

VALIDATION FACILITIES FOR VISION BASED RV GNC IN ELLIPTICAL ORBITS

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INTRODUCTION

This paper presents the simulation environment developed by DEIMOS Engenharia, in collaboration with the Faculty of Sciences of the University of Lisbon, aiming at the validation of vision-based GNC for automated RendezVous (RV) in elliptic orbits. This consortium has been collaborating in a strategic programmatic line of ESA projects, namely GNCO (“Development of GNC algorithms for Rendezvous and Formation Flying in Non-Circular Orbits”), GNCOMAT (“GNC Maturation and Validation for Rendezvous in Elliptical Orbits”) and PROBA-3 Rendezvous Experiment projects. The nature of this technology also allows future use in other missions, such as Mars Sample Return (MSR). The objectives of the GNCOMAT project are the increase up to TRL 4 of Vision Based RV GNC in elliptical orbits, paving the way to the PROBA-3 RV in-flight experiment, aiming to reach TRL 8/9. In the (sequential) development of these projects an intensive reuse of simulation infrastructures and lessons learnt has been followed, due to the evolutionary nature of the projects objectives and outcomes.

The simulation infrastructure consists on two implementations: a non-realtime Functional Engineering Simulator (FES) and a Realtime Test Bench (RTTB). The last is subdivided in a Processor in-the-loop (PIL) configuration and Hardware in-the-loop (HIL) configuration based on an image processing (IP) laboratory mock-up.

The objective of the FES is to provide support for functional validation of GNC/IP algorithms.

On the other hand, the IP laboratory is used to achieve HIL objectives. Proper evaluation of IP performance in realistic conditions is of paramount importance because IP is a slave subsystem to GNC that provides information on the chaser/target relative positions, i.e. provides optical navigation observables used in the closed-loop chain.

GENERALS ABOUT PLANETARY RV IN ELLIPTIC ORBITS

Recent years have seen a growing interest towards the development of the GNC functions associated to RV and Formation Flying (FF) scenarios, motivated by the need of increasing the TRL of different technologies required to successfully accomplish several of the future space missions. Moreover, different sources have demonstrated the benefits of running planetary RV in non-circular orbits, since though circular relative motion is better known and tested (ISS-ATV), elliptical option was identified as interesting for a more cost-effective implementation of these missions delivering heavy vehicles for planetary exploration.

In order to successfully perform the approach to the ‘target’ spacecraft (i.e., the passive one, that will be captured by the active satellite, called ‘chaser’ or ‘flyer’), it is necessary to take some measurements of the relative motion, apart from the classical inertial ones (i.e., those coming from accelerometers, gyroscopes or star trackers, which do not depend on any relative-motion variable). The RTTB presented in this paper is based on a vision based GNC, meaning that the only measurements of the relative motion are those provided by an optical sensor, in this case a camera. Other options could be possible, for instance lidar or radio-frequency (RF) sensors. However, the GNC integrated in this RTTB and the simulators that preceded it in other projects are based on just camera measurements for relative motion. While this solution is more robust from an operational point of view (less sensors means simpler), one of the main questions this RTTB tries to address is if having just camera, which lacks of range observable or the great part of the RV profile, is enough to perform a successful capture. In this sense, having also an RF sensor, for instance, (which provides very good

range observations) would improve the GNC performances, but for sure would imply also an additional complexity for the GNC system itself.

For all the reasons exposed above, this RTTB is being used to validate and mature in a real time environment the RV GNC functions based on just camera measurements. Only a real-time implementation, with a real camera taking images on a real target (a sphere, in this case), and working together with the real algorithms performing the image processing in order to derive (measure) the relative motion, is able to upgrade the current TRL [1] level of the associated GNC algorithms, from the current 2 level up to 4. Next Figure 1 provides the working principles of such RV GNC.

