object. If the RSO is tumbling, a sequence involving active stabilization may be necessary before and during grappling.
6. Execute the grappling maneuver or attach a device to the object. Again, this may be done by ground station personnel or in situ astronauts.

Whichever way is taken to rendezvous and grapple the RSO, after grappling and attachment, it would be better to pull the object with a tether or net rather than push it with just a thruster, because in the latter case the control of the pair would be subject to the destabilizing consequence of having offset torques relative to the center-of-mass of the debris object.

**D. Angular Momentum Reduction**

Large objects that have significant angular momentum will have to be stabilized by reducing any tumbling action to a steady spin about a geometrically agreeable axis, or by eliminating the angular momentum altogether. This will require an actuator system capable of applying sufficient torque to the object in order to reduce angular rates. Once this is done, a grappling device can attach a module containing a small $\Delta V$ thruster that would cause the object to be removed from a congested orbital region. However, thrust must pass through the center of mass and be pointed in the proper direction. So, there will have to be an attitude control system associated with the grappling device.

The level of angular momentum coupled with the mass and geometrical properties of a particular object will limit the grappling options. For example, in order to grapple a large object that is found to be rotating very slowly about a single axis should require the attachment device to only synchronize its rotation with that of the object along the axis of rotation. Then there would be no relative motion of the grappler/object combination. On the other hand, if an object is found to possess significant angular rates about multiple axes, then some form of pre-stabilization may be required prior to mechanical grappling.

A few general statements regarding spinning and tumbling are in order. If a body has any angular momentum, that momentum may be distributed about the three body axes. In such a case the body is said to be tumbling. However, it is generally thought that a body exposed to uncontrolled motion over a long period of time will find a state of steady simple spin about its major principal inertia axis. Furthermore, unless the body was originally spin-stabilized, its angular rates should be low. However, a body that was originally spin-stabilized will tend to retain a high rate of spin about its major principal axis of inertia after it is no longer operational. There are several variations of these states. For example, collision events can impart angular momentum to otherwise non-spinning bodies. Levels of resulting angular rates may be small or large. In addition, there are potentially destabilizing drivers due to the interaction of gravity gradient and aerodynamic torques.[22] Fortunately, the angular rates associated with these natural phenomena are very low.

In summary, if a body was not originally spin-stabilized, it is unlikely to contain residual high angular rates and it should be in simple slow spin about its major axis. A body that was originally spin-stabilized will tend to retain a high spin rate about its major axis. A body that at some point was tumbling will eventually find steady spin about its major axis due to mechanical energy dissipaters within the body. A debris object that was recently hit by other debris may be tumbling and will eventually stabilize about the major axis. It should be noted that the major inertia axis may not be aligned with a geometric axis of convenience for the purpose of grappling. Thus, a body that is, in fact, in steady spin may appear to be nutating. This situation could complicate a grappling procedure.

In those cases where a tumbling object is encountered there are several options for stabilizing the debris. The DTV could standby until passive damping does the job. If the debris does not contain an effective damping mechanism such as liquid in propellant tanks, this approach may take too much time. The tender could deploy an efficient passive damper, but the process of attachment can impose a high level of risk. Angular rates could be reduced by increasing the inertia about an axis, but this could prolong the tumbling.

Another approach could employ fluid sprays[23] or thruster exhausts to induce torques for reducing momentum. However, this may lead to the expulsion of excessive mass from the tender. Finally, it may be possible to create a grappling mechanism that can handle the tumble motion such as a net, agile grasping arm or a compliant brush.

Once the object's spin is under control, the removal process requires the application of a $\Delta V$ in a prescribed direction. To de-orbit an object the $\Delta V$ must be oriented to reduce orbital speed. To raise the orbit, the $\Delta V$ must be directed to increase orbital speed. In fact, the orbit-raising option requires two $\Delta V$s, one to start the increase and one to circularize the orbit at a higher altitude. However, the process of de-orbiting requires only a single $\Delta V$, because atmospheric drag completes the process of eliminating enough speed to assure reentry and disintegration. A hard-contact grappling device could be used to attach a $\Delta V$ device to the object, or the tender could drag the object out of its current orbit to a safer orbit or to an altitude from which it would reenter.

If the tender attaches a separate $\Delta V$ module, that module must also provide attitude control and guidance to insure the proper direction of burn and stability during the burn. Furthermore, the module must align the thrust vector through or very close to the center of mass direction of the object. Some of the alignment issue might be avoided by spinning the object before the $\Delta V$ is applied, but this requires that spin take place about the major or minor principal inertia axis.

An alternative to the $\Delta V$ device might be to attach a large-area, low-mass parachute-like surface to increase natural drag. This approach seems to offer the benefit of low complexity and low cost. Of course the size of the surface is a function of the altitude of the object, since there is less drag at higher altitudes.

Each time an old GEO is despun a certain amount of propellant must be expended. Take the example of a typical dual-spinner such as the HS376, shown in Fig. 1. Between 1978 and 2002, almost 60 of these spacecraft were placed in GEO. Now they are spinning in a flat-spin configuration at high rates. One capture scenario requires elimination of that angular momentum by a debris tender. The propellant required to remove this angular momentum is determined from:

$$M_p = H/(I_{sp}\, g\, L)$$

where:

$H \equiv$ angular momentum about the spin axis = $I\omega$

$I \equiv$ moment of inertia about spin axis $\approx 200$ kg-m$^2$

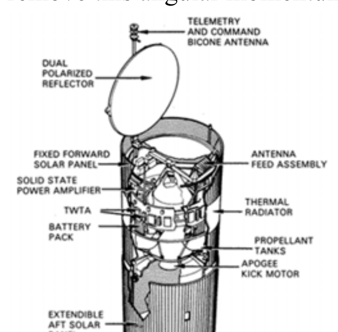
$\omega \equiv$ original angular rate = 50 RPM = 5.24 rad/sec

$I_{sp} \equiv$ specific impulse of tender's thrusters, assumed to be 300 sec.

