Proceedings of the EuroGNC 2013, 2nd CEAS Specialist Conference
on Guidance, Navigation & Control, Delft University of Technology,
Delft, The Netherlands, April 10-12, 2013

GNC challenges and navigation solutions for Active Debris Removal mission

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Abstract Active removal of large space debris has been identified as a key mission to limit growth of debris jeopardizing missions of active satellites. In particular, orbits of economic and strategic importance, Low Earth Orbits, are pervaded with objects such as upper stages of launchers or defunct satellites: collision between large debris has become a likely event in the next five years according to simulations done in Space Agencies. Willing to anticipate such event and limit collision risk, Agencies and industrials investigate feasibility of Active Debris Removal (ADR) mission. Many critical points have yet to be solved, such as legal aspects, cost, debris to be removed and technological challenges to successfully complete the mission. This paper will first initiate a discussion around challenges that has to face the Guidance, Navigation and Control (GNC) sub-system during the ADR mission. Then, two navigation solutions that meet most of navigation challenges for ADR mission will be introduced in this paper. The first solution relies on an active, 3D camera, fused with IMU data in a navigation filter. The second solution relies on a passive, 2D camera and a state-of-the-art Image Processing that provides pseudo-measurements, also fused with IMU data in the navigation filter.

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1 Active Debris Removal: main challenges

For the past forty years, space debris have been identified as a growing risk for present and future space missions, especially for Low Earth Orbits (LEO). As suggested by Kessler [1], there would even be a critical number of debris for which risk of cascading effect due to collisions in LEO would be inevitable. In 2009, two artificial satellites – Iridium 33 and defunct Kosmos-2251- actually collided at 789 kilometres above Siberia [2] and therefore created clouds of debris on LEO, illustrating not only the risk generated by defunct satellites on orbits but also the detrimental, cascading effect of debris clouds. Recent studies of Space Agencies such as European Space Agency (ESA) [3], Centre national d'Etudes Spatiales (CNES for French Space Agency) [4], Deutsches Zentrum für Luft und Raumfahrt (DLR for German Space Agency) [5], National Aeronautics and Space Administration (NASA) [6] or Japan Aerospace Exploration Agency (JAXA) [7] identified removal of large debris as one of the solutions to limit growing numbers of hazardous objects in LEO, orbits of economic and strategic importance. Interest of Space agencies and consequently space industries has been significantly growing in Europe for the last years, and several feasibility studies of Active Debris Removal (ARD) mission have been investigated.

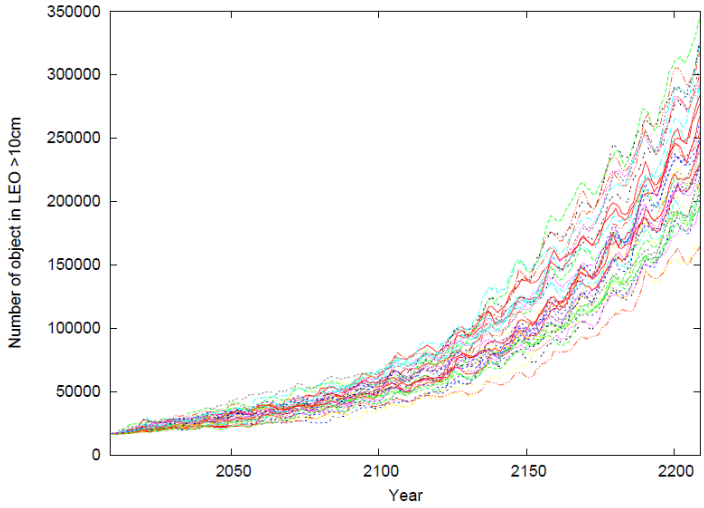

Fig. 1 Projections of debris environment in Low Earth Orbits, considering objects larger than 10 cm, from 2009 to 2209, [3]

In light of numerous papers throughout the world, there are yet many challenges to be overcome from a technological perspective (e.g. ways to approach debris and capture them, mission design to capture one or several targets, selection of targets), from a legal perspective (e.g. property transfer of debris owner to debris remover, insurance, risk transfer), and financial perspective (e.g. business case, cost of mission). For the sake of completeness, a short list of technological issues to be solved is populated below:

- Mission design: numbers of debris, populations of debris to be removed, initial orbit of chaser/launcher, duration of mission, support from ground, level of autonomy, strategy for relative navigation and approach, target identification, capture and de-orbit phases
- Propulsion: required ΔV and thrust level as function of mission design, compatibility with available launchers and targeted set of orbits, available propulsion (electrical vs. chemical)
- Navigation sensors: sensors to be used for relative navigation w.r.t. target during different phases of the mission, able to provide measurements for target identification, estimation of rotating rates and estimation of relative position and velocity, within required accuracy, prior to capture.
- Fault Detection, Isolation and Recovery strategies and safe mode: The global FDIR of an ADR mission with one or several un-cooperative targets has never been investigated yet while close navigation, capture or docking inherently imply risk of collision with or without failure of onboard sensors or actuators. De-orbiting strategies consisting in bringing the debris in low altitude or graveyard orbit also bring up issue on FDIR. Safe mode has to be deeply investigated, in particular during terminal rendezvous (just prior to capture) or de-orbiting phase. Indeed, a typical safe mode relies on Sun –pointing strategy which could be not compatible with capture requirements or de-orbiting guidance.
- Capture devices: harpoon, net, claws, arm have been discussed in many papers and demonstrated on ground or in space. However, no firm baseline has yet been selected and demonstrated on actual debris removal mission.
- De-orbiting strategies and devices: drag sail, de-orbit sail, propulsive packs and active de-orbitation by the chaser are considered.

