CNES — CENTRE NATIONAL D'ÉTUDES SPATIALES	**Communauté de Compétence Technique** **CCT/COMET ORB –** Orbital Mechanics	CCT — Centres de Compétence Technique http://cct.cnes.fr

Seminar:

WORKSHOP ON SPACE RENDEZVOUS

Tuesday, December 5th 2017 (9:00 – 16:30)

At the Meeting Business Center, Toulouse

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Rendezvous in space is a key capability for many challenging projects and missions, comprising distributed sensing instruments, on-orbit servicing, debris removal, assembly in space of large structures, asteroid exploration or sample return. Despite the recent achievements in this field (for example with the ATV, the PRISMA formation-flying demonstrator or the Rosetta mission), there remains a considerable need for innovative technology and methods able to support and even enable the future dreams of the space endeavor.

The workshop intends to provide a short snapshot of the current research done in this domain, which involves many disciplines. The morning session will be dedicated to the relative guidance and control during a rendezvous, including many topics like fuel optimization, use of different kinds of propulsion, safety and operational aspects or rendezvous at a Lagrangian point.

The afternoon session will instead focus on the technology necessary to navigate to a target object and especially on the sensors able to track and measure the state of a fully noncooperative target: using angles-only navigation at far-range or using a large variety of technologies at close-range (pose estimation, infra-red camera, Photonic Mixing Device).

Getting to Meeting Business Center : see information at the end of the document

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Program:

09:00 – 09:20	***Welcome & Coffee***	
09:20 – 09:50	*New Glideslope Guidance Algorithm for Minimum-Fuel Fixed-Time Elliptic Rendezvous Using Semidefinite Programming*	S. Urbina, LAAS-CNRS
9:50 – 10:20	*Autonomous Maneuver Planning for the AVANTI Experiment: Implementation and Flight Results*	G. Gaias, DLR
10:20 – 10:50	*Coffee break*	
10:50 – 11:20	*A new symbolic-numeric method for linearized impulsive fixed-time fuel-optimal space rendezvous*	M. Joldes, LAAS-CNRS
11:20 – 11:50	*Thrust Augmented Horseshoe Orbits in the Restricted Three-Body Problem*	C. S. Arnot, University of Strathclyde
11:50 – 12:20	*Rendezvous strategies in the vicinity of the Earth-moon Lagrangian points*	S. Lizy-Destrez, ISAE-Supaero
12:20 – 14:00	***Lunch***	
14:00 – 14:30	*Infrared based relative navigation for uncooperative targets*	Ö. Yılmaz, Cranfield University
14:30 -15:00	*High-order filters for spacecraft relative pose estimation*	P. Di Lizia, Politecnico di Milano
15:00 – 15:30	***Coffee break***	
15:30 – 16:00	*Visual Navigation for On-Orbit Servicing Missions using PMD sensor*	K.Klionovska, DLR
16:00 – 16:30	*Enabling a safe rendezvous from 50 km to 50 m: the power of line-of-sight navigation*	J.-S. Ardaens, DLR

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Abstracts:

PART I: RELATIVE GUIDANCE AND CONTROL

1) New Glideslope Guidance Algorithm for Minimum-Fuel Fixed-Time Elliptic Rendezvous Using Semidefinite Programming (S. Urbina, LAAS-CNRS)

This talk presents a new minimum-fuel glideslope guidance algorithm for approaching a target evolving on an elliptic orbit. In addition to the usual rectilinear profile to follow as in Hablani's seminal paper, two new features are requested for the new algorithm. The first one imposes bounds on the guidance error inherent to chemical propulsion glideslope guidance, such that the chaser's trajectory does not escape from an admissible domain. The second one minimizes the consumption during rendezvous. Indeed, unlike the classical glideslope algorithm for which there is no direct control on the fuel consumption, additional degrees of freedom and relevant decision variables may be identified. By combining a useful parametrization of the Tschauner-Hempel relative equations of motion and results from polynomial optimization, a semidefinite formulation of the constraints on the maximal guidance error is obtained. For a fixed-time glideslope rendezvous with a pre-assigned number of maneuvers, a fuel-optimal solution with a bounded guidance error is obtained by solving a semidefinite programming problem. Two numerical examples illustrate the usefulness of the method compared to the classical ones when the approach corridor has to verify stringent geometrical restrictions such as line-of-sight constraints.

