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GNC Aspects for Active Debris Removal

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Abstract The access to space in the medium term future is being compromised by the exponentially growth of space debris, including launchers, stages, obsolete space objects and different objects that have resulted from break-ups in space. Orbits like LEO polar Sun-synchronous (very used for Earth Observation purposes) and GEO (very used for commercial telecommunication purposes) orbits are specially contested and the risk of a collision between a debris object and an operative mission is starting to be non-negligible.

Technologies for debris removal using active means are nowadays being seriously studied. Among the needed technologies, the Guidance, Navigation and Control (GNC) related technologies are especially critical because of the complexity in the operations to be performed and the possibility to collide with the debris and generate a much higher amount of debris objects than those that are intended to be removed. This paper includes a discussion about the main critical GNC related aspects that are involved in the Active Debris Removal (ADR) scenarios.

1 Active Debris Removal

Due to the intensive activities in the space during the last half century, the population of man-made space objects is playing an increasingly relevant role in the space environment. Today more than 6000 satellites are orbiting around the Earth but only 900 are operational and the problem is not going to an end: almost 1200 new satellites are expected to be launched in the next 8 years (Euroconsult forecast).

The remarkable risk of collision of space debris with operational satellites has been proven in early 2009 with the collision of the Iridium-33 satellite with the decommissioned Cosmos-2251 spacecraft. This catastrophic event has led not only to the loss of an operating mission but also, which is even worse, to the dra-

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matic increase of the number of uncontrolled objects in the neighborhood of many other objects. This has therefore led to the subsequent increase in the probability of collision with other (operational –and, therefore, avoidable- or not) objects which would lead to a spiral of collisions (Kessler syndrome).

Thus, in recent years, this constantly growing population of uncontrolled man-made objects orbiting the Earth has provoked the multiplication of operations leading to, among others, the proposition of several debris mitigation measures (graveyard orbits definition, de-orbiting techniques and space debris removal concepts).

Active Debris Removal (ADR) is therefore a necessary mitigation measure for the space debris problem. However, up to date many technologies have still to be developed and fully validated in order to successfully conduct ADR missions. This paper focus on the GNC aspects related to the ADR missions, by first introducing the most promising ADR candidate techniques, then defining a typical ADR Space Mission and then analyzing the most critical aspects of such missions related to GNC.

2 ADR Candidate Techniques

Before defining the ADR space scenario and the implications at GNC level, it is necessary to analyse the ADR candidate techniques that are being studied and developed nowadays.

The following table provides a summary of the most known and mentioned ADR candidate techniques.

Table 1 Active Debris Removal Techniques

N.	ADR Mechanism Principle/Type	Contact Needed?	Robotics Needed?
1	Conductive tethers (electrodynamics/Lorenz force)	YES Installation of tether	YES Installation of tether
2	Drag augmentation devices: balloons, sails, expandable foam …	YES Installation of device	YES Installation of device
3	Grappling	YES	YES
4	Momentum exchange tethers (non-conductive)	YES Installation of tether	YES Installation of tether
5	De-boost engine kit	YES	YES
6	Tentacle (bionics concepts)	YES	YES (Simple)
7	Harpoon	YES Rigid/Non-rigid	Boom/NO
8	Nets	YES	NO

N.	ADR Mechanism Principle/Type	Contact Needed?	Robotics Needed?
		Non-rigid	
9	Paunching/pushing airbag	YES (uncontrolled)	NO
10	Foam projection	NO, but high prox. ops need	YES (Arm/boom for foam projector)
11	Ion Beam shepherd	NO	NO
12	Chemical shepherd	NO	NO
13	Electrostatic tractor	NO	NO
14	Sweeping/retarding surfaces	NO	NO

The different ADR techniques can be categorized (from a GNC point of view) as follows:

- Contactless techniques (e.g. #10, 11, 12, 13, 14 in the table). They do not require novel GNC technologies, but a tailoring and extension of the already existing ones for typical rendez-vous and capture/docking especially to adapt them to target uncooperativeness.
- ADR techniques requiring rigid contact (e.g. #1, 2, 3, 4, 5, 6 in the table). They require a rigid capture (e.g. through a robotic arm). The de-orbiting can be done directly by transmitting a force/torque to the debris through the rigid capture device (e.g. #3 and 5 in the table) or by installing an ADR kit on the debris object (e.g. #1, 2, 4, 5) and activating it after separating our ADR vehicle from the debris object.
- ADR techniques requiring a non-rigid contact (e.g. #4 after the installation of the kit, #6 if tentacles are flexible, #7, 8, 9). Those are techniques that require a much higher effort from the GNC system of our ADR vehicle, since the non-rigid capture and posterior evolution of the associated dynamics is very complex and no complete studies have been performed till now.

Note that, in the ADR problem, space debris are considered as a non-cooperative target, as opposed to the situation where a cooperative target can assist the rendez-vous with a chaser by, for instance, hosting sensors or navigation aids that facilitate proximity operation. The targets non-cooperative aspect has several implications to the GNC, especially navigation.

In addition, another aspect that has to be carefully considered in ADR missions is the nature of debris that has to be removed. Most urgent removal candidates space debris span from non-operating satellites to rocket bodies. These debris can therefore vary largely in terms of mass, dimensions, orbit and rotating state.