$g \equiv$ conversion constant = 9.8 m/s$^2$

$L \equiv$ thruster moment arm to create torque, assumed to be 1 m

Thus, the amount of angular momentum to be removed is: $H \approx 1{,}048$ kg-m$^2$/sec. The corresponding propellant to remove this is: $M_p \approx 0.36$ kg. Thus, each time a HS376 might be captured, the tender must expend $\approx 0.36$ kg of propellant to simply stop the rotation.




Source: Boeing Satellite Systems

**Figure 1. HS 376 Configuration.**

### E. Capture Techniques

If direct removal devices are to be used on large objects they will have to somehow attach themselves or another device to the objects. Objects targeted for removal cannot be assumed to have convenient places to attach grapples. This is an inherent relaxed constraint relative to capture requirements for on-orbit docking or servicing of intact cooperative or non-cooperative spacecraft. In such cases, grapple fixtures engineered for capture operations exist or feasible attach points to spacecraft hardware of known configuration can be determined a priori. Thus for pieces of satellites and rocket bodies, a generic grappling device must be capable of attaching itself to an object of almost any shape such that removal operations can continue. In some cases this will require that a retro-rocket thrust vector be aligned to pass through the object's center of mass. In other cases it may simply mean a physical link can be made between a tender and the object. If a retro-rocket is to be used, the grappling/controller device must additionally orient the object such that the proper velocity change is assured. Alternatively, the object can be grappled for stowage in a collector spacecraft, e.g., a space trash scow, for later de-orbit.

A variety of grappling approaches for intact RSOs are possible that vary in complexity according to the motion of the object and whether it has feasible grapple points such as payload attachment fittings, solar panel masts, antennae, etc. For robotic tenders grappling operations are likely to be performed in part via ground-based teleoperation. Some degree of onboard sensor-based autonomy will be needed to safeguard the grappling device against unintended collision with a non-cooperative debris object that may further perturb its motion. The same is true for safeguarding against unintended introduction of excessive impulses to the object. In most cases, safeguarding may rely on grapple mechanism force/torque sensing (and control) and optical vision and range sensing. The vision/optical systems and algorithms must be robust to the extreme lighting conditions found in space and to the reflective nature of many blanketing materials.

Grappling approaches and mechanisms intended for capturing cooperative spacecraft, including satellites and space station modules, may be suitable or adaptable for grappling certain large debris objects. An end-effector developed at the NASA Johnson Space Center[24] for grappling and berthing payloads was flown onboard Space Shuttle Columbia on the STS-62 mission under the task title of "Flight Demonstration of Dexterous End Effector" in 1994. That device, mounted to a robotic arm, was two-fault tolerant in grapple and release and force-torque sensing-enabled. The associated control and sensing problem in micro-gravity is particularly demanding when large (or extended) objects are handled by a robot arm, since the specification of a single Cartesian goal position is usually insufficient for establishing valid contact of the large object with an extended designated location.[25] This is a typical situation when, for example, the 17-meter Remote Manipulator System on the Space Shuttle has to berth a satellite with a base size of several square meters to its berthing place in the Shuttle Bay. Such payload berthing tasks can be likened to stowing collected large debris in a space trash scow. Contact forces and torques to be controlled appear under a variety of robot arm motion conditions, and the dominant dynamical factor is the simultaneous control of impact and load transfer (force time history) at widely separated points in the task space.

Prospective grappling devices have been developed for satellite servicing tasks and remain viable for certain debris removal jobs. The DARPA Orbital Express arm is flight-proven in a technology experiment on servicing a satellite that was pre-designed for robotic servicing.[26] The DARPA Front-end Robotics Enabling Near-term Demonstration (FREND) project[27] developed prototype hardware for a chaser spacecraft that would use robotic arms to position a grappling tool at a customer spacecraft structural hard-point, and dock the two spacecraft together by first rigidizing the tool, then rigidizing the positioning robotics.[26] At the Naval Research Laboratory's Proximity Operations Testbed, FREND successfully demonstrated advanced, autonomous, unaided grappling of a simulated spacecraft with no a priori knowledge of the spacecraft and with no standard, robotic-friendly targets or interfaces on the spacecraft. The project developed techniques to actively hold relative pose at ranges of less than 2 meters with objects tumbling up to 1 deg/sec in any axis. FREND has shown the ability to grapple both types of the hard-point launch vehicle interfaces commonly found on existing satellites allowing capture of satellites that were not pre-designed for servicing. FREND is ground test-proven for unaided grappling of unknown satellite mockups.

Grapple mechanisms were also developed by the NASA Goddard Space Flight Center for the Hubble Space Telescope (HST) Robotic Servicing and De-orbit Mission (HRSDM).[28] This mission involved the rapid development of a spacecraft with a robotic grapple arm, a two-armed dexterous robot, a vision system, 24 robotic tools, robot-compatible Orbital Replacement Units, and ground stations to support the robotic operations. Evaluations were completed using protoflight hardware.

