PAVING THE WAY FOR FUTURE ON-ORBIT SERVICING MISSIONS: THE AVANTI EXPERIMENT

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Abstract: *The Autonomous Vision Approach Navigation and Target Identification (AVANTI) experiment is an in-flight demonstration of vision-based far- to mid-range autonomous rendezvous, scheduled in 2016. This paper addresses the design challenges, and the related technical advances, to develop an autonomous guidance navigation and control software able to achieve the experiment's ambitious objectives. Autonomy, software flexibility, applicability to various orbit environments, and inclusion of a robust safety concept are indeed fundamental requirements for a general on-orbit-servicing mission. In this frame, AVANTI represents the in-flight technological demonstrator of one of the on-orbit servicing essential enabling technologies: the capability to approach, identify, rendezvous with a noncooperative, passive client from large distances in an autonomous, fuel efficient, and safe manner. The expected experiment performances are discussed in conclusion to this paper.*

Keywords: *On-Orbit Servicing, Noncooperative Rendezvous, Angles-Only Navigation, Autonomy, Formation Safety.*

1. Introduction

Unmanned on-orbit servicing (OOS) and debris-removal missions are currently drawing the attention of national and international space agencies due to the versatile and strategic applications they could enable. The earliest unmanned OOS technological demonstrations date back to 2003-2005 with the U.S.'s Air Force Research Laboratory (AFRL) Experimental Spacecraft System XSS-10 [1] and XSS-11 missions. These projects employed specifically-designed microsatellites which respectively embarked a visible sensor assembly consisting of a star tracker and a imager systems (XSS-10) and a Rendezvous Laser Vision (RLS) scanning lidar system (XSS-11) as sensing instruments for the relative navigation. Subsequently, within the U.S.'s Defense Advanced Research Projects Agency (DARPA) Orbital Express mission, launched in 2007, a prototype servicing satellite accomplished autonomous rendezvous, capture, maintenance, and servicing of a surrogate next-generation serviceable satellite, by exploiting its Autonomous Rendezvous and Capture Sensor System (ARCSS) sensors' assembly [2]. In the European framework, the most remarkable in-flight demonstration of formation flying and proximity operations is represented by the Prototype Research Instruments and Space Mission Technology Advancement (PRISMA) mission, launched in 2010 [3]. During the more than two years of operational life, in fact, several guidance navigation and control (GNC) architectures (i.e., different sensors' sets with associated onboard GNC software modules) developed by the prime contractor and/or by the other members of the project have been tested and successfully demonstrated. Concerning large-scale and/or commercial OOS applications, the following projects have been investigated: the SMART-OLEV (Orbital Live Extension Vehicle) mission [4] and the DEutsche Orbitale Servicing (DEOS) mission [5]. The former envisioned a chaser satellite that docks at a client geostationary communication spacecraft in order to recover eventual fuel depletion or anomalies of the attitude and orbit control system (AOCS). The latter dealt with two purpose-built satellites, respectively playing the roles of *client* and *servicer*, to be released in a low Earth orbit (LEO) and subsequently to perform several proximity activities, comprising rendezvous, docking, berthing, and servicing. Nevertheless, both these projects never entered the satellites' production phase, mainly due to the high costs induced by the systems' level of complexity and related development costs. Currently, more sustainable alternative design strategies are under investigation. In addition, feasibility studies of debris-removal missions, either employing robotic arms or different clamping devices, are considered and traded-off within the European Space Agency (ESA) Clean Space programme [6]. Electro-dynamic tether technology is instead proposed by the Japan Aerospace Exploration Agency (JAXA) [7], as further proof of the versatility of the OOS mission concept.

Indeed OOS are demanding missions, which require the raising of the technology readiness level in several involved key technological fields (e.g., GNC algorithms, robotics and clamping devices, communication architectures). In this frame, the Autonomous Vision Approach Navigation and Target Identification (AVANTI) experiment, scheduled to be executed in 2016, represents the in-flight technological demonstration of one of the OOS essential enabling technologies: the capability to approach, identify, rendezvous with a noncooperative, passive client from large distances (e.g., > 10 km) in an autonomous, fuel efficient, and safe manner. To this end, in fact, a fully vision-based approach becomes appealing, since it simplifies an aspect of the servicer spacecraft design by exploiting simple passive low-cost sensors (e.g., optical or infrared cameras) or, as performed in AVANTI, by using a camera head of the star-tracker, already available onboard to fulfill the attitude determination task.

The development of the AVANTI experiment represents a further step in the German Aerospace Center (DLR) roadmap to enhance the expertise in the field of noncooperative rendezvous. A preliminary activity is represented by the Formation Re-acquisition experiment performed in 2011, at the end of the nominal mission timeline of PRISMA, in preparation of the operations re-handover from the German Space Operations Center (GSOC) back to the OHB Sweden facilities [8]. Afterwards, during the extended phase of the PRISMA mission (April 2012), DLR executed the Advanced Rendezvous Demonstration using GPS and Optical Navigation (ARGON) experiment [9]. In this occasion, the maneuvering spacecraft of the PRISMA duo accomplished a noncooperative approach towards the client from 30 to 3 km of inter-satellite separation over one week. The relative navigation system exploited solely the angles-only measurements coming from the star-tracker vision-based sensor. Then, a dedicated ground-based flight dynamics system carried out the routine processing of the camera images collected onboard, for the estimation of the relative orbit of the servicer with respect to the client vehicle, and for accomplishing the maneuver planning. The availability of independent and precise navigation information from carrier-phase differential GPS techniques has been exploited *post-facto* to properly evaluate the achieved performance, after the conclusion of the technology demonstration.