Spinning debris objects pose a challenge to any concept that involves making physical contact with the debris. Relatively little data is available on the spin rate of existing space debris, although some theoretical considerations based on the torques acting on debris have been made [1]. Electromagnetic (eddy currents and magnetic hysteresis) and gravity gradient torque are expected to bring the spacecraft into a slow tumbling state of 1 to 2 revolutions per orbit.

3 ADR Space Scenario Analysis

The typical ADR space scenario in terms of operations and GNC phases can be defined as follows:

- P0: far distance approach. Devoted to arrive to the proximity (100s of meters) of the debris object from the starting position of the ADR vehicle. It can be split in two sob-phases: a ground controlled phase takes the ADR at few kilometers from the debris, from where the autonomous rendezvous phase starts.
- P1: final approach with un-cooperative target. Devoted to the final approach phase (till few meters). An “angular synchronization” with the debris object angular velocity might be needed or not (depending on the ADR technique).
- P2: capture. Either rigid or non-rigid capture. In general, a de-tumbling phase of the combo ADR vehicle/debris object will be needed.
- P3: de-orbitation. For techniques that do use an ADR kit installed in the debris object, this phase means to release the debris object in the appropriate orientation and activate the ADR kit package. For techniques that do not use an ADR kit installed in the debris object, this phase means to transmit (rigid or non-rigid) force and torque to the debris object through the capture mechanism.

The rendezvous and capture phases shall make use of safe orbits. The safe orbit has the advantage that no collisions can occur, because each of the plane crossings (crossings of the xy plane and the xz plane; crossing of the xy plane is less important) occurs some distance away from the origin. The right hand side of the following figure shows that when crossing the orbital plane xz, the chaser is always at some altitude z above or below the xy-plane, and when the chaser crosses the xy-plane, the chaser is always at some distance y to the left or to the right of the target. This feature ensures that the safe orbit is protected against along-track drift.

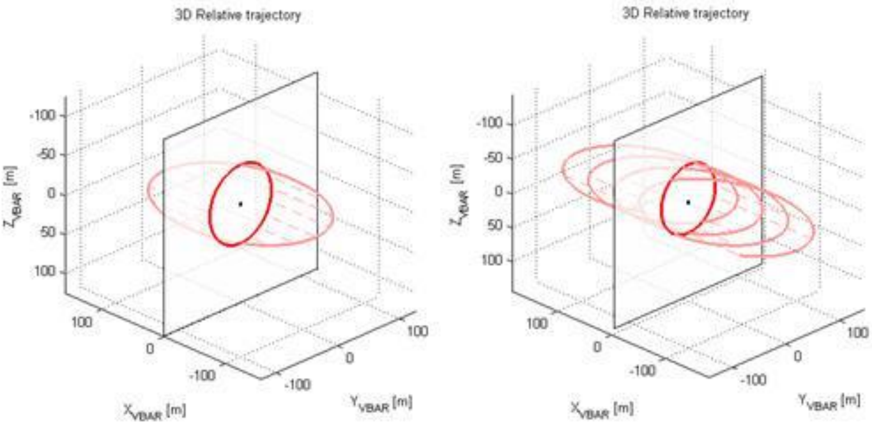

Fig. 1 Safe Orbit concept

Fig. 1 shows a 3-dimensional plot of the safe orbit, including its projection on the yz-plane. The left-hand side of the shows the true safe orbit, and the right-hand side shows how the safe orbit is protected against drift. Although the trajectory is clearly drifting, the projection on the yz-plane is still a circle around the origin. In other words, the origin of the reference frame is never reached and the trajectory is safe.

Fig. 2 shows the autonomous rendezvous subphase of P0 up to an approach to the target of ~30 m. The rendezvous starts in point S1 at ~20 km distance and ends in point S7 at ~30 m distance. It is assumed that proximity operations start at this point.

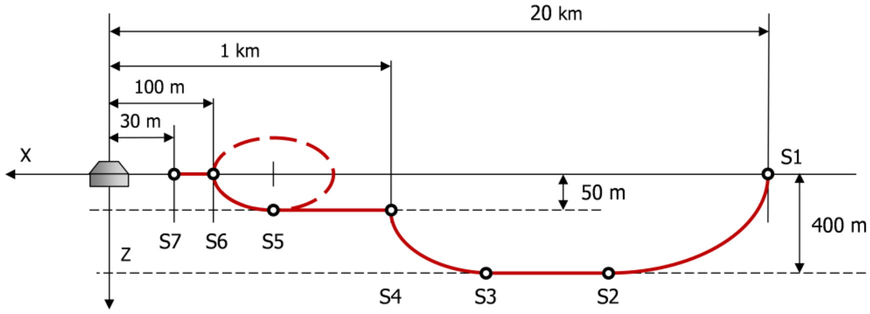

Fig. 2 Rendez-Vous strategy with Debris in the origin.

The strategy can be broken down into the following steps:

- S1: 1st ΔV of Hohmann transfer to drift orbit 400 m below V-bar
- S2: 2nd ΔV of Hohmann transfer to insert into a drift orbit 400 m below V-bar
- S3: 1st ΔV of Hohmann transfer to drift orbit 50 m below V-bar
- S4: 2nd ΔV of Hohmann transfer to insert into a drift orbit 50 m below V-bar
- S5: ΔV to stop drifting and optionally to insert into safe orbit. This would require an additional out-of-plane component to the ΔV. The chaser could remain in safe orbit for several orbits at this point. When the chaser exits safe orbit, an out-of-plane ΔV is performed at S5 to remove the out-of-plane motion component.
- S6: ΔV to arrive in a hold-point on V-bar at 100 m distance from the target.
- S6 to S7: forced motion approach over V-bar

At this point, proximity operations start, which can vary depending on the ADR technique which is used to remove the debris from its orbit.