Robotic grapple arms can be teleoperated depending on availability of ground stations or relay satellites. Grappling of an object typically calls for progressive stiffening of the arm following initial capture/grasp.[29] Associated technical risks include de-tumbling or de-spinning of the object within arm torque limits followed by reorientation, attaching a de-orbiting device to an unprepared target, etc. Single arms and multiple arms have been used or proposed for grapping satellites. Since the 1980s until recently, dual-arm systems have been under development.[30-31] A dual-arm telerobot with parallel grippers was demonstrated in lab experiments on grappling a slowly spinning (up to 2 rpm) ~160 kg satellite mockup in the late 1980s using a computation-limited control rate of 36 Hz (with 200 Hz feasible with computer upgrades). In those experiments, contact is sensed by the force/torque sensors after which the basis for motion control is changed from vision-based servoing to force servoing until the forces are nulled. Since the satellite mockup cannot be stopped instantaneously once it is grappled, software decelerates the mockup according to a trajectory generated based on the initial velocity at the moment of contact. Once the satellite mockup is stopped, it is pulled to the docking fixture and active force control nullifies the force built up due the dual-arm coordinated motion. The Canadian Space Agency recently performed similar laboratory experiments involving validation via trans-Atlantic Ocean communications. Both activities are representative of on-orbit robotic manipulation for satellite-capture tasks where the environment is known and structured, but dynamic since the satellite to be captured is in free flight. Bandwidth limitations and communication dropouts dominate the quality of the communication link. A key concern is controlling the arm so that no excessive forces or torques are exerted on the satellite or arms.

As part of the difficult task of robotic servicing or debris removal, the requirement to handle large objects that are spinning or tumbling is one of the most challenging. The research community has investigated approaches that make use of robotic arms and special end-effectors to facilitate de-spinning or de-tumbling prior to grappling objects in space. Some of the operational complexities and challenges include controlling a grapple device such that the target grapple point arrives at a rendezvous point with the same velocity to enable the chase vehicle to mechanically connect with the target using the grapple device, maintaining interaction torque magnitudes between the arm and target within limits, and aligning the interaction torque vector along the direction opposite to the instantaneous angular momentum vector direction.[32]

Robot arms and associated advanced control algorithms have been proposed that would brake the rotation of a non-cooperative debris target with unknown inertia using an end-effecter with a brush used to reduce the target's rotation rate.[33] In addition, approaches have been proposed that employ elasticity within the grapple mechanism's end-effector to brake residual motions that are unanticipated beforehand.[34] Following the assessment of target motion, a feasible grasping point on the target is selected and the tender begins to move to initiate the capture. The impact of the load at the time of capture is relieved by means of force/torque control of arm joint compliance while the capture load is relieved by elastic members in the grasp mechanism. After target capture, the robot arm is gradually slowed down using joint force/torque control, transferring momentum from the target to the tender. Technical challenges of such approaches include avoiding tracking errors which will lead to loading causing undesired momentum transfer to occur during the capture process, unknown debris mass and inertia properties which complicate impedance matching of the capture arm force control system, and the need to slow any high speed rotation of the target to a rate at which capture can be accomplished by a robotic arm using, for example, visual feedback control.

Simulations and laboratory hardware experiments have shown feasibility of such approaches. Most solutions focus on the force impulse generated during the contact. The problem can also be addressed by focusing on angular momentum. Attempts to grapple a target satellite without considering its momentum will lead to difficulties for post-impact control and likely failure of the operation. Most methods require information about the target's angular velocity and inertia parameters prior to a grapple attempt. A strategy (verified by numerical simulation) that aims to favorably distribute angular momentum in the tender in order to facilitate its attitude control post-impact has been proposed.[35] The idea is to preload bias angular momentum in the chaser's manipulator with the (known/estimated) target's angular momentum of equal magnitude and opposite direction so that after capture the combined manipulator and target will have zero angular momentum.

Novel grappling mechanisms have been proposed that take less conventional approaches to the problem. A coupling system for capturing, braking and deploying an object which rotates about a principal axis prior to capture was patented.[36] Its design effects capture and release of a spinning satellite offering both the ability to bring the rotation of the satellite to a halt on capture and to impart a rotation of the satellite when released. This grapple mechanism is comprised of a housing with a passive turntable mounted within it along with a braking clamp. The passive turntable is mounted on the adaptor so as to be free to rotate about the rotational axis of the spinning object. The brake clamp initially engages the passive turntable and thereafter applies a braking torque to the adaptor housing.

The Grapple, Retrieve, And Secure Payload (GRASP) net is representative of another less conventional mechanism. It uses lightweight inflatable booms to deploy a large net structure, which can be maneuvered around a space debris object and then collapsed to securely capture the object.[37] With lightweight and relatively simple design such mechanisms are purported to be deployable by small spacecraft to capture objects that are tumbling or do not have the convenient grappling fixtures required by robotic arm-based capture systems. Capture of a tumbling object using a prototype of the GRASP grappling device was successfully demonstrated in microgravity (Zero-G Corp. aircraft test) at TRL 5. An open engineering issue for such systems is how to reliably control momentum transfer between the object and small debris tender to facilitate subsequent de-orbit maneuvers.

