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ABSTRACT

Removal of debris from orbit becomes an increasing urgency because the growing amount of non-controlled spacecraft, residuals from launchers and other items orbiting around the Earth pose an increasing threat of collision with operational satellites. Also, for larger bodies in lower orbits the threat of uncontrolled impact on ground after re-entry exists. Whereas in very low orbits all bodies will decay after some time due to the residual atmosphere, in higher orbits they will stay for considerable time or practically forever. For objects in higher orbits and for those posing the threat of uncontrolled impact, active removal will be the sole remedy. The tasks to be performed from approach to contact and the technical challenges to be mastered to achieve capture and removal from orbit are discussed in this paper. The major challenges are the far range approach without navigation interfaces on the target, relative position control of the chaser in close vicinity of a tumbling target, capture of such target without capture interfaces and the establishment of a structural connection, which is stiff enough for controlled deorbitation.

1 DEBRIS IN DIFFERENT ALTITUDES

In Low Earth Orbits (LEO), orbiting bodies will due to the residual atmosphere be slowed down, loose altitude, and will eventually burn up in the atmosphere, with the residuals of larger and denser bodies falling back to ground. The higher the orbital altitude, the longer the body will stay in orbit, e.g. a couple of days in a 250 km orbit, of the order of 100 years in a typical 800 km Sun-synchronous orbit (SSO), and practically forever in navigation satellite orbits (Medium Earth Orbits, MEO, \( \approx 20000 \) km) and in communication- or meteorological satellite orbits (Geosynchronous Earth Orbit, GEO, \( \approx 36000 \) km).

Whereas in all orbits, uncontrolled bodies form a potential collision hazard, in GEO, if not removed to a higher graveyard orbit, incapacitated spacecraft cause also an additional commercial loss. Uncontrolled objects in GEO will, as a result of orbital disturbances, drift slowly in East/West direction, but also in North/South direction, crossing the equator twice each orbit. Eventually they will sweep over a relatively large area on the geostationary rim. This is of considerable commercial concern, as it may cause at times the non-availability of valuable orbital slots. For this reason, as a rule, GEO-satellites are transferred by their own means to a graveyard orbit at end of life. Nevertheless, there are incapacitated satellites left in GEO, which could not be de-orbited.

Except for the above mentioned cases of bodies in LEO, that will eventually be removed from orbit by decay and burn up in the atmosphere, the only possibility of removal from orbit is the capture and active de-orbiting of the body in question to ground or to a safe orbital altitude. However, even when they decay slowly, such as for objects in higher LEO which will stay for a long time in orbit, capture and active de-orbiting would be the only way to mitigate the collision risk for other spacecraft. Active de-orbiting could become necessary also for large and dense bodies in LEO, because of the danger of uncontrolled impact on ground, they may create.

The highest density of debris and, therefore, the highest threat of collision in orbit exist in LEO in near polar orbits (Fig. 1). Since all these orbits intersect in the two pole regions, the probability of collision is additionally increased. Even if these orbits have the same inclination, because of the unlimited possibilities for the location of the ascending node, they can intersect even at large angles.
The ‘right ascension of the ascending node’ (RAAN) is the second angle defining the orbital plane in inertial space.

Because of the unlimited possibilities of inclination and RAAN, a servicing spacecraft in LEO and MEO has to be launched into the particular orbital plane of the target spacecraft in question and can rendezvous only with this particular target. Larger plane changes are very costly (in LEO $> 1300$ m/s for $10^°$) and may not be achievable. With electric propulsion they would need very long time.

It is obvious that such ‘one-off’ mission would be economically viable only, if the threat posed by the target vehicle is very high, either due to the potential damage by collision with other spacecraft, or due to the potential damage to ground features at re-entry. In any case, the amount of investment, which can be made for a servicing vehicle for such mission will be limited.

In MEO, which is mainly populated by navigation satellites, both the population and the collision risk of spacecraft is low. For this reason, in the following only LEO and GEO cases will be be considered.