Starting from the so tested ground-based GNC system, the development of the AVANTI experiment required further effort to achieve the technical advances entailed by its ambitious objectives. As a whole, the main challenge lies in passing from a ground-based approach to fully autonomous onboard operations. Nevertheless, besides this change of paradigm, several other aspects related to the specific orbit scenario, to the hosting platform, and to communication and ground segment requirements influenced the design and the implementation of the AVANTI GNC software. As a result, AVANTI constitutes indeed a realistic technological demonstrator since it aims at validating practical solutions to the aforementioned crucial topics, relevant for a general OOS scenario. Therefore, after a brief description of the experiment, this paper discusses the main design challenges and the related advances in the key GNC algorithms developed for AVANTI. In conclusion of this manuscript, the expected performance of the experiment are addressed.

2. The AVANTI Experiment

AVANTI is one of the secondary scientific experiments to be accomplished within the FireBird mission, which is a DLR small-scale scientific mission for Earth observation and hot spot detection [10]. FireBird comprises a loose constellation of two satellites: TET-1, launched in July 2012, and the Berlin InfraRed Optical System (BIROS) [11], scheduled for launch in 2016. Despite the fact that BIROS is mainly designed on the TET-1 satellite bus, it embarks a cold-gas propulsion system whose nozzles provide a single-direction thrust vector. Two views of the BIROS spacecraft are shown in Fig. 1, where also some of the devices relevant for AVANTI are highlighted.

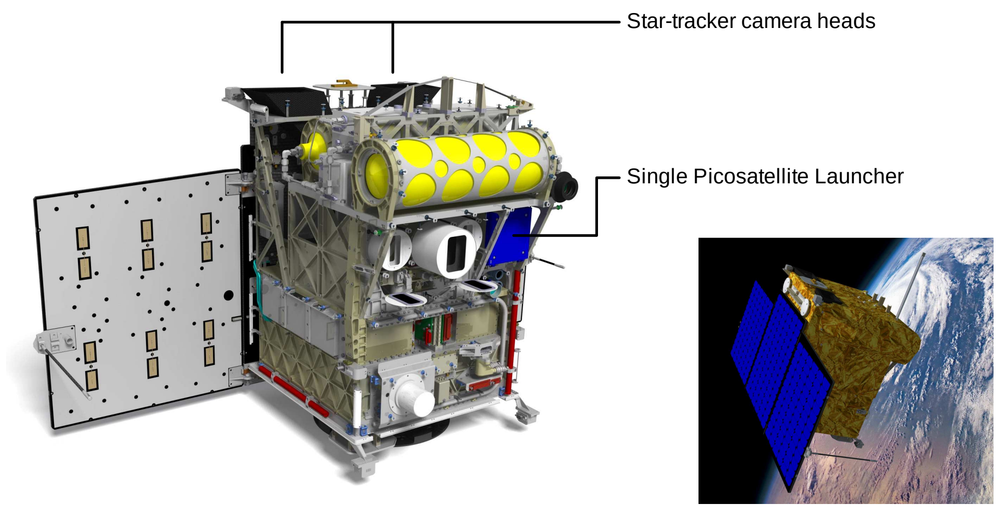

Figure 1. BIROS bus and payload assembly (left); artistic view of BIROS in orbit (right).

Among the various technology demonstrations, BIROS carries onboard the BEESAT-4 picosatellite (one-unit CubeSat) developed by the Technical University of Berlin [12]. BEESAT-4 is released in-orbit by means of a spring-based Single Picosatellite Launcher [13, 14], and, during the subsequent period of time, it is used as *noncooperative target* for the sake of the AVANTI experiment. The operational timespan allocated in the FireBird timeline for AVANTI amounts to one month. At its conclusion, the formation will naturally evaporate, with BIROS resuming its ordinary operational tasks.

The objectives of AVANTI consist in demonstrating the capability to perform autonomously far- to mid-range (i.e., 10 km to few hundreds of meters of separation range) noncooperative approaches and recedes making use of angles-only measurements. Therefore, BIROS plays the role of the active servicing satellite and uses its star-tracker as far-range camera to take images of portions of the sky. Then the autonomous AVANTI GNC system accomplishes the target identification process to extract the line-of-sight (LOS) angles to the picosatellite, the relative navigation to estimate the current relative state of the picosatellite with respect to the servicer spacecraft, and the maneuver planning to safely achieve an aimed target relative orbit defined via telecommand (TC) from ground.

The AVANTI experiment consists in different phases performing rendezvous, receding motions and formation keeping of BIROS with respect to BEESAT-4. Each phase is referred as to experiment *scenario* and it is defined by one or more relative orbit configurations to be achieved at certain acquisition times. During the course of the experiment, the up- and down-link contacts foreseen for the FireBird mission are used to send TCs and to retrieve the stored telemetry (TM), which also includes the images collected in-flight. The *post-facto* reprocessing of the retrieved TM allows monitoring on-ground the behavior of the flight SW and assessing the accuracy performances.
The typical commanding activity during AVANTI involves the group of TCs that define a scenario and the lists (i.e., start and end times) of the scheduled ground contacts. Since AVANTI is an autonomous GNC system, once that these high-level instructions are sent to the spacecraft, the GNC SW autonomously computes locations and magnitude of the maneuvers and selects the required attitude mode.
A more detailed description of the AVANTI experiment is provided in [15].

3. Design Challenges for the GNC software

The design challenges affecting the development of the AVANTI experiment are schematically sketched in Fig. 2. The central aspect is represented by the need of transferring onboard the ground-based, man-in-the-loop, flight dynamics system employed during ARGON. Nevertheless, at the practical realization level, it turns out that several particular features of the AVANTI framework, in Fig. 2 gathered around the central goal, greatly impact the SW design.

In the followings each topic is addressed, in the specific context of AVANTI.