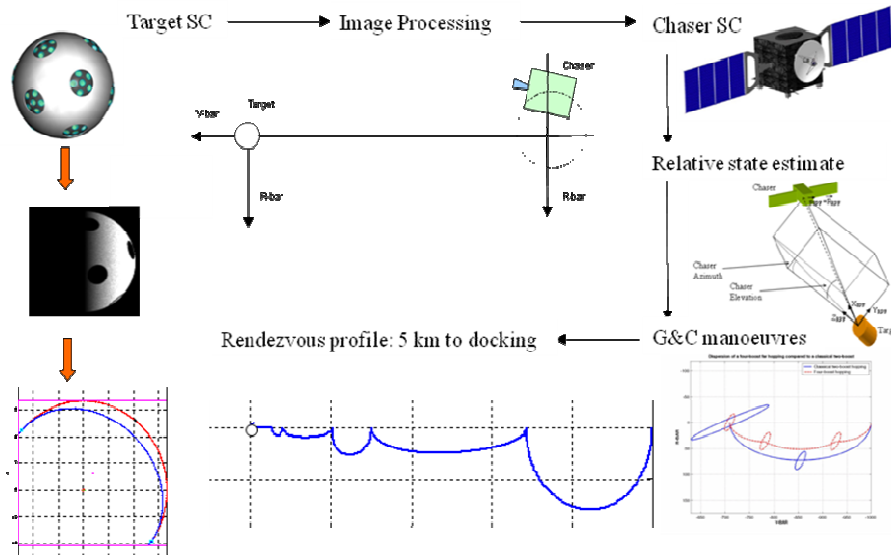


Fig.1. Automated RV based on relative state estimation from camera measurements

REALTIME TEST BENCH - GENERALS

The RTTB works in two different configurations: PIL & HIL, the last one supported by an IP laboratory.

The specific objectives of the **IP laboratory** are:

- Test IP methods with real images taken on a spherical canister (different from a more classical distributed beacon light pattern), which may lead to a variety of scenarios;
- 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 all camera performances based on parameters that are not available most of the times.

The **RTTB (PIL+HIL configurations) objectives** can be enumerated 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 (by means of real time performance evaluation) when integrated in a real time V&V environment, chosen to be 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/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.).

The relationship between these implementations/configurations is a large contributor for efficient and reliable evolution of the infrastructure complexity. Thus, the FES/RTTB development follows an incremental approach, which is depicted in Figure 2. The important remarks to retain are:

- The RTTB PIL configuration will contain the Real World, inertial sensors and thrusters models coming from the GNCO project FES design, with minor changes, ported to the new target environment. In this RTTB these models will run in real time (in the dSPACE® machine) while the GNC algorithms runs in the LEON3 processor;

- The RTTB HIL configuration will be based on a merged integration of the RTTB PIL configuration and the IP laboratory, with the intrinsic development of modules to allow this integration.

The GNC and validation facilities development cycles are driven in parallel, so that GNC/IP algorithms can be validated in the applicable environment, i.e. the respective implementation and configuration.

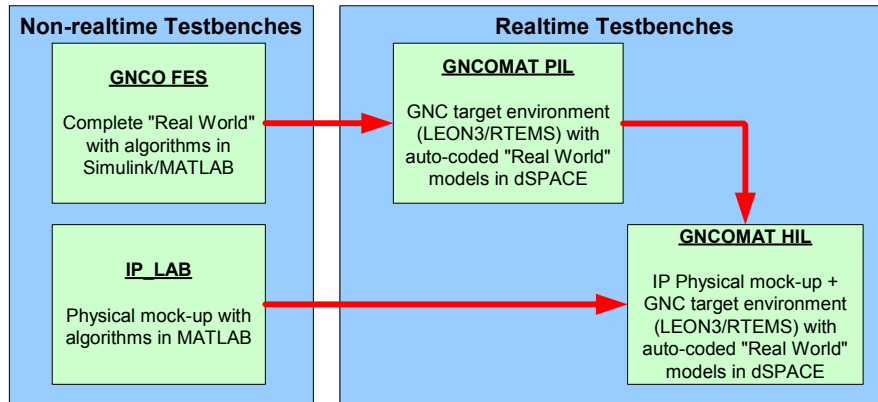


Fig.2. Validation facilities' development approach

REALTIME TEST BENCH WITH PROCESSOR IN-THE-LOOP (PIL)

Architectural Overview

Figure 3 presents an overview of the PIL configuration, with 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.

Description of Main Elements

PX dSPACE Box

It is a dedicated framework provided by dSPACE® that allows a custom Simulink model to be run in a real time environment, which is then customized for a specific purpose. The Simulink models are auto-coded by Real Time Workshop® and compiled by dSPACE tools for realtime operation. Moreover, it allows hardware interfacing (e.g. serial link) whose engineering values data is converted to proper physical links formats.

The “DKE/Sensors/Actuators” module implements the “Real World” models, i.e. it simulates a realistic mission environment, provides the necessary sensors/actuators measurements/commanding interfaces for GNC and provides telemetry for visualization of simulated Chaser-Target state and behaviour. This module is customized for RV missions and optimized for accurate numerical simulation whilst keeping the execution performance compatible with real time applications.