Many technological issues are indeed related to the Guidance, Navigation and Control (GNC) sub-system as it lies in the heart of the critical phases of the ADR mission. This paper will henceforth focus on the GNC challenges to be faced during the different phases.

2 Challenges of GNC for ADR mission

The design of the GNC sub-system for an ADR mission is a complicated and challenging task as the GNC system shall be adaptable to many environmental conditions (Sun elevation, eclipse, Earth, Moon in background), many targets, and a large span of relative distances between chaser and target while being reliable, autonomous to some extent and CPU efficient. The following discussion will be articulated around the different phases of the ADR mission, presented in the following paragraphs.

2.1 Typical phases of an ADR mission

By analogy with rendezvous mission, ADR mission can be divided into five distinct phases for each target: phasing, approach, fly around/inspection, capture and de-orbitation phase.

Phasing

The phasing phase typically consists of estimating orbital parameters of the target's orbit and then "aligning" plane of chaser orbit w.r.t. that of target. Inclination, Right Ascension of Ascending Node (RAAN) and argument of periapsis are main parameters to be corrected in this sequence. Unlike typical rendezvous in LEO, phasing and subsequent phases can be rather challenging as target's orbit can have significant eccentricity.

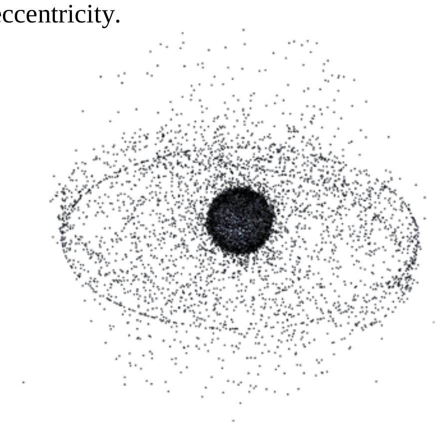

Fig. 2 . Approximately 19,000 manmade objects are larger than 10 centimetres in Earth orbit as of July 2009, most orbit close to the Earth, credit NASA Earth Observatory

As far as removal of debris on Earth orbits is concerned, there are no specific needs in autonomy from the chaser during the phasing sequence. Navigation can easily be done with ground in the loop. For instance, the chaser orbit can be estimated through GPS data while the debris orbit can be estimated from ground observations. Several networks are capable of detecting debris as small as 10 cm on LEO [8] implying radar or optical observations. Several studies and projects for improving performances of radar system dedicated to debris removal missions are being conducted [9], [10]. In such configuration, a conservative figure for the accuracy of estimation of relative position between the chaser and the debris is around 400 m (3σ), based on the 300 m (3σ) accuracy of US Air Force published performances [11] and a typical 10 m (3σ) accuracy for chaser position estimation with GPS on LEO, along with conservative margin. The phasing phase, with ground in the loop, should end at about 1 to 2 km from target.

Approach

The approach sequence is initiated at about 2 km from target. Relative navigation takes over ground-based navigation as the chaser needs to get closer and closer to the target (up to 10 meters) through dedicated manoeuvres. Owing to smaller and smaller distance between the chaser and the target, collision risks are growing and some autonomy is required, in particular to trigger anti-collision manoeuvres if needed. By analogy with typical rendezvous manoeuvres, V-bar and R-bar "hops" can be performed and perturbations due to atmospheric drag (for LEO), gravity gradient, magnetic torque or solar pressure (for higher orbit) acting on both chaser and target are corrected along manoeuvres.

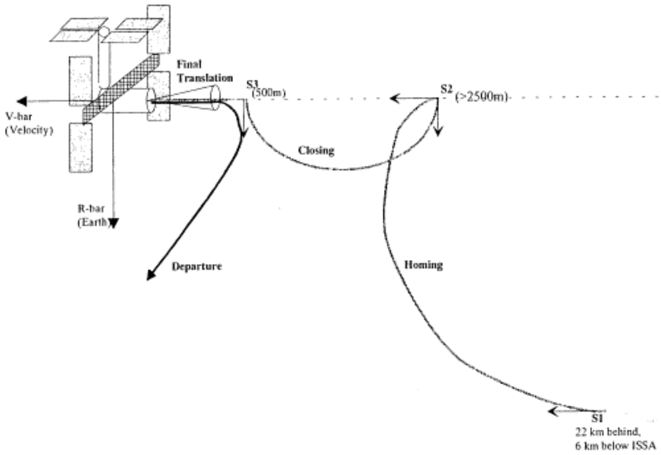

Fig. 3 Example of Rendezvous manoeuvres with objects in LEO: ATV trajectory from phasing to docking with the International Space Station

Fly around/inspection

Unlike typical rendezvous on LEO, missions for debris removal inherently imply un-cooperative targets. Besides, typical debris on LEO would be flying for several years; they should hence be poorly known (uncertainties on dimensions, mass, inertia…) because of aging effect, collisions with smaller debris, etc. A better "understanding" of the debris is needed. Depending on capture devices, rotation rates, rotation axes, possibly mass and inertia should be estimated. A spot to "grasp" the debris might be designated which inherently implies a mapping of the debris as well. To that end, inspection sequence would consist in stable orbit around the target (e.g. football orbit) or a station keeping at safe distance from target if the target is tumbling enough to allow for complete observations. On the inspection orbit, onboard sensors of chaser can take as many 2D or 3D pictures as needed to estimate necessary parameters. Attitude of the chaser is controlled for optimal inspection operations. Acquired data can either be processed onboard the spacecraft for debris estimation or sent to ground, provided the relative orbit is stable enough during the inspection sequence.