The final phase of the rendezvous is a forced motion approach down to about 20 meters. At this point, debris characterization operations commence. The chaser spacecraft performs station-keeping on V-bar and takes long measurement series of the debris by means of optical cameras and / or LIDAR. These measurement series are analyzed on ground to determine an accurate shape model and the rotation state. During most of the characterization phase, the chaser will perform station-keeping. During certain intervals the chaser will perform free flight such that the location of the center of gravity of the debris object can be determined. The debris characterization phase ends when an accurate model is available of the spacecraft shape, rotation state and the location of its center of gravity.

The guidance for the angular rendezvous is based on successive reference frame changes and simple forced motion algorithms. The rendezvous proceeds by successively aligning the chaser with the target centered inertial and the target body frame. The forced motion algorithms used are a straight line forced motion algorithm, a reference frame switch algorithm that stops the rotation with respect to another frame and a fly-around algorithm. In each reference frame the fictitious forces associated with that reference frame are computed such that these can be compensated for.

Three different close range RvC scenarios can be envisaged at operational level:

1. Full angular synchronization: the ADR vehicle will acquire a station keeping situation in debris body frame in front of the selected capture point. This is the simplest operational scenario from the point of view of the capture device, i.e. stationary dynamics between the capture device and the target debris and the least demanding for the ADR vehicle/debris combo control system at the capture instant and later on, but it is the highest delta-V demanding and the most control system demanding before the contact.

   For a fast spinning satellite, it may be necessary to perform a first approach over the spin axis of the body, followed by a fly-around that is as short as possible to save propellant. Fig. 3 shows an approach sequence for approaching a fast-spinning satellite.

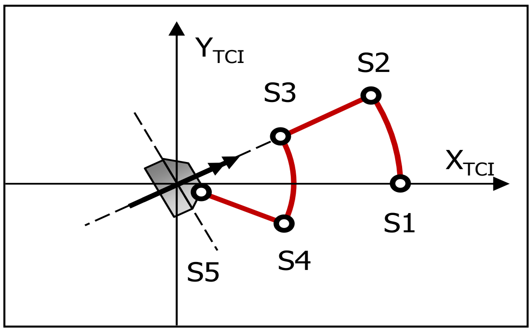

Fig. 3 Proximity operations for a fast-spinning satellite.

2. Axial angular synchronization: the ADR vehicle will acquire a station keeping situation in debris body frame and located along the debris rotation axis. The rigid capture will be done by laterally deploying the capture mechanism and capturing the debris at the selected capture point (not in front of the ADR vehicle, but still static with respect to the capture device). This is a

more complex operational scenario from the point of view of the capture device than the full angular synchronization scenario but it is less delta-V demanding. In case of using a foam-based or net-based ADR technique, there will be a higher complexity derived from the fact that the debris orientation and reference point/s for applying such ADR techniques are constrained to be along the debris rotation axis.

3. Inertial capture/approach: the ADR vehicle will acquire a station keeping situation in debris orbital (non-rotating) frame. The rigid capture will be tangentially grapping the selected capture point, which will have a relative motion with respect of the ADR vehicle that shall be handled by the capture mechanism motion. This scenario is the simplest from an ADR vehicle pre-contact control system but it presents the highest complexity for the robotic arm structural and control system and the subsequent ADR vehicle/debris combo control system. It has similar delta-V consumption than the axial angular synchronization scenario. The inertial approach will be the baseline approach in case of contactless approaches.

An example of the approach trajectory to a debris is shown in figures below, one depicted in Local Horizontal Local Vertical (LVLH) frame, while the second in Body Fixed Frame (BFF) frame. The trajectory is composed of (i) a first forced motion in LVLH frame, up to 30 meters, (ii) a station keeping in Earth Centered Inertial frame (ECI), (iii) a station keeping in BFF, (iv) a full angular synchronization phase and (v) the final approach up to capture point. The total nominal DV for covering the whole trajectory depends on the debris angular velocity. Considering for example 1 deg/s, 3.05 m/s are obtained.

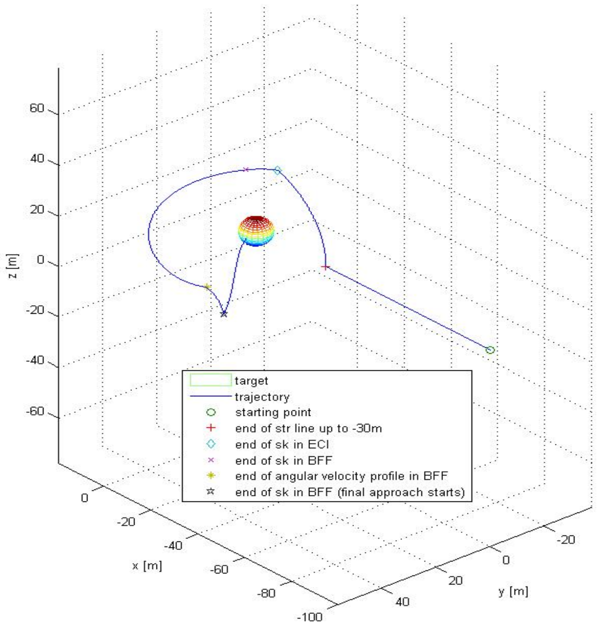

Fig. 4 Approach trajectory in LVLH frame.

