IAC–15–A6,6,1,x28851

Agora: Mission to demonstrate technologies to actively remove Ariane rocket bodies

Kartik Kumar
Dinamica Srl, Italy, kumar@dinamicatech.com

Natalia Ortiz Gómez
University of Southampton, UK, N.Ortiz-Gomez@soton.ac.uk

Marko Jankovic
German Research Centre for Artificial Intelligence, Germany, marko.jankovic@dfki.de

Juan Manuel Romero Martin
University of Strathclyde, United Kingdom, juan.romero-martin@strath.ac.uk

Dr. Francesco Topputo
Politecnico di Milano, Italy, francesco.topputo@polimi.it

Dr. Scott Walker
University of Southampton, United Kingdom, sjiw@soton.ac.uk

Prof. Frank Kirchner
German Research Centre for Artificial Intelligence, Germany, frank.kirchner@dfki.de

Prof. Massimiliano Vasile
University of Strathclyde, United Kingdom, massimiliano.vasile@strath.ac.uk

We present a feasibility study for an Active Debris Removal (ADR) mission called Agora (Active Grabbing & Orbital Removal of Ariane), aimed at removing discarded Ariane rocket bodies (R/Bs). The Agora mission goal is to demonstrate technologies to autonomously remove an Ariane R/B in a controlled manner, using an active detumbling device and a robotic grabbing mechanism, within a cost cap of 200 MEuro FY2015, by 2025. R/Bs belong to a growing class of space debris objects that pose a sizable risk to operational satellites. The threat of on-orbit collisions must be addressed within the near-future to ensure that the risk of catastrophic events, like the Iridium-Cosmos collision in 2009 (Kelso, 2009; Tan et al., 2013), is mitigated. Liou et al. (2010) indicate that at least five large objects will need to be removed per year, over the next 200 years, from the Low-Earth Orbit (LEO) region, to stabilize the current debris population. This necessitates development and demonstration of key Active Debris Removal (ADR) technologies, including robust Guidance, Navigation Control (GNC) for autonomous close-proximity operations. We detail the payload systems incorporated on the chaser spacecraft to rendezvous, detumble, grab, and de-orbit an Ariane 5 R/B. The de-tumbling payload will aim to reduce the tumbling rate of the R/B to enable safe attachment of a de-orbiting kit. The de-tumbling phase is a dissipative process based on Joule's Law: eddy currents are generated on the target due to an enhanced magnetic field, generated actively by an on-board electromagnetic coil (Ortiz & Walker, 2015). The robotic payload will ensure (semi-)autonomous capture of the R/B and deployment of a de-orbiting kit, while compensating for dynamic coupling between the chaser and the robotic manipulator that will arise during actuation of the latter (Jankovic, et al., 2015). We present an analysis of a semi-rigid clamping mechanism, based on an anthropomorphic robotic finger design, for the capture of the target, and a manipulator, for deploying the de-orbiting kit. The framework for Agora complements the European technology roadmap for ADR, and is aligned with missions such as e.Deorbit (European Space Agency) and DEOS (German Aerospace Center).

I. Introduction

Unabated growth of the space debris population is a mounting concern for the community. The rapid increase of the number of debris objects on-orbit within the last decade has triggered an important discussion about the threat posed to vital space-based assets, employed for, e.g., weather-forecasting, navigation, communication etc., and to life on Earth. Crowded orbital slots and a growing population of non-cooperative objects in near-Earth space exacerbate the specter of the Kessler Syndrome: a collisional cascade process that could render certain regions of near-Earth space unusable in the future.[1]

Efforts are underway to address the challenges posed by space debris. These include: research into improving tracking capabilities to better understand and mitigate the risk of collisions, development of reliable and robust End-Of-Life (EOL) technologies for future satellites to be equipped with to mitigate population growth, and active strategies to remove high-risk objects within the current population. Research and development along these lines is actively pursued within space agencies and commercial enterprise.

The Iridium-Cosmos collision[2,3] in 2009 has demonstrated the impact that collision events can have on the debris population. Studies have been conducted to estimate the frequency of collisions across the energy spectrum, with some suggesting that the current situation is untenable and necessitates the use of active mitigation strategies. Liou, et al.[4] draw the conclusion that five large debris objects will have to be removed from Low-Earth Orbit (LEO) per year to stabilize growth of the population.

Within the current debris population, Rocket Bodies (R/Bs), i.e., spent upper stages, represent an important subset to consider, given their large mass, large cross-sectional area and orbits. They account for a significant mass fraction of the current debris population and pose a sizable threat to operational satellites.[5] In addition to collision risk, there is also concern about on-orbit explosions, triggered by ignition of residual fuel. In order to safeguard the future space environment, it is imperative that Europe develops the capabilities and infrastructure necessary to mitigate the threat posed by these R/Bs. Ariane R/Bs can be found both in LEO and Geostationary Transfer Orbit (GTO) and are targets of interest for the European Space Agency (ESA).[6] In light of this, in this paper we present an Active Debris Removal (ADR) mission concept geared towards tackling Ariane R/Bs.

In Section II, we present an overview of some key ADR technologies under development. Subsequently, in Section III, we present our ADR mission concept to actively remove Ariane R/Bs: Active Grabbing and Orbital Removal of Ariane (Agora). We provide an overview of the overall mission goal and top-level requirements. Based on these requirements, we generated a mission concept, which is presented in Section IV. Along with a synopsis of the design of the chaser spacecraft, we also provide insight into some of the key trade-offs performed, to elucidate the decisions taken to arrive at the mission concept. Our preliminary design enables us to identify the key technologies drivers that need to be addressed, in order to raise the Technology Readiness Level (TRL) of the overall concept. A summary of these key technologies and their impact on the mission concept is presented in Section V. Finally, some concluding remarks are provided in Section VI.

II. Active debris removal technologies

Research into ADR has led to the development of a suite of technologies to tackle debris objects that pose a significant threat. In this section, we provide a brief overview of the ADR technologies that have been proposed to mitigate the threat posed by large debris objects, e.g., satellites and R/Bs.

Many high-level studies have been conducted to characterize the nature of ADR and the types of systems required to tackle hazardous debris objects.[7] ADR technologies can be generally classified into two groups: contact and non-contact.[8] Contact methods require the chaser spacecraft to acquire physical contact with the target debris object, whereas non-contact methods operate at distance. These two categories are characteristically different and lead to a number of distinct design, manufacturing and operating challenges. Popular contact technologies include:

- Robotic manipulators: Manipulators have been used on-orbit for a variety of tasks; hence are generally considered to have a high TRL.
- Throw-nets: Throw-nets are deployed from a canister and are used to envelop the target, which can then be pulled by a tether attached to the chaser.
- Harpoons: Harpoons are fired to attach to the target, and using a tether, the chaser is able to pull it.

Non-contact methods include:

- Ion-Beam Shepherd (IBS): IBS employs ions generated by electric propulsion on-board the chaser to exert a force on the target, which can be re-orbited, de-orbited or de-tumbled it.
- Electromagnetic forcing: electromagnetic forces are generated on the target using electric and/or magnetic fields, which can be used for de-orbiting, re-orbiting or de-tumbling.
- Laser ablation: lasers are employed to ablate the surface of the target and generate a small but continuous resulting force for de-orbiting, re-orbiting or de-tumbling.

The literature is rich with studies into the design of these technologies and methods, touching upon their efficacy and efficiency.[8] At present, the TRL of these methods is generally low, resulting in an open discussion within the community about the most suitable technology for ADR. In the coming decade, the hope is that these technologies will mature through a concerted effort to provide in-orbit demonstration. This will undoubtedly lead to a process of consolidation, through which the suitability of these methods for given target classes will be established.

