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

Vision Based Rendezvous GNC Techniques and Test Benches for Active Debris Removal

Juan C. Bastante[1], J. Vasconcelos[1], Luis F. Peñín[2], João Dinis[3] and José Rebordão[3]

1 DEIMOS Engenharia, Lisbon, Portugal

2 Deimos Space, Madrid, Spain

3 Laboratory of Optics and Laser, Faculty of Sciences of the University of Lisbon, Portugal

Abstract: In the context of the European Clean Space initiative, several relevant technologies are being preliminarily traded-off as promising for Active Debris Removal (ADR). This paper presents the features and strengths of a Vision-based Rendezvous GNC system covering the close proximity operations up to the contact phase, either docking or capture, with the specific debris. Not only the GNC system and associated techniques are described in detail, but also the environments specifically developed to test the performances of such system, including a MATLAB/Simulink simulator, and two real time test-benches, one with processor in the loop, and other with hardware in the loop.

1. Introduction

Last years are seeing a growing environment awareness of the impacts of space programs on the Earth, its atmosphere and space in general. These concerns are found not only in general population, but mainly in the space community, since a good quantity of these impacts are directly related to the sustainability of space as a privileged playground for scientific and technological activities. Among these environmental effects, the overcrowding of the Earth surrounding space appears as the most prominent example of how a not foreseen consequence of space exploration may compromise its continuity.

In this context, ESA is devoting increasing attention to the environmental impact of its activities, not only for future developments, but also in what regards the mitigation, as much as possible, of the currently observed undesirable effects. This is the framework in which the Active Debris Remediation (ADR) initiative is being pushed forward as an opportunity for ESA to play an active role in the mitigation of some of the most detrimental environment impacts.

Practically all of the ADR strategies intended for passive debris removal must, sooner or later, rely on the operation of a second active satellite in the proximity of the body to be removed, requiring the design of GNC systems capable of coping with the particular characteristics of such scenario. These characteristics are a consequence of the uncertain (and probably fast) rotational state that non-cooperative targets may possess, hence challenging not only the control of the final approach trajectory and attitude, but also the identification of the debris dynamic state.

This paper will present the design of a Rendezvous GNC system based on only camera measurements (images) taken on a completely passive target. The main advantage of this solution is its simplicity, from the point of view of data fusion, but imposes important requirements to the image processing (IP) and eventual feature points recognition function, since as stated above, the uncertainties in the knowledge of the debris dynamic state may be important. On the other hand, the required agility of such ADR satellite is a main driver for the design of the associated GNC system. Optimal or sub-optimal trajectory and attitude pointing profiles must be computed and controlled in real time to allow for the success of the mission.

The main drawback of the use of vision based sensors for ADR is related to the impact of eclipses on the proper working of this technique. Several technologies are being developed and matured to enable continuous operations in this context, among them the use of laser based 3D sensors and thermal imagers seem to be the most promising ones. However, and whenever possible, it must be considered that traditional vision based sensors (i.e. cameras), combined with reliable and robust IP algorithms, provide an extremely compact and simple option that can hardly be replaced by other better option in many tasks, such as target identification and estimation of dynamic state.

DEIMOS has been investigating in several technological ESA studies during last years for the development of a vision-based GNC system for Rendezvous that would match the needs of the ADR mission. This GNC system, currently in TRL 5, includes not only consolidated capabilities for the fast and real-time compatible computation of RV manoeuvres in circular or elliptical orbits, but also the integration of an image processing function that, working together with a relative motion estimation filter, enables the controlled evolution of the chaser towards the proximity of target. This GNC system has been validated and tested in several different simulation environments, including:

- A RV Functional Engineering Simulation (RV-FES), allowing the fast prototyping and testing of GNC system by evaluating its performances in a simulation considering most updated and detailed environmental models, and realistic simulation of sensors and actuators.
- A Real Time Test Bench with Processor in the Loop (RTTB-PIL), prepared to compile and run the GNC in a LEON real time processor, in this way enabling the real time performances evaluation of the GNC system;
- A Real Time Test Bench with Hardware in the Loop (RTTB-HIL), which adds on the PIL simulator a camera that, by taking images on a mock-up of

target, closes the loop in what regards the IP measurements, allowing the test of both GNC and IP integrated within the real time processor.