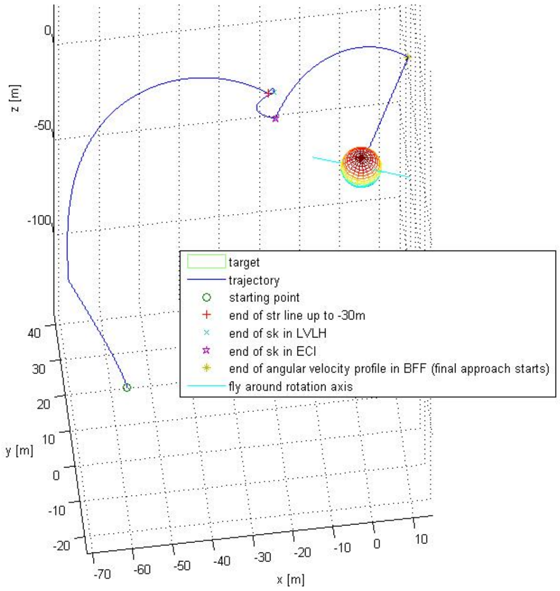

Fig. 5 Approach trajectory in BFF.

4 GNC aspects for ADR

In general, ADR missions will need to cope with uncooperative rendezvous, where the attitude of the debris object is neither controller nor stable. The population of debris includes a large variety of objects, from old died satellites to launcher upper stages, with very different physical properties and MCI parameters. Most of the debris objects with known status present a rotational status which is below or around 1 rpm.

The main aspects to be analysed from a GNC point of view are:

- Understanding and modeling the tumbling state of debris is one of the most important aspects that needs to be analysed for what respect the associated GNC technologies.
- The "angular" rendezvous is a particular type of forced motion fly around where the ADR vehicle is to be seen as stationary from the debris object reference frame. Despite being a “classical” forced motion phase, it implies strong operational constraints, controllability issues and safety issues that shall be further matured.
- The rigid capture and later de-tumbling and de-orbiting of the ADR vehicle/debris object combo is a phase which certainly implies many GNC related

challenges, i.e. the combo will have totally different mass, inertia and controllability properties with respect to the stand-alone ADR vehicle.
- The non-rigid capture and later de-tumbling and de-orbiting of the ADR vehicle/debris object combo is a phase which clearly exceed current GNC capabilities and need dedicated and extended analysis.

The GNC (Guidance Navigation and Control), together with FDIR (Fault Detection Isolation and Recovery) and AMM (Autonomous Mission Management), are the brain of an ADR spacecraft, the subsystems that, based on observations and events coming from the environment through the sensors, computes and applies, commanding properly the actuators, the attitude and orbital manoeuvres needed to accomplish the requirements and the final goal of the mission. As anticipated, in case of an ADR mission, the GNC presents a number of very critical aspects, to be taken carefully into account during the whole DDV&V (Design, Development, Validation and Verification) process. In the following subsections, the functionalities of the three main functions composing the GNC are detailed, pointing out the most critical aspects to be taken into account in order to fulfill the complex ADR mission necessities.

4.1. Guidance

Guidance is the function devoted to the computation of reference trajectory and attitude profiles, and of the feed forward actions (accelerations and torques) to follow them. The final objective of the guidance will be computing reference profiles permitting the approach and the capture of the debris. In case of an ADR mission, the following modes/functionalities can be identified:

- Attitude Guidance modes:
  - Safe pointing mode (SPAG): this is the nominal pre-approach attitude, maintaining a spacecraft axis toward a fixed inertial direction, e.g. typically the axis perpendicular to the solar arrays appendages (if any) toward the Sun or the axis perpendicular to the face hosting the antenna in the orbital plane. It will be also used as reference pointing profile during the de-tumbling phase, during which the rotation of the composite ADR-debris spacecraft shall be stopped.
  - Scanning Attitude mode (SCAG): this mode is used to compute the attitude manoeuvres to search the target inside an uncertainty region (in case the angular uncertainty corresponding to this region is higher than the camera FOV). The uncertainty region is returned by navigation, which propagates the initial knowledge on target position returned by ground. Typically, the region is split in tiles (each one of an angular dimension equal to camera FOV), and a tile-by-tile spiral profile (starting from the centre of the uncertainty annulus) is followed.

  - Target pointing mode (TPAG): this is the pointing maintained during the impulsive approach phase. The attitude profile is computed in order to keep the debris inside the camera FOV. This mode needs to receive from navigation (i) the estimation of the current attitude in inertial reference frame and (ii) the estimation of the debris line of sight (LoS), with the corresponding uncertainty.
  - Angular synchronization pointing mode (ASAG): in this mode, the attitude of the ADR vehicle is maintained fixed in the debris body reference frame, in order to make possible the grapping operations. The knowledge of the target attitude in inertial reference frame, and the corresponding angular velocity, shall be available from navigation function before triggering this mode. Depending on the capture strategy, this mode could provide partial or full synchronization or could be even unnecessary (typically for contactless techniques).
  - De-orbiting pointing mode (DEAG): in this mode, (one of) the main thrust axis of the spacecraft shall be pointed toward the orbital velocity direction, in order to permit the execution of a de-orbiting manoeuvre. The third d.o.f. can be fixed in whatever way (e.g. maintaining the communication antenna toward Earth).