In this paper, we present the results of an ADR mission concept study that employs manipulation technology to mitigate the threat posed by Ariane R/Bs, leveraging the expertise available at DFKI*. Given that grabbing is a precarious task and that the rotational state of R/Bs is generally unknown, we employ a non-contact technique based on impinging eddy currents on the target to de-tumble it.[9]

III. Mission goal and requirements

As was stated in the previous sections, developing the capabilities for ADR is imperative to control the current growth of the space debris population. In particular, R/Bs are important targets, given that they belong to a growing class of space debris objects that pose a sizable risk to operational satellites, with a population of more than 790 R/Bs in LEO and more than 1085 in Medium Earth Orbit (MEO).[10,11] However, ADR for R/Bs is a highly challenging enterprise due to the non-cooperative nature and unknown rotational state of the targets. This requires development and demonstration of key ADR technologies, including robust Guidance, Navigation Control (GNC), including the Attitude and Orbit Control System (AOCS) for autonomous close-proximity operations.

* http://www.dfki.de

In order to support that global research effort, we conducted a feasibility study to investigate a mission concept called Agora: Active Grabbing and Orbital Removal of Ariane. Agora is a demonstration mission geared towards the development and in-orbit testing of technologies to actively and autonomously remove an Ariane R/B using a contactless de-tumbling system, based on eddy currents, and a robotic grasping mechanism. The primary goals of Agora are:

- to raise the TLR of ADR technologies, especially for the eddy current de-tumbling and robotic grasping systems;
- to reveal key ADR technology drivers;
- to provide a test bed for future mission development;
- and to serve as a reference to establish a roadmap to full-scale ADR on a real target.

The main top-level mission requirements defined for Agora are:

- Target object: Ariane 5 R/B
- Target cost cap: 200 MEuro (Fiscal Year 2015)
- Target launch date: 2025
- Use of an active de-tumbling system based on eddy currents to reduce the tumbling rate of target $< 1\,\mathrm{deg/s}$
- Use of a semi-rigid robotic grasping mechanism
- Use of a de-orbiting kit for controlled re-entry

The requirement for the residual target rotation after the de-tumbling phase (i.e., $< 1\,\mathrm{deg/s}$) is the baseline considered in our mission scenario. Further in-depth studies assessing the capabilities of the de-tumbling device and the grasping mechanism are needed to validate this requirement.

IV. Mission concept

The Agora chaser is a robotic spacecraft that will rendezvous with and capture an Ariane-5 EPS upper stage (target R/B). The target for this mission is the same upper stage used to place the chaser on-orbit. This allows us to eliminate the need for phasing since, after the launch phase, it is expected that the chaser and target R/B will find themselves separated by tens of kilometers, but in the same orbital plane. In case of failure, the risk of contributing to the growth of the space debris population can be minimized, since the Ariane-5 EPS upper stage can be de-orbited in a controlled manner by re-igniting itself.[12]

The Agora chaser is based on the bus structure of ESA's Automated Transfer Vehicle (ATV) with a total wet mass of 1815 kg. It is equipped with: a de-tumbling device that will be employed to reduce the tumbling rate of the target R/B and enable safe attachment of a de-orbiting kit, a semi-rigid clamping mechanism to grab the target R/B and to compensate for any residual relative motion, and a robotic arm to deploy a de-orbiting kit. The de-orbiting of the target R/B will be performed in a controlled manner using the kit installed by the chaser. The use of the de-orbit kit provides an opportunity to scale up Agora in future to a multi-target scenario by including multiple de-orbit kits on the chaser.

Due to the non-cooperative nature of the target and the limited reaction time available to address any anomalies and/or communication problems that might occur, the chaser is equipped with a high degree of autonomy. The most demanding autonomy is necessary during the final phases of the mission (close-range rendezvous and final approach). The primary proximity phases for the mission, illustrated in Figure 1, are described in the following:

1. **Far-range rendezvous phase:** The chaser will reduce the relative distance between itself and the target from kilometers down to a few hundreds of meters, in order to meet the requirements for the close-range rendezvous phase, composed of sub-phases, given in the following.

2. **First fly-around phase:** The pose of the target will be estimated and visual inspection of the target will take place.

3. **De-tumbling phase:** The tumbling rates of the target will be reduced below the threshold of $< 1\,\mathrm{deg/s}$ using an enhanced magnetic field generated by on-board coil,s from a distance of ten meters with respect to the Center-Of-Gravity (COG) of the target.

4. **Attitude estimation phase:** The attitude of the target will be determined once again, to verify that the tumbling motion about all three axes satisfies the maximum specified threshold.

5. **Approach phase:** The chaser will gradually approach the target, reducing the relative distance down to a few meters with respect to the COG, with full contingency measures in place.

6. **Capture and stabilization phase:** A semi-rigid clamping mechanism will be used to capture the target object, while dumping any residual relative motion. The AOCS will be used in this phase to actively stabilize the composite system.

7. **De-orbit kit insertion phase:** A robotic arm will be deployed and used to manipulate and insert the de-orbit kit inside the nozzle of the main engine of the target.

8. **Disengagement phase:** After installation of the de-orbit kit, the chaser will reorient the composite system to the required position and orientation and will disengage from the target, retreating to a safe distance.

9. **De-orbiting phase:** The de-orbit kit will be ignited and will carry out a controlled re-entry of the target object (see Section V.3 for further details about the de-orbit kit). Afterwards, the chaser will reorient and de-orbit itself using its own Orbit Control Thruster (OCT).

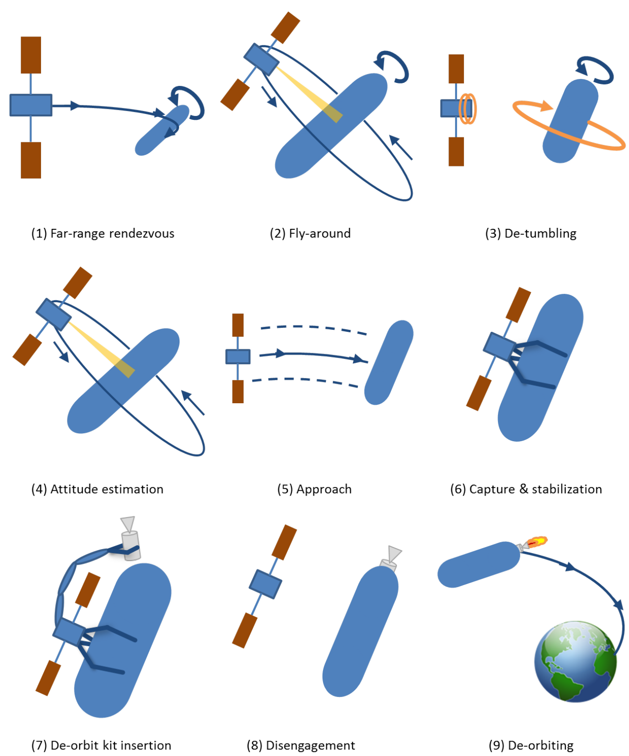

Fig. 1: Schematic illustration of primary mission phases for Agora.

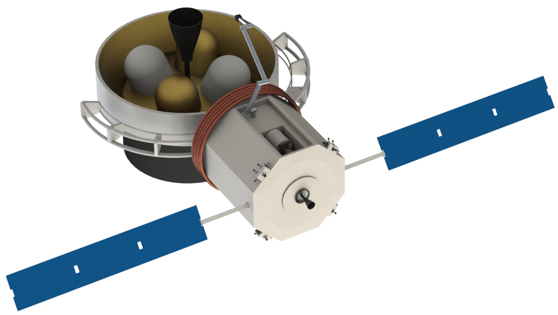

Fig. 2: Agora chaser spacecraft concept[13]

IV.i Chaser design and main budgets

The chaser concept for the Agora mission is illustrated in Figure 2 and features: a base spacecraft, a deployable, semi-rigid clamping mechanism, a robotic arm, a de-tumbling device and a de-orbit kit. The semi-rigid clamping mechanism is used to capture the target and rigidly secure the chaser-target composite, while the robotic arm is only only for inspection of the target and placement of the de-orbit kit. The main design drivers of the concept were:

- the dimensions and configuration of the chosen target,
- the dimensions of the Ariane 5 SYLDA "+2100" dispenser, where the stowed chaser will be stored during the launch,
- the pointing requirements of the chaser during the de-tumbling phase,
- the degree of gimbal movement of the main engine of the target
- and the precision requirements during the placement of the de-orbit kit.