The paper will present in first place the overall vision based GNC concept applicable for ARD. Secondly, specific GNC techniques, particularly in the area of guidance and navigation for both circular and elliptical orbits will be described with special emphasis on the analysis of their applicability for the ARD scenarios. Finally, the GNC verification and validation approach through the different existing interconnecting facilities will be described, addressing the particularities and challenges posed by ARD systems.

2. RV GNC for Vision based ADR

As part of mission requirements consolidation, those referred to GNC play a key role in the definition of a feasible and fruitful mission, particularly in a challenging mission as the ADR, having as objective the rendezvous and fly around a non-cooperative debris, with an uncertain dynamic state, probably tumbling, and decelerate it until (eventual) re-entry.

The GNC system in a Rendezvous scenario is in charge of controlling the relative motion between the two involved bodies in accordance to a previously defined set of requirements and objectives. In the particular case of an ADR mission, there are a set of specific challenges related to the rendezvous GNC, summarised in the following bullets:

- Location of the target spacecraft at long range, which implies the definition of appropiate Narrow Angle Camera (NAC) sensors and the identification of the target spacecraft in the FoV considering other objects in view.
- LoS based navigation at long range, as range estimation is not fully reliable due to poor existing observables. This will need the use of robust relative navigation techniques coupled with guidance algorithms capable of managing large estimation errors in range.
- Estimation of the target spacecraft rotational motion at close range, in order to assess final approach trajectories and capture methodology. The estimation of the rotational motion shall be based on dedicated (optical) sensors (e.g. Wide Angle Camera or LiDAR technology) and might imply also the need of dedicated circumnavigation manoeuvres.
- Identification of the target shape in case it is not apriori known (for example for satellites which failed in the deployment of antennas or solar panels, or debris originated after previous collisions). The identification would imply the use of advanced image processing and shape recognition techniques.
- Passive safe relative approach trajectories, in the sense that natural dynamics does not lead to a collision in case of actuator malfunction. This implies the computation of non-drifting approach trajectories based on the estimated relative state.

- Final approach to the target spacecraft for capture and the synchronisation with its rotational state. This is a particularly complex manoeuvre that requires a fine relative control in many cases fighting against natural relative orbital dynamics of the two spacecraft.
- Coupled target-chaser spacecraft dynamics and control after capture. This is a new challenge not usually addressed in typical rendezvous scenarios in which both spacecraft are cooperative and there is no need to perform complex manoeuvres in docked configuration.
- Multi-debris GNC for the provision of an ADR service. It will imply having a modular GNC scheme capable of adapting to different target configuration, rotational motions and approach trajectories.

All these challenges must be addressed by relying on a technology development mature enough, mainly in three areas:

- Relative navigation sensors (mainly optical devices such as cameras & LiDAR). Current devices for automated rendezvous are visual sensors operating in the visible wavelength, LiDAR sensors and RF sensors. The consideration of not only other types of sensors, but other technologies associated to these sensors (for 2D and 3D cameras, thermal imagers, infrared sensors, etc) is of crucial importance to adequately tackle the challenges posed by the ADR scenario.
- Image processing and shape recognition techniques; closely linked to the point above, algorithms processing the images and raw data captured by the close proximity sensors is one of the key points of the system to be designed. This is due not only to the quite demanding nature of these algorithms, in terms of RAM memory, CPU and data rates, that call for a detailed analysis and technology upgrade, but also to the fact that the required autonomy level imposes a set of very constraining requirements that put these techniques in the core of the GNC design for ADR scenarios.
- GNC processing algorithms and techniques; the maturation of the required Guidance, Navigation and Control functions for rendezvous with a passive target, probably rotating in a not controlled and fast motion, with the need of having to avoid some hazardous parts of such targets (masts, antennas, panels, etc) imposes a very demanding set of requirements and constraints to the associated GNC: it must be not only highly autonomous, but also extremely robust and reliable, and must cope with the agility requirements that are a must in the last stages of the approach.