2) Autonomous Maneuver Planning for the AVANTI Experiment: Implementation and Flight Results, (G. Gaias, DLR)

This presentation addresses implementation and flight results of the onboard relative orbit guidance and control module developed to support the Autonomous Vision Approach Navigation and Target Identification (AVANTI) experiment.
Carried out in late 2016, AVANTI demonstrated the viability to perform far- to mid-range proximity operations with respect to a noncooperative target, using only optical line-of-sight angle measurements. Within this experiment, the DLR Earth-observation BIROS satellite approached down to less than 50 m of inter-satellite distance the BEESAT-4 CubeSat, previously released in orbit by BIROS itself.
Such proximity operations required the capability to plan autonomously several maneuvers, taking into account operational and platform related constraints, collision avoidance needs, and minimization of the fuel consumption. Both the highly perturbed low Earth orbit scenario and the performance of the onboard relative navigation filter impacted the design of the maneuver planner, which had to provide deterministically formation reconfiguration solutions at a very low computational cost.
Over one month of in-flight activities, the AVANTI maneuver planner commanded more than 150 maneuvers, which allowed performing several rendezvous and receding phases in a fully safe fashion.

3) **A NEW SYMBOLIC-NUMERIC METHOD FOR LINEARIZED IMPULSIVE FIXED-TIME FUEL-OPTIMAL SPACE RENDEZVOUS (M. JOLDES, LAAS-CNRS)**

In this talk we present the computation of validated impulsive optimal control for the rendezvous problem of spacecrafts. Specifically, we consider the fixed-time minimum-fuel rendezvous between close elliptic orbits, assuming a linear impulsive setting and a Keplerian relative motion. Firstly, the optimal velocity increments and impulses locations are numerically obtained with a new iterative algorithm with proven convergence. This is based on discretizing a semi-infinite convex optimization problem.
Secondly, the obtained numerical solutions are validated by propagating the trajectories solutions of the linear differential equations of the dynamics. These are computed as truncated Chebyshev series together with rigorously computed error bounds.
Different realistic numerical examples illustrate these results. This talk is based on joint works with D. Arzelier, F. Bréhard, N. Brisebarre, N. Deak, C. Louembet, A. Rondepierre.

4) **THRUST AUGMENTED HORSESHOE ORBITS IN THE RESTRICTED THREE-BODY PROBLEM (C. S. ARNOT, UNIVERSITY OF STRATHCLYDE)**

In the circular restricted three-body problem, horseshoe orbits which encircle the Lagrange points L3, L4, and L5 occur naturally within a certain range of Jacobi constant values. Such orbits are interesting because they appear to exhibit 'repulsive gravity', as the gravitational attraction of the smaller primary pulls the infinitesimal third body from a lower orbit into a higher orbit, thereby changing its orbit period and causing it to recede from the smaller primary in the rotating frame of reference. This process is mirrored when the third body approaches the smaller primary from the opposite side, and is pulled into a lower orbit. In this work, two steering laws are proposed for a spacecraft under continuous thrust within the restricted three-body problem. The first law adds a constant acceleration towards the smaller primary, and the second towards the larger primary. The augmented pseudo-potential and Jacobi integral is derived in each case, and the effect of constant thrust on the critical horseshoe curve is analysed. The addition of continuous thrust with such steering laws provides a free parameter with which new and interesting horseshoe orbits can be designed. A novel application is presented in which a thrust augmented horseshoe orbit is used for a close rendezvous with an asteroid. Operational advantages of this kind of rendezvous include the natural approach and recession of the spacecraft, and that there is no requirement for any component of thrust to be directed towards the asteroid itself, thereby avoiding exhaust plume impingement and contamination of the surface.