- Trajectory Guidance modes:
  - No translational guidance mode (NOTG): in this mode a free drift trajectory is simply followed. It is needed for defining GNC modes where no manoeuvre shall be applied (e.g. navigation initialization modes). Ground controlled manoeuvres during long range phases would be applied during this mode.
  - Impulsive Manoeuvres mode (IMTG): this mode computes the manoeuvres necessary to approach the vicinities of the debris, starting from few km away till to a distance of typically few meters from the target envelope. Thanks to the short distances, a linearized formulation can be used to compute the manoeuvres. To maintain generality with respect to the debris orbit, a formulation considering a generic eccentricity can be proposed (e.g. Yamanaka-Ankersen). The following manoeuvres will be available in this mode:
    - Cotangential manoeuvre, needed to correct errors in semi-major axis and eccentricity (wrt. the target orbit). Only errors in relative true anomaly will be left, meaning that this manoeuvre will take the ADR vehicle onto the target orbit, at a certain distance from it.
    - Radial hopping, needed to decrease progressively the error in relative true anomaly by mean of eccentricity manoeuvres. This kind of approach guarantees passive safety in case of control loss. Of course, it can be also used to increase the relative distance in case of a retreat.

    - Two-impulses transfer, needed to transfer from a current state (position/velocity) to a generic desired state in a given time. It can be used for example to transfer from V-bar to a generic station keeping point around the debris.
    - Fly around, needed to maintain a periodic motion around the target with small propellant consumption. Typically it is used to observe the target from different point of view (e.g. for collecting information about shape, possible grasping points, etc.) or to perform low-cost station keeping (e.g. during eclipses).
    - Correction manoeuvres, needed to correct the trajectory when the error between estimated and reference profile exceeds a given threshold. This task, conceptually belonging to control, is usually performed by translational guidance, which already contains the linearized formulation needed to compute these manoeuvres (indeed is a kind of two-impulses manoeuvre seen above).
    - De-orbiting manoeuvre, needed to compute the deltaV necessary for the re-entry of the composite ADR-debris vehicle.
  - Forced motion mode (FMTG): this mode is used to (i) performing station keeping (either in target orbital reference frame or in target body reference frame) or (ii) approach the debris following a straight line in the target body reference frame (to complete the capture operations). The mode computes the relative trajectory to be followed in the target orbital reference frame (where the dynamics equations are typically written), and the feed forward acceleration to follow this trajectory. The attitude motion of the target is needed from navigation in order to compute the trajectories in the target body reference frame.
  - CAM mode (CATG): this mode is used to compute CAM manoeuvres in case of any contingency causing risk of collision and shall ensure a safe escape from target vicinities and the achievement of a safe distance with no return toward the target.

4.2. Navigation

The navigation function is in charge of estimating/predicting the state vector (position, velocity and attitude sensor/dynamics biases) based on sensor measurements and internal knowledge of the real world dynamics. For an ADR mission the following navigation modes/functionalities can be envisaged:

- Safe Navigation mode (SAFN), in charge of estimating the satellite attitude based on gyroscpope and sun sensor measurements. It is triggered during the phases preceding the approach, and during contingency situations that require a low power consumption.

- Absolute Navigation mode (ABSN), in charge of computing (i) attitude estimation based on star tracker and gyros measurements and (ii) absolute position estimation based on GPS and/or ground tracking measurements.
- Relative Navigation mode (RELN). It follows estimating the absolute states such ABSN mode and adds up the estimation of the relative position/velocity in LVLH reference frame based on camera measurements.
- Terminal Approach Navigation mode (TAN). It follows estimating the absolute and relative states such as the previous modes and adds up the estimation of the target attitude motion based on short range camera measurements.

The critical aspect with respect to other type of rendezvous missions is the estimation of the target non-controlled (and so completely random) attitude motion. Considering that the target is non-cooperative this functionality is not straightforward, also because it is highly influenced by the illumination conditions along the orbit, which make even more difficult the task of the image processing function.

4.3. Control

The control function receives in input the estimated state from navigation function and ensures following, by mean of a feed backward action opportunely computed to fulfill robustness, performance and stability requirements, the reference trajectory and attitude profiles provided by guidance. During the impulsive approach phases, the task of computing the trajectory control action is usually assigned to translational guidance by mean of correction manoeuvres. Considering this, the following control modes/functionalities can be foreseen:

- No-control mode (NOC): in this mode no feedback action, either for attitude or for translation is applied. It is needed for defining GNC modes where no autonomous manoeuvre shall be applied (e.g. navigation initialization modes).
- Safe Control mode (SAFC): attitude control based on thrusters or magnetotorques, with low pointing accuracy and high robustness to initial conditions (angular and angular rate) and navigation uncertainties, used during safe pointing phase. Thanks to the high robustness to initial conditions, this mode will be used also during the de-tumbling operations.
- Coarse pointing control mode (CPC): attitude control based on thrusters, with medium pointing accuracy, typically used for fast re-orientations, or when a translational manoeuvre is being commanded. It guarantees small deltaV realization errors.
- Fine pointing control mode (FPC): attitude control based on reaction wheels, with fine pointing accuracy (compatible with sensor pointing performance and stability), typically used during target pointing free drift phases.
- Station Keeping control mode (SKC): 6 d.o.f. control mode for the station keeping during the approach, outside the terminal approach phase.