2 APPROACH & CAPTURE TASKS

To actively remove a body from orbit, a vehicle has to be placed into the target orbital plane, has to approach and eventually to connect to such body. However, in contrast to regular rendezvous operations, such as for servicing of space stations, the target is not designed for rendezvous and capture, will neither have absolute navigation sensors operating, nor dedicated interfaces for relative navigation and also no dedicated interfaces for capture and physical connection. As an additional problem for capture, an incapacitated spacecraft may rotate about unknown axes (tumbling).

For approach and successful capture the following actions must be performed:

- Prior to start of the approach, the orbital parameters of target body must be determined by measurements from ground as precisely as possible.

- The chaser must be injected into an orbital plane close to that of the target. After plane corrections, it must be guided by ground measurements of the target and absolute navigation of the chaser as closely as possible to a relative range between chaser and target, from whereon relative navigation needs to commence.

The minimum range at which relative navigation measurements between the two vehicles needs to be
started, depends on the accuracy of the orbital parameters of the target measured by ground (see section 4.1). Not only the accuracy of the position, but also that of the velocities in x-, y- and z-direction will determine the range, where relative navigation needs to start in order to ensure approach safety. From this range onwards the chaser must approach the target body by its own relative navigation without any cooperation by the target.

- Using onboard relative navigation means, the chaser must be transferred to close vicinity of the target body, where it must assume position-, attitude- and rate conditions, which allow capture by a mechanical capture device. This may have to include fly-around manoeuvres to reach particular features of the target surface, and possibly the motion of the capture tool needs to be synchronised with that of the tumbling target body.

- After capture, a connection between chaser and target body must be achieved, which is stiff enough to allow for controlled deorbitation, i.e. allows for attitude- and trajectory control of the compound.

- De-orbitation in LEO will eventually end by burn-up in the atmosphere or, depending on the risk of ground damage, in a controlled re-entry, where any residuals will hit the ground surface at safe areas. In GEO and MEO, the target body will have to be de-orbited into a higher ‘graveyard orbit’.

3 CHALLENGES TO BE MASTERED

According to the tasks listed above, the most important questions to be answered, before a mission to retrieve a debris object in LEO or GEO can be conceived, are:

- How close do we get to the target with absolute measurements from ground for position and velocities, before relative navigation by sensors on the chaser needs to be started?

- What types of sensors can we use for relative navigation measurements between the chaser vehicle and the target, from far range down to a range where it can be captured, with a target which does not provide any sensor interfaces?

- How can we control the position of the chaser at very short range, when the attitude of the debris object is not known and when this object is rotating (tumbling) with unknown rates about unknown axes?

- How can we capture an incapacitated spacecraft or other debris object, which was not designed for this purpose and which has very fragile structures such as solar panels and antennas on its surface?

- How can we establish after capture a stiff enough structural connection between chaser and target that allows for a controlled deorbitation (orbit- and attitude control)?

If all these issues can be solved, the final step, de-orbiting by a set of dedicated boosts, is a standard operation, which requires the availability of sufficient propellant on the chaser vehicle, but does not pose any additional technical challenge. Proposals have been made to attach large sails, inflatable balloons or expanding foam to debris objects after capture, which would accelerate their decay (see section 8.3). This makes sense, however, only for objects which will fully burn up during reentry. Where the risk exist that residuals fall back to ground, it must have an acceptable value, or the de-orbiting and reentry must be controlled by using a servicing vehicle.

4 FAR RANGE PROBLEMS

4.1 General navigation problems

Starting the approach, guided by ground measurements of the target’s absolute values of position and velocity, the range where relative navigation needs to start, is dictated by the accuracy of such measurements and by safety considerations. It can be e.g. argued that if the next measurement by ground can be performed only after ‘n’ orbits, the range, down to which ground measurements are sufficient must be not shorter than the progress due to drift caused by the possible position- and velocity errors within ‘n+1’ orbits.