Figure below presents a summary of the preliminary identification of the more relevant technologies for each of the elements of a complete GNC subsystem.

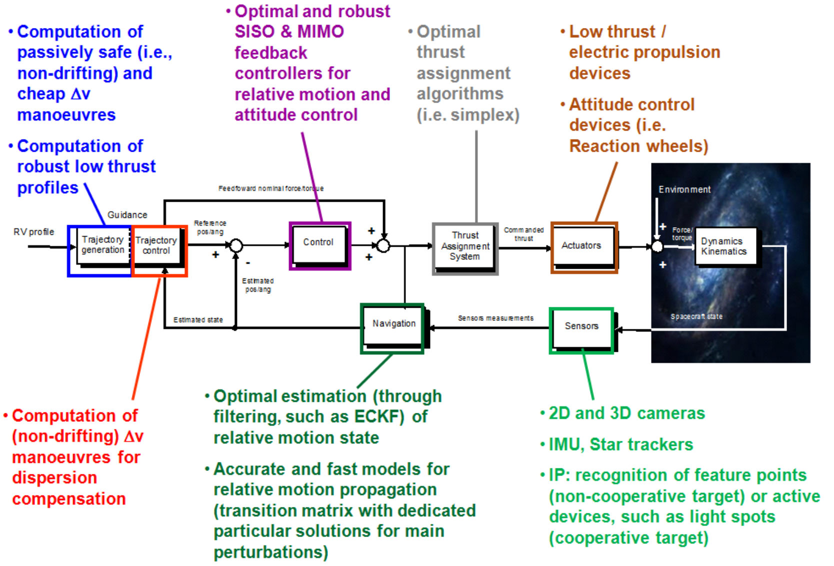

Figure 1: Summary of the most relevant GNC technologies for ADR

Relative Navigation Sensors for ADR

Large part of the technological analysis must be devoted for the assessment of the best sensor technology. The ADR scenarios include a wide range of distances and different measurement requirements, and it will certainly not be possible to adapt one single instrument. Therefore, different mission phases might require different optical sensors systems:

- Narrow Angle Camera (NAC) for the detection of the debris from a far distance. The NAC typically looks for and acquires the actual target position; in later mission phases it offers high resolution landmark detection.
- Wide Angle Camera (WAC) for operations near the target in order to maintain the context and safety for autonomy, while keeping full visibility of target while in close proximity operations.
- LIDAR technology or 3D cameras that are able to extract 3D information from the target, not directly possible with a 2D camera, and that might be necessary for specific needs of the ADR mission in terms of shape and motion reconstruction.

Table below provides a summary of some characteristics over currently available qualified cameras (except the NPAL one which is currently under development).

Table 1: Relevant properties of some space qualified cameras

Camera	OSIRIS NAC	OSIRIS WAC	AMIE	Framing camera	ONR	AMICA	µASC	NPAL
Pixel matrix	2048 x 2048	2048 x 2048	1024 x 1024	1024 x 1024	1024 x 1024	1024 x 1000	-	1024 x 1024
FOV (º)	2.35 x 2.35	12.1 x 12.1	5.3 x 5.3	5.5 x 5.5	1.4 x 1.4	5.83 x 5.69	18 x 14	70
Focal length (mm)	717	140	155	150	-	120.8	200	-
Aperture (mm)	89.6	25.0	15.5	20.0	-	-	-	-
f	8	5.6	10	7.5	-	-	-	-
iFOV µrad	20.0	103.1	90.3	93.7	23.9	98.0	-	1.2 mrad
Lim. Mag.	16	-	-	16 in 10 min exp.	12	-	11 (1 s exp.); 14 (16s exp)	SNR 400, up to 10 bit per pixel
Mass (kg)	13.2	9.5	2.1	2.5	2.7	-	0.4	0.5
Power (W)	-	-	9	6	5	-	0.3	4
Missions	Rosetta	Rosetta	SMART-1	Dawn	MRO	Hayabusa	Several	-