An extensible and foldable robot arm prototype for capturing tumbling, non-cooperative targets was also proposed[38] to be carried by a small satellite referred to as a "space debris micro-remover." It relies on structural flexibility and joint compliance control to buffer unanticipated residual motion of a target object. In operation, it would rendezvous with a debris object, measure its motion, fly around the target and make a final approach to capture it using an extensible arm terminated by a tentacle-like end-effector.

An example of a concept that avoids physical connection between a DTV and a large RSO until the RSO is stabilized is the TAKO-Flyer system.[39] This concept seeks to make a non-cooperative RSO cooperative by attaching a separable, free-flying daughter-vehicle to the RSO that is adorned with grapple fixtures and optical fiducials to aid vision-based capture by existing robotic technologies. The daughter-vehicle is essentially a capture mechanism that functions as a set of compliant pressurized tentacles to "softly" encapsulate an RSO. While coupled to the object, its propulsion and attitude control systems would then stabilize the object's attitude sufficient to enable conventional robotic capture by its mother-ship; the concept permits the alternative possibility for the daughter-vehicle to serve as a de-orbiting kit. Sizing analysis for such a system suggested 300 kg for the mother-ship and 100 kg for a daughter-vehicle.

Table 2 provides a qualitative summary of engineering figures of merit and caveats for a variety of techniques proposed for large RSO in situ capture systems. In addition to encapsulating nets and tentacle-like robotic mechanisms, tethered systems based on a harpoon, gripper, or lasso at the end of a tether apparatus have been conceived for space debris capture. The merits of tethered systems are discussed further in later paragraphs.

Table 2. Large RSO Capture Techniques: Figures of Merit and Caveats (VL-Very Low, L=Low, M=Medium, H=High, N/A=Not Applicable).

| Figures of merit / Implementation | Mass per unit length/ area/volume | Maximum length/area/ volume | Strength or load capacity | Bending radius of curvature | Required actuator power | S/C-debris force/torque isolation | Number of controlled DOFs |
|---|---|---|---|---|---|---|---|
| Conventional robotic grappler | H | M | H | S | H | M-H | 6-8 |
| Encapsulating net | L | M | M | S | L | H | N/A |
| Inflatable longeron | VL | H | L | H | L | H | 1-2 |
| Harpoon with tether | L | H | H | S | M[a] | H[b] | 1 |
| Articulated tether (lasso) | M | M | M | M | M | M-H | 3 |
| Electrostatic/adhesive blanket | VL | M | L | S | L | H | N/A |
| **Caveats** | | | | | | | |
| Conventional robotic grappler | Optimal for close contact grappling requiring high torque or structural hard points in lieu of grapple fixtures; mature technology; DOFs facilitate thrust alignment. Representative size: 65 x 49 x 186 $cm^3$ pre-launch; mass: 70-90 kg; power: 130 W | | | | | | |
| Encapsulating net | Low mass, low cost; does not control angular debris DOFs, but maybe suitable for irregularly shaped debris or appendages | | | | | | |
| Inflatable longeron | Extremely lightweight and low cost; may be able to employ Velcro for capture; may be suitable for drogue chute deployment; susceptible to leaks | | | | | | |
| Harpoon with tether | a. High impulse power, low average power; b. Although force/torque isolation is good, lack of control/stability of angular DOFs is problematic; may be suitable for tractor thruster | | | | | | |
| Articulated tether (lasso) | Controls angular DOFs using multiple radial actuators; has anti-torque advantages over simple cable tethers | | | | | | |
| Electrostatic/adhesive blanket | Very lightweight; may be suitable for initial contact and precursor attachment | | | | | | |

**F. Requirements for a ΔV Module**

Individual ΔV modules may be required for removal of large RSOs, and there are several ways to use these devices. For LEO debris, it is highly desirable to completely de-orbit most RSOs, although it is possible to simply raise the altitude and place these objects in higher, less dense regions. However, there are two reasons that de-orbiting is preferential. First, the amount of ΔV needed to cause atmospheric entry is small and roughly the same as needed to raise the orbit. Second, satellites in higher orbits may eventually become hazards to future operational spacecraft.

There are two approaches to de-orbiting a LEO RSO. One way is to simply apply a single ΔV that will create a perigee that is low enough to insure that atmospheric drag completes the decay of the orbit over a period that is less than the U.S. Government guideline of 25 years. The other way is to apply a single ΔV that will create a direct entry into the atmosphere. The latter approach might be used in those cases where there is concern that the RSO will survive the entry and present some risk on the ground.

For medium and high altitude RSOs, de-orbiting requires a great deal of ΔV as compared to simply changing the orbits. Since the density of MEO RSOs is very low, there is no need to remove these for the foreseeable future. GEO RSOs consist primarily of expired satellites. Although the density of these large RSOs is low, there is interest in removing them from this orbit and placing them in graveyard orbits above GEO. The ΔV requirements for this are low.

In summary, there are no large ΔV requirements for large RSO removal. Nevertheless, any ΔV module that may be attached to a large debris object will surely be complicated. In fact, in some cases this module can be thought of as a small spacecraft. It must generally control the RSO orientation while applying the ΔV in the proper direction. Thus, it will probably have to incorporate an attitude control system, a power supply, communication links and a propulsive device. As an alternative to this kind of ΔV module, tether devices have been proposed in lieu of a traditional thrusting unit. However, tether devices, while representing a possible solution for this application, have not been proven. Finally, if the RSO is below about 600 km, a simple drag enhancing device could be effective.