Given the versatility of a robotic manipulator and general agility of the spacecraft, different approaches for the placement of the de-orbit kit can be envisioned. During the trade-off study an alternative concept, consisting of a robotic spacecraft with only the robotic manipulator (no clamp) was also considered and analyzed. However, due to (unconstrained) passive gimbal movement of the nozzle of the main engine and substantial dynamical coupling between the base spacecraft and robotic arm, it was assessed that this alternative would raise safety concerns and require a highly stringent control strategy for the arm; thus it was set aside in favor of the illustrated concept.

The main characteristics of the baseline concept are: (a) total dry mass of 1452 kg, including 20 % margin and without considering the launcher adapter mass of 150 kg, (b) maximum average power consumption of 718 W and (c) fully deployed configuration dimensions of the chaser of 6.89 m(L) × 17.38 m(W) × 3.37 m(H) (the launch configuration is expected to have the following dimensions 5.32(L) × 4 m(W) × 3.37 m(H)). The chaser subsystems were sized using scaling laws that are commonly employed in spacecraft design[14, 15] and by consulting reference literature, which we cite in the rest of the paper. In Section V, we describe some of the detailed analysis conducted to obtain insight into some of the key technology drivers for our concept.

The main subsystems are defined in what follows:

Payload: A semi-rigid clamping mechanism composed of two finger-like tentacles, a robotic arm and an active de-tumbling device based on eddy currents.

Bus: An octagonal structure made of two top and bottom panels, eight side panels and internal elements (e.g., corner brackets, fasteners and stiffeners, etc., similar to what was defined in the ESA e.Deorbit study[16]).

Attitude and Orbit Control: One main, 400 N, bi-propellant OCT, 24 ON/OFF bi-propellant attitude control thrusters (ACT) (22 N each), four Control Moment Gyros (CMGs), two near-field cameras, two 3D Flash LIDAR systems, two far-field infrared cameras, two Sun sensors, three star trackers, three IMUs and two GPS receivers.

Power: Two independent, sun-tracking solar array (SA) wings, each composed of three ATV panels, 2.1 m^2[17, 18] each, for a total area of 6.3 m^2 per wing and two strings of Li-Ion rechargeable *30 Ah* batteries. Existing ATV panels were chosen to minimize the cost of the whole mission, given that they have been successfully deployed and used in space.

Telecommunication: three omni-directional X-band antennas for direct connection with ground stations and three TDRS S-band antennae.[19]

The main technical budgets are:

Mass: 276 kg for the structure, 88 kg for the thermal control subsystem, 20 kg for the mechanisms, 16 kg for the communications subsystem, 18 kg for the data handling subsystem, 137 kg for the

GNC/AOCS, 93 kg for the propulsion subsystem, 97 kg for the power subsystem, 3683 kg for the payload and 96 kg for the harness.

Power: The power requirements are mainly driven by the payload and the GNC/AOCS system requirements. The maximum average power consumption is 718 W and maximum peak power consumption is 759 W. The calculated requested power from the SAs to power the entire spacecraft during an orbit is 1568 W,[14] while the available power is estimated to be 1703 W (851 W per wing, End-Of-Life (EOL), solar-pointing mode). During the mission, the power output per SA wing can vary from 250 W to 851 W per wing (similar to the ATV).[20]

Propellant: The propellant required for the mission was assumed to be equal to the 25 % of the chaser dry mass,[14] thus equal to 363 kg. However, this is only a preliminary estimate and will change with the further refinement of the mission phases and maneuvers to be performed.

Cost: The cost cap for the concept was set to 200 MEuro FY2015, out of which 100 MEuro are allocated for the launch. A detailed analysis of the cost of the Agora mission is still pending and will be performed in the near future.

IV.ii Main Trade-offs

Figure 3 depicts the key mission trades-offs that were carried out. These trade-offs are explained in more detail in the subsequent sections.

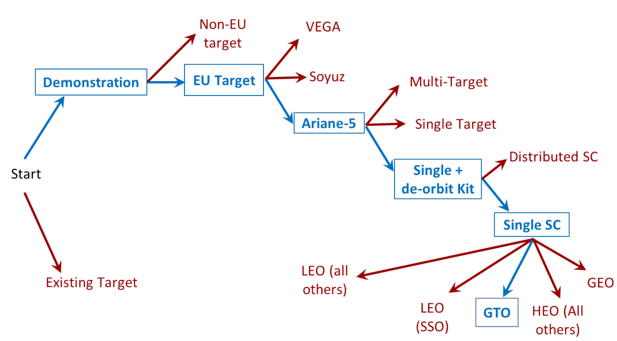

Fig. 3: Illustration of decision tree explored to arrive at Agora mission concept.

Mission type

Definition of the mission type was considered as a key trade-off early on during the study. The two options considered were: a demonstration mission which captures and de-orbits the mission R/B or a real mission which targets an existing R/B in orbit. The technologies and processes needed for an ADR mission are still immature (low TRL) and the main goal of the Agora mission is to raise the TRL of these technologies whilst incurring minimal risk. In light of this, it was decided that for Agora to serve as a stepping stone for future ADR, it would make sense to execute a demonstration mission. The outcome of Agora could be used to design and implement a subsequent mission to target a real R/B.

In order to minimize the risk of collision and to monitor all close-proximity phases, the target will be equipped with specific sensors that will be used to assess the performance of the GNC system on-board the chaser. These sensors will measure the relative position and the target's tumbling rate.

Target

A European target was selected, as legal framework to tackle non-European targets within the context of a European mission has not yet been established. Choosing a European target poses less schedule risk and is likely to face less political opposition.

Among the current European R/Bs on orbit, we selected the Ariane-5 EPS[21] as our baseline target and the Ariane-5 ESC-A[21] and Vega AVUM upper stages[22] as back-up options. The Ariane-5 EPS offers a significant advantage with respect to the other two options by providing the possibility of re-ignition and therefore, controlled re-entry in case of failure of the mission.[12]

The selected target consists of three main parts; the Storable Propellant Stage (EPS), the Vehicle Equipment Bay (VEB) and the Separation and Distancing Module (SDM). The mass considered for the target object is 3055 kg (including 505 kg of residual propellant on-board) and the approximate inertias are: $I_{xx} = 11148$ kg/m^2, $I_{yy} = 8058$ kg/m^2 and $I_{zz} = 6479$ kg/m^2.[23]

The European Space Guidelines on re-entry casualty risk acceptance require targeted, controlled re-entry if the casualty risk level exceeds 1 in 10000.[24] As a rule of thumb, spacecraft larger than 500 kg will require controlled re-entry.[25] For Agora, if the de-orbit kit cannot be inserted in the target's nozzle as required, the Ariane-5 EPS R/B is able to de-orbit itself.

Single/multi target

Given that ADR is a fairly new concept, the economics have not been fully understood yet. For large,

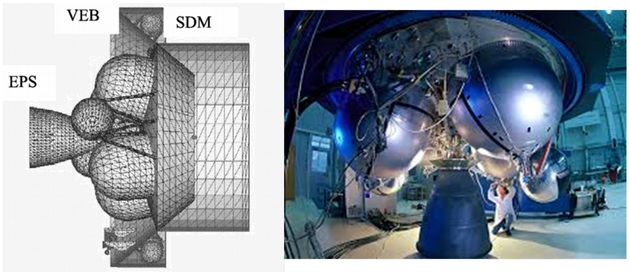

Fig. 4: Ariane-5 upper stage EPS[23] (right photograph from Airbus Defence and Space).

expensive missions, there are in principle two architectures that can be selected that have distinctly different implications on mission-level economics and risk: single-target or multi-target.