After completion of debris estimation, the capture can be triggered.

Capture

The capture is triggered as soon as necessary data have been estimated by the chaser. Operations and manoeuvres to be performed during the capture highly depend on the selected capture devices. Many capture technologies are being investigated, some have been demonstrated on ground mostly.

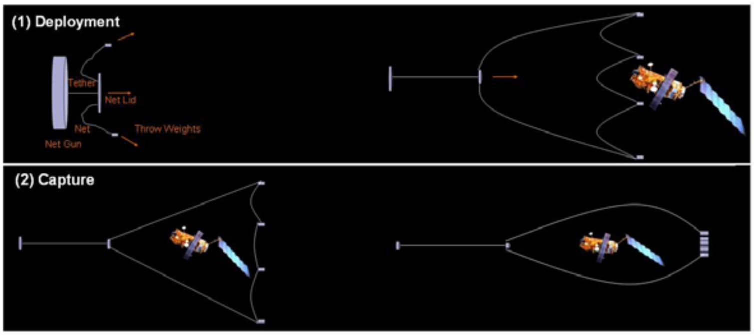

Fig. 4 . Deployment and capture sequence using a net

Net has for instance been developed and demonstrated in 0-g flight [12] and can be launched from about 5 meters from target. Provided net diameter is much larger than debris, such a solution should be impacted by performances of attitude control.

Harpoon was also demonstrated in laboratory [13]. It needs to be fired on a specific location of the debris, several meters away from debris.

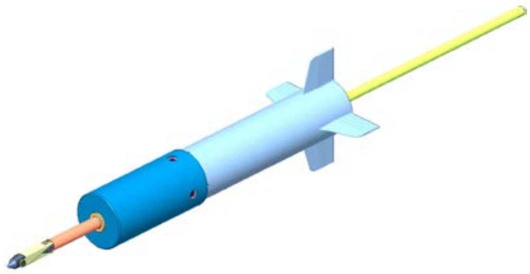

Fig. 5 sketch of harpoon for terrestrial demonstration, made up of conical tip to avoid debris generation and crushable cartridge to limit depth of penetration within debris.

Many other devices such as articulated arm [14] need the chaser to get close to the target (a couple of meters) and grasp the debris on a specific location. If the debris rotation rate is too high (above 1 deg/s), the chaser might need to align with the target's main rotation axis and eventually spin with the same rotation rate. Such strategy would eventually allow to lower the braking torque in the arm at capture. The concept of arm as capture device was demonstrated on Orbital Express. Claws can also be used as capturing device. Other solutions such as Ion Beam [15] [16] or electrostatic tractor force [17] are approaches that do not need to grasp the debris, only forcing the debris at lower altitude for de-orbitation.

Once the debris is captured, the de-orbit operations can be initiated.

De-orbitation

Once the captured is confirmed, the very first step is to stabilize the captured debris, through control of the chaser-debris system by the chaser's Attitude and Orbit Control System (AOCS). Then, the debris is towed by the chaser either on graveyard orbit or to a lower orbit for atmospheric re-entry and destruction. This can be also done via dedicated "de-orbiting" packs that are separated from the chaser once the debris is captured [18]. The de-orbiting pack, linked to the debris and able to thrust, will then tow the debris while the chaser will continue its journey toward another target. Other device such as electrostatic tether [19] or drag augmenting device [20] can be fixed to the debris and will lower the debris orbit till re-entry.

2.2 GNC challenges and possible solutions

As depicted above, an ADR mission is divided into several phases. From a GNC perspective, there are stringent requirements to be met in order to allow for successful completion of mission as detailed above. Since a definitive concept is not known yet, there are no specific figures for requirements. Several GNC technologies still need to be developed, demonstrated and validated for ADR mission in order to face the following challenges:

- Robust guidance during approach and then de-orbiting phase, with uncooperative target
- Robust control during approach, capture (stabilization of composite chaser-debris) and de-orbiting
- Identification of critical parameters of the un-cooperative and poorly known target
- Online estimation of relative position, velocity and attitude prior to capture

Robust and autonomous guidance

As previously stated, phasing sequence should mainly rely on ground for the navigation and trajectory computation: distance to target and duration of operations are large enough w.r.t. relative dynamics of chaser and debris. Then, as the chaser is getting very close to the target, some autonomy could be needed. Relative distance and implied dynamics might be such that time needed to get a command forth and back from ground would be too large, the chaser should hence be able to autonomously elaborate withdrawal strategies if needed. Careful design of capture sequence and trajectory along with dedicated monitoring system (based on GEO satellite relay for instance) may alleviate need in autonomy. In any case, guidance and control should be able to meet safety requirements which, to some extent, call for robustness to environment uncertainties, robustness to system and sub-system uncertainties and most critically, robustness to debris uncertainty.

During the approach and inspection phases, ground should monitor operations, relative trajectory and possibly correct manoeuvres if needed. Guidance of the chaser should compute in line the best trajectory to reach close vicinity of debris under minimal ΔV budget (especially if several debris removals are considered) and with maximal safety. Typical V-bar and R-bar hops, along with Station Keeping points - allowing ground to monitor and correct operations -, should be the main features of approach's trajectory. V-bar manoeuvres are known to be more ΔV efficient but can lead to collision with debris if there is some thrusters' failure for instance as the manoeuvres consists in a drift in the direction of V-bar axis. R-bar manoeuvres are more ΔV demanding but less safety critical as the motion along V-bar is bounded. In particular, if no ΔV correction is done after a R-bar hop, the chaser will stay on a football orbit (neglecting perturbations), at a relatively stable distance from the debris which is not only safe but also favourable to debris observation if needed. As a consequence, typical manoeuvres plan of such mission should result from a combination of both manoeuvres. Recent advances in domain of guidance for space rendezvous should also benefit to ADR mission for optimal manoeuvre plan computation and correction under uncertainties. For instance, guidance algorithms relying on direct, indirect or analytical methods have shown high performances for typical rendezvous and formation-flying missions (prisma, Simbol-X, ATV) [21]. In particular, such methods can allow to optimize manoeuvres as function of uncertainties on relative navigation, thrust realizations and environment perturbations. They should also compute optimal trajectories to reach target on an eccentric orbit. The next step should therefore to validate CPU efficiency of such algorithms.