The “Monitoring Interface” module allows the interface between the Simulation Core (aka “Sensors-DKE-Actuators”) and two entities: “Monitor and Control PC” and “Drivers and Communications Layer” (the last handles the dSPACE hardware interfacing). The first sends all “telemetry” to visualize the simulation status and the second sends all the signals required for proper operation of dSPACE H/W, serial links and ultimately interface with the GNC software item. To conclude the “RT Kernel” handles the dSPACE hardware processor execution, namely tasks, data exchange and other realtime resources.

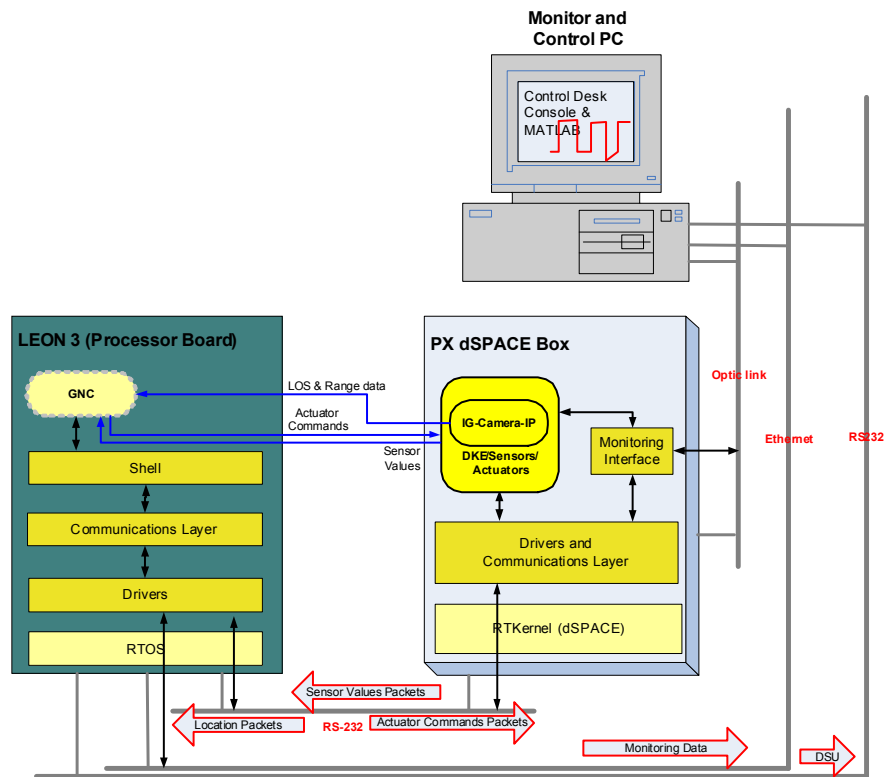


Fig.3. RTTB PIL configuration architecture

Monitor and Control PC

This is a recent standard PC running specific software applications that can be divided in two conceptual groups: Monitoring and Control Software.

The Monitoring S/W is a set of tools that allow the RTTB Validation engineer to properly debug and evaluate the correctness of the execution of every module of the Test Bench, e.g. LEON3 processor architecture debug and GNC debug tools.

The Control S/W directly influences the execution state of the RTTB. These will be capable of sending instructions to the RTTB and define run time variables. The following tools are used within this group:

- dSPACE ControlDesk: it is used to access/modify the state of running variables of the DKE model, e.g. allowing perturbations to be enabled/disabled such as Air drag, SRP, Gravity or third body. This is visible in Fig. 4. Moreover, the control of the initialisation/termination of the real-world simulation running on dSPACE can be made, allowing the identification of the status and correctness of test execution. ControlDesk also allows saving DKE simulation variables in a log that can be then analysed in MATLAB®.
- GNC Debug tool: it allows controlling the start/end of the GNC execution on the LEON3 Processor Board. One can also input parameter values to the GNC if necessary, before initialising the Test Run. GNC data will be stored in the log file for post-analysis (in a format compatible to MATLAB®).

LEON3 Processor Board

In the PIL case, the Processor Board comprises one main module, named “GNC Execution Platform”, which in turn includes several sub-modules, as depicted in Fig. 5: the Shell, Communications Layer, Drivers and RTOS. The interfaces and exchanged data are also shown in the referred figure.