A single-target mission architecture will in general be smaller and less expensive. In the case of Agora, this comes from the fact that only one de-orbit kit is required. In principle, even if the de-orbit kit is unavailable for some reason, the single target architecture would still be possible, with the chaser-target composite de-orbiting as a whole. In addition, a single-target mission is simpler in terms of operations. However, if ADR grows to meet the capacity stipulated by studies such as by Liou, et al. (2010),[4] then it will be important to consider the cost-per-target-removed. By scaling mission concepts like Agora with multiple consumable de-orbit kits, the fixed cost for the mission could be distributed over multiple targets, potentially reducing the cost-per-target-removed. The main consideration to assess this cost is the total ΔV required for a multi-target mission.

A multi-target mission however is likely to require greater on-board redundancy to ensure that the chaser is able to execute a longer mission. Additionally, failure of the chaser early in the mission timeline would jeopardize the entire mission. This risk would have to be accounted for in the design, resulting in elevated costs. In the case of Agora, which employs a semi-rigid clamping mechanism to attain rigid contact with the target, the multi-target architecture would only make sense if multiple targets could be identified that could be clamped, e.g., the targets would all have to be similar R/Bs.

The distinct advantage of a multi-target mission is that, if successful, it would mitigate the threat posed by multiple hazardous debris objects, e.g., satellites, R/Bs etc., in a single mission. To achieve the same result with a single-target architecture, multiple chaser spacecraft would have to be commissioned and possibly multiple launches too.

For the purposes of our study, we elected to work with a single-target mission architecture, as for a demonstration mission it would be important to demonstrate all relevant technologies on a single target first.

Orbit type

Since the goal of Agora is to test ADR technologies within a representative mission scenario, the choice of orbit would play a role in dictating the outcome of the overall mission. R/Bs can be found in LEO and GTO in general; hence, our consideration was to determine which of the two would suit the needs of the Agora mission.

The option of launching to Sun-Synchronous Orbit (SSO) and operating the Agora mission in that band was discarded, as the risk of collision would be too large. The advantage of operating in a non-SSO LEO is that it would give us the possibility to de-orbit the target efficiently, including in case of mission failure. Moreover, the natural decay time for low LEOs would likely satisfy the "25-year rule" adopted in the Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines.[26] For GTO, passive de-orbiting in this manner would not satisfy this rule; hence this brings greater risk to the overall mission and means that contingencies have to be put in place to ensure that we do not add to the current debris population. Controlled de-/re-orbiting in GTO would also have to take into account the possibility of elevated collision risk, as multiple orbital bands are crossed in the path of the target.

Adopting a LEO as the baseline for Agora would also favor the mass considerations, since the launcher would be able to place a greater total mass on-orbit. However, it is important to consider the most likely secondary launch opportunity available for Agora. Considering the typical Ariane 5 launch, it is much more likely that a future launch would place us in GTO[11,27] Hence, from a programmatic perspective, designing around the baseline of GTO would likely result in much lower overall risk to the mission goals.

The inertial velocities involved in LEO are also higher than for higher orbits. This brings with it a degree of complexity for proximity operations. In the case of GTO however, the complexity is not reduced; on the contrary, GTO is likely to pose greater risk to the mission, given the large difference in velocity between perigee and apogee. LEO is characterized by high Earth albedo and thermal radiation, significant eclipses and high temperature gradients. These would all have to be taken into account, especially in case operations for Agora are extended over weeks.

The most compelling reason for us to select GTO for Agora is that it allows us to map directly the outcome of the mission to a follow-up aimed at removing an Ariane R/B in GTO. There are many Ariane R/Bs in GTO; hence there would be a 1-to-1 correlation between the outcome of Agora and any subsequent mission to remove a real R/B. In LEO, at present there are a number of Ariane 4 R/Bs and only a select few Ariane 5 R/Bs. Hence, we opt for GTO as the baseline, with the option to fall back on a LEO during further studies if needed.

V. Key technologies

The goal of our study was to investigate an ADR mission concept and highlight the steps forward to materialize it. In light of this, we present some of the key technologies that we identified as being drivers for the overall concept. These technologies are deemed either low TRL, requiring further studies to prepare them for Agora, or have significant impact on the mission. The key technologies that have been identified during our study are:

- Coil design
- Thermal subsystem design
- AOCS/GNC design

We elucidate the challenges and possible solutions relating to these technologies in the following subsections.

V.i Coil design

Since the de-tumbling system is novel and has not been flown in space, we identify it as a key driver for Agora. It is imperative that future studies characterize the impact of the coil design on the overall performance of the mission. In this study, the de-tumbling system has been analyzed and a baseline concept has been generated, taking into account the underlying physics and the mission constraints and goals.

The coil employed for the de-tumbling subsystem is fixed to the chaser, accounting for the maximum radius allowed by the fairing of the Ariane-5 SYLDA launcher. Our nominal design for the coil will have a radius of 1.65 meters and 500 turns. Moreover, we selected a standard high temperature superconducting wire of second generation (HTS 2G) for the coil (e.g., SCS4050 wire manufactured by SuperPower).[28] The total mass of the wiring needed is 18.5 kg. The coil will operate at 65 K and the current intensity of the coil is baselined as 115 Amperes, which is below the critical intensity at this temperature. This guarantees that the coil will always work in the superconducting state and avoid the quench of the wire.[29] In order to keep an isothermal temperature along the coil, the wire is insulated and embedded in a loop heat pipe (LHP) and a cryocooler is used for the heat extraction.[30]

An important aspect to be considered in the chaser design is the possible electromagnetic interference caused by the coil. The maximum field will appear at the center of the coil and for the baseline design it corresponds to 0.06 Teslas. Sensitive equipment such as magnetometers should be avoided or shielded with mu-metal alloy.[31]

V.ii Thermal subsystem

Given that the operating temperature of the HTS wires is critical to the performance of the de-tumbling system, the design of the thermal subsystem was identified as an important driver for the sizing of the chaser. Firstly, we analyzed the complete system using a passive thermal insulator, to ascertain if it is possible to keep the HTS wires below the critical temperature. The different sources of heat exchange between the coil and the environment are depicted in Figure 5. The magnetic coil is insulated with MLI (Multi Layer Insulation), which has a low thermal conductivity at low pressures. The MLI is modeled as a solid insulator with a thermal conductivity of 0.0004 $W \cdot m^{-1} \cdot K^{-1}$ at a pressure of 10^{-5} Torr.[32] In addition, the whole system is covered with a containment material that has a low absorptivity and high emissivity like silvered teflon, which has an absorptivity of $\alpha = 0.08$ and an emissivity of $\epsilon = 0.66$.[32]

The thermal balance equation (Equation 1) applied to the magnetic coil takes into account the heat received from external and internal sources and the heat radiated to space,[15] where Q_{sun} is the solar radiation, Q_{albedo} is the albedo radiation, $Q_{infrared}$ is the infrared heat radiated from the Earth and Q_{coil} is the conductive heat transferred from the insulation layer to the HTS wires. In this analysis, it was assumed that the largest projected area of the coil is seen both by the Sun and the Earth, which corresponds to the worst-case scenario. Figure 6 shows the heat flow that must be prevented from flowing into the wires, to prevent the temperature from rising above 65 K. For the baseline GTO orbit, the highest heat flow takes place at the perigee of the orbit. For an insula-

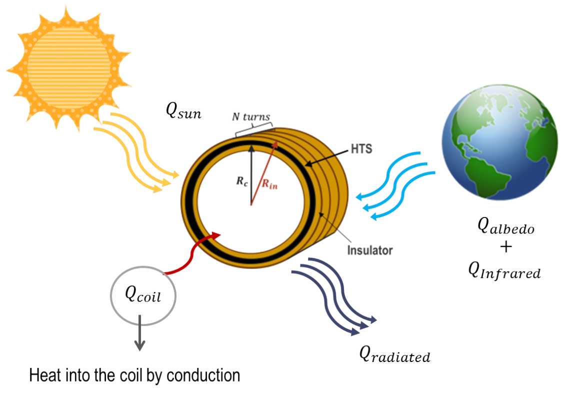

Fig. 5: Heat exchange between the coil and the environment.

tion thickness of 1 cm, the heat flow corresponds to 6 W.

$$Q_{sun} + Q_{albedo} + Q_{infrared} = Q_{radiated} + Q_{coil}. \quad [1]$$

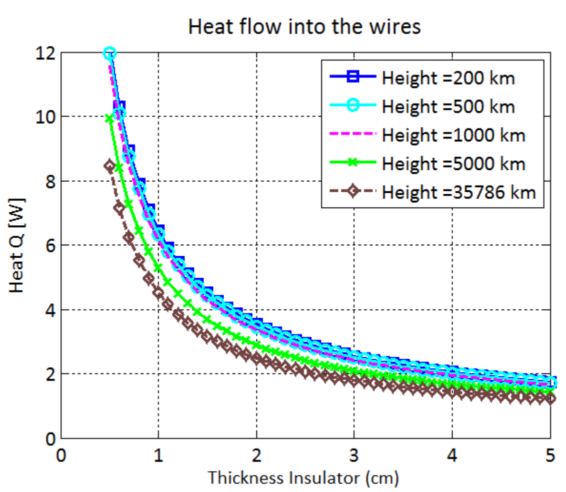

Fig. 6: Convective heat flow to the HTS wires at different altitudes.