PRELIMINARY MISSION ANALYSIS AND SYSTEM MODELLING

The rendezvous phases for an ADR mission are the following:

- Target search phase, in which the spacecraft identifies and locates the target, estimating its orbital parameters in order to start the approach manoeuvres.
- Intermediate or Approach RV phase, with distances of up to several thousand km, characterised by orbital manoeuvres, instead of the classical RV manoeuvres. During this phase, the chaser gets up to distances in the order of kilometres
- Terminal RV phase, typical of the last 10km of the approach, in which linear theory of relative motion applies and hence the classical hopping RV manoeuvres. This phase can be also divided into three sub-phases:

    - Far closing: typical Hohman transfers manoeuvres to align the orbit between the spacecraft, including starting and braking V-bar impulses.
    - Closing (including circumnavigation): in first place closing manoeuvres through the application of R-bar impulses, reaching a relative close distance to the target (e.g. 250 m). Then application of manoeuvres to circumnavigate the target spacecraft in order to obtain as much information on its state.

- Final approach: forced approach along a specific direction until capturing / docking the target spacecraft. This might be an expensive manoeuvre as it requires continuously thrusting against natural orbit dynamics.

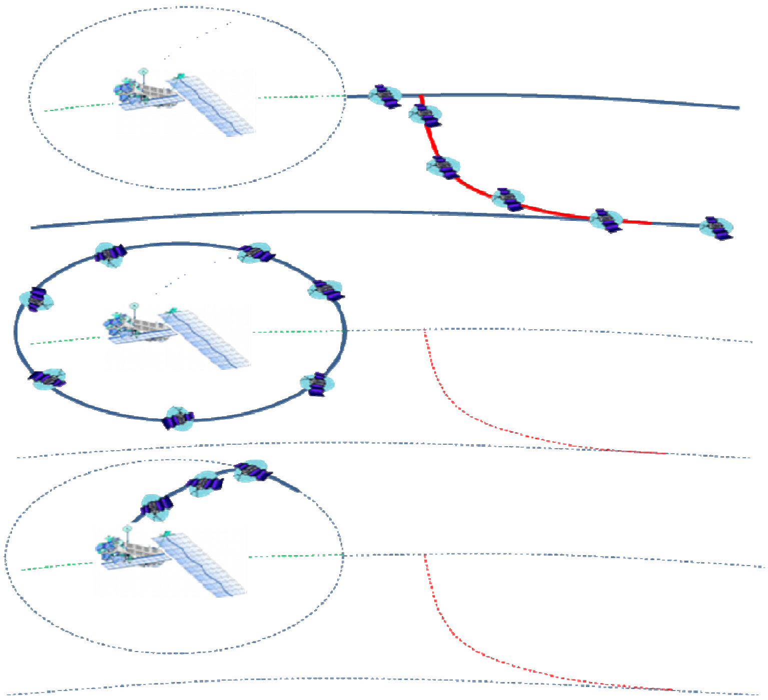

Figure 2: Example of terminal RV sub-phases: far closing (top), closing (middle) and final approach (bottom)

The definition of the RV profiles of the different phases is determined by the absolute and relative orbital dynamics of the spacecraft, and well established methods exist to compute accurate manoeuvres for each of the phases. Figure below shows a preliminary definition of the mission profile in terms of the different manoeuvres to be performed from target acquisition up to capture. This serves to consolidate the overall mission concept and budgets.