With absolute measurements, the relative navigation error is the sum of the absolute errors. So, even if the chaser has its own navigation means on board, the uncertainty of position and velocities of the target governs the relative errors (Fig. 4.1). E.g. in LEO, the chaser may have satellite navigation on board, which may provide an absolute position accuracy of 15 - 30 m, and an absolute velocity accuracy of < 0.1 m/s. However, if e.g. the target position in all directions is not known better than a few 100 m and its velocities not better than 0.5 m/s, the unobserved relative progress between the two bodies may be as much as 8 km per orbital revolution. For the minimum range, where relative navigation needs to start, 20 - 50 km are generally assumed.

![Figure 5: Navigation errors of chaser and target [2]](image-url)
Since the target will not provide any aids for rendezvous-sensors, such as transponders or reflectors, only sensors are suitable, which can detect the reflections of the surface of the target object or the radiation of the body due to its temperature. These can be RF-sensors, such as radar, or optical sensors, such as laser range finder and camera type of sensors. Power requirements for sensors without dedicated interfaces will be, however, high at far range, if no external illumination can be used.

Rendezvous and capture operations with incapacitated spacecraft are feasible, e.g. if the chaser vehicle can provide sufficient resources to operate a skin-tracking radar with a range of more than 20 km and an accuracy of at least 1 % of range. This was first demonstrated by the Space Shuttle on flight STS-51-A in November 1984, when the Orbiter retrieved two communication satellites, PALAPA B-2 and WESTAR VI, which were stuck in LEO after the transfer stage PAM-D had in an earlier STS-mission failed to ignite after deployment. The Ku-band radar of the Shuttle had a mass of more than 130 kg and a power consumption of more than 400 W in the skin tracking mode, providing a max. range of about 22 km. It has to be pointed out that the power requirements for such sensors increase with the 4th power of the range.

In contrast to the US Space Shuttle, any spacecraft, that cannot return to ground, can operate after launch only in one particular orbital plane, with very limited possibilities for plane change. As a result, if for each removal a new servicing spacecraft will be required, it is questionable whether it can be afforded to make such dedicated spacecraft large enough and provide it with sufficient resources to support a heavy, bulky and power demanding radar installation for such a range. Also laser range finder/LIDAR type of sensors for ranges of more than a few kilometres would cause too heavy problems concerning power consumption and additionally would cause problems concerning safety.

This leaves a gap between the range, down to which absolute navigation measurements by ground can be used and the range, from where on navigation by laser range finder /LIDAR type of instruments can commence.

### 4.2 Range sensing by angle measurements

If power-, mass- and volume requirements for skin-tracking radars with an operational range of a few tens of kilometres cannot be afforded for a chaser vehicle of reasonable size, the sole possibility is, to use external illumination for the sensors, i.e. illumination by the Sun. This immediately leads to cameras, which are small, lightweight and do not need much power. Cameras at far range can, a priori, only measure angles to the target and can not directly obtain range information. This can be obtained by triangulation. However, the lateral extensions of a satellite, seen at distances of a few tens of kilometres, are too small. The navigation problem in the far- and medium range rendezvous phases needs thus to be solved in a different way.

With a camera, at distances of a few tens of kilometres, suitable range information can possibly be obtained only by triangulation of the lateral extensions of the trajectory, as shown in Fig. 4.2. If the maximum lateral excursion is known, the range $R$ can unambiguously be determined by propagating the trajectory with the line of sight (LOS) angle $\theta$ and the time $t$.

However, for a general drift trajectory, e.g. at start of relative navigation, the lateral excursion will not be known, rendering the case unobservable. Generally, without a calibrated manoeuvre, measurements will be ambiguous, since two scaled trajectories may have at the same time the same measured angles, but at two different ranges. Once a manoeuvre is performed, which would yield a known maximum lateral excursion, the initial ambiguity of the range can be resolved [3]. The trajectory can be propagated in an onboard navigation filter, starting with the initial knowledge of the range by ground measurements and lateral manoeuvres, updated continuously with the measured LOS-angles, time and the applied forces.