A number of different thermal control systems were considered during trade-off analysis. Passive thermal shields have been discarded for several reasons. First of all, the coil needs to be protected from both the Sun's and the Earth's radiation and this would require a large shielding area, which would pose a major challenge to package within SYLDA. Moreover, the chaser may need to acquire different relative orientations with respect to the target object in order damp all the components of the angular velocity vector[9] and this may not be possible with a thermal shield that highly restricts the relative orientation of the chaser with respect to the Sun and the Earth.

The next two options considered are a dewar-based system or a cryogenic LHP system. The dewar-based system is a simpler solution but it has two main disadvantages: it requires additional volume to carry accommodate cryogenic liquid on-board and the thermal subsystem lifetime is finite. Figure 7 depicts the mass of nitrogen needed for different heat loads and operational times. For 6 W heat flow and 1 month of operational time, the mass needed is approximately 80 kg, which is not negligible.

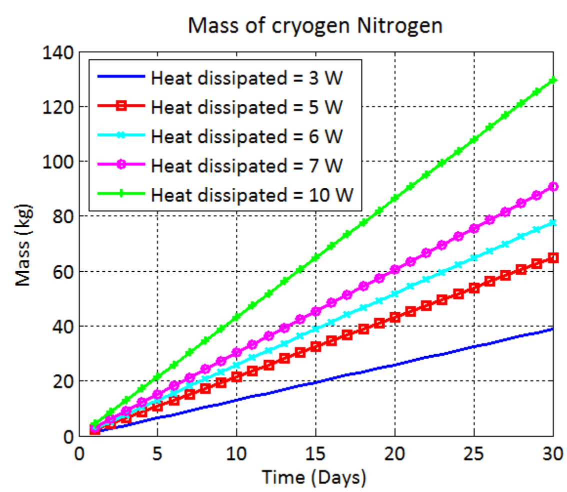

Fig. 7: Mass of nitrogen needed for a dewar-based system for different heat loads and times of operation.

In order to avoid restrictions in the operational time and reduce the volume of the cooling system, the cryogenic LHP system has been chosen as the baseline. Kwon et al. (2012) published a patent for keeping a superconducting coil at cryogenic temperatures.[30] The coil is embedded in a LHP and the working fluid is cooled down by a cryocooler in one of the sides of the LHP.

With respect to the cryocoolers that can be used, there is a major difference between this application and other space missions. Space-qualified coolers are usually built to operate for multiple years in space. In order to ensure such a high reliability, their cost is very high.[33] However, the de-tumbling phase should be of the order of weeks and a non-space cryocooler could be suitable, which then would lead to a significant reduction in cost. The major reason why this type of cooler is not used in space is the fact that they have seals (e.g., o-rings) and bearings that cannot be relied upon for a typical 10-year mission. Nonetheless, such a cryocooler should still need to go through an exhaustive test campaign in order to guarantee that it can survive the launch vibrations, space environment, etc. This process has already been carried out for the VIRTIS instrument on the Rosetta mission by RICOR.[34] Cryocooler K535, manufactured by RICOR, has been selected as baseline for the thermal subsystem, as it meets the requirements for Agora.[35]

V.iii AOCS/GNC

The GNC subsystem for Agora is highly complex, given the stringent demands for on-board autonomy, the fact that the target is non-cooperative, and the fact that the baseline orbit is GTO, i.e., an elliptical orbit. Hence, it is imperative that a robust Rendezvous and Capture (RVC) control system is designed for the mission. The GNC subsystem on-board the chaser plays an important role in the whole RVC control system. The RVC control system has to ensure the success of the following tasks:

- Safe rendezvous with the target
- De-tumbling of the target, while maintaining a constant relative distance and orientation between the chaser and the target
- Capture of the target, while damping out any residual tumbling of the target and stabilization of the composite system.
- Manipulation and placement of a de-orbit kit inside the main engine nozzle of the target
- Reorientation of the composite system and disengagement from the target

Figure 8 illustrates the architecture of the RVC control system for Agora, which includes: (a) navigation, (b) guidance, (c) control, (d) detumbling, (e) robotics, (f) Mission Vehicle Management (MVM) and (g) Failure Detection, Isolation and Recovery (FDIR).

The modules that determine the autonomy of the RVC control system are the MVM and the FDIR modules. The MVM module is responsible for activating the relevant hardware and software modes according to the current mission phase, as well as managing any hardware redundancy.[36] The FDIR module is responsible for detecting any anomaly at the lowest level possible. Once a potential failure has been detected, the FDIR module is responsible

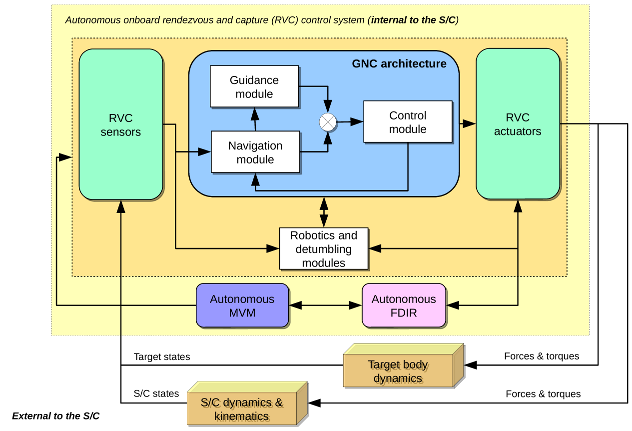

Fig. 8: Autonomous onboard rendezvous and capture control system architecture.[13]

for reconfiguring the system to recover from the contingency. If the system does not recover from the anomaly, the mission is interrupted or aborted.[36]

The GNC system is critical for optimal mission performance. For example, during the de-tumbling phase, the chaser has to maintain a fixed relative distance and relative pointing with respect to the target. The relative distance is important, since the de-tumbling process is more efficient if the chaser is closer to the target, as the magnetic field is inversely proportional to the cube of the distance.[9] In addition, maintaining the relative pointing with the target is important to optimize the de-tumbling process. For instance, if the magnetic field induced at the COG of the target is parallel to the angular velocity vector, the eddy current torque will be zero; the torque reaches its maximum if the magnetic field is perpendicular.[9] However during the de-tumbling operation, the chaser is subject to external torques and forces that must be counteracted by the AOCS. The main external perturbations are generated by the de-tumbling process itself, due to the interaction of the coil with the Earth's magnetic field, and the interaction of induced magnetic field between the chaser and the target. For the nominal Agora mission orbit, the Earth's magnetic field exceeds the eddy current torque by several orders of magnitude in the vicinity of the perigee in GTO.

Fly-around phase

The fly-around phase is important as the de-tumbling and capture phases depend strongly upon it. During the fly-around phase, the pose (relative position and orientation) of the target is estimated and visual inspection of the target is conducted. A high degree of accuracy is required in the estimation to provide the data required to maximize the efficiency of the de-tumbling system, or to design a safe path (passively safe) for the capture of the target.