The Shell provides a set of services that allow a (flight) representative platform for GNC code execution. These include a GNC Scheduler Task, a Model-DKE Exchange and additional services responsible for formatting the data messages that are sent/received to/from the “DKE/Sensors/Actuators” module (i.e. emulates sensors and actuators measurements/commanding interfaces). One important metric for real time performance evaluation is the LEON3 CPU load, which is sent by the Shell to the “Monitor and Control PC” via the Ethernet telemetry bus.

The RTOS running on the Processor Board is RTEMS. It provides all the necessary device drivers and a robust real time kernel support to the user-space applications, properly customized for RV GNC applications.

The “Communications Layer” abstracts the access to the communication lines (Ethernet or Serial RS232). It is composed by a set of functions to initialise/terminate the communication drivers, verify packet integrity and handle I/O accesses.

The “Drivers” and “RT Task Scheduler” layers are the bridge between the software application and the hardware. Basically, the drivers provide means for real time tasks to send, receive and verify the integrity of packets, and the scheduler handles the LEON3 processor resources.

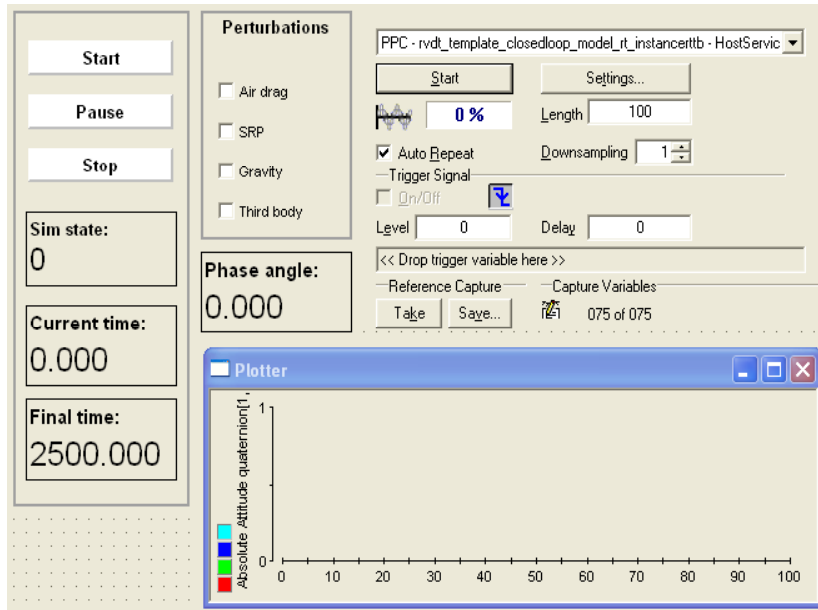


Fig.4. ControlDesk Layout implemented for the DKE

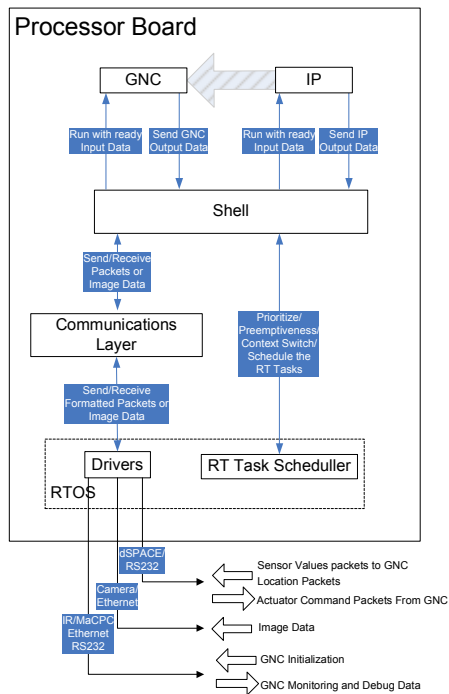


Fig.5. LEON3 Processor Board modules and interfaces

REALTIME 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. The architecture is depicted in Fig. 6, and as overview operates in the following way:

- The HIL configuration involves an IP mock-up with several hardware and software units (described hereafter);
- The HIL configuration executes IP routines in real time, in turn using images acquired from the camera;
- Again, the “PX dSPACE Box” runs in realtime the “Real World” models but now no Camera-performance model is needed. It also has to manage the Pan & Tilt, Zoom 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, operating in closed loop.