![Figure 6: Range determination by angle-only measurements and orbit propagation [2]](image)

Range determination by angle-only measurements and orbit propagation can be performed only, as long as the target is visible. As discussed below in section 5, suitable illumination will be available in LEO only during a part of the orbit. Whenever measurements are not available, chaser control will have to continue without relative navigation information and without starting new manoeuvres.

Thus, with cameras only, it can be envisaged that the acquisition of relative navigation measurements in LEO will have to start at a larger range to allow for successive navigation improvement and trajectory corrections. Whereas in regular rendezvous strategies, such as for the ATV, relative navigation starts at about 30 km range, and for the space Shuttle, at 20 km, in rendezvous with non-cooperative targets with ‘camera only navigation’ a range of 50 km or more may be necessary.
5 ILLUMINATION PROBLEMS

Radial boost manoeuvres [4] create relative trajectories, which describe a full revolution per orbit (Fig. 5). In GEO, with an orbital period of 24 h, such trajectory is synchronised with the relative motion of the Sun. Communication windows are available (Fig. 5).

A solution to this problem could be the use of infrared sensitive cameras, which must be able to detect at long distance the infrared radiation of a body warmed up during the illuminated part of the orbit.

Figure 7: Radial boost trajectory

Figure 8: GEO, good illumination over entire orbit (courtesy SENER)

This allows to devise an approach trajectory sequence, with subsequent 1/2 orbit transfers on the target orbit and with fly-arounds at close range, for which the target at all times has favourable illumination conditions. Eclipses by the Earth shadow will be relatively short (max. 74 min) and will occur only at ± 23 days around the equinoxes. Under such conditions, angle only navigation with camera measurements will be possible practically all along the approach. An approach strategy with such features (Fig. 5) has been proposed by SENER for the Orbital Life Extension Vehicle (OLEV) project [6].

Unfortunately, illumination conditions in LEO are much worse. With an orbital period of the order of 90 - 100 min, the Sun direction changes relatively quickly and for a large part of the orbit the spacecraft are in the shadow of the Earth, making measurements by a camera impossible. To illuminate the target surface in front of the chaser, the Sun must be behind the chaser. As a result, practically only during about 1/4 orbit suitable illumination is available (Fig. 5).

6 COMMUNICATION ISSUES

During periods, where no measurements of the target by the camera are possible, the navigation filter of the chaser must propagate the trajectory, possibly augmented by absolute navigation measurements from its satellite navigation device (GPS, Galileo).

Figure 9: LEO illumination, principle

Also, during those periods without relative navigation, present trajectory elements may be ended by a stop boost, but a new trajectory cannot be started, because the navigation accuracy will be uncertain. Free drift or hold points controlled by absolute satellite navigation will have to follow, until relative navigation measurements are available again. This will increase the duration of the approach but also the range, where relative navigation must be started, as mentioned above.
altitude (similar to Envisat) with all ground stations of the ESA ESTRACK network. In Fig. 6, visibility periods for a satellite in a 400 km altitude orbit but the same other parameters are shown.

Use of relay satellites will render the service vehicle systems more complex (antennas, transmitters, receivers) and its operations more costly (rent of relay satellite services). However, it would ease rendezvous and capture operations significantly. A single relay satellite covers somewhat less than 50 % of the orbit. The NASA TDRSS fleet presently consists of 9 Relay satellites located at various locations on the geostationary rim, which provides for LEO spacecraft continuous communication capability around the orbit. ESA will start up the European Data Relay System (EDRS) by launching the first EDRS payload with an commercial Eutelsat communication satellite in 2014 and a second one in 2016.

7 SHORT RANGE APPROACH

The task of the short range rendezvous operations is to bring the chaser into close vicinity of the target and to align the capture tool either with the target as a whole, or with a particular feature on its surface, at which the capture tool can engage. The approach may include fly-arounds to inspect the target object, to identify suitable features for capture, to identify attitude and attitude rates etc. and to access the feature to be captured.