In order to achieve this task, the GNC system has been equipped with a GoldenEye 3D Flash LIDAR† to generate a 3D reconstruction of the target geometry. The chaser also includes a set of cameras (optical and infrared) to provide vision-based navigation. Both scanning LIDAR and 3D Flash LIDAR provide good relative position accuracy at distances of up to several kilometers and good relative orientation accuracy at short distances. We selected 3D Flash LIDAR because in a single flash laser pulse, it provides a three-dimensional mapping of the target without the need for moving parts. 3D Flash LIDAR systems enable ten to hundred times the rate of conventional scanning systems, which can be translated to a maximum of thirty three-dimensional images per second.[37] In contrast to scanning LIDAR systems, 3D Flash LIDAR systems do not have moving parts. Together with the rapid acquisition of data, 3D Flash LIDAR provides measurement without blurring or inaccuracies due to platform motion.[38] In addition, the 3D Flash LIDAR can be used as a redundant video guidance system. The major drawback at the moment is that 3D Flash LIDAR systems do not have the same flight heritage as scanning LIDAR systems; hence, although the 3D Flash LIDAR has been nominally selected as baseline, further studies must analyze the risk of the lower TRL to the overall mission. We maintain the scanning LIDAR as a backup option.

The drawbacks of LIDAR systems are its high power consumption and minimum range limitation due to a small Field-Of-View (FOV). In order to overcome the high power consumption requirement, a set of inexpensive camera sensors are used to provide power-effective and accurate relative pose estimation during high-power phases, like the de-tumbling phase.

It is not only crucial to estimate the pose of the target with a high degree of accuracy but also the state of the chaser. In order to eliminate the ambiguity between the pure rotation and translation,[39] the GNC system has been equipped with a set of classical AOCS sensors, Inertial Measurement Units (IMUs), and a set of Sun and Star extero-receptive sensors, to compensate for IMU output drift.[36]

† Advanced Scientific Concepts Inc. (ASC)

De-tumbling phase

We determined the magnetic tensor of the target object based on the four aluminium propellant tanks, as they contain the majority of metallic materials within the structure. The tanks have been modeled as spherical shells: 1410 mm in diameter[40] and 4 mm thickness[41] made of Al7020,[42] which is a typical aluminium alloy used for cryogenic propellant tanks in space. The total percentage of conductive mass versus the total mass of the target is 8.8%. An efficiency loss of 5% has been included due to the non-uniformity of the field generated by the coil.[9]

The mean characteristic time of decay of the angular velocity has been obtained by averaging the principal inertias of the target provided in Section IV.2.2. This parameter indicates the exponential rate of decay of the angular velocity of the target and has been evaluated for different relative distances between the coil and the COG of the target, as shown in Figure 9.

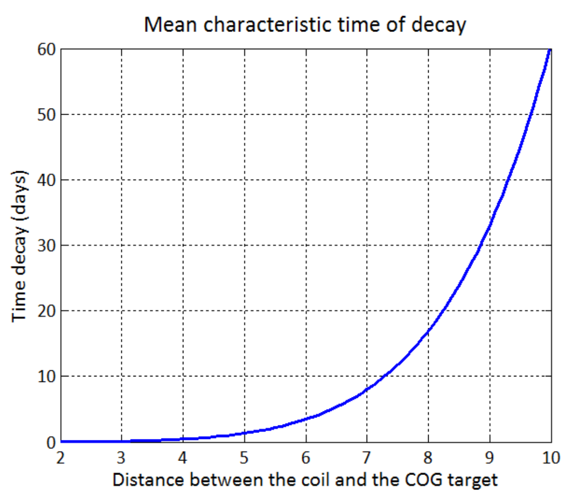

Fig. 9: Mean characteristic time of decay of the angular velocity of the target.

The results obtained for the mean expected de-tumbling time may be conservative if additional metallic components are present, other than the aluminium tanks considered in our analysis. However, these initial results show that the necessary operational time to reach final angular rotations of < 1 deg/s may be of the order of months at the selected relative distance of ten meters, which would have a high impact on the overall mission. A possible solution is to add an additional phase, between the de-tumbling and the capturing phases, to synchronize the relative motion between the chaser and the target once the angular rate is below 5 deg/s. This might help reduce the operational time of the de-tumbling process. Moreover, there are several design parameters that can be modified in order to enhance the eddy current phenomenon. The magnetic dipole of the coil, m_c, can be computed as:

$$m_c = \pi R_c^2 N_c I_c, \qquad [2]$$

where R_c is the radius of the coil, N_c is the number of turns and I_c is the intensity of the current passing through the coil. The radius of the coil cannot be increased due to restrictions in the available volume of the fairing. However, the number of turns and the current intensity can both be increased by reducing the working temperature below the baseline 65 K. In this way, the critical current intensity and magnetic field of the coil are not surpassed and the superconductive state is guaranteed. This, however, necessitates further analysis of design of the thermal subsystem, to ensure that a lower operating temperature can be maintained, without pushing the overall mission concept beyond the top-level constraints (total mass, cost cap, total volume).

Approach and capture

The final approach and capture starts from a relative distance of 10 m and consists of four individual phases (attitude estimation till de-orbit kit insertion; see Section IV). Our design requires the first three phases to be performed on batteries, with a considerable degree of autonomy due to the close proximity to the target and thus limited reaction time available for dealing with contingencies.

The clamping mechanism will be in the stowed configuration until the approach phase for safety purposes. During the approach, the chaser tracks a forced trajectory that can ensure passive safety of the spacecraft (akin to the path employed for ATV approach to the International Space Station (ISS)[43]), while at the same time satisfying the requirements for the capture, i. e., moving along the plane parallel to the one containing the center of mass of the target and perpendicular to the axis of symmetry of the main engine. Any residual relative motion is matched at this point. The AOCS is completely shutdown 1-2 m from the target, to avoid random reactions of the system as a consequence of contact between the chaser and the target that could lead to damage.[19] In the event of contingency, a Collision Avoidance Maneuver (CAM) would return the spacecraft to a holding point at 50 m distance from the target.

The capture of the target is to be assumed successful when the clamp has been closed around the target and the self-locking mechanism has been activated.[44] At this point, the AOCS is reactivated with the purpose of stabilizing the chaser-target composite and re-orienting it to achieve maximum performance of the SAs. The main challenge of capturing the target with the clamping device stems from the need to achieve the right timing and closing speed of the fingers, such that the "capture before touching strategy"[8] can be applied at the designated capture area. The speed of 5 deg/s has been proven to be suitable in a similar mission study,[19] thus it is considered here as a baseline.

The robotic arm is used in the following phase to inspect the target and manipulate the de-orbit kit. The free-floating, "supervised" control strategy for the chaser is employed during this phase, making the system susceptible to the dynamical coupling between the base and the arm, but more robust, with regards to the error of the End-Effector (EE) position and orientation and energy efficiency.[44] The insertion of the de-orbit kit inside the nozzle is performed so as to achieve compliant contact with internal surfaces of the nozzle. The fixture of the de-orbit kit could occur using a corkscrew mechanism,[45] however its design was outside the scope of this paper. For the baseline concept, we elected to employ the D3 de-orbit kit[46] under development at D-Orbit[‡], which is slated for a first test flight in 2016.

We generated a preliminary, custom design for the clamping mechanism, since a ready-to-use device is currently unavailable for this kind of mission. All the solutions we found were either too massive and stiff to implement on a spacecraft or too flexible to dissipate any residual relative motion. Thus, a solution was needed to embrace the target without touching it, capable of dissipating any bouncing energy, resulting from off-nominal closure of the clamping device, while at the same time being light and stowable. The concept developed, illustrated in Figure 2, is inspired by the design of a finger of a humanoid robot (Figure 10). The design is stowable and light, while complying with the requirements for capture of the target. The physical characteristics of each finger of the clamping mechanism are: maximum length of 4.73 m, maximum width of 0.62 m, and mass of approximately 48 kg. The total estimated mass of the device, including its supporting structure, is approximately 120 kg. The control of the clamping device is relatively simple, given the mechanical nature of the design, consisting of open/close commands to be executed by a proportional-derivative (PD) controller.