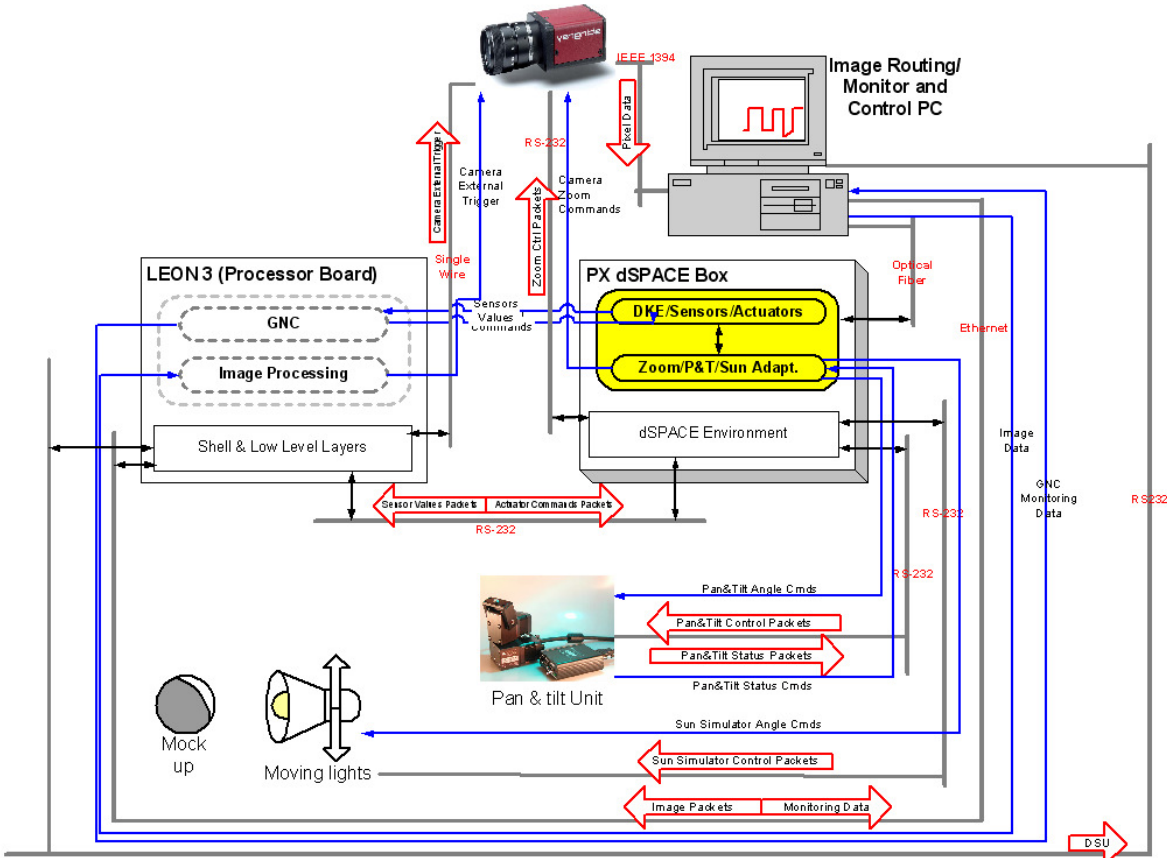


Fig.6. LEON3 Processor Board modules and interfaces

In this sense, a few differences exist with respect to the PIL configuration, enumerated as:

- IP Laboratory (new)
 - Mock-up
 - Camera, Pan/Tilt, Zoom and Sun Simulator Units
- PX dSPACE Box
 - No IP performance model
 - IP Laboratory Adapters (new)
- Monitor and Control PC: as PIL configuration, but with “Image Routing” (new)
- LEON3 Processor Board: as PIL configuration, but with “Image Triggering and Acquisition” services (new)
- RTTB HIL Buses: as PIL configuration, but with dedicated buses for IP Lab units control

As it can be checked, the only new element with respect to the PIL configuration is the IP laboratory, composed of the hardware elements necessary to simulate the image generation – camera – image processing chain. This IP laboratory is detailed in next paragraph.

IP Laboratory

The laboratory setup is depicted in Fig. 7. A Pan & Tilt unit supports the camera and attached lens. The lens is placed at a fixed distance (2.5m) of a target ball (40mm diameter), painted with an appropriate texture emulating the canister retro-reflectors. The centre of the ball is aligned with the lens optical axis (without any camera tilt or pan). The ball is attached at the top of a small rod, which is attached to the axis of a motor. Overlapped with this motor is a rotary table (horizontal table). The horizontal rotary table supports a second rotary table (vertical table), placed vertically, and connected at a right angle. In turn, the vertical rotary table is connected to the light source by another right angle.