- *Autonomy*
  The development of an autonomous embedded GNC system impacts the design of both vision-based navigation and maneuver planning systems. The former, in fact, needs to guarantee robustness and simplicity of use without sacrificing the navigation performance. To this end, the most challenging task is the ability to provide reliable LOS measurements to the navigation filter, which is related to the capability to identify the target object (i.e., the client satellite) among all the luminous spots present in the image, despite different illumination conditions and varying inter-satellite separations. The latter solves an optimum formation flying reconfiguration problem over large periods of time and in the presence of time constraints on the locations of the maneuvers, so that passive safety and delta-v consumption minimization are pursued. Simplicity and determinism are the drivers for this system, with the goal to deliver under every operational circumstance a guidance profile solution, being maneuvers also needed to improve the observability properties of the angles-only relative navigation problem. Finally, in addition to these robustness related needs, the characteristics of the BIROS onboard computer ask for GNC algorithms with low computational load, in

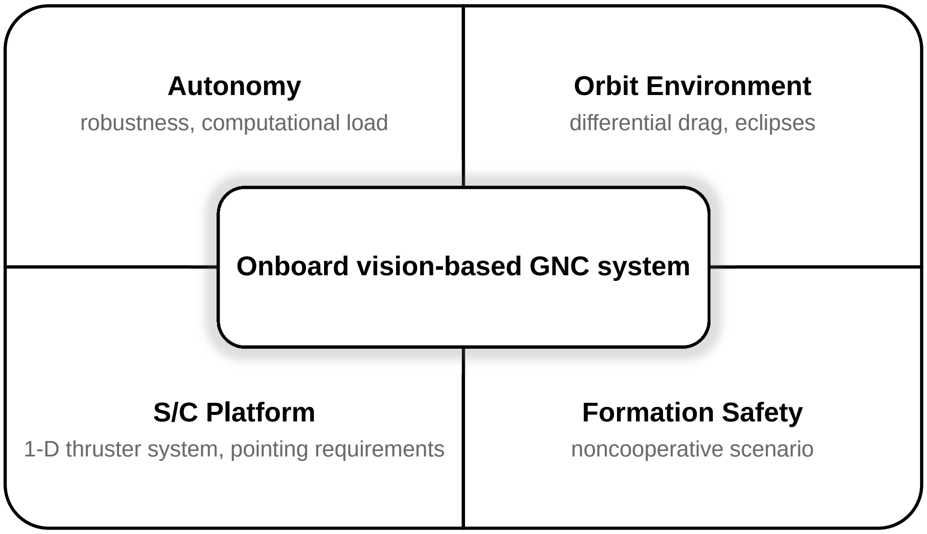

Figure 2. Features that influence the AVANTI SW design.

order to be executed in real-time.

- *Orbit Environment*
  BIROS will be injected into an almost circular, ≈515 km high, Sun-synchronous orbit with a local time at the ascending node of 2130 hrs. At this height, the difference in the ballistic coefficients of the two satellites determines a strong effect of the differential drag perturbation on the relative dynamics; aspect that was negligible during PRISMA (i.e., orbit height of 750 km at launch). In addition, and again contrarily to the PRISMA scenario (i.e., dusk-dawn Sun-synchronous orbit), BIROS experiences all year long eclipses and blinding of the camera due to the Sun, which impact the distribution of the available optical measurements. Both the inclusion of the differential drag action and the aforementioned illumination circumstances, demand for a deep revision of the algorithms developed for ARGON, to ensure optimal performance and reliability.
- *S/C Platform*
  The FireBird mission is devoted to Earth observation and hot spot detection and offers the unique opportunity to accomplish, as secondary objectives, several technology demonstrations, among which AVANTI. Accordingly, BIROS is not designed *ad-hoc* for an OOS demonstration, and therefore some of its peculiarities become restrictions, when accomplishing a purely vision-based rendezvous. An example is represented by the single-direction propulsion system. At every execution of a maneuver, in fact, the spacecraft has to slew to point the nozzles in the desired direction, resulting in a interruption of the visual tracking. A further break in the imaging of the client satellite occurs during active ground contacts, in order to allow the nadir pointing of the high-gain antenna to transmit to Earth the large quantity of data accumulated onboard during AVANTI. From the one hand, BIROS slewing activity results in gaps of images that again concern the robustness of the relative navigation system. On the other hand, in the attempt to obtain a more continuous distribution of observations, it is convenient to control the time occurrences of the maneuvers within the experiment timeline. This is obtained by defining time slots where no maneuver activities shall occur, in the form

of time constraints on the locations of the maneuvers for the onboard maneuver planner.

- *Formation Safety*
  AVANTI exhibits a truly noncooperative scenario, since during the experiment execution no picosatellite tracking data will be available, except for the images taken by the far-range camera. During AVANTI, BIROS and BEESAT-4 do not communicate through an inter-satellite link. Moreover, although BEESAT-4 embarks a Phoenix GPS receiver, being the picosatellite itself a third-party experimental activity, it is operationally ruled out that a technology demonstration depends from another one to accomplish its objectives. Alternative data sources to perform the picosatellite absolute orbit determination could be two-line-elements (TLE) and radar tracking observations. Nevertheless, within AVANTI, both these options cannot be exploited. TLE, in fact, if available at all, are typically accurate only to 1.5 km in the along-track direction. Whereas the radar tracking facility foreseen within FireBird to support the in-orbit release of the picosatellite requires a minimum inter-satellite distance of 5 km in order to distinguish the signals from the two spacecraft.
  In these circumstances the collision avoidance strategy adopted during PRISMA [16], which by the way remained active in background also during the ARGON demonstration, is not realizable. Thus, the need of formation safety influences the GNC SW design, since it has to include also a dedicated safety monitoring application, able to provide reliable outcomes in the challenging condition of the truly noncooperative AVANTI scenario.

3.1. Design Challenges as OOS requirements

The design challenges encountered in AVANTI are, as a matter of fact, ordinary requirements for realizing a realistic and general OOS mission. As evidence, the aforementioned challenges are hereafter shortly unveiled as OOS basic requisites.