Consider an example case in which a LEO RSO is to be removed by creating a perigee altitude of 300 km, starting from a circular orbit at altitude, h. This would require only a single ΔV application[40] given by the equation:

$$\Delta V = \sqrt{\mu/r_a} - \sqrt{(2\mu/r_a)[\,1 - r_a/(r_a + r_p)\,]}$$

where

$\mu \equiv$ Earth's gravity constant, 398,600 $km^3/s^2$
$r_a \equiv$ Initial RSO orbit radius, $R_{Earth} + h_0$
$h_0 \equiv$ Initial orbit altitude
$R_{Earth} \equiv$ Mean radius of the Earth, 6.378 km
$r_p \equiv$ Perigee radius, 6,678 km

Table 3 lists the results for orbits that have initial altitudes of up to 1,100 km.

**G. Sweepers**

Sweepers are large inflatable structures that are placed in orbit to encourage small (Category 1) debris to randomly impact with the surface material, causing energy loss or capture. These were investigated for viability and practicality.

Preliminary calculations indicate that current launch vehicles have payload mass limitations for such inflatable structures. The upper limit on payload mass translates into an inflatable with a maximum diameter to 625 m. At this size the estimated number of small debris hits per year is only ~ 4 in the region of highest debris density. Thus, the hazards of deploying a large inflatable that could generate more debris appear to outweigh the benefit in mitigating small debris.

Many have suggested magnetic sweepers. However, there is very little ferrous material in spacecraft, limiting the effects of magnets. And, magnetic field strength drops off rapidly with distance. Thus, the possible use of magnets has been discarded.

Table 3. ΔV Needed to Lower the Perigee of a RSO.

| Initial Altitude (km) | Delta V (m/sec) |
|---|---|
| 1100 | 209.3 |
| 1000 | 185.4 |
| 900 | 160.8 |
| 800 | 135.7 |
| 700 | 109.9 |
| 600 | 83.5 |
| 500 | 56.4 |
| 400 | 28.5 |
| 300 | 0.0 |

**H. Tethers as Orbit-Changing Modules and as Orbiting Debris Tenders**

Two types of tethers have been suggested for debris removal. One type attaches to large RSOs in order to induce electrodynamic drag and cause slow altitude reduction until atmospheric entry takes place, sometimes referred to as the "Terminator Tether."[41] The other type is an orbital maneuvering spacecraft that functions like a debris tender, but is propelled by the electrodynamic interaction of the Earth's magnetic field. The former approach would replace the use of a ΔV module and offer the possibility of a simpler way to cause orbit decay. The latter approach, while the theory and physics are well understood, does present huge engineering challenges.

The Terminator Tether offers to produce a drag force that can be programmed to change the orbit of a large debris object. Such a device would be a module attached to the object either before launch or after capture by a

DTV. The underlying physical principles are straightforward. The motion of a conducting tether through the Earth's magnetic field generates a voltage along the length of the tether. A current produced through the use of an electron emitter at one end of the tether can expel electrons into the surrounding ionosphere. Motion of this current loop through the magnetic field results in a Lorenz force that can be used to lower or raise the orbit of an object.[41-42] Various prototypes have been proposed using tethers on the order of 5-10 km with total system masses in the 25-50 kg range that could potentially draw their necessary power from the tether itself at the expense of reduction in the de-orbiting forces. While the concept seems appealing, there are engineering challenges that must be dealt with. The use of these tethers on existing RSOs does require they be attached to the debris in orbit. A prerequisite to attachment is that angular momentum must be reduced to near zero in order to allow tether deployment without complications. Another concern is the survivability of the tether in a debris-congested region of space. One study estimated that during the process of moving a 2,000 kg object from 1,500 km to 500 km using a 10 km single strand 3 mm wide tether, there is a 40% chance that small debris will sever the tether.[43] The study did, however, note that a potential solution to this problem is the use of a multiple-strand tether with periodic connecting points such that the severing of one segment does not sever the entire tether. To reach a 99% survivability level these connecting points would be needed every 2.5 m. To further complicate the use of tethers for orbit changing applications, long tethers exhibit certain libration modes that have been shown to be unstable. Therefore, any proposed tether system must include a stabilization solution. The effectiveness of electrodynamic tethers is reduced at high inclinations because the Earth's magnetic field lines are generally aligned with the orbital velocity vector. In fact, for inclinations above 75 deg, the ability to generate an electrodynamic force is greatly reduced.[41]

Tether systems that maneuver between debris objects and act as tenders have been suggested.[44] Such devices would similarly take advantage of the interaction between the Earth's magnetic field and electrodynamic currents generated by the tether to create thrust without propellant for orbital maneuvering. These tether systems would have to rotate in order to maintain stability and structural stiffness, imposing several engineering challenges for debris collection and removal operations. Rotating systems produce large tensile forces in tethers that may have limited strength given their length and low mass. The acceleration at the tip of a tether is given by $v^2/L$, where v is the velocity relative to the center of mass of the object and L is the distance from the center of mass. For example, a velocity of 100 m/s at the end of a tether that is 10 km long would produce accelerations on the order of 0.1 g. Limitations on acceleration levels due to tether strength could pose severe limitations on allowable debris object mass.

One operational scenario for such tethers involves approaching a debris object, attaching an end-effector to the object and accelerating the object to the tether rotational speed. This would effectively make the object a part of the tether mass structure. Once attached, the debris object could be removed from a congested region of space and released. The release process could be risky in that it might impart a "slingshot" reaction causing the tether to collapse. The complex operational scenarios required of these tether systems appear to pose serious limitations. In summary, there appear to be serious challenges related to any operational implementation of rotating tether systems.