Approach safety requires that from ranges of the order of two or three kilometres downwards continuous measurement of relative position or of range and LOS angles is available with an accuracy of better than 1% of range [4]. Whereas in GEO, because of the favourable illumination conditions cameras can be used down to very close range or even to contact, in LEO, the sensors will have to provide their own illumination, so that they can provide measurements over the entire orbit. Since RF-type of sensors, such as Radar, would not provide sufficient accuracy in the very close range, and since for cameras the power requirements for illumination of the complete field of view (FOV) will become very high beyond a few hundred metres, the best choice for the short range approach appears to be scanning laser range finder or LIDAR type of sensors (Fig. 7). Such sensors can measure range and LOS angles for each point of their FOV, which can also be used to determine attitude and tumbling rates. The max. range of such instruments will be of the order of 1 - 2 km.

This does not take away of course that for the capture operations at very short range additionally cameras with artificial illumination may be needed.

In GEO, as the target satellite is known, a camera sensor could initially use the solar panels as the largest features of the target satellite to determine the range. At closer range, the extension of features of the satellite body on

In addition to the illumination problems in LEO, if no relay satellite can be used, the lack of frequent and long enough communication windows would complicate the approach to a non-cooperative target and would require high onboard autonomy of the chaser vehicle. Also, the
The focal plane can be used to determine range, attitude and attitude rate (Fig. 7). During all the approach down to the close vicinity of the target, Sun illumination will be sufficient for the sensor measurements. However, since at very close range the body of the chaser vehicle may cast shadow on the target features to be evaluated, either artificial illumination for the camera or a LIDAR type of sensor may still be needed.

In the short range approach, disturbances play a larger role concerning the evolution of the trajectory. The most important disturbances are the drag of the residual atmosphere in LEO [4] and solar pressure in GEO [5]. The presence and strength of these disturbances require that short range trajectories must be controlled first by mid-course corrections and eventually, at close range, by closed loop control.

The last part of the approach will depend on the attitude, tumbling rates and features chosen for capture of the target object and on the method of capture selected for the case in question. The approach may include fly-arounds, final approaches at various angles and hold points out of the target orbit and out of the orbital plane.

8 CAPTURE AND ATTACHMENT

8.1 Capture tools

As incapacitated satellites and other debris bodies do not provide dedicated interfaces for capture, there are only two options, either to find a structural feature on the surface, which can serve as capture interface, or to embrace the complete body. If a structural feature suitable for capture can be found, the capture tool of the chaser must be brought into a position and attitude to be able to attach to that feature.

If the attitude of the target is stable, such operation can be performed by a manipulator arm on the chaser, as shown in the example of Fig. 8.1, or even by direct docking, if a suitable interface can be found. For communication satellites in GEO, the exhaust nozzle of the apogee boost motor (Fig. 8.1) has been identified as the most suitable interface [7]. For spinning satellites, it has been proposed to put the docking tool on a spun-up table mounted on the chaser and to spin down the compound after docking with help of the chaser thrusters.

If the target body rotates about more axes (tumbling), capture becomes more complex. A large number of different types of capture tools have been proposed, such as large arms and grippers (Fig. 8.1), flexible grippers [14], teth-
ers with grippers or large nets as front ends (Fig. 8.1), and even harpoons [15]. The figures shown, shall serve just as examples to illustrate the principle. Some of these concepts may work with target objects, which have a stable attitude, but may have problems with tumbling bodies, others may face difficulties with targeting of their nets, grippers or harpoons, others with the de-tumbling of the target object after capture and eventually with the establishment of a structural connection with the chaser, which is stiff enough to allow for attitude and trajectory control during reentry. Some of the more important problems are discussed below.

![Figure 16: Example: Capture by large gripper [8]](image)

Targeting of tethers with nets, harpoons or a grippers will not be straight forward. Orbital dynamics will bend the trajectory of the front-end according to the ejection velocity applied. Figures 8.1 show the trajectory evolution for ejection velocities of 0.5 m/s in x- (V-bar) and z- (R-bar) direction in a 400 km orbit, calculated from the tangential and radial thrust equations [4]. It is assumed in these figures that the tether will not apply significant forces on the front-end during flight. Ejecting the tether tools in z-direction requires that the chaser flies on a different orbital altitude than the target. This will add an additional complexity to the targeting, as the chaser will move with a velocity in ± orbit direction of \( \dot{x} = 3/2\omega \Delta z \) relative to the target [4]. An interesting method of controlling the trajectory based on tether tension is described in [10].