- *Autonomy*
  OOS missions are definitely complex and costly space projects. In this frame, a certain level of autonomy is appealing since it helps in reducing the operational costs.
- *Orbit Environment*
  Contrarily to the case of technological demonstrators, the environmental scenario of an effective OOS mission is determined by the orbit of the client (e.g., satellite or debris). The point in time of the servicing intervention can also be dictated by contingent circumstances. Therefore, if the servicer adopts a purely vision-based strategy for the far- to mid-range approach, its GNC system has to be robust with respect to less favorable illumination conditions. In addition, whenever a mission targets a client in LEO, the effect of the differential drag perturbation most likely becomes relevant, since the servicer spacecraft might have a definitely different ballistic coefficient with respect to the client.
- *S/C platform*
  In order to cope with the BIROS design, the AVANTI GNC SW owns a certain level of flexibility. Doubtlessly, it is very unlikely that a purpose-built servicer satellite of a complex OOS mission presents platform restrictions. Nevertheless, a flexible GNC system represents a design asset for a space mission, since it can support time-tagged high-level task planning, with consequent reduction of operations burden and costs.
- *Formation Safety*
  Noncooperative scenarios arise whenever the target is a debris or an inoperative satellite or

to reduce the costs for setting-up a communication architecture between client and servicer satellites. In these cases, a formation safety monitoring tool similar to what developed for AVANTI is needed. Of course, if any additional tracking data of the client satellite (e.g., more accurate TLE, radar tracking data, laser ranging data) are available, the safety monitoring approach could benefit from them. Nevertheless, whenever a far- to mid-range rendezvous is performed fully autonomously based on solely angles-only observations, an AVANTI-type formation monitoring tool is anyway required, in order to detect eventual anomalies in the functioning of the relative navigation system. Given the weak observability of the angles-only relative navigation problem, in fact, it might be very difficult to set-up robust internal coherency checks able to detect that the navigation solution is converging to a sub-optimal solution.

4. Solutions adopted in the AVANTI GNC SW

This section presents the solutions adopted within the AVANTI GNC SW to upgrade the algorithms developed for ARGON and, in the meantime, to satisfy the design challenges discussed in Section 3..

4.1. Improved model of the relative dynamics

In continuation with several recent DLR formation flying in-flight activities, the relative motion between satellites flying in near-circular LEOs is parametrized through relative orbital elements (ROEs). The validity of this approach, in fact, is not confined to close inter-satellite separation ranges. Moreover this ROE-based formulation offers several benefits such as a direct geometrical visualization of the effects of the J_2 perturbation on almost-bounded relative orbits, the easy inclusion of the concept of passive safety of the formation through a certain relative eccentricity/inclination vector separation, and a straightforward geometrical interpretation of how the geometry of the relative orbits changes under the effect of impulsive maneuvers.
Within the development of the AVANTI experiment, the aforementioned model of the relative motion has been improved by taking advantage of the post-analysis of the flight data collected during ARGON, and by introducing the effects determined by the differential aerodynamic drag. The former contribution lead to the improvement of the modeling of the J_2 effects by including also the changes that this perturbation produces in both relative mean longitude and relative inclination vector during a drifting phase, when a non-vanishing relative semi-major axis is required. The latter step brought to augmenting the relative state expressed by ROEs with three constant additional parameters, characterized by a straightforward geometrical interpretation. The first additional quantity is the time derivative of the relative semi-major axis. The remaining two parameters are the time derivatives respectively of the x and y components of the relative eccentricity vector, which are non-vanishing in the presence of atmospheric density oscillations produced by day and night transitions.
Together these improvements resulted in a simple, though accurate over extended time periods, and complete model for the relative motion in near-circular LEOs. Being such model fully linear in the initial, extended, relative state, its complete state transition matrix has been promptly employed in the AVANTI GNC software. Specifically, it serves as backbone for the relative orbit estimation problem, for the onboard autonomous maneuver planning problem, and for the onboard relative motion propagator of the formation safety monitoring module.

The complete formulation of the model together with its theoretical background are addressed in [17].

4.2. Robust spaceborne autonomous vision-based navigation system

The autonomous vision-based navigation system developed for AVANTI comprises two main modules: an image processing unit and a relative navigation filter. The first processes the pictures coming from the star-tracker to extract the LOS measurements. The second dynamically filters the obtained measurements. Although the implemented algorithms inherit the know-how gained during ARGON, given the robustness and performance requirements widely discussed before, several advances have been introduced.
Regarding the target identification task, priority has been given to simplicity and generality, which lead to adopt a pure *kinematic* approach to identify the possible targets and to use the luminosity information only if there is a need to discriminate between several candidates. Thus, no knowledge of the current onboard relative state estimate is exploited, since it could misdirect the search of the target-candidate in case of navigation errors. In the meantime, a very limited use of the luminosity information of the imaged spots is made, since ARGON shown that the apparent magnitude of the client object, at far-range, strongly depends on its unknown attitude and on the illumination conditions. Therefore, the kinematic approach retained for robust target identification is based on the fact that, when flying on a similar orbit, the apparent motion of the target object differs completely from the apparent motion of unrecognized stellar objects or non-stellar objects flying on different orbits, making possible to recognize unambiguously this peculiar trajectory. To this end, several images are combined and a Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm is employed, in order to isolate the spots constituting the trajectory of the client satellite. In addition, a final integrity check based on the cluster luminosity is performed, to improve the detection performance when several candidate clusters are very close to each other, thus almost equivalent for the curve fitting criterion.
Regarding the relative navigation filter, instead, differences with respect to the ARGON algorithms concern the employed filtering technique and relative motion model. In AVANTI, in fact, an extended Kalman filter is used, in order to allow its execution in real-time. In addition, such filter benefits from the improved model of the relative dynamics (discussed in Section 4.1.) and provides also the estimation of the time derivative of the relative semi-major axis, given its relevant role in the experiment scenario.
The whole vision-based navigation filter has been tested and validated in a highly realistic simulation environment and using flight data from the PRISMA formation flying mission, leading to the results presented in [18].