**I. Electrostatic Forces**

The use of electrostatic forces for large RSO removal has been proposed for moving expired satellites and other large objects from geosynchronous orbits to graveyard orbits which are well above the zone of active spacecraft.[45] This concept uses electrostatic trackor forces in combination with electric thrusters and charge balance generators over a several week period to add orbital energy to large GEO RSOs. There are two potential advantage claims offered by this approach. Physical grappling of, or attachment to, a debris object is not required. And, any residual angular momentum need not be eliminated prior to object removal. Figure 2 illustrates the process.

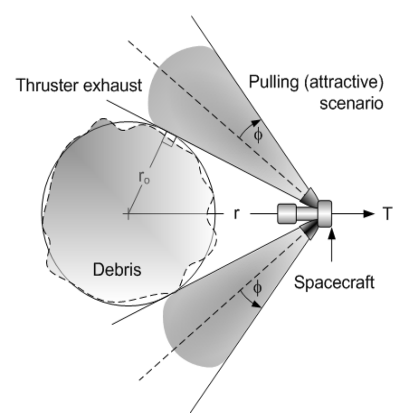



**Figure 2. Electrostatic Tractor Pulling a GEO RSO**

While it is the electrostatic charge that determines the attractive force between a debris object and a tractor spacecraft, the charge levels associated with creating the needed electrostatic forces are characterized as being in the tens-of-thousands of volts. Exact levels depend on many variables such a debris shape and size. Consider an example of a 1,000 kg roughly spherical object that is 3 m in diameter.[45] A large electrostatic charge results in a Coulomb force between DTV and debris of 4 mN at a standoff distance of 20 m. This would lead to an acceleration of $4x10^{-7}$ g, resulting in an orbit altitude increase of about 9 km/day. Decreasing the standoff distance would increase the force available to pull the debris. However, close standoff distances are limited by the size, shape and angular motions of the object. For example, there are several expired satellites in geosynchronous orbits that are rotating and have long solar arrays and large antennae that extend as much as several meters from the center of mass. The primary risk factor is inadvertent physical contact between tractor and object due to variations in tractor forces as the object rotates in the electrostatic field. This poses a risk of collision and an increase in GEO debris.

There are several engineering issues associated with this concept. The tractor vehicle must be hardened against the effects of unbalanced charge to prevent arcing in various regions of the spacecraft that are at high charge levels. Such arcing would result in damage to the surfaces involved. Solar cells are particularly vulnerable to this, and electronics would have to be well shielded. Damage to the debris object need not be a consideration unless arcing could result in an unanticipated or dangerous situation, e.g., inadvertent firing of thrusters or the ignition of stored propellants.

Unbalanced charge on an object naturally tends to self-neutralize. In low orbits, this effect rapidly removes any large charge artificially induced on an object. However, at geosynchronous altitudes charges tend to be relatively stable. Local voltage gradients at sharp points and edges may provide enough energy for electrons to overcome the work function of the surface and result in the escape of charges. The level of charge at which this becomes a problem has not yet been worked out.

It must be noted that electrostatic attraction forces between DTV and debris are unstable. As the distance between object and tractor decreases attractive force increases, causing a tendency to move even closer. As the distance between object and tractor increases attractive force decreases, thus, resulting in an unstable separation drift. However, this instability is controllable through the use of an active feedback servo system which controls the balance between charge and separation distance. Fortunately, the attractive forces are small and the body masses are large, allowing control system response times to be long.

One area of concern is charge variation due to RSO rotation. A rotating object will be subjected to a varying amount of force if its center of charge and center of mass do not coincide. Furthermore, if the surface of the debris is conducting, then the charge will migrate as it rotates, tending always to accumulate on surfaces closest to the attracting DTV. Nearest surfaces will not necessarily be at constant distances to the DTV if the object is asymmetrical, causing even more variation in the mutual attraction. Given the small forces and large masses involved, the reaction time due to this effect will be much longer than that of the variation in the forces involved. Even at a tractor acceleration of $4 \times 10^{-7}$ g, the time to close from 20 m separation to 10 m would be almost 38 min. But, over this time period an object may have experienced several revolutions. In such cases only a time-averaged electrostatic force need be considered.

Since the force between DTV and debris object is aligned with the velocity change direction, the object must remain in line with the DTV's ion engine exhaust. This exhaust will likely impinge on the object, at least partially cancelling the acceleration of the DTV/object system. Also, the engine exhaust could provide a medium for self-neutralization of the debris if not properly controlled.

Consider the use of electrostatic forces at low altitudes. Due to the high flux density of charged particles, the use of electrostatic DTVs for removal of large objects is impractical. However, the use of electrostatic forces on Category 1 objects has been suggested. For example, a hypothetical large grid might be charged to a very high voltage. As small neutral particles pass through the grid, they would temporarily acquire a small charge, leading to interaction with the grid and causing particles to lose orbital speed. With help from atmospheric drag, the result would be the rapid de-orbiting of small objects. However, there are several issues with this approach. In order to be effective the charged grid must be very large. Even if the grid cross-section is very small the electrical charge will increase its interaction with the plasma environment, effectively increasing drag. Since such grids would seem to effectively have low densities, the expected ballistic coefficients would also be low, implying rapid deceleration unless countered by drag make-up forces possibly achieved with ion engines. Another force is created by the interaction of the charged grid and the Earth's magnetic field. However, this force is expected to be much lower than that of drag and probably not usable to counter drag.