5) **RENDEZVOUS STRATEGIES IN THE VICINITY OF THE EARTH-MOON LAGRANGIAN POINTS (S. LIZY-DESTREZ, ISAE-SUPAERO)**

In the context of Human Spaceflight exploration mission scenario, with the Deep Space Gateway (DSG) orbiting about Earth-Moon Lagrangian Point (EML), Rendezvous and Docking (RVD) operational activities are mandatory and critical for the deployment and utilization of the DSG (station assembly, crew rotations, cargo delivery, lunar sample return).
There is extensive experience with RVD in the two-body problem: in Low Earth Orbit to various space stations, or around quasi circular Low Lunar Orbits, the latter by Apollo by means of manual

RVD. However, the RVD problem in non-Keplerian environments has rarely been addressed and no RVD has been performed to this date in the vicinity of Lagrangian points where Keplerian dynamics are no longer applicable. Dynamics in such regions are more complex, but multi-body dynamics also come with strong advantages that need to be researched in depth by the work proposed here.
At ISAE-SUPAERO, researches have been conducted to first set up strategies for far and close rendezvous between a target (the DSG, for example) and a chaser (cargo, crew vehicle, ascent and descent vehicle, station modules …) depending on target and chaser orbit. Semi-analytical tools have been developed to compute and model families of orbits about the Lagrangian points in the Circular Restricted Three Body Problem (CR3BP) like NRHO, DRO, Lyapunov, Halo and Lissajous orbits.
As far as close rendezvous is concerned, implementation of different linear and non-linear models used to describe cis-lunar relative motion will be discussed and compared, in particular for NRHO and DRO.

PART II: RELATIVE NAVIGATION

6) INFRARED BASED RELATIVE NAVIGATION FOR UNCOOPERATIVE TARGETS (Ö. YILMAZ, CRANFIELD UNIVERSITY)

Infrared (IR) technology has been used for a long time on Earth sensors but its use for navigation and guidance has been very limited so far in Europe. The ATV-5 experiment in 2014 carrying a COTS infra-red sensor, with the collection of a set of image sequences that could be later post-processed on ground, was a first step in de-risking the use of IR technology for object detection in space. This presentation addresses the use of IR images for feature identification and tracking in order to get a continuous and robust navigation solution for Active Debris Removal missions, even during parts of the orbit in eclipse where cameras in the visible range of the spectrum cannot work.

7) HIGH-ORDER FILTERS FOR SPACECRAFT RELATIVE POSE ESTIMATION (P. DI LIZIA, POLITECNICO DI MILANO)

The estimation of the relative pose is crucial for safe proximity operations during rendezvous with uncooperative targets. It requires complex on-board computations, with a frequency that guarantees the fulfillment of the accuracy requirements. Therefore, a key point is the development of efficient algorithms that limit the computational burden without losing out performance.
To this aim, we developed nonlinear filters based on the use of differential algebra (DA). Classical extended Kalman filters rely on the linearization of the equations of motion and the measurement equations. However, the linear assumption may fail due to the nonlinearity of the dynamics and of the measurement equations. DA is used to move away from linearity and to implement arbitrary order Kalman filters, which are proven to outperform the linear counterpart. The use of DA is also proposed in unscented Kalman filters, where the computational burden of propagating multiple points is alleviated by replacing the numerical integrations with the evaluation of Taylor polynomials. ESA's e.deorbit mission is used as reference test case to assess the performance of the filters in terms of accuracy and efficiency. Moreover, the developed algorithms are implemented on

a processor with limited computational resources in order to demonstrate the on-board implementability.

8) VISUAL NAVIGATION FOR ON-ORBIT SERVICING MISSIONS USING PMD SENSOR (K.KLIONOVSKA, DLR)

Proximity operation is a key part in a future Space Debris removal and On-Orbit Servicing (OOS) missions. One main challenge is estimation of the 6 degrees-of-freedom pose of the noncooperative spacecraft in real-time onboard of the chaser during the close rendezvous phase (from 10 to 1 m). The Photonic Mixer Device (PMD) sensor is proposed and investigated as potential candidate for the visual navigation in order to initialize the pose (position and orientation) of the target with its follow tracking in a sequence of the images. The PMD sensor represents a range system, which provides for every frame a raster depth and/or a 2D gray-scaled image generated by the amplitude channel of the camera. The navigation system has been developed and currently is being tested with the real-time testbed, namely, European Proximity Operations Simulator (EPOS 2.0) and the engineering sample DLR-Argos3D - P320 camera at the German Space Center (DLR). The current results, pros and cons of using PMD sensor for close range rendezvous will be presented and discussed

9) ENABLING A SAFE RENDEZVOUS FROM 50 KM TO 50 M: THE POWER OF LINE-OF-SIGHT NAVIGATION (J.-S. ARDAENS, DLR)