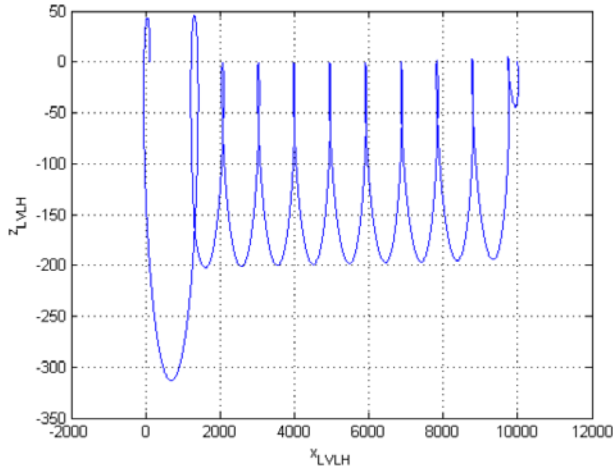

Fig. 6 . Rendezvous performed using analytical guidance algorithm on quasi circular orbit (Prisma). The rendezvous duration is 64620 s (10 orbits) The error on the final state for this rendezvous is less than 1 cm in position, and around 1 mm/s in velocity.

After successful capture and tranquilization of the new composite (discussed in paragraph dedicated to control), a major challenge for the autonomous guidance is to compute manoeuvre plan in order to “tow” the debris from initial orbit to de-orbitation state. This task is all the more challenging since debris could be initially poorly known. As a consequence, significant uncertainty on debris mass, inertia, drag coefficient or impact on thrust realization, is to be considered in autonomously computed trajectory while ensuring no collision. Composite behaviour is currently the most critical tasks as no mathematical model is widely accepted by space industries, nor representative demonstration was yet flown. In particular, the composite behaviour with non rigid link (a cable is used to track the debris if capture by a net, a harpoon or claws) is of most importance. Guidance should therefore take into account perturbations due to towed debris and avoid collision. Sensitivity of guidance algorithms to debris uncertainty and guidance strategies taking into account composite behaviour should be investigated in order to ensure efficient and safe de-orbitation.

Should the de-orbit strategy rely on ion beam or electrostatic tractor force, optimal conditions to “push” or “tract” the debris should also be considered in guidance. Behaviour of such composite (under electrostatic force for instance) should therefore be widely investigated and understood to compute efficient, robust and autonomous guidance.

Robust and adaptive control

Alike the guidance, ADR mission will significantly challenge design of control function. Although there is large, world-wide skills to design efficient control loop with high performances for satellites in LEO or GEO, control for tranquilization of debris at capture and efficient towing (depending on capture solution) is still to be investigated.

During phasing and approach, AOCS should be very similar to that of a typical, large satellite. Such designs have been well validated for many years. Attitude control may be wheel-based or thruster-based. Control of relative position and velocity could be done with main engines oriented or not by attitude control. However, capture and towing sequences bring up unusual issues, depending on selected capture devices and de-orbiting strategies.

During the capture, the capture device could be ejected from chaser. Depending on the location of the capture device, it will inevitably create a disturbance torque to be damped by control function as soon as possible in order to resume operations. Right after ejection, the chaser control might have to “tranquilize” the new composite (debris linked to the chaser).

If the link is rigid (e.g. arm) part of the structure might be designed to damp part of the disturbance torque. The remaining of parasite torque should then be controlled and damped by the chaser.

Provided the link is indeed not rigid (a cable for instance); specific strategies to tranquilize the debris have to be investigated and control is to be designed accordingly. Indeed, de-orbit ΔV can be transferred to motion of the debris if not “tranquilized”. It could yield to a change in ΔV direction of the whole composite because of debris “free” motion. To tranquilize the composite, the cable should first not be wrapped around the debris as it rotates: a constant force should be applied on the cable. De-spinning force could then be transferred from chaser to debris until tranquilisation is reached, i.e. when parasite torques and forces are within requirements.

However, the tranquilisation sequence might imply the control to be robust enough to large change in mass and inertia between chaser and composite (before and after the capture) as well as flexibility. As a matter of fact, the control function is initially designed to cope up with requirements of phasing, approach, inspection phases and stabilization for capture. Similarly to typical controller tuning for satellites, tuning of control is partly function of accuracy requirements and expected margin for a given set of mass and inertia. With the coupling to the debris, change in mass and inertia is probably much larger than considered uncertainty and the controller might have very degraded performances or even be unstable. A scenario could be considered to face such a challenge.