- Terminal approach control mode (TAC): 6 d.o.f. control mode (attitude/translation including couplings) for the final forced translation and station keeping in target body reference frame. It shall permit following the (in general) challenging attitude/translational approach profile provided by guidance and shall be particularly robust to:
  - A high range of possible debris attitude motions
  - Navigation uncertainties on the estimation of the target attitude motion and on the relative state
  - Actuators misalignments/noises/delays
  - Fuel sloshing and flexible modes
- Capture and de-orbiting control mode (CDEC): thruster-based attitude control mode used during the capture operations and during the application of the de-orbiting manoeuvre. The complexity of this mode depends greatly on the de-orbiting mechanism that is being considered. Considering the worst case of rigid/non-rigid contact approaches the mode becomes quite challenging, as it shall guarantee robustness to the following aspects:
  - The change of M.C.I. (Mass, CoG, Inertia) properties due to the movement of the capture mechanism (e.g. in case of robotic arm/tentacles capture)
  - In case of rigid contact, the M.C.I. properties of the composite satellite will have in general a high degree of uncertainty and the high flexibility of the composite satellite
  - The set of thrusters could have an important lateral displacement with respect to the CoG of the composite system, resulting in a lower controllability during the manoeuvre application.
  - Any motion of the arm/tentacles will impact the dynamics of the body so that the control is challenging and requires advanced control techniques to cope with inertia matrix and center of mass variations and with the efforts applied by the arm on the body.
  - In case of non-rigid contact, the forces and torques transmitted from the debris angular motion through the tether during capture and de-orbiting could be meaningful (depending on the relative ADR/debris) and the controller shall be designed in order to be stable to these external disturbances.
  - In case of rigid contact, the control of the combo after the capture includes three phases:
    - the stiffening of the arm degrees of freedom in order to get a combo configuration that is compatible with chaser body actuators
    - the detumbling of the combo
    - the de-orbitation manoeuvre. A pulling option or a pushing option are possible. In the pulling option (use of thrusters mounted on the face towards the debris), the control is simpler because the combo

center of mass will naturally align along the thrust direction (this option could be unfeasible if for any reason the plume impingement cannot hit the debris, e.g. non-passivized satellite). In the pushing option (use of thrusters mounted on the face opposite to the debris), the attitude is naturally unstable and the relative positioning of the debris with respect to the chaser shall be optimized in order to keep a good controllability of the whole system by the chaser actuators.

For the case of contract-less debris removal techniques (like the ion beam shepherding and chemical thruster shepherding), the basic GNC is relatively straightforward. The chaser performs station-keeping on V-bar, while at the same time both a pushing thruster and a balancing thruster are active. The balancing thruster needs to provide a slightly higher thrust to compensate for the acceleration imparted onto the debris object. Two options exist for the control system; either the debris attitude is left uncontrolled, or the control attempts to control the rotation around the axes perpendicular to the line connecting the centers of mass of the spacecraft and the debris. In the first case the control is simpler, but additional ΔV will be spent on station-keeping and energy is lost spinning up the target. In the second case, the pressure distribution on the debris object is modified to achieve control torques on the debris object. This changing pressure distribution can be realized by changing the attitude of the chaser, physically changing the direction of the thruster. Alternatively, if the pushing thrust is generated by more than one thruster, control can be exerted by switching these thrusters on and off.

4.4. GNC Modes

Based on the previous subsections and on GMV experience in GNC S/S design/prototyping for RdD/RvC, the following autonomous GNC modes can be defined for an ADR mission.

Table 2 GNC modes

GNC Mode	GNC Sub-mode	Description	TG Mode	AG Mode	N Mode	C Mode
SAFM	SAFM1	Safe Pointing Free drift after ADR-target mechanical/DV separation	NOTG	SPAG	SAFN	SAFC
ABSM	ABSM1	Absolute navigation initialization	NOTG	SPAG	ABSN	NOC
	ABSM2	Inertial pointing acquisition	NOTG	SPAG	ABSN	CPC
	ABSM3	Target search	NOTG	SCAG	ABSN	FPC
RELM	RELM1	Relative navigation initialization/Free drift after manoeu-	NOTG	TPAG	RELN	FPC

GNC Mode	GNC Sub-mode	Description	TG Mode	AG Mode	N Mode	C Mode
		vre application				
	RELM2	Impulsive manoeuvre application	IMTG/cot_hop_cm	TPAG	RELN	CPC
	RELM3	Station keeping in holding point	FMTG/sk$_{LVLH}$	TPAG	RELN	SKC
FAM	FAM1	Terminal Approach Navigation initialization	FMTG/sk$_{LVLH}$	TPAG	TAN	FPC
	FAM2	Fly-around for target inspection	IMTG/fly	TPAG	TAN	FPC
	FAM3	Station keeping/Forced approach in target body frame	FMTG/sk/fm$_{TBF}$	ASAG	TAN	TAC
CDEM	CDEM1	Station keeping during capture operations	FMTG/sk$_{TBF}$	ASAG	TAN	CDEC
	CDEM2	De-tumbling operations	NOTG	SPAG	ABSN	CDEC
	CDEM3	De-orbiting operations	IMTG/deorb	DEAG	ABSN	CDEC
CAMM	CAMM1	CAM application	CATG	TPAG	RELN	CPC
CAMM	CAMM2	Free drift after CAM application	NOTG	TPAG	RELN	FPC
CAMM	CAMM1	CAM application	CATG	TPAG	RELN	CPC

The following diagram shows, in a graphical form, the same information contained in the previous table together with the conditions necessary to trigger from one mode/submode to the other. The different conditions are reported in Table 3.