The AVANTI experiment has been relying solely on line of sight measurements to perform a rendezvous with its noncooperative target. The experimental conditions were pretty challenging for the relative navigation task: the target satellite was only visible at one single location of the orbit, for a very short time (10 minutes) so that only a tiny part of the relative motion could be observed. In addition, the chaser spacecraft was orbiting at a low altitude (500 km) inducing a strong unknown differential drag which had to be estimated as part of the navigation process. Finally AVANTI had to cope with large maneuver execution errors which added even more uncertainties to the onboard relative motion model.
Despite all the aforementioned difficulties, line-of-sight navigation was found to be a powerful means of approaching safely a noncooperative target. Two rendezvous in space could be successfully performed autonomously, covering an intersatellite separation from 50 km to only 50 m. The onboard navigation filter was able to support the onboard controller with a navigation solution accurate at the meter level in the lateral direction and to about 10% of the inter-satellite separation in the boresight direction.

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Please note that, unlike previous CCT ORB seminars:

This seminar will take place at Meeting Business Center

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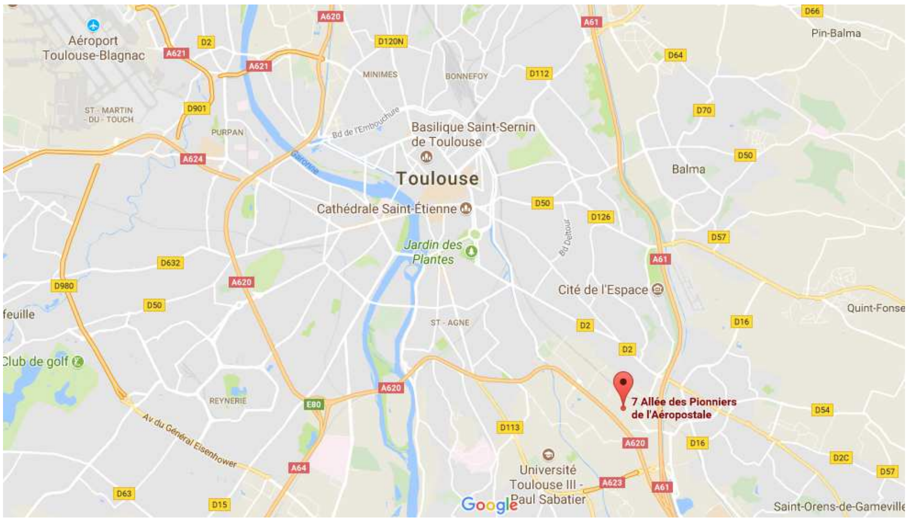

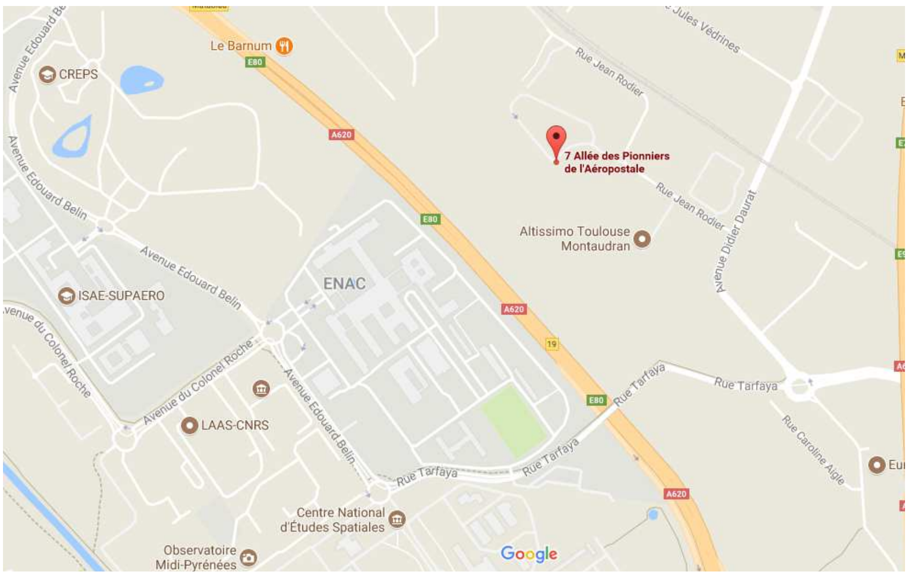

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