![Figure 18: Trajectory evolution for ejection of capture tools in x- and z-direction](image)

In a similar way as for targeting with nets, harpoons, grippers and other tether front-ends ejected by the chaser, the haul-back of the tether with the captured object will be affected by the orbital dynamics. Whereas on ground, in water and air, drag provides a counterforce opposite to the pull-direction, such braking force is not available in orbit. However, orbit dynamics will produce a lateral (in-plane) motion component. Also, if the pull-force does not go through the centre of mass of the captured body, a torque is produced and a rotation result. As tether forces act on both bodies in opposite direction, all tether actions will have also repercussions on attitude and trajectory control of the chaser. Only little information is available on the haul-back tether dynamics between two bodies in orbit, and overall feasibility is not yet established.

The same issues apply to the idea of a ‘space tug’, where the captured body is attached during de-orbiting by a tether to the active vehicle. To avoid the tether becoming slack, either a constant thrust force needs to be applied by the servicer or the tether needs to be pulled inwards. The
tethered space debris will make more or less undamped oscillatory lateral motions, which will have repercussions on the attitude of the servicer. A lot of analysis and verification needs to be performed, before this could become a viable solution.

In contrast, with a manipulator arm a more stiff connection will be established already at capture. Interactions between manipulator and chaser attitude and position can be controlled more easily, as chaser and target are firmly connected. If necessary, attitude and position control can be switched off as long as the manipulator operations go on, and chaser attitude be reestablished thereafter [11].

8.2 Chaser control at capture

To establish a relative position of the chaser to the object to be captured, the chaser needs to measure the range to that object. If the attitude of the target orbit is stable, a measurement surface to surface will be sufficient. However, if the target is tumbling, control by a surface to surface measurement (distance “d” in Fig. 8.2) alone would result in a wobbling of the chaser position. To achieve a stable position, the distance “D” between the two centres of mass (CoM) must be used for position control. For calculating this from the measurement of the distance “d”, the shape of the target body, the location of its (CoM) and its 3-axis rotation rates must be known. The tumbling rates can be established (possibly evaluated by ground) by measurements with a camera or an imaging LIDAR from a safe point prior to the final approach. If the target is a satellite, the exact dimensions will be known and a precise modelling can be uploaded to the chaser. With such modelling and the measurements of “d”, the position of the chaser CoM with respect to that of the target can be controlled.

8.3 Attachment & control for de-orbiting

After capture, a connection between chaser and target must be established, which is stiff enough to transmit the control forces an torques acting for trajectory- and attitude control during deorbitation. The surface features of satellites are, however, very fragile and only few structural features can support any loads. Most parts of the surfaces are covered by solar arrays, antennas, scientific instruments etc., which are neither suitable for capture nor for attachment. The most suitable feature for attachment will be the interface ring, which attached the satellite to its launcher. Since capture- and attachment feature may not be on the same side, the captured object may have to be rotated and translated to fit the suitable attachment surfaces of chaser and target to each other.

Attachment of the two bodies to each other by force (preload) will be sufficient, as long as the control forces and torques do not become larger than the preload, and as long as low stiffness of the connection does not affect the control loop. The necessary preload can be applied by the manipulator, tether or other tool used. Fig. 8.3 shows the principle of such an attachment which has been proposed for the attachment of a servicer (OLEV) to communication satellites in GEO. The preload will here be applied by a capture tool for docking as indicated in Fig. 8.1.

The connection of chaser and target by a large gripper (Fig. 8.1) may be sufficient, provided the structural stiffness of the connection allows for attitude- and orbit control of the compound. For captures using tethers with nets, harpoons or grippers as front ends, it may become difficult to attach the most suitable feature of the target body to the attachment location on the chaser without the help of an additional manipulator.