However, use of the clamp poses more stringent requirements on the AOCS, in comparison to a

‡ http://www.deorbitaldevices.com

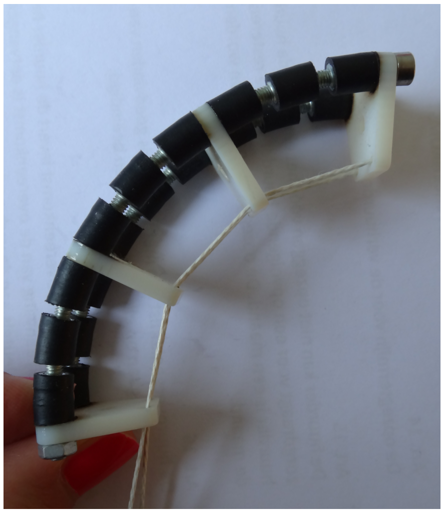

Fig. 10: Prototype of the finger of the clamping device[13]

robotic-arm-only configuration,[19] where the robotic arm would be used to place the de-orbit kit inside the nozzle without the chaser capturing the target. To analyze both scenarios, we executed multi-body simulations using the MSC ADAMS[§] simulation software. The results from these multi-body simulations indicate that for the same problem definition, the clamp configuration introduces significantly less attitude disturbance to the base spacecraft during the manipulation of the de-orbit kit. Moreover, in the arm-only configuration, the gimbal nature of the main nozzle poses an additional constraint on the precision of the final pose of the EE. These constraints are more relaxed in the clamped configuration, given that the chaser and target are rigidly connected and no relative motion results from non-compliant impact. In case of a complete shutdown of the spacecraft, the rigid, mechanical connection will be maintained, reducing the overall safety risk of the mission.

The robotic arm used to place the de-orbit kit is assumed to be a modified version of the manipulator designed for the DEOS mission,[47] consisting of seven rotating, torque-controlled, joints connected with a lightweight structure made of an aluminum alloy. The peak consumption of the arm is estimated to be around around 100 W in the operational mode and around 50 W in the stand-by phase.[48] The physical characteristics of the manipulator are: maximum length of 5.25 m, diameter of 0.14 m and weight of 55 kg. The control strategy for the manipulator is twofold depending on the phase. During the inspection and approach phases, the manipulator is controlled using a Bias Momentum Control (BMC), in order to reduce the disturbance of the base spacecraft. Immediately before the insertion of the de-orbit kit inside the nozzle, the control strategy is changed to impedance control, in order to generate compliant contact.[44]

De-orbit phase

After the de-orbit kit has been firmly attached to the main engine of the target, the robotic arm will return to its stowed configuration and the chaser will initiate the disengagement phase, consisting of the re-orientation of the composite to the predetermined position and orientation, in the Earth-Centered Inertial (ECI) reference frame. Subsequently, the chaser will release the target and retreat to a safe distance of at least 50 m. At this stage, the de-orbit kit will be ignited and a single-burn, controlled re-entry of the target object will be executed.

Full, on-board autonomy is not necessary during these final phases, since all operations can be performed safely via remote commands from the ground. The D3 de-orbit kit selected is capable of effectively and safely disposing a target object via controlled reentry. It is an autonomous kit, based on solid propulsion, with an estimated mass of 144 kg and equipped with its own avionics system.[46]

VI. Conclusions

In this paper, we presented an ADR mission concept called Agora to target Ariane R/Bs. We detailed the top-level mission requirements and boundary conditions used to engineer the concept. Subsequently, we provided a brief description of the overall concept and detailed some of the key trade-offs conducted. We presented details of some of the key trade-offs to provide insight into the most important factors that influence the overall sizing of the mission.

The major outcome of this study is to identify the key technologies that drive the concept. These are technologies that have a large impact and/or are deemed a risk at the current stage. Characterizing these key drivers and their impact on the overall mission helps map the future work required to translate Agora into a feasible proposal.

It is clear that further work has to be done on the de-tumbling system to ensure that the associated risk can be minimized. The de-tumbling system represents a unique technology to tackle the difficulty of a wide spectrum of rotational states of the target and is a viable alternative to synchronization of the chaser

§ http://www.mscsoftware.com/product/adams with the target. To ensure that the de-tumbling system can be employed for this purpose for Agora, further studies should be dedicated towards full characterization and optimization of the design of the coil. In addition, simulations should be conducted to more precisely estimate the control effort required to maintain the configuration during the de-tumbling phase. Additionally, since the de-tumbling process is likely to last longer than a single orbit, it is important to understand the impact of passing through perigee on the rotational state of the target.

Furthermore, the de-tumbling system also impacts the rest of the design of the chaser. In particular, it is evident that analysis of the thermal subsystem is essential to determine the performance envelop of the chaser. Further work should be geared towards understanding the interplay of these systems and developing a more in-depth design of the cooling system on-board the chaser.

The GNC and AOCS systems are also identified as key drivers for the overall concept. The performance of the Agora mission depends on the ability of the GNC and AOCS systems to deliver the necessary accuracy and precision during close-proximity operations. The GNC system must ensure that close-proximity operations are safe and that the approach path is passively safe, such that anomalies do not raise collision risk. In addition, given the short reaction times, it is important that the chaser is fully-autonomous during close-range phases. Hence, the requirements on the MVM and FDIR must be established carefully in further research, to characterize the nature of the autonomy required on-board. Furthermore, rendezvous and close-proximity operations in an elliptical orbit also pose a challenge. Simulations are necessary to provide insight into the optimal guidance path, required sensor suite and necessary control effort to maintain and release relative position and velocity with respect to the target.

Agora fits within the global framework of ADR technology development and is a counterpart to missions such as ESA's e.Deorbit and DLR's DEOS. It is important that future work takes this into account, to ensure that parallel studies can be continued, whilst at the same time leveraging shared effort to move forward towards the realization of ADR.

VII. Acknowledgements

The research work here presented is supported by the Marie Curie Initial Training Network Stardust,[49] FP7-PEOPLE-2012-ITN, Grant Agreement 317185. Thus, the authors would like to thank the European Commission and the Research Executive Agency for their support and funding.

References

[1] D.J. Kessler and B.G. Cour-Palais. Collision frequency of artificial satellites: The creation of a debris belt. *Journal of Geophysical Research*, 83 (A6):2637, 1978.

[2] T.S. Kelso. Analysis of the Iridium 33 Cosmos 2251 collision. Technical report, 2009.

[3] A. Tan, T.X. Zhang, and M. Dokhanian. Analysis of the Iridium 33 and Cosmos 2251 collision using velocity perturbations of the fragments. 3 (1):13–25, 2013.

[4] J.-C. Liou, N.L. Johnson, and N. M. Hill. Controlling the growth of future LEO debris populations with active debris removal. *Acta Astronautica*, 66(5-6):648–653, 3 2010.

[5] J.-C. Liou. An active debris removal parametric study for LEO environment remediation. *Advances in Space Research*, 47(11):1865–1876, June 2011. ISSN 02731177. URL `http://goo.gl/cF3HlX`.

[6] ESA. Statement of Work: Phase B1 of an Active Debris Removal mission (E.DEORBIT Mission. Phase B1). 2015.

[7] C. Bonnal, J.M. Ruault, and M.C. Desjean. Active debris removal: Recent progress and current trends. *Acta Astronaut.*, 85:51–60, April 2013. ISSN 00945765.

[8] K. Wormnes, R. Le Letty, L. Summerer, H. Krag, R. Schonenborg, O. Dubois-Matra, E. Luraschi, J. Delaval, and A. Cropp. ESA technologies for space debris remediation. In *6th European Conference on Space Debris*, pages 1–2. ESA, Darmstadt, Germany, April 2013.

[9] N. Ortiz Gómez and S.J.I. Walker. Eddy currents applied to de-tumbling of space debris: Analysis and validation of approximate proposed methods. *Acta Astronautica*, 114:34–53, 2015.