First, the initial controller is switched to another controller right after the capture. It could yield to a quite unstable situation due to controller transient created by the switch in controller, worsen by torque inherited from debris rotation rates. Then, the new controller – designed to be much more robust to mass and inertia uncertainty - could eventually tranquilize the composite. Nonetheless, due to the large margins to be considered, expected performances should be degraded. As a consequence, right after the tranquilisation is completed, another switch to higher performance controller should be done as de-orbit manoeuvres might need fine pointing accuracy. However, the third controller should consider mass and inertia of the composite in order to meet mission requirements. By definition, the debris is unknown and there are therefore two possibilities to compute the control of such new composite. The first possibility is to consider that the debris is roughly known and that mass and inertia can be estimated a priori. Uncertainty on mass and inertia to be considered for control design should however be large enough to be robust to actual mass and inertia of debris. In all likelihood, performances would not be optimal. The second possibility is to estimate in line mass and inertia of composite through dedicated manoeuvres. Such operations should be complex as it should involve dedicated manoeuvres and ground operations.

To conclude, there are possibly several approaches to meet ADR mission requirements and it seems the control should be as robust as possible to prompt change in mass and inertia, capable of damping sporadic high torques due to capture firing and tranquilisation of debris and capable of fine pointing performances. A possible solution should be to rely on different set of controllers with hard switch. Recently, recent breakthroughs on Linear Parameter Varying design have increased possibility to used adaptive and modern control within space industry [22]. Such solutions would allow to design an unique controller, capable to adapt to different AOCS mode and inherent requirements. Such solutions would be worth investigating further in the frame of the control design of ADR mission.

Identification of critical parameters of debris

By definition, debris are poorly known. Their mass, inertia, dimensions, center of gravity, rotations axes and rotation rates are needed for guidance, control and proper capture as discussed previously.
Some debris such as defunct satellites should be roughly known by the owner and to some extent, a fair initial guess should be available to the chaser. Some other debris such as collided satellite for instance might be rather un-known by the chaser. In both cases however, an in-line identification of parameters should be needed.

Identification of shape, rotation axes and rotation rates are the first needed parameters as they are critical for relative navigation. This estimation should be run during identification phase, a few meters away from the target after approach is completed. As discussed in previous chapter, two different strategies could be considered: either the chaser stays on a station Keeping point while the debris is tumbling – which should provide enough information for complete shape and rotation estimation - , or the chaser is set on a football orbit (radial ΔV) to “orbit” around the debris and observe it for reconstruction. From an identification perspective, the two different strategies should be equivalent.

Reconstruction is a very challenging step that could be critical depending on captures devices (e.g. arm because it might be needed to align the chaser with main rotation axis, or harpoon because it might be needed to precisely hit the debris). However, although there are several papers describing different algorithms or strategies, the reconstruction chain, which includes sensor and image processing algorithms, has to be consolidated. Effort on design, validation and verification is yet to be provided.

Based on existing technologies throughout Europe, there are two main families of sensors: active and passive sensors. Passive sensors such as visible camera like NPAL-based solution (monocular, passive camera) have already been investigated in frame of rendezvous phase [23]. Infrared sensors are also sensors of high interest; it has been off line demonstrated in the frame of Orbital Express rendezvous for instance [24]. Such sensors are known to be power efficient, light weighted, but sensitive to environmental conditions or reflectance of debris. Active sensors have been more recently considered as space rendezvous sensor thanks to recent improvements in active technology. Scanning lidar has been considered by several space agencies [25] [26]. More recently, flash lidar also called 3D camera [27], have been investigated and demonstrated as they do not feature mechanical devices (as opposed to scanning lidar) and can provide an instantaneous 3D picture of the target. A flash lidar, the STORRM mission, was demonstrated by Ball Aerospace on STS-134 in May 2011, in rendezvous and docking with ISS [28]. Nonetheless, such flashing sensors require higher power as the laser energy is to be spread over the Field Of View (as opposed to scanning lidar that focuses laser energy on a single spot, mechanically spread over the FOV).

For the past decade, image processing domain has made significant improvements for reconstruction, based on 2D or 3D data. Several techniques are currently being investigated to reconstruct an unknown target. A recent Innovative Triangle Initiative with ESA, Astrium and INRIA has demonstrated the capability of 3D reconstruction from 2D pictures, based on Structure From Motion (SFM) and Shape From Shading (SFS) methods.

However, techniques based on SFS might suffer from an apriori knowledge of materials reflectance which might not be compatible with MLI of defunct satellites for instance. Illumination conditions are also to be considered. Other technique such as Shape From Silhouette (SFSi) [29] could be a valid algorithm for reconstruction of unknown objects as it relies on building a 3D model from 2D silhouette.

Reconstruction performances of such algorithm have still to be demonstrated on typical debris. Besides, another major step to be overcome is the computer efficiency of such algorithms on space processors.

After reconstruction of the 3D model of the target, the identification phase is completed. Ground can decide the best way to capture the debris.

Online estimation of relative state

As discussed previously, the relative navigation should start during approach phase, i.e. at about 2 km from target and should provide necessary outputs for optimal manoeuvres toward target and anti-collision avoidance. The main challenge of the relative navigation function is to work under many environmental conditions, (Sun elevation, eclipse, Earth, Moon in background), for many different targets, and within a large span of relative distances between chaser and target while being reliable, autonomous and CPU efficient. A few solutions, coupling sensors and innovative algorithms, could meet such stringent requirements. For instance, simple and CPU efficient solution can be considered as long as relative position and velocity are only needed (typically during approach phase). Then, more complex algorithms should be considered for estimation of relative attitude once the target has been reconstructed.

Relative position and velocity

Relative position and velocity can be easily computed with simple image processing algorithms, relying on passive or active sensors, as discussed for identification phase. It could be computed from 3D data or 2D data.