Table 3 Conditions for GNC modes triggering

Condition	Description
C1	GO command received
C2	Desired initial distance reached
C2_1	ABSN navigation (attitude and position) converged
C2_2	CPC control converged (stable attitude reached)
C3	Target detected and stably acquired with the camera
C3_1	Relative navigation converged/New approach manoeuvre to be applied
C3_2	Approach manoeuvre applied, free drift required
C3_3	Approach manoeuvre applied, station keeping point reached
C3_4	Station keeping completed, approach to be followed
C4	Final phase point reached
C4_1	Terminal approach navigation converged
C4_2	Fly-around manoeuvre applied and SK in target body reference frame required.
C4_3	Return to fly around mode required
C4_4	Terminal approach starting point reached and GO command received

Condition	Description
C5	Capture operations starting point reached
C5_1	Capture correctly achieved
C5_2	Attitude stabilization completed. De-orbitation manoeuver needed.
C6	De-orbitation completed

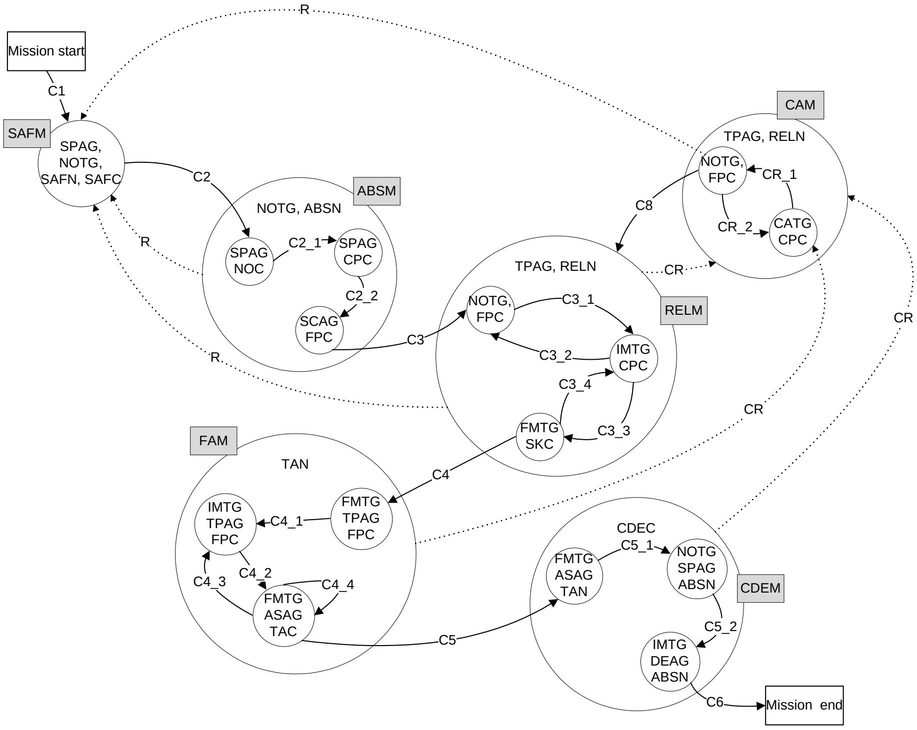

Fig. 6 GNC modes transitions.

4.5. Achievable Performances

The following figures show an example of achievable relative navigation performances based on the use of Narrow Angle Camera based relative navigation. The cyan colored lines are covariance values, depending on the inter satellite range. The other three lines are X, Y and Z components in Local Vertical Local Horizontal (LVLH) frame.

The navigation error is the dominant one, so full GNC accuracy can be approximated (at first order) to the navigation error.