The light source can be rotated around the ball in any direction, with the exception of a small neighbourhood around the ball support. Obviously, it is also not possible to illuminate the ball by the optical axis direction since it would obstruct the image formation. The ball can rotate without restrictions by the vertical axis.

The (flight) representative camera is a Stingray F-145B (Allied Vision Technologies) [2], which has a monochromatic Sony ICX285 CCD with an image size of 1388x1038 pixels, and a resolution of 6.45x6.45 micron.

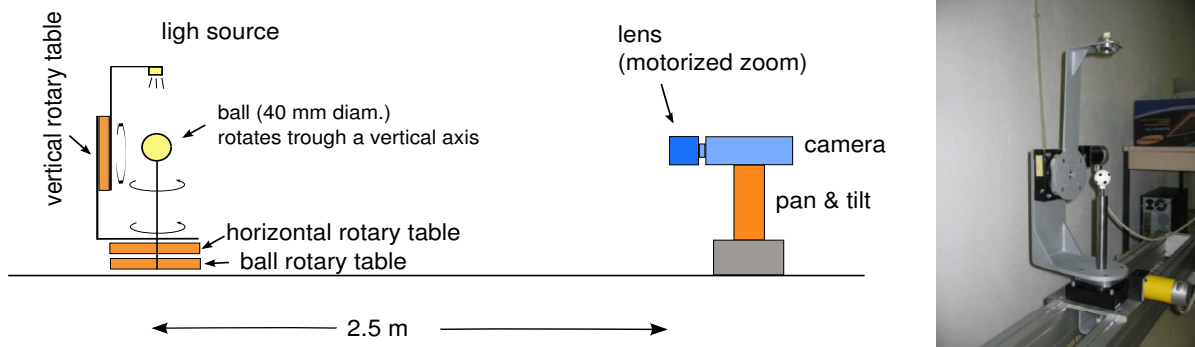


Image Acquisition, Routing and IP Lab Units Adapters

The “LEON3 Processor Board” S/W services, “Image Routing PC” and “PX dSPACE Box” perform the image acquisition, routing and closed-loop control of the IP Lab Units, respectively, as described next paragraphs. The acquired image is routed to the GNC code via “Image Routing software”, residing in the “Image Routing PC”. It is a software application that simply receives image data from the camera and handles a conversion from FireWire to Ethernet protocols.

The RTTB HIL configuration has the following additional services in the “LEON3 Processor Board”: Image Acquisition, Image Receiver, Image Transmission Starter and Image Buffer. Moreover, it includes an “IP Scheduler Task”, which executes the IP code once an image is ready and signalled by the “Image Buffer” service.

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:

- Lens Zoom Unit: based on the simulated relative Chaser-Target distance;
- Camera Pan/Tilt Unit: based on the simulated Chaser camera to Target line-of-sight;
- Sun Simulator light source position: based on the simulated camera to Sun and camera to target directions.

SUMMARY

The simulator environment presented in this paper is being used (at the moment of writing this paper) for the validation of the referred GNC for autonomous RV in planetary elliptical orbit. As explained in the body of the paper, this RTTB is composed of two different configurations, one with just processor in the loop (PIL), the other one including an Image Processing laboratory in the loop (HIL) allowing the consideration of real images to close the loop with the IP algorithms and the GNC.

Though in the current state this RTTB is being used to validate this RV GNC relying just on visual sensors for relative motion (and upgrade the associated TRL as a consequence), its nature allows its evolution to allocate other types of GNC algorithms for automatic RV, for instance relying on other types of sensors, different types of GNC algorithms, or even

the integration of new avionics to close the loop. In this sense, the RTTB has been conceived as a test bench allowing the connection and validation of any kind of RV GNC: the customisation of interfaces from sensors to GNC and from GNC to simulated thrusters allows for a fruitful and easy reuse of the SW/HW environment here described for future real time simulators.

REFERENCES

- [1] John C. Mankins, "Technology Readiness Levels, A White Paper" *Advanced Concepts Office, Office of Space Access and Technology, NASA 1995.*
- [2] <http://www.alliedvisiontec.com/us/products/cameras/firewire/stingray/f-145bc.html>