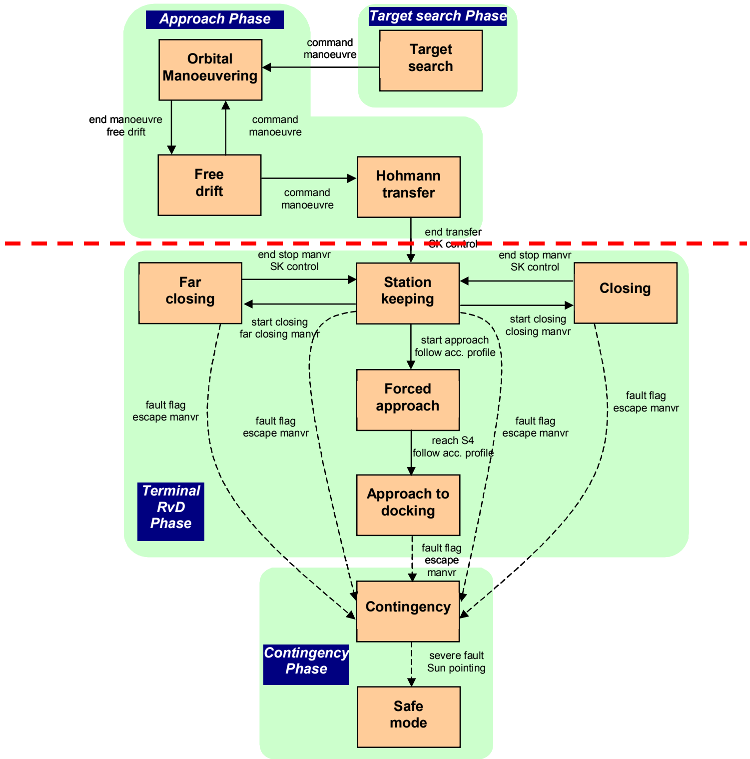

Figure 3: Preliminary definition of the mission profile in terms of the different manoeuvres to be performed from target acquisition up to capture

3. Guidance and Navigation Techniques for ADR

Guidance and Control Algorithms

Based on blocks shown in Figure 1, guidance and control functions have the following responsibilities, in a typical GNC for rendezvous:

- Trajectory Generation: in general, it provides the closed loop position controller with the reference state (in terms of relative position & velocity, and attitude). In this case, this is only needed for continuous thrusting phases (forced approaches & station keeping): during approach and closing phases, on the other hand, a terminal point guidance scheme is commonly followed for having better performances. During the forced approach phases, a typical phase plane profile with exponential deceleration is proposed for being more robust and not significantly more expensive than other strategies.

- Trajectory Control: it generates a feed-forward command to follow an intended path, based on the knowledge on relative dynamics. This function is covered by the following algorithms:
  - Transition Matrix Inversion.
  - Non-drifting injection algorithm using a reduced transition matrix formulation based on the differential elements approach given in [1], chapter 14.
  - Mid-Course Manoeuvre, targeting to the nominal state after a given time and implementing in practice the Terminal Point guidance approach.

Particularly interesting for the rendezvous with uncontrolled debris is the non-drifting injection algorithm: the objective is the computation of transfer manoeuvres without creating a drifting motion between target and chaser. Intensive use of the formulation found in [1], chapter 14, is made, by imposing explicitly a null difference after manoeuvre of semi major axes. Further details can be found in [2].