Once attached, the joint CoM needs to be determined, to enable attitude and orbit control of the compound. The captured debris must then be deorbited, either to a graveyard orbit for GEO debris or for eventual burn up in the atmosphere in case of LEO debris. The latter will be done by a number of perigee lowering manoeuvres, as indicated above in Fig. 2.

To save propellant, the use of large sails, balloons or even expandable foam [17] augmenting deorbiting, has been proposed. The decay rate depends on the residual density at the orbital altitude and on the area to mass ratio of the decaying body. In Fig. 8.3, the relation between the area to mass ratio and the decay time is shown. Typical satellites have a ratio of area/mass > 0.01. A deployable
sail can easily increase this ratio by a factor of 2, which will decrease the decay time by a factor of >2. Obviously, such sails cannot replace perigee lowering manoeuvres, but it will accelerate the decay significantly, once the perigee is getting into the denser layers of the atmosphere.

9 CONCLUSIONS

Active deorbiting of space debris will become necessary to remove incapacitated spacecraft and other debris objects from orbits, where they form a hazard for collision or uncontrolled impact on ground, or cause a commercial loss (GEO). Except for the servicing of still active GEO satellites, removal of space debris will require a dedicated service vehicle and launch for each single item, because all these items move in different orbital planes, and any change of plane will require a large amount of energy.

Since a spacecraft and a launch for each capture will be required, active removal by a service vehicle will be costly. Thus, it will initially be economically interesting for the capture and de-orbiting of very large non-functioning satellites (e.g. ENVISAT, METOP-A), either to prevent collision with functioning satellites in key strategic orbits like the Sun-synchronous orbits (SSO), or to prevent hazards of uncontrolled impact on ground. In addition to the collision danger, there may be the above mentioned case of GEO satellites, where removal could economically be justified by the value of the location.

ESA and NASA have started programmes concerning the mitigation of space debris, and other agencies pursue related activities. Such activities include studies and research & technology programmes for debris object removal and even demonstration missions.

Active removal of space debris will be a very complex operation, including a number of technical challenges, which need to be mastered, if such mission shall be successful. In LEO, the operations will be complicated by the lack of continuous Sun-illumination and, if relay satellites cannot be used, of communication with ground. The technical challenges include:

- the relative navigation in the far rendezvous range, for which no suitable sensors and sensor interfaces on the target are available,
- the control of the chaser vehicle in terms of relative position and attitude, to enable capture,
- the physical capture of an object, which provides no dedicated interfaces,
- the establishment of a connection between chaser and target, which is stiff enough to allow for attitude and orbit control of the compound during deorbiting.

Many papers have been published on concepts, how to capture and remove from orbit incapacitated spacecraft and other large debris. Most of these publication deal with mechanical problem of capture of non-cooperative bodies, fewer publications deal with the problem of the interaction between control of the chaser spacecraft and the capture process by a manipulator, and very little has been published so far on the problem of navigation and guidance in the far range without direct range measurement.

The discussion shows that valid solutions for each of the challenges can be found only, when also the other technical problems are considered, i.e. when solutions are developed in the proper context of a complete mission design.

10 REFERENCES

1. On-Orbit Servicing
   (retrieved: 2. September 2013, 08:14 UTC)


11. P. Rank et al., *The DEOS Automation and Robotics Payload*, ASTRA 2011, 12-14 April 2011 ESA/ESTEC, Noordwijk, the Netherlands


13. D. Reintsema et al., *DEOS - The In-flight Technology Demonstration of Germany’s Robotics Approach to Dispose Malfunctioned Satellites*, ASTRA 2011, 12-14 April 2011 ESA/ESTEC, Noordwijk, the Netherlands


18. Guillermo Ortega Hernando et al., *Guidance, Navigation, and Control Techniques and Technologies for Active Satellite Removal*, 6th IAASS Conference Safety is Not an Option, 21 - 23 May 2013, Montreal, Canada
7th IAASS Conference
International Association for the Advancement of Space Safety

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