Regarding 3D data, several solutions can be considered. For instance, relative position and velocity can be estimated from a mean estimation of 3D points, provided by active sensor (flash lidar, scanning lidar). Fused with data from Inertial Measurement Unit (IMU) within navigation filter, this would easily provide mean distance and velocity to target. Indeed, measurements of rotation rate (provided by gyroscope) are needed by the filter to tell rotation from translation of debris in the sensor FOV. Typical accuracy of active sensors is about a few centimetres at beginning of identification phase. The mean distance should therefore be accurate enough for safe operations, at low CPU cost. Another approach could also consist in considering the closest point of the cloud of 3D points provided by the sensor. The distance would then be used as measurement of distance and be provided to the navigation filter along with IMU data. This solution however will not be robust to outlier. However, as direct 3D measurements are provided by active sensor, such solution should be more power demanding than passive sensor-based solution.

Regarding relative navigation based on 2D data, infrared or visible images could be used and should be able to provide enough information to compute relative distance, provided state of the art image processing. One solution is discussed further in coming paragraph, for which an a-priori model (a priori 3D model or reconstructed model) of the target should be needed to compute relative position and velocity. As 2D data can be provided by passive sensors, such solution should be less power demanding and however highly CPU demanding.

Relative attitude

Prior to capture, i.e. right after identification phase, the relative navigation should also provide estimation of relative attitude. This estimation can be done as soon as a target's model is available. Onboard image processing could hence rely on 3D model of target and match measurements (2D or 3D) with model to estimate the relative attitude, along with position and velocity. Once the relative attitude is estimated, capture operations can be planned. Solution for comprehensive relative navigation is discussed in the following paragraph as well.

Alike image processing for identification, image processing for relative navigation (in particular for estimation of relative attitude) have yet to be investigated further.

3 Solutions for relative navigation with debris

As discussed previously, relative navigation with debris is a critical issue for ADR mission. Two solutions for relative navigation have been investigated by Astrium in collaboration with INRIA, with sensors investigated under ESA or European Commission (FP7) studies. The first solution relies on an active, 3D camera - currently developed by CSEM in frame of FP7 Fosternav study - fused with IMU data in a navigation filter. The second solution relies on a passive, 2D camera and a state-of-the-art Image Processing that provides pseudo-measurements, also fused with IMU data in the navigation filter.

3.1 3D/3D matching

The first relative navigation relies on 3D pictures, provided by active sensor, and 3D model of the debris, either a priori known or estimated during identification phase. 3D pictures are provided by state of the art 3D flash imaging lidar, currently developed in the frame of the FP7 project "Fosternav".

The key components of flash imaging lidar are the laser illuminating the target and the receiver detector array. These two elements are operated in full synchronisation to generate three dimensional images of the target. The device determines the time-of-flight (TOF) of photons by measuring the phase difference between the modulated illuminating laser beam and the incoming back-reflected light per pixel. One of the main challenges is the design of the laser head that should cover the range chaser-debris over which the relative navigation should be performed, under varying environmental conditions with, possibly, Earth as background and within power capabilities of spacecraft. The current solution considered in the frame of FP7 project should have a range measurement precision of 2-3 cm and a power consumption of 3W (laser illumination not included, no duty-cycle).

Direct 3D measurements should therefore be provided to the image processing algorithms that would filter measurements.

Regarding image processing, many publications on 3D cloud matching are available [31] [32]. Basically, it would be model-based, as it would aim to match the 3D model of the debris with the 3D point cloud provided by the camera. Many algorithms have been developed in the computer vision domain to solve this problem, but for different applications such as search in 3D database or object recognition.

The relative navigation solution therefore consists in a 3D camera that provides 3D pictures to image processing for matching with a known model. As there is always an ambiguity between pure rotation and translation of the target within FOV, fusion of IMU data within navigation filter is needed. As a result, reliable estimation of relative position, velocity and attitude are provided by the proposed navigation solution.

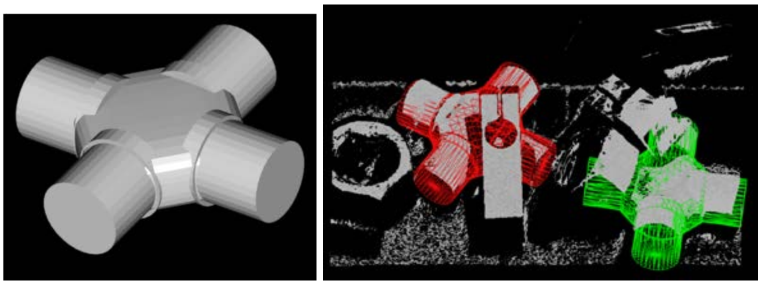

Fig. 7. - Example of 3D/3D matching algorithm. (left) a priori known 3D model of object. (right) matching of partial 3D point cloud (depth map) with 3D model [33].

3.2 2D/3D matching

One of the investigated solutions by Astrium in collaboration with INRIA relies on 2D pictures, post processed to match a 3D model of the target. It therefore can only be used when the 3D model of the debris is a priori known or estimated during identification. Alike the 3D/3D matching, it can provide estimation of relative position, velocity and attitude, necessary conditions for successful capture. Such approach is divided into two steps: initialization and tracking.

Initialization

Initialization aims at detecting the target in an image sequence and at providing the tracking with an initial guess of the target pose, without any prior information on the pose. It consists in matching (detection/matching stage) the image contours with a database of views built during the identification phase. This initialisation is done stepwise.

identification learning. A hierarchical model view graph leading to prototype views of the model is built. Each node of the view graph contains an image projection of the target contours at a particular point of view. The points of view are sampled on a sphere. The sampling of the views is optimized to limit the memory size of the database and to insure the whole coverage of the space of possible views.