Consider a simple square or circular conducting grid. Charges will tend to accumulate on the edges or corners, even though the entire grid may be at a uniform potential. This accumulation phenomenon may cause large external voltage gradients at these locations. Such voltage gradients in the presence of the local plasma currents will likely enhance the tendency for the charge to self-neutralize. This may in turn lead to excessively high electrical power requirements to keep the grid charged. Finally, even if the physical grid has a low area fill factor, there may be occasional damage from collisions with small debris particles, and the chance of creating further debris in these collisions must be assessed.

### J. Aerogels and Hypervelocity Impact without Material Escape

Category 1 and 2 debris do not warrant the use of grappling devices on individual objects. The only reasonable approach is to create "passive" collectors that allow themselves to be struck by debris objects such that the debris is either collected or slowed in order to encourage de-orbiting. There are several key points to be considered regarding the use of aerogels for small- and medium-sized RSO removal. Materials used for this application must not create more debris than is collected. The effectiveness of aerogels must be sufficient to provide a net positive impact of reduction. This means the cost of deploying and operating these devices must match the benefit in terms of improving safety to operational satellites. The passive collection of debris does not mean these collector satellites can be uncontrolled. They must be somewhat maneuverable in order to avoid collisions with operating satellites and large RSOs. This requirement will impact collector size limitations. The combination of required control authority, launch vehicle limitations and other operational procedures must be balanced before such systems can be seriously considered.

Aerogel as a capture medium for small hypervelocity particles has been demonstrated in the laboratory and for cosmic dust in space with a long history of research on impact dynamics, effect of aerogel properties and tailoring the aerogel nanostructure.[46] Thus, for a limited domain of micrometeoroids and small RSOs, aerogels can be considered a mature technology. However, no research has been conducted on the use of aerogels for the capture of medium RSOs. Even within the micrometeoroid size domain, complete capture is considered rare. Secondary debris from impacts can be expected in the case of Category 2 RSOs. However, this would likely result in decreased sizes, potentially reducing medium RSOs to small RSOs, which may improve spacecraft survival during debris collisions.

Critical trade-off parameters include material composition, surface area and thickness, and total mass. Material selection requires that a consideration of collateral debris production be addressed. The surface area must be sufficient to provide reasonable impact probabilities over mission lifetime that are large enough for effective remediation. Material thickness must be great enough to ensure debris capture or velocity degradation. The associated total mass of aerogels to effectively impact debris clean up will lead to the cost of deployment.

An evaluation of trade space parameters was made based on a scaled-relationship between penetration depth and projectile diameter for aerogel in combination with the approximate dependence of impact crater depth and material properties in penetration and cratering-limited regimes. Results indicate that the required surface area and material thickness would result in total mass requirements which are prohibitive. For example, one 12,000-kg shell of radius > 30 m has little chance of significantly slowing down debris that is greater than 4 cm, independent of material.

Aerogels may have another application in debris removal. They may be used to decrease the ballistic coefficient, thus, strongly impacting orbital decay time for altitudes less than 600 km. The concept is to attach an inflatable aerogel to a large RSO. Once inflated the cross sectional area is increased without significant increase in RSO mass, thus, reducing the ballistic coefficient.

## IV. Conclusions and Overview of Findings

Several significant findings can be identified. First, debris smaller than 5 mm need not be addressed in a removal program, because impact damage can be countered by shielding operational spacecraft. Furthermore, natural processes may eliminate these objects over time from LEO altitudes. Second, RSO sizes from 5 mm to 10 cm represent ongoing risks to operational satellites, but the technology to practically address this size range does not exist. Satisfactory materials for passive and active sweepers are not available. Any removal efforts for this size range must employ macro methods in which individual RSOs cannot be addressed. Third, RSOs in the 10 cm to 1 m range are too small for individual removal in terms of cost, even though there may be more than 15,000 debris objects in this size range. These RSOs can be tracked, and they pose ongoing serious risks to operational satellites. Economical systems and needed technologies to address this size range simply do not yet exist. Debris of sizes > 1 m number in the 3,000-5,000 range, and these represent ongoing risks to operational LEO and GEO satellites. They will be major contributors to future increases in the debris population. Fortunately, technologies needed to address this size range exist, but systems do not. For example, tethers lack engineering maturity. Nevertheless, such large RSOs will most likely require the use of some kind of tender system for removing individual objects.

In summary, there are many technology shortfalls. For example:

- Passive and active sweepers are impractical for debris removal.
- Tethers as tenders lack a great deal of systems engineering and design solutions.
- Satisfactory materials for hypervelocity impacts do not exist.
- General purpose robotic and teleoperator sensors and grapplers for removal of most large RSOs are in varying stages of development.
- Removal of debris in the 5 mm to 1 m size range is impractical, given available technology and projected economic considerations.

Current technology capabilities will allow selective removal of certain very large debris objects in LEO in the short term. Some GEO RSOs that are expired satellites can be moved to graveyard orbits through the use of special tender-satellites. However, the cost will be very high.