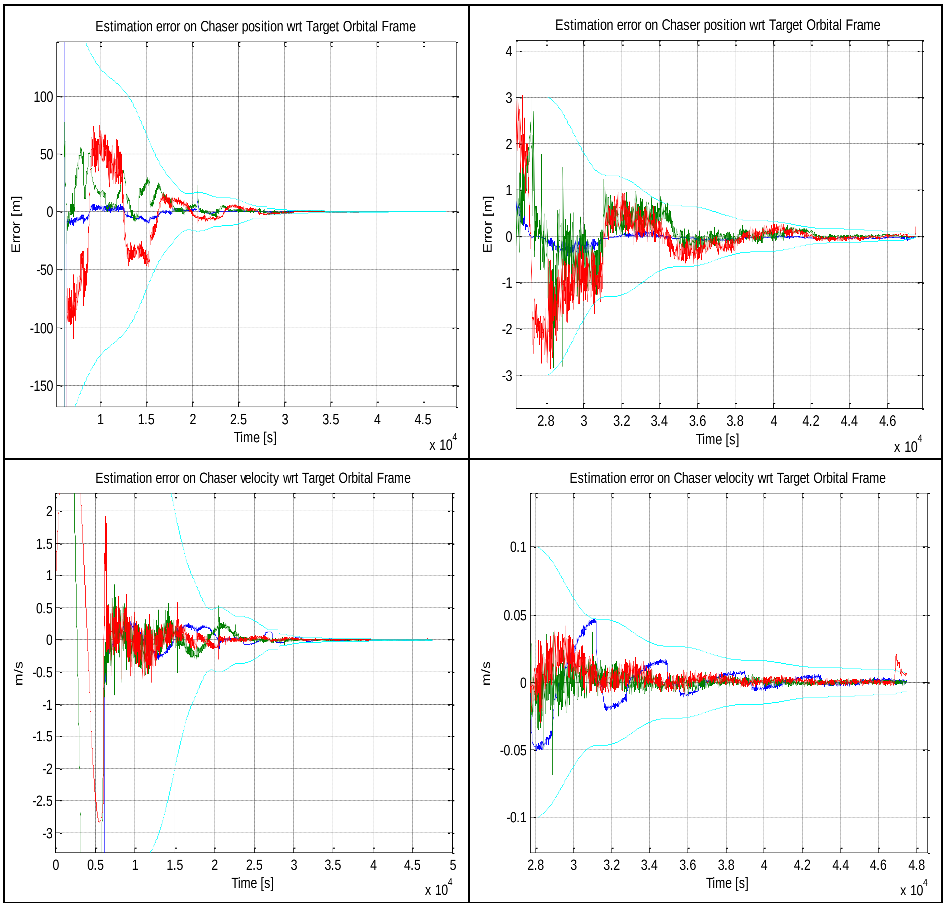

Fig. 7 Relative navigation error obtained during approaching scenario (starting at 300 km distance till few meters distance. Position error (top line) and velocity error (bottom line). The right column is the zoom on short range.

5 GNC technologies TRL and IOD

Currently, no full mission of removing a non-cooperative object from orbit has been performed. This section addresses the current maturity status of the technologies related with GNC aspects of an ADR mission. The maturity of these technologies has been evaluated with the scale in [2].

The sensors which are foreseen to be used in the ADR mission have already been developed and tested in-orbit. This is valid for both Narrow and Wide Angle Camera, as well as for the LIDAR. Therefore, TRL can be stated as 9 for them.

The GNC for autonomous formation flying has been already demonstrated with hardware-in the loop on ground ([3]). It is however needed a customized tailoring of the on-ground HIL facilities to replicate the specific ADR needs.

Regarding the rigid contact capture GNC, robotic arm in space have already flown: what is special for an ADR mission is the combined control of the spacecraft with the robotic arm in the proximity of an uncooperative target, as well as the end effector control of the robotic arm towards a target which does not possess a customized grasping handle. The in-development German mission DEOS ([4]) partially covers these aspects.

Regarding the non-rigid contact capture, several aspects have still to be addressed and demonstrated in orbit. For instance, in the case of using a net as debris capture mechanism, the control of the chaser during the net deployment, as well as the momentum transfer of the combo once the debris is linked to the chaser by a tether have still to be validated. Currently, analysis has shown proof of concept, with simulators based on mass-spring models of the net elements and of the chaser/debris combo.

With respect to the contact-less GNC, this highly depends on the technique to be used. In the case of the chemical shepherd, for instance, a detailed and validated model of the chemical propulsion plume impingement is needed in order to be integrated, for the design and development of the GNC.

Regarding the maturity of the image processing which is needed for navigation in the ADR mission, some distinctions among the different phases has to be done. Additionally, one has to take into account that while a whole range of image processing algorithms have already been developed and tested on ground, their applicability to ADR missions can only take place after specific tailoring and validation to the space scenario.

For instance, so far only the far range approach with a non-cooperative object has flown on a mission which has, for this phase, some similarities. The AutoNav experiment on NASA’s Deep Space 1 mission ([5]) can be considered applicable to the far range ADR image processing.

Regarding the close range image processing with an uncooperative object, one can mention the Tridar sensor ([6]), which has flown on Space Shuttle mission, where it has been used to reconstruct the pose of a target whose size and geometry was already known from the IP algorithm. In this sense, the meaning of uncooperative object has to be carefully used even in ADR missions, as a scenario where a geometric model of the debris to be captured is known is different to another scenario where the current configuration and geometry of the targeted debris cannot be stated a priori.

Based on the previous considerations, Table 4 provides a summary of the TRL for the main GNC technologies.

The maturity of the GNC system for ADR mission is still to be further developed in order to guarantee a success of the mission, especially by testing GNC critical technologies in a representative space environment. In this context, the need of In-orbit demonstrations (IOD) seems to be the next step in order to validate an ADR mission, where the GNC as system (sensors, capture and deorbiting techniques) can be validated.

Table 4 Current Technology Readiness Level of GNC technologies for ADR

GNC ADR technologies	**TRL**
Rendezvous sensors	
LIDAR	9
NAC (Narrow Angle Camera)	9
WAC (Wide Angle Camera)	9
GNC for autonomous rendezvous and FF	5
GNC for rigid contact capture	4
GNC for non-rigid contact capture	3-4
GNC for contact-less deorbit	3
Image Processing (uncooperative)	
Far range IP for ADR purposes	7
Short range IP for ADR purposes	3-4
LIDAR processing for ADR purposes	3

6 Conclusions

This paper has presented the ADR problematic, focusing on the most important aspects to be taken into account in the design and development of a GNC system for such kind of missions. The different ADR capture techniques studied so far have been surveyed, cataloguing them in three main groups (rigid, non-rigid, contactless) and showing the strong impact that the capture technique could have on the GNC system. This latter aspect has surely one of the highest weights in the tradeoff for the selection of a technique or another. An assessment of the TRL of GNC technologies has been performed in the last part of the paper, where it is pointed out that an important effort is still necessary to further develop the maturity of the GNC system in order to guarantee the success of an ADR mission, especially by mean of representative space environment demonstrations.

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