Navigation Algorithms

In the assumption of visual based RV, a camera placed in the chaser (the 'active' satellite) takes images of the target (the 'passive one', to be captured or docked). The images taken are processed by a dedicated set of algorithms for IP, resulting on an estimation of the relative position:

- Range (i.e., distance) can only be derived at distances in which some of the physical characteristics of the target are discernible: size and some its features. A very first estimation of distance can be derived by comparing the image size (in pixels) against the known size of the debris. Commonly, these range estimations are derived from WAC cameras, if what is to be analysed is the size; and WAC and NAC, if some features of the target are being tracked for the estimation of the target dynamics. In whatever case, this distance estimation is only available for close distances, being only possible to navigate in LOS for the first stages of the mission.
- Line of sight (LOS) is derived from the position of the target image within the camera focal plane. The combination of this info with the measured chaser attitude provides the measured relative position in a camera frame, normal to range direction. When the target is an extended body in camera CCD, some particular algorithms must be put in place to estimate the LOS; at least, a good geometrical model of the target must be part of the information to be provided to this estimator, along with the information about target dynamic state and sun phase angle.

The above means that chaser has to command a good part of the RV profile relying only on LOS measurements for relative motion, since only for close distances is there a range measurement available. Three other 'inertial' sensors are necessary: accelerometers, star tracker, and gyroscopes. To be able to convert these inertial measurements into the local reference frame (the traditional Local Vertical Local Horizontal, LVLH), it is necessary to assume some knowledge (up to a uncertainty) of the target absolute orbit.

The estimation of the relative position and velocity, as provided by Navigation filter, feeds the Guidance and Control functions, which, on one side, generate the reference relative position/velocity (when needed) and attitude to be followed, and on the other hand compute the feed forward laws (either computed as impulsive, either low thrust profiles) and the feed back control actions to follow the required reference states.

4. GNC Validation and Verification Approach

After implementation of the GNC system presented above, and further performance assessment in a dedicated RV-FES (Functional Engineering Simulator), a real time laboratory was developed by DEIMOS to test this GNC system in real time conditions. The resulting Real Time Test Bench (RTTB) presents two different configurations:

- RTTB with Processor in the Loop (PIL);
- RTTB with Hardware in the Loop (HIL), this one supported by an Image Processing Laboratory (IP-LAB).

The specific objectives of the IP-LAB are:

- Test IP algorithms with real images of a target model;
- Test specific sequences especially during the transition between IP modes or states;
- Work with real camera parameters (optoelectronic noise, MTF, etc) and real delays, instead of simulating camera performances based on a performance model.

The RTTB (PIL+HIL configurations) objectives can be enumerated, on the other hand, as:

- Evaluation of the GNC algorithms real time performance in a target environment, chosen to be a LEON3 processor, which includes basic (RTEMS) operating system and application programming interface (API) functionalities for realistic integration;
- Assessment of FES architecture suitability when integrated in a real time V&V environment, specifically a dSPACE® real time simulation environment.
- Evaluate the integration and performance of the entire GNC and IP chain, i.e. from image acquisition down to navigation and control outputs;
- Test the algorithmic and real time performance of IP routines under realistic imaging conditions (e.g. light and shape conditions, CCD properties, etc.).

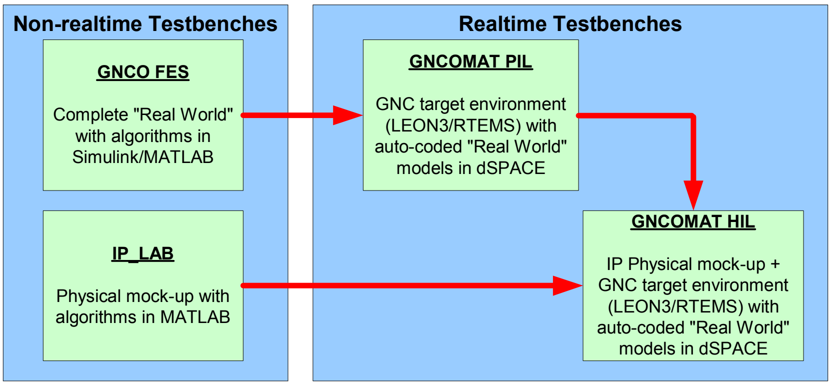

Figure 4: Development approach for the several simulators used to assess GNC for RV real time performances