One of the prime objectives here was to gain engineering insights into the challenges of in situ debris capture. Another objective was to offer as much information as possible concerning enabling technologies, engineering challenges and systems requirements for success. Here are several insights that should be refined in future work:

- Debris object classification by size is a first level separation of the categories needed to eventually arrive at the realistic engineering solution to debris removal. Large RSOs must be removed individually due to their large size. This can be achieved by a debris tender that has a dedicated mission to remove one object or a tender that removes a series of objects.
- Large debris removal will require that we determine certain characteristics of each object a priori. These include size, shape, mass properties and angular motion prior to capture. Further categorization may be required in terms of: size; configuration; angular rates; country of origin; history of the RSO; potential hazards in terms of explosives and residual propellants; and orbit parameters vis-à-vis risks to operating satellites.
- In situ sensor suites must be designed to accommodate the real-time requirements associated with robotic debris tenders. Sensors may include visual, radar, lidar, gravitometer and IR, etc.
- Modules to be attached to debris for removal may contain a complete attitude control system and retro rocket, a drag enhancing device, or a tether mechanism.
- For those large debris objects that possess significant angular rates, grappling devices and techniques are far from ready for flight. Large angular rates offer high risks for debris tenders and grapplers. Fortunately, few RSOs in LEO are expected to possess large angular rates. This is based on the fact that few LEO satellites employed high angular momentum techniques for attitude stabilization. It is the older spin-stabilized GEO satellites that contained high angular momentum techniques which would be retained after expiration. There are well over 100 of these in and near GEO.
- Current tracking capabilities for rendezvous and standoff should be sufficient for tenders if onboard sensors can detect the debris from a kilometer away.
- Grappling activities present several types if risks. Inadvertent transfer of momentum, attitude destabilization, thrust misalignment for $\Delta V$ maneuvers, moving parts on the debris object, propellant slosh and hazardous reactions to attitude control.
- The use of tether tenders presents numerous unique risk factors and engineering challenges. Large rotating tethers are extremely hard to maneuver in short time frames. Proximity operations are exceedingly complex. The ability to produce thrust properly is largely dependent on the orbit and power available to produce current in the tether. The tether structure is complex and of limited strength and flexibility. Maneuver transit times seem very long. Any CONOPS will be very complicated due to retracting and extending a rotating tether device. A number of trade-offs will be necessary to determine if the propellant savings will offset the complexity.
- The use of electrostatic DTVs has several issues. There may be extensive electrical arcing that could cause damage to power sources and result in unanticipated firing of thrusters, etc. Attractive forces are unstable and must be controlled with feedback circuits. Asymmetrical objects that are rotating will induce variation of attractive forces with time. Tractor thrusting plumes will impinge on the objects, thus cancelling part of the desired $\Delta V$ and providing a medium for the neutralization of the accumulated charge.
- Category 1 objects present minimal risks to operating satellites, and these can be mitigated through the use of shielding and attitude maneuvering techniques. Category 2 objects can cause more damage, but the economics of individual removal just do not work. Passive Category 2 debris collectors may work, but they will be quite large and must be capable of withstanding hits by 10 cm objects at relative speeds of up to 14 km/sec. Aerogel options need to be further investigated.

## Appendix
## Glossary of Key Definitions

**Aerogel** = a manufactured material with low bulk density. For debris removal and capture applications being addressed here this material can be thought of as an expanded polystyrene or styrofoam. A form of this material may prove ideal for passive debris collection, provided it does not create more debris than it collects. A further requirement is that the material must be stowed for launch and capable of expanding in the vacuum of space.

**Ballistic coefficient** = measure of a body's ability to overcome air resistance in flight. It is defined as the ratio of body mass to the product of drag coefficient and cross-sectional area, or

$$B = M/C_dA$$

Note that B is inversely proportional to deceleration, i.e., a high value of B indicates low deceleration.

**Computer vision or structure from motion** = the process of finding the three-dimensional structure by analyzing the motion of an object over time. Humans perceive a lot of information about the three-dimensional structure in their environment by moving through it. When the observer moves and the objects around him move, information is obtained from images sensed over time.

**Debris size category** = Debris sizes have been categorized as a first step in differentiating the complexity and methods for removal. Category 1 refers to debris in the one micron to 0.5 centimeter range. Category 2 refers to debris in the 0.5 to 10 centimeter range. Category 3 refers to debris in the 10-centimeter to several-meter range.

**Debris tender** = A spacecraft specifically designed and operated to approach and capture large debris objects for the purpose of removing them from hazardous regions of space.

**Epipolar geometry =** geometry of stereo vision. When two cameras view a 3D scene from two distinct positions, there are a number of geometric relations between the 3D points and their projections onto the 2D images that lead to constraints between the image points. These relations are derived based on the assumption that the cameras can be approximated by the pinhole camera model.

**GRASP** = Grapple, Retrieve and Secure Payload. In 2003, Tethers Unlimited designed a system called GRASP, which used a net made of Kevlar yarn to snare a small object and steady it enough for a tether to be attached. With funding from DARPA, the company got as far as testing a prototype during short stretches of weightlessness on a zero-G airplane.

**HRSDM** = Robotic Servicing and De-orbit Mission. This mission involved the rapid development of a spacecraft with a robotic grapple arm, a two-armed dexterous robot, a vision system, 24 robotic tools, robot-compatible Orbital Replacement Units and ground stations to support the robotic operations.

**LIDAR** = Light detection and radar, an optical remote sensing technology that measures properties of scattered light to find range and/or other information of a distant target.

**Terminator Tether™** = A proposed low-cost, low-mass device that could provide a reliable way for removing large debris objects, satellites and upper stages from LEO.

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