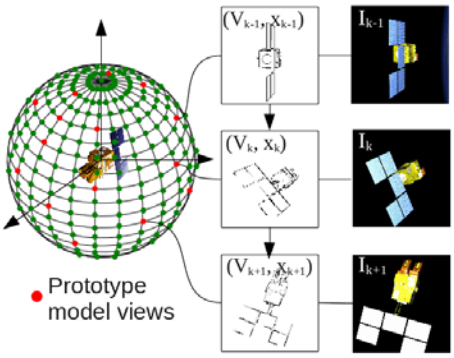

Fig. 8 Principle of initialization. Several views on a sphere are selected to produce prototype views stored in a hierarchical model view graph. Target is then extracted by segmentation and matched over successive frames with closest prototype.

Online target detection. Silhouette of the target is extracted in the image using bi-layer segmentation techniques. This method consists in minimizing an energy function combining motion and color, along with temporal and spatial priors. It allows distinguishing the foreground shape from the background and has the advantage to be real-time.

Online matching and pose initialization. The view graph is then explored to find the prototype view whose contours correspond the most to the extracted silhouette. The used similarity metric derives from [30]. It considers both the distance and the orientation of edges to match: Once the closest prototype view is found, its associated pose is considered as initialization of the target pose.

The matching stage can be rather time consuming. To cope with real time, a Bayesian framework is set to spread the initialization over several images (temporal initialization). It enables to provide an up to date pose initialization to the GNC system.

Tracking

Once the target has been detected in image, and its pose has been initialized, a frame to frame edge tracking is performed.
Like initialization, tracking is then 3D model based. It aims at finding the target pose which makes best match the projection of the 3D model with the image edges. Tracking and pose estimation are thus simultaneous. Unlike initialization, the edge matching is local. As a consequence, tracking runs in real time but is less robust to high differences between edges, meaning that predicted target pose shall be close enough (tens of pixels) to real one.

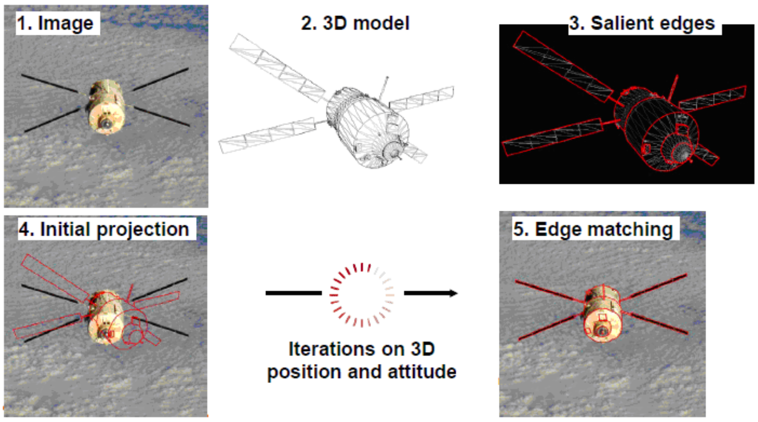

Fig. 9 . Principle of tracking. Tracking is performed using a frame (1) and the 3D model of the target (2). The salient edges of the target are extracted (3) and projected into image (4), given an initial pose. Pose is iteratively refined to make projection edges match with image edges (5).

4 Conclusion

Mission dedicated to Active Debris Removal will have many challenges to face. Aside financial and legal issues, several technological solutions have still to be designed, consolidated and validated. From a GNC perspective, there are still many issues to be solved. First, a comprehensive model of debris – chaser behaviour, when linked through a non rigid or rigid link, is to be derived and validated. Then, robust guidance to environmental uncertainties, navigation dispersion, realization errors and most importantly to uncertainties on debris should be consolidated and validated. Adaptive control to prompt change in mass and inertia or sporadic high torques due to capture is also to be investigated. G&C solution for the de-orbiting phase, with towed debris in particular is to be considered further. Lastly, solution of relative navigation capable of reconstructed any kind of debris under changing environmental conditions have to be consolidated and validated as well. The selected navigation solution shall also be capable of real time estimation of relative position, velocity and attitude. These blocks all together should finally be designed to ensure anti-collision, efficient FDIR and possibly safe mode during the very critical phases of approach, identification, capture and de-orbiting.

Many building blocks are already available for these different functions and current industrial studies or academic work in modern control, robust guidance, state of the art image processing or active sensors provide consolidated designs to build upon. In particular, two navigation solutions are being thoroughly investigated by Astrium, CSEM and INRIA. These solutions, either based on a 3D flash sensor or a 2D passive camera coupled with image processing, are capable of providing relative position, velocity and attitude of the chaser w.r.t. unknown debris.

References

1. D.J. Kessler, Collisional cascading: the limits of population growth in Low Earth Orbit – Advances in Space Research, 11 (12) 63-65, 1991
2. Orbital Debris Quarterly News, NASA, Vomue 13, issue 2, April 2009.
3. H. Krag, B.B. Virgili, Removal Target Selection and its environmental effet, Cleanspace Workshop on Active Space Debris Removal, 17th-18th September, 2012, ESOC facility, Darmstadt, Germany
4. C. Bonnal, F. Alby, Introduction to 2nd European workshop on Active Debris Removal, 18th – 19th June, 2012, CNES Headquarters, Paris, France.
5. M. Metz, DLR Perspective on Sustainable Use of Space, Cleanspace Workshop on Active Space Debris Removal, 17th-18th September, 2012, ESOC facility, Darmstadt, Germany
6. J.C. Liou, Challenges and Opportunities for Orbital Debris Environment Remediation, 2nd European workshop on Active Debris Removal, 18th – 19th June, 2012, CNES Headquarters, Paris, France