The relationship between these implementations/configurations is a large contributor for efficient and reliable evolution of the infrastructure complexity. Thus, the FES/RTTB development followed an incremental approach, which is depicted in Figure 6. The important aspects are:

- The RTTB PIL configuration contains the Real World, inertial sensors and thrusters models coming from the FES with minor changes, ported to the new target environment. In RTTB-PIL these models run in real time (dSPACE® machine), while GNC algorithms runs in the LEON3 processor;
- The RTTB HIL configuration is based on a merged integration of the RTTB PIL configuration and the IP laboratory, with development of new modules as required.

Real Time Test Bench with Processor in the Loop (PIL)

PIL configuration presents the following features:

- "PX dSPACE® Box" runs the "Real World" or "Dynamics-Kinematics-Environment" (DKE) models in real time, where sensors and actuators are modelled in Simulink. The PIL configuration does not include any explicit image generation and processing but an IP performance model of the image generation-acquisition-processing chain;
- The "Monitoring and Control PC" is connected by an optic link to the "PX dSPACE® Box" to monitor and control the execution of the DKE, sensors, actuators models and also the IP performance model;
- The "Monitoring and Control PC" is also connected to the "LEON3 Processor Board" via Ethernet for monitoring purposes;
- The "LEON 3 Processor Board" runs the GNC model, being connected in closed loop to the "PX dSPACE® Box" using an RS-232 serial interface.

Real Time Test Bench with Hardware in the Loop (HIL)

The HIL configuration is an enhancement of the PIL configuration and includes a (flight) representative of a navigation camera, among other HW elements cited below. The architecture is depicted in figure below.

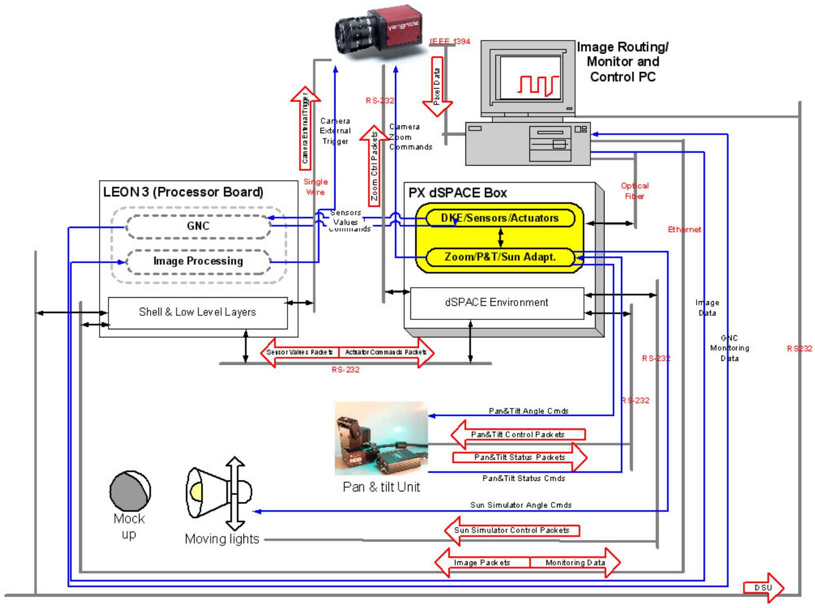

Figure 5: Architecture of the RTTB-HIL

It operates as explained here below:

- The HIL configuration involves an IP mock-up with several HW & SW units;
- It executes IP routines in real time within the LEON3 processor (i.e., GNC and IP integrated in the same real time processor), in turn using images acquired by the camera;
- The PX dSPACE® Box runs in real time the "Real World" models but now no Camera-performance model is needed, since a real camera provides for the images to be processed by IP. It also has to manage the Pan & Tilt, and Sun Simulator units;
- The camera is connected to an external computer ("Image Routing PC") from where the images will be routed to the "LEON3 Processor Board";
- The "LEON3 Processor Board" runs the GNC model and the IP in closed loop.