4.3. Flexible autonomous guidance module

The onboard guidance module developed for AVANTI accomplishes two main tasks: the computation of the orbit maneuvers' profile and the selection of the suitable attitude mode in compliance with experiment's timeline and spacecraft requirements.
The authority on the attitude profile selection has been retained in the AVANTI GNC SW, in order to achieve a flexible management of the pointing definitions required during the experiment. The BIROS ACS offers an AVANTI-dedicated attitude mode, called client observation mode, which

allows directing the boresight of the active camera head of the star-tracker to a given direction computed onboard. The attitude is then completed by a rotation with respect to such direction, which can be defined in several ways, depending on the power, thermal, and GPS antenna pointing requirements. The remaining attitude modes used during AVANTI are: the thruster firing mode, to point the single-direction thruster in a desired direction, and the Earth pointing mode, to direct the high-gain antenna towards Earth during active ground contacts.

The onboard maneuver planner unit computes the open-loop impulsive maneuvers' profile to reconfigure the relative motion from a current state to an aimed formation acquired at a certain acquisition time, with both final state and time defined via TC. The minimization of the total delta-v consumption is sought. Whereas all the flexibility requirements, motivated by the necessity to handle different attitude modes or propulsion system needs (e.g., time to first maneuver, time spacing between consecutive burns), translate into time constraints that define forbidden time intervals for allocating orbit maneuvers. Indeed this is a complex constrained optimization problem, where a final state as to be achieved minimizing a cost that is function of the time when the maneuvers are executed. The originality of the solving approach adopted for AVANTI consists in exploiting the geometrical meaning of the ROEs together with the peculiarities of the relationship between delta-v cost and ROE changes, to split the whole optimization problem into two phases. A first one which computes the sequence of ROE states, compliant with the time constraints, to achieve the aimed final state in a delta-v minimum way. At this level, in fact, the effect of different groups of maneuvers is simply seen as a *discontinuity* in the ROE space. And, consequently, the optimization reduces to a linear convex problem, due to the structure of the state transition matrix mentioned in Section 4.1. and of the relations between ROE-changes and delta-v cost. In the second phase, the maneuvers required to establish the precomputed ROE discontinuities are scheduled in the permissible time slots, by exploiting a fully analytical 4-burns maneuvering scheme (i.e., 3 in-plane, 1 out-of-plane maneuvers) that guarantees locally the delta-v minimization [19].

The solution implemented in the AVANTI maneuver planner, not only allows solving in a simple and deterministic way a complicated task. It also guarantees that, if a passively safe final state is reached from an initial one with similar relative eccentricity/inclination phasing characteristics, then the relative trajectory is passively safe during the whole reconfiguration time, provided that the drifts are small enough (i.e., the reconfiguration takes place over a long enough time horizon). This, in fact, derives from how the ROEs move in the ROE space in order to proceed along a delta-v minimum path. Further explanations and the mathematical proofs are provided in [20].

4.4. Safety concept and monitoring tool

The peculiarity of the safety concept retained to mitigate the collision hazard during the execution of the AVANTI experiment is that it does not rely on the continuous availability of tracking data of the client spacecraft but rather exploits the concept of passive safety of special relative trajectories. These are relative orbits characterized by a safe (anti-)parallel configuration of the relative eccentricity and inclination vectors. In addition, the safety concept is completed by the following safety measures: an onboard preventive action and a ground-based long-term reaction. The former prescribes that each maneuver command generated by the autonomous maneuver planner is forwarded to the AOCS system and executed only if the post-maneuver relative orbit is considered to be safe at least during the 24 hours following the evaluation time. The latter imposes that any required orbit correction maneuver (e.g., via generation of new TCs for AVANTI or directly

commanded to BIROS) is assessed on-ground, based on the analysis of the retrieved TM.
The onboard preventive action is accomplished by a dedicated unit of the AVANTI GNC SW, called onboard safety monitoring (OSM) module. This performs a precise relative orbit propagation based on the model described in Section 4.1. starting from the latest ground-based best available knowledge of the true relative state. Then, at every newly computed orbit maneuver command, it evaluates the safety of the post-maneuver relative trajectory. To this aim, the formation safety criterion based on the minimum distance normal to the flight direction has been extended in order to be applicable also to drifting relative orbits, resulting from non-vanishing relative semi-major axis encountered during a rendezvous or produced by the action of the differential aerodynamic drag. As a result, the implemented formulation of the extended safety criterion, based on the one-orbit minimum radial-normal distance, leads to an extremely light computationally methodology that provides a reliable assessment, moreover valid over long-lasting periods of time. Further details are provided in [21].

5. Expected Experiment Performance

In this section an example of rendezvous is presented, in order to provide an overview of the performance that AVANTI can achieve. These results have been accomplished by a purely software-based simulation. According to it, the two spacecraft fly in a realistic environment where all possible orbital perturbations are included. After activation, the AVANTI flight software is executed every 30 seconds, whereas all BIROS-related functions are emulated at a faster sample time, so that their characteristic behavior is faithfully reproduced (e.g., attitude guidance and control accuracy, thruster modeling). The star-tracker images are generated by a camera model that reproduces the tangential and radial distortion of the lens of the optic system, the stellar aberration, and the behavior of the charge-coupled device sensor. Regarding this last component, a radiometric model of the visible stars, a Gaussian point spread luminosity function, hot spots, and background noise are implemented. Finally, to complete this trustworthy set-up, also eclipse phases and star-tracker blinding angle are included.

The incoming plots refer to a rendezvous from 8 km of mean along-track separation, parallel relative eccentricity/inclination vectors with $\approx$ 500 m of size, to respectively 400 m separation, parallel configuration, and $\approx$ 100 m relative eccentricity/inclination vectors size. The approach starts at 2016/10/03 08:30:00 UTC and endures approximately 70 hours. During this time frame, few groups of time-tagged TCs are sent to properly steer the AVANTI SW. At the beginning the maneuver planner is set to *station keeping* mode to maintain a relative state in the vicinity of the initial conditions provided to the onboard relative navigation filter. In this way, in fact, the guidance module plans relatively small maneuvers that help the navigation filter to converge, while avoiding the potential waste of delta-v caused by undertaking a formation reconfiguration which starts from a poorly accurate initial state. Afterwards, the planner is set to *maximum observability* mode (see [20]) to accomplish the rendezvous in a step-wise manner through a user-defined number of intermediate configurations. This is the way, in fact, to realize some control on the time-distribution of the maneuvers, while avoiding that large values of relative semi-major axis are prescribed. At the end of the rendezvous, the planner is set again to *station keeping*, to coarsely keep the final relative state.