[10] ESA. Discos (database and information system characterising objects in space). On-line, 2015. URL `http://www.esa.int/`.

[11] Scitor under contract to JFCC SPACE/J3. Space-track website. On-line, June 2015. URL `https://www.space-track.org`.

[12] M. Jaeger and G. Lassourd. Re-ignitable EPS upper stage providing full versatility for Ariane-5. In *59th International Astronautical Congress*, 2008.

[13] M. Jankovic, K. Kumar, N. Ortiz Gómez, J.M. Romero, F. Kirchner, F. Topputo, S.J.I. Walker, and Vasile M. Spacecraft Concept for Active De-Tumbling and Robotic Capture of Ariane Rocket Bodies. In *ASTRA 2015 Proceedings*. ESA, European Space Agency, Noordwijk, the Netherlands, May 2015. URL http://goo.gl/uM4x7Z.

[14] J.R. Wertz and W.J. Larson. *Space Mission Analysis and Design*. 1999.

[15] P. Fortescue, J. Stark, and G. Swinerd. *Spacecraft Systems Engineering*. John Wiley and Sons., 2003.

[16] R. Biesbroek. The e.Deorbit CDF Study. 2013.

[17] ESA. ATV Service Module. On-line, July 2015. URL http://goo.gl/K7cImB.

[18] P. Blau. Automated Transfer Vehicle-Spacecraft Information. On-line, 2013. URL http://goo.gl/6woq7D.

[19] L. Innocenti. CDF Study Report: e.Deorbit. e.Deorbit Assessment. Technical report, European Space Agency, Noordwijk, the Netherlands, September 2012.

[20] EADS Astrium. ATV JULES VERNE: Launch Kit. On-line, March 2008. URL http://goo.gl/fuWVVK.

[21] Arianespace. Ariane 5 user's manual. Technical report, Arianespace, July 2011.

[22] Arianespace. Vega user's manual. Technical report, Arianespace, April 2014.

[23] G. Koppenwallner, B. Fritsche, T. Lips, and H. Klinkrad. SCARAB - A multi-disciplinary code for destruction analysis of spacecraft during re-entry. *Proceedings of the Fifth European Symposium on Aerothermodynamics for Space Vehicles*, November 2004.

[24] ESA. ESA Space Debris Mitigation Compliance Verification Guidelines. Technical Report ESSB-HB-U-002, European Space Agency, February 2015.

[25] ESA. Position paper. space debris mitigation. Technical Report SP-1301, European Space Agency, February 2006.

[26] Inter-Agency Space Debris Coordination Committee. IADC Assessment Report for 2011. (April), 2013. URL http://www.iadc-online.org/Documents/IADC-2012-06,%20IADC%20Annual%20Report%20for%202011.pdf.

[27] Arianespace. Arianespace - Launch log, 2015. URL http://www.arianespace.com/news-launch-logs/2013-2015.asp.

[28] D. Hazelton, Y.Y. Xie, V. Selvamanickam, R. Anthony, J.C. Llambes, and T. Lehner. High-Performance 2G HTS Wire for Efficient and Reliable Electricity Supply. *Proceedings of the IEEE Conference on Innovative Technologies for Efficient and Reliable Electricity Supply*, September 2010.

[29] W. Yuan. *Second Generation High Temperature Superconducting Coils and Their Applications for Energy Storage*. Springer, 2011.

[30] D.W. Kwon, R.J. Sedwick, and D-W. Miller. Method of both cooling and maintaining the uniform temperature of an extended object. Technical Report US Patent 20120036870 A1, Massachusetts Institute of Technology, February 2012.

[31] NASA. Assessment and control of spacecraft magnetic fields. Technical Report NASA SP-8037, National Aeronautics and Space Administration, September 1970.

[32] D.G. Gilmore. *Spacecraft Thermal Control Handbook. Volume I: Fundamental Technologies.* The Aerospace Press, El Segundo, California., 2002.

[33] R.G. Ross and R.F. Boyle. An Overview of NASA Space Cryocooler Programs. June 2006.

[34] R. Bonsignori, A. Coradini, P. Drossart, and G. Arnold. VIRTIS Visual and Infrared Imaging Spectrometer for the Rosetta Mission. 1997.

[35] RICOR: Cryogenic and Vacuum Systems. Cryocoolers for scientific instruments. URL:http://www.ricor.com/products/cryocoolers-for-scientific-instruments/. Accessed: 11/05/2015.

[36] W. Fehse. *Automated Rendezvous and Docking of Spacecraft*, volume 13. Cambridge University Press, 2003. ISBN 1139440683. URL https://books.google.com/books?hl=en&lr=&id=sX7TacxPrP4C&pgis=1.

[37] J.D. Weinberg, R. Craig, P. Earhart, I. Gravseth, and K.L. Miller. Flash Lidar Systems for Hazard Detection, Surface Navigation and Autonomous Rendezvous and Docking. 2007.

[38] F. Amzajerdian, V.E. Roback, A.E. Bulyshev, P.F. Brewster, A. Carrion, D.F. Pierrottet, G.D. Hines, Larry B. Petway, B.W. Barnes, and M. Noe. Imaging Flash Lidar for Safe Landing on Solar System Bodies and Spacecraft Rendezvous and Docking.

[39] E. Kervendal, T. Chabot, and K. Kanani. GNC Challenges and Navigation Solutions for Active Debris Removal Mission. In Qiping Chu, Bob Mulder, Daniel Choukroun, Erik-Jan van Kampen, Coen de Visser, and Gertjan Looye, editors, *Adv. Aerosp. Guid. Navig. Control*, pages 761–779. Springer Berlin Heidelberg, 2013. ISBN 978-3-642-38253-6.

[40] H. Holsten. Development of the Ariane-5 upper stage. *Acta Astronautica*, 29(2):117–120, 1993.

[41] ESA. Cryogenic Main Stage (EPC). On-line, November 2005. URL http://goo.gl/sishji.

[42] A. Teissier. Ariane 4 third stage tanks with stiffened shells. In *28th Joint Propulsion Conference and Exhibit*, 1992.

[43] D. Pinard, S. Reynaud, P. Delpy, and S.E. Strandmoe. Accurate and autonomous navigation for the ATV. *Aerospace Science and Technology*, 11(6):490–498, 9 2007.

[44] M. Jankovic, K. Kumar, N. Ortiz Gómez, J.M. Romero, F. Kirchner, F. Topputo, S.J.I. Walker, and M. Vasile. Robotic System for Active Debris Removal: Requirements, State-of-the-Art and Concept Architecture of the Rendezvous and Capture (RVC) Control System. In *5th CEAS Air & Space Conference Proceedings*. CEAS, Delft, the Netherlands, September 2015. URL http://www.ceas2015.org/.

[45] P. Tadini, U. Tancredi, M. Grassi, L. Anselmo, C. Pardini, A. Francesconi, F. Branz, F. Maggi, M. Lavagna, L.T. DeLuca, N. Viola, S. Chiesa, V. Trushlyakov, and T. Shimada. Active debris multi-removal mission concept based on hybrid propulsion. *Acta Astronautica*, 103:26–35, 10 2014.

[46] D-Orbit Inc. D-Orbit Product List. URL http://www.deorbitaldevices.com/site/our-technology.

[47] D. Reintsema, B. Sommer, T. Wolf, J. Theater, A. Radthke, J. Sommer, W. Naumann, and P. Rank. DEOS: The In-flight Technology Demonstration of German's Robotics Approach to Dispose Malfunctioned Satellites. In *11th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA2011)*. ESA, Noordwijk, Netherlands, May 2011.

[48] M. Jankovic, F. Curti, R. Lampariello, and A.J. Esclusa. A Ground Experiment to Simulate a Free-floating Robot Capturing A Spacecraft. Master thesis, University of Rome, Rome, Italy, January 2012. URL http://goo.gl/PSUTKo.

[49] P. McGinty. Stardust programme: Advanced research network on asteroid and space debris manipulation. On-line, 2013. URL http://www.stardust2013.eu/.