IP Lab

The laboratory setup is depicted in figure below. A Pan & Tilt unit supports the camera and attached lens. The camera is placed at a fixed distance (2.5m) of a target (a ball, in the case shown in the figure), painted with some texture, relevant for the IP function. Two additional rotary tables (horizontal & vertical) allow the rotation, in 2 degrees of freedom, of a lamp emulating the Sun illumination conditions in the target along the profile simulation.

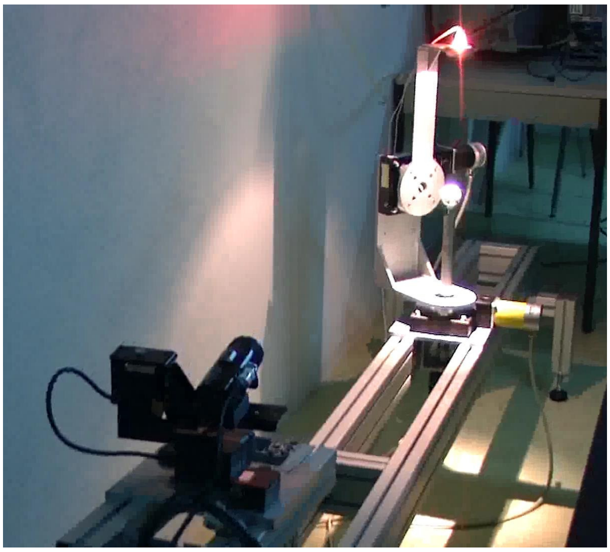

Figure 6: IP Laboratory

The centre of the ball is aligned with the lens optical axis at the neutral position of the two pan & tilt axes. To do so, a previous calibration process must be run in the lab, in order to successfully match the simulated variables (those coming from dSPACE® box) and the physical ones (i.e. at the lab). The ball is attached at the top of a small rod, which is attached to the axis of a motor, in order to generate a rotating motion in the ball.

The light source can be rotated around the ball in any direction. The (flight) representative camera is a Stingray F-145B (Allied Vision Technologies) , which has a monochromatic Sony ICX285 CCD with an image size of 1388x1038 pixels, and resolution of 6.45x6.45 micron.

In order to allow the interface (for closed-loop control) between the “Real World” models and the camera/light hardware, one must provide means to translate the simulation engineering values to a meaningful format to send commands to IP Laboratory hardware units. The information used from the simulation, for each unit, is:

- Digital Zoom: based on the simulated relative Chaser-Target distance;
- Camera Pan/Tilt Unit: based on the simulated Chaser camera to Target LOS;

- Sun Simulator light source position: based on the simulated camera to Sun and camera to target directions.

5. Conclusions

A complete development approach for GNC systems suitable for the Active Debris Removal has been presented. As explained above, such a system must rely on the development of technologies in the fields of relative motion sensors (vision sensors assumed in this paper), image processing and GNC algorithms. While for the first issue this paper proposes the use of visual based sensors, the second question (that of image processing developments) is strongly dependent on the kind of target to be removed, though at least a strong emphasis must be done in the development of feature extraction and processing algorithms.

Finally, in what regards GNC algorithms, this paper presents an end-to-end development approach, from performance assessment of the prototyped algorithms to its validation in a real time environment, with HW in the loop and working together with the IP algorithms in a flight-like processor.

6. References

1 H. Schaub, J.L. Junkins, "Analytical Mechanics of Space Systems", AIAA 2003

2 B. Parreira et al, "Mission Profile Design Tool for Intermediate and Final Rendezvous in Circular and Elliptic Reference Orbits", 4th International Conference on Astrodynamics Tools and Techniques, Madrid, Spain, May 2010