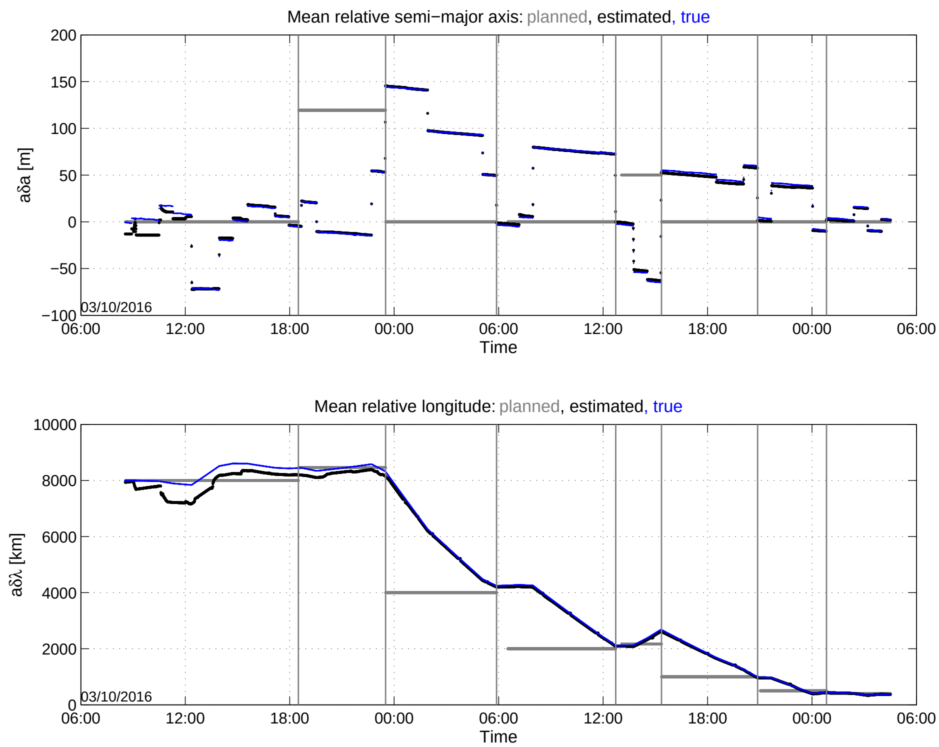

Figure 3. Navigation and control accuracy: true (blue), estimated (black), and step-wise planned (gray) trends over time of relative semi-major axis (top) and relative mean longitude (bottom).

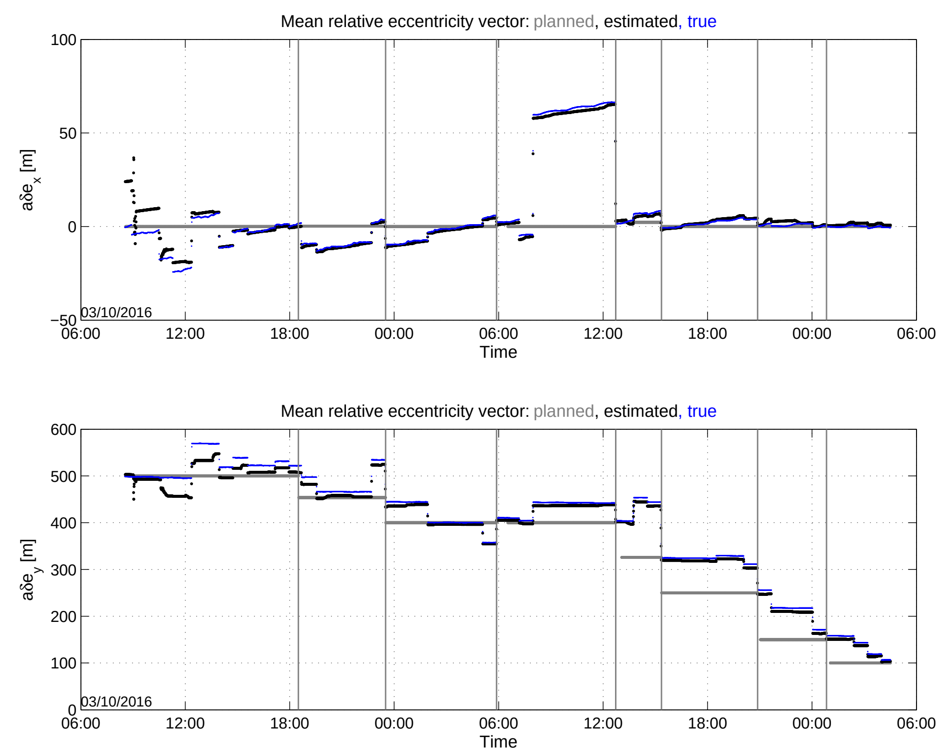

Figure 4. Navigation and control accuracy: true (blue), estimated (black), and step-wise planned (gray) trends over time of the x-component (top) and y-component (bottom) of the relative eccentricity vector.