7. S. Kawamoto and al., Current Status of studies on Active Debris Removal at JAXA, 2nd European workshop on Active Debris Removal, 18th – 19th June, 2012, CNES Headquarters, Paris, France.
8. Technical Report on Space Debris, United nations Publication, Sales On. E.99.I.17, ISBN 92-1-100813-1.
9. M. Weigel, A. Patyuchenko, Orbit Determination error analysis for a future space debris tracking radar, European Space Surveillance Conference, INTA headquarters, Madrid, Spain, 7th_9th June 2011
10. Lockheed Martin Space Fence Radar Prototype Tracking Orbiting Objects, www.lockheedmartin.com
11. Report on Space surveillance, Asteroids and Comets, and Space Debris, Volume1, SAB-TR-96-04, US Air Force Scientific advisory Board, June 1997.
12. I. Retat, B. Bischof et al, Net Capture System : a potential orbital Space Debris Removal System, 2nd European workshop on Active Debris Removal, 18th – 19th June, 2012, CNES Headquarters, Paris, France.
13. J. Reed, Development of a Grappling System for Capturing Heavy Space Debris, 63rd International Astronautical Congress, October 2012, Naples, Italy
14. R. Rembala, A. Allen, F. Teti, Robotic Capture of Large Orbital Debris, Cleanspace Workshop on Active Space Debris Removal, 17th-18th September, 2012, ESOC facility, Darmstadt, Germany
15. S. Kitamura et al, A reorbiter for large GEO debris Objects using Ion Beam Irradiation, 2nd European workshop on Active Debris Removal, 18th – 19th June, 2012, CNES Headquarters, Paris, France.
16. C. Bombardelli, A plan to Deorbit Envisat, 2nd European workshop on Active Debris Removal, 18th – 19th June, 2012, CNES Headquarters, Paris, France.
17. H. Schaub, D.F. Moorer, Touchless reorbiting of large geosynchronous debris, 2nd European workshop on Active Debris Removal, 18th – 19th June, 2012, CNES Headquarters, Paris, France.
18. B. Gerber, C. Cougnet, D. Alary, J. Utzmann, A. Wagner, The debritor: an “off the shelf” based multimission vehicle for large space debris removal, 63rd International Astronautical Congress, October 2012, Naples, Italy
19. P. Janhunen, U. Kvell, H. Seppänen, Electrostatic plasma brake tether for deorbiting small satellites, 2nd European workshop on Active Debris Removal, 18th – 19th June, 2012, CNES Headquarters, Paris, France.
20. V. Lappas, Deorbiting an active debris removal using Gossamer systems and small satellite technology, 2nd European workshop on Active Debris Removal, 18th – 19th June, 2012, CNES Headquarters, Paris, France.
21. P. Blanc-paques, E. Gogibus, C. louembet, M. Kara-Zaitri, State of the art guidance techniques for rendezvous and withdrawal strategy, 4th International Conference on Astrodynamics Tools and Techniques, Madrid, Spain, 2010
22. Flandin, G., M. Dinh, G. Scorletti, V. Fromion, C. Beugnon, J. Lemaire, M. Ganet, C. Bérard-Chiappa et J-M. Biannic: “LPV techniques applied to industrial space applications”, 7th ESA GNC Conference, Tralee, Irlande, 1-5 juin 2008.
23. N. Despré, S. Kerambrun et al, HARVD, an autonomous visioni-based system for rendzvous and docking, 4th International Conference on Astrodynamics Tools and Techniques, Madrid, Spain, 2010
24. T. Weissmuller, M. Leinz, GNC technology demonstrated by the orbital express autonomous rendezvous and capture sensor system, 29th annual AAS guidance and control conference, Breckenridge, Colorado, 2006.
25. B. Moebius, M. Pfennigbauer, J. Pereira do Carmo, Imaging lidar technology - development of a 3D lidar elegant breadboard for rendezvous and cosking, test results, and prospect to future sensor applilcation, International conference on space optics, Rhodes, Greece, October 2010

26. A. C.M Allen, C. Langley, R. Mukherji, A.B. Taylor, M. Umasuthan, et al, rendezvous lidar sensor system for terminal rendezvous, capture and berthing to the international space station, Proc. SPIE 6958, Sensors and systems for space applications II, 69580S
27. A. Pollini, Flash optical sensors for Guidance, navigation and control systems, 35th annual AAS control and guidance conference, Breckenridge, Colorado, February 2012
28. I. J. Gravseth, R. Rohrschneider, J. Masciarelli, Vision Navigation Sensor (VNS) results from the STORRM mission, 35th annual AAS control and guidance conference, Breckenridge, Colorado, February 2012
29. K. Cheung, S. Baker, T. Kanade, Shape from silhouette across time part I: theory and algorithms, International Journal of Computer vision, Volume 62, Issue 3, pp 221-247, May 2005
30. C. Reinbacher, M. Ruether, and H. Bischof. Pose estimation of known objects by efficient silhouette matching. In 20th International Conference on Pattern Recognition (ICPR), 2010.
31. J.Huang, Point cloud matching based on 3D self-similarity, computer vision and pattern recognition workshop, IEEE computer society conference, 2012
32. T. Suzuki, M. Kitamura, Y. Amano, T. Hashizume, 6_DOF localization for a mobile robot using outdoor 3D voxel maps, IEEE/RSJ international conference on Intelligent robot and systems, Taipei, Taiwan, October , 2010
33. B. Drost, M. Ulrich, N. Navab, S. Ilic, “Model Globally, Match Locally: Efficient and Robust 3D Object Recognition”, IEEE Conference on Computer Vision and Pattern Recognition (CVPR) (2010)