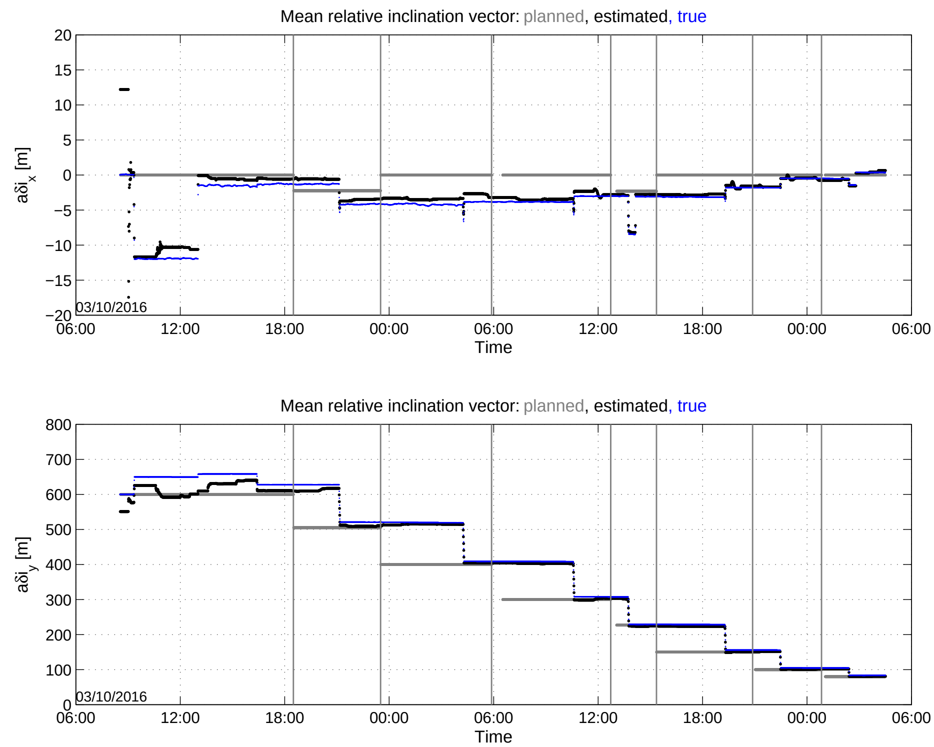

Figure 5. Navigation and control accuracy: true (blue), estimated (black), and step-wise planned (gray) trends over time of the x-component (top) and y-component (bottom) of the relative inclination vector.

The obtained profiles of the relative orbital elements over time are depicted in Fig. 3, 4, and 5. Here black dots identify the estimated values, whereas in blue it is marked the *true* profile, available from the simulation environment. The piece-wise continuous gray lines are the output of the planner. Since the guidance proceeds through intermediate reconfigurations, the control accuracy is measured by how close black and gray trends are, at the times marked by vertical thin-gray lines.
Figure 6 shows the maneuvers required to accomplish the rendezvous in consideration, with a total commanded delta-v of 1.34 m/s. According to the planner functioning, only tangential and normal burns have been performed.

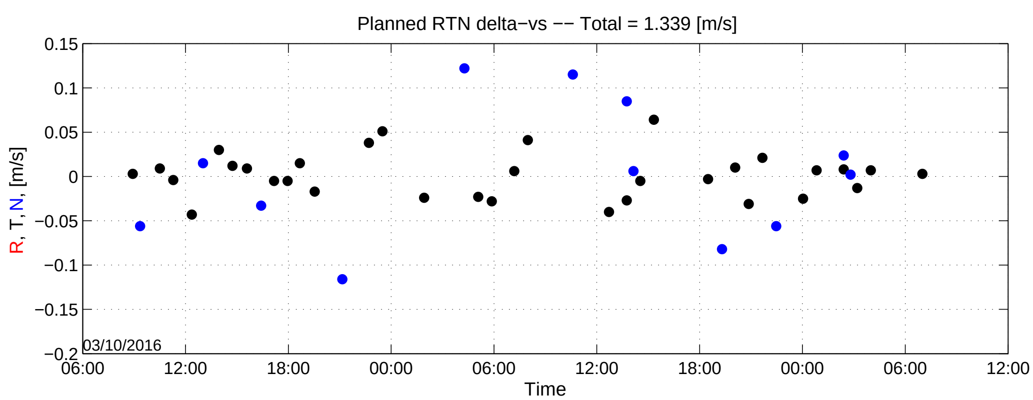

Figure 6. Commanded delta-vs over time.

The left view of Fig. 7 shows the projection of the rendezvous trajectory on the radial-normal plane. The curve presents a spiraling aspect so that passive safety is guaranteed along the whole rendezvous. The dimension of the relative orbit decreases while reducing the inter-satellite separation, whereas, in this case, the phasing of the relative eccentricity and inclination vectors is kept the nearest possible to zero. The right view of Fig. 7, instead, depicts the functioning of the safety monitoring OSM module. Points correspond to the output provided every time that the Maneuver Planner commands a new maneuver. Specifically, each point marks the lower bound of the minimum radial-normal distance criterion at the evaluation time. Recalling [21], it is computed as the expected value of the minimum RN distance distribution minus three time its standard deviation at a prediction time, here fixed as 24 hours later than the current evaluation time. By observing Fig. 7 it can be noted that, the smaller the magnitude of the relative eccentricity vector, the closer the lower bound gets to the safety margin. In other words, the effective closest approach achievable during AVANTI is determined by the adopted safety concept, which in turn is driven by the absence of independent sources of picosatellite tracking data (see Section 4.4. and [21]).

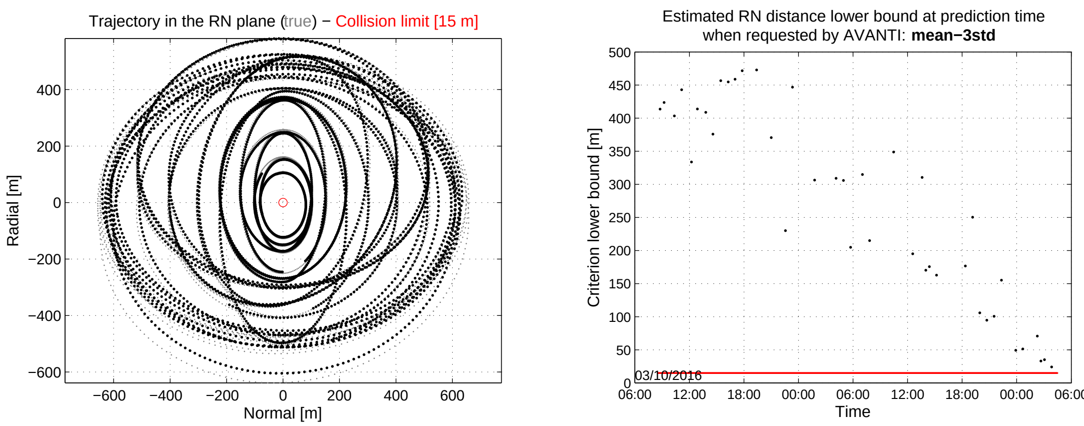

Figure 7. Estimated (black) and true (gray) trajectory projected on the radial-normal plane (left). Lower bound of the safety criterion (right).

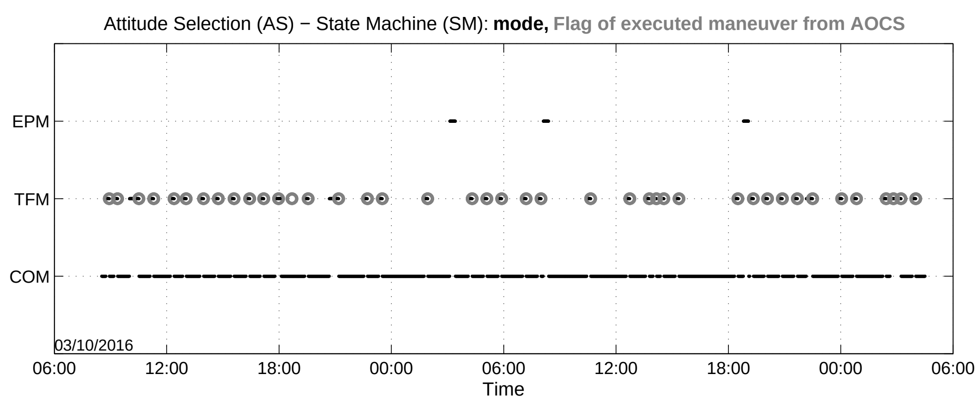

Figure 8. Selected attitude modes during the rendezvous.

Finally, Fig. 8 shows the selected attitude modes during the rendezvous. Default mode within AVANTI is the Client Observation mode (COM), in order to allow collecting images. Additionally, thruster firing (TFM) and Earth pointing (EPM) modes can also be chosen. Although the current

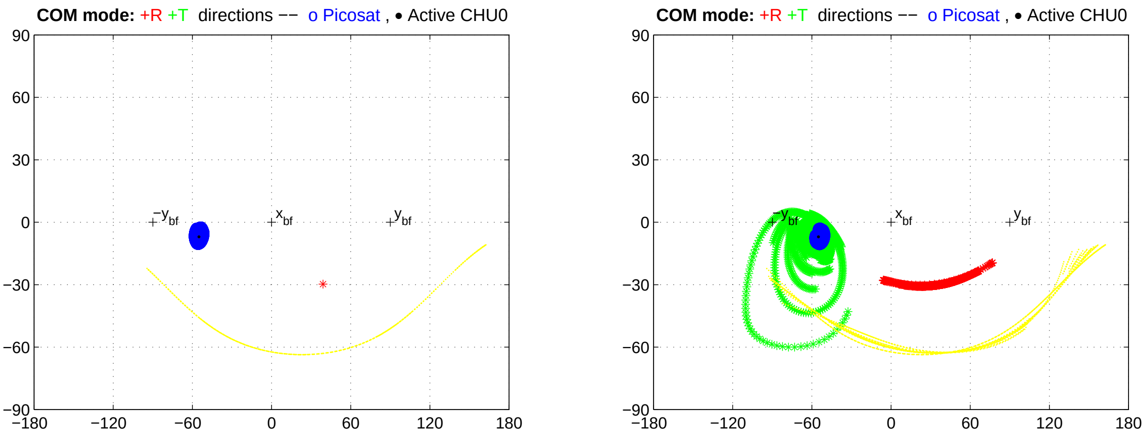

Figure 9. 2D BIROS body-frame plot of the two Client Observation Mode (COM) attitude profiles employed during the rendezvous: camera boresight aligned to the flight direction (left); camera boresight aligned to the target LOS (right).

scenario exploits three daily ground station contacts, the AVANTI GNC SW selects EPM only when no maneuver activity is overlapping, to minimize the number of times that the picosatellite exits the field of view of the active camera head. Since maneuvers can only occur in the tangential-normal plane, in fact, during TFM the high-gain antenna is anyway Nadir pointing.
Regarding the COM mode, different attitude profiles can be achieved. An example is provided in Fig. 9. In the left view the camera boresight is aligned to the positive flight direction and the picosatellite draws a relative trajectory around it (blue points). In the right view, instead, the camera boresight is aligned to the LOS to the target at a given time. Therefore, with the decrease of the inter-satellite separation, the positive tangential (i.e.,+T) direction depicts growing tracks around the center of the image (green points). In this latter case, the blue spot is due to the estimation error, since blue points are computed from the *true* picosatellite relative position. In both profiles of Fig. 9 the attitude definition is completed so that the y axis of the camera frame keeps a fixed angle of rotation with respect to the projection on the image plane of the positive radial direction. This is motivated by the attempt to improve the Sun angle with respect to the normal to the solar panel (i.e., -z_{bf}) without worsening to much the angle between the GPS antennas (i.e., -z_{bf}) and the Zenith direction (i.e., +R).

6. Conclusions

This paper addresses the Autonomous Vision Approach Navigation and Target Identification experiment, an in-flight demonstration of fully vision-based far- to mid-range autonomous rendezvous. Special focus is given to the various design challenges involved in the development of the autonomous guidance navigation and control software. In this frame, the solutions implemented to satisfy all design requisites are described. And, at the same time, the paper critically discusses how the considered design challenges represent ordinary requirements for realizing a general on-orbit-servicing mission. Realistic performance simulations show that a fully autonomous noncooperative approach, based on solely an angles-only relative navigation system, can be safely performed till few hundreds meters of mean along-track inter-satellite separation.

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