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AUTONOMOUS AEROSPACE TECHNOLOGIES IN SPACESYSLAB – A ROBOTIC-BASED RENDEZVOUS AND DOCKING SYSTEM

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ABSTRACT

Autonomous aerospace technology is an innovation activity currently included in NATO's operation areas having a profound impact on security and defense. SpaceSysLab facility is the new Laboratory from Romania, able to test control algorithms for autonomous missions and to develop hardware (coupling mechanisms, navigation sensors and actuators). This robot-based test lab is used to test, verify and validate the R&D systems. The degree of novelty is expressed by the fact that the SpaceSysLab designed as a SIL+HIL (Software-in-the-Loop+Hard-in-the-Loop) simulator is a combination of hardware and software simulator that can test and verify space robots, autonomous VTOL (Vertical Take-off and Landing) of UAVs on mobile platforms in complex coupling phases. This technology allows hardware/software robotic broadband systems to be controlled by simulating every phase. SpaceSysLab consists of a virtual platform (VP) based on GNC system (guidance, navigation, and control) and an experimental platform (EP) based on a robotic system. This system permits to simulate the meeting and coupling maneuvers of the robots. VP+EP test system is a hybrid simulator, designed to simulate simultaneously the relative dynamics of two motion bodies on relatively short distances in meeting/coupling maneuvers (rendezvous, proximity and docking – RP&D, VTOL).

KEYWORDS: Rendezvous & Docking, GNC software, VTOL system, floating robots, robotic system

1. Introduction

Rendezvous and docking maneuvers of two autonomous space vehicles include a set of orbital maneuvers. The application of R&D process in spatial missions has been extensively developed in the area of autonomous approach and landing of multicopters on mobile ground vehicles or marine platforms. There is an increasing demand for more autonomy in the use of unmanned aerial vehicles, particularly in the field of surveillance, safety and defense applications. Utilizing the UAVs in the above fields offers some benefits due to their capability to encompass a large area from a high altitude or to access points that are difficult to reach by traditional land and sea vehicles. The practicability of a mobile landing for VTOL vehicles is challenging.

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Advances in autonomous on-board guidance, navigation and control seem to be essential in preparing for a large variety of future missions. To achieve this objective, the latest results, show that the development of GNC algorithms must take place alongside a change in architecture, hardware, and software. The rendezvous phase or approach phase consists of different controlled maneuvres in which an active vehicle (named "Chaser") comes near to a passive vehicle (named "Target") on the same trajectory. The key phase for this type of mission is the correct docking to the targeted vehicle.

Emerging technologies such as a broad selection of aerospace technologies have attracted increased attention in security and defense in recent years. NATO's innovation activities are currently focusing on a number of priority technology areas including: autonomy, hypersonic technology, space and novel materials.

INCAS is aware of the importance of developing emerging technologies in the aerospace domain with regard to the security and defense sector, focusing on the following: resilience in the field of emerging technologies as well as resilience of the transport infrastructure.

Autonomous aerospace technology is an innovation activity currently included in NATO's operation areas having a profound impact on security and defense. ADS-33-PRF, the US Army's rotorcraft was initially intended for ground-based operations and is currently expanded to the sea area, as the necessity to cover land and maritime UAV operations becomes more and more apparent. Shipboard operations are a huge provocation for navies worldwide. Elsewhere, the developments of new systems enabling unmanned aerial vehicles, commonly referred to as UAVs, to execute missions autonomously, is an emerging tendency in aerospace research.

In the past years, many missions have been initiated to test different techniques for the safe deployment of R&D or VTOL operations (Ducard & Allenspach, 2021; Saeed, Younes, Cai & G. Cai, 2018; INCAS technical report, 2019).

In order to ensure safe operation, numerous ground tests are needed to demonstrate that the GNC algorithm complies with the performance requirements. The ground-based demonstration system can offer suitable accuracy for validation and verification of GNC algorithms.

Over the last five years INCAS has been implementing an experimental infrastructure "SpaceSysLab" located and developed on the South – Muntenia Region, Prahova, Măneciu district. This research capacity includes a virtual platform and an experimental platform for aerospace applications (erris.gov.ro). Our institute has two main objectives: the first one is to develop the software for guidance, navigation, and control of aerospace vehicles, to design and implement the hardware equipment (coupling mechanisms, navigation sensors, actuators, communication lines) while the second is to validate a facility, based on integration of the experimental activities with an advanced simulation tool for the design of the components for flying vehicles.

In this paper, a new robot-based test laboratory used to simulate R&D and VTOL operations and examples of simulation and testing are presented.

One of the objectives of conducting a Hardware-in-the-Loop (HIL) simulation on robotic system (ABB robots and Stewart platform) is to simulate the approach and landing to a mobile platform (ship or oil platform) in order to verify and validate the rendezvous GNC System.

Another objective to conduct a Hardware-in-the-Loop (HIL) simulation is to simulate air-cushion robot proximity operation guidance. This closed-loop checking simulation is affected by the response time delay of the whole control loop and the high stiffness of the robots.

The requested default behaviour is dictated by a mathematical impact model for the two air-cushion robots.

2. SpaceSysLab – A Conceptual Framework

To the best of our knowledge, SpaceSysLab is the first Laboratory in Romania capable of developing hardware (coupling mechanisms, navigation sensors and actuators) and testing control algorithms for autonomous missions. This robot-based test lab is used to test, verify and validate the R&D systems.

A survey of relevant test bed has been presented exhaustively on EERIS Platform. In recent times, in the space industry, there are several international cooperation programs and infrastructures directly connected to our laboratory, such as EPOS facility (European Proximity Operations Simulator) (Benninghoff, 2017) located and developed at DLR (German Aerospace Center) in Oberpfaffenhofen, together with ESA (European Space Agency) for R&D simulation of robotic systems. The infrastructure is used to test and verify sensors of European ATVs and Japanese HTVs, as they approach the International Space Station (ISS). Other research centres use three degree-of-freedom (3DoF) test beds with aerodynamic translation bearings that translate on an epoxy, granite or glass surfaces.

Two different test beds to be mentioned here are the 3DoF test bed in Naval Postgraduate School (NPS) of Monterey (Zappulla, Virgili-Llop, Park, Zagaris & Romano, 2016) and the 3DoF test bed in Thales Alenia Space Turin (Guglieri, Maroglio, Pellegrino & Torre, 2012) due to the fact that both test beds can only analyse proximity maneuvers.

The degree of novelty is expressed by the fact that the SpaceSysLab, designed as a SIL+HIL simulator, is a combination of hardware and software simulator that can test and verify spatial space robots and UAVs in complex coupling phases. This technology, based on knowing "intelligent specialisation" and "facility simulation", allows hardware/software robotic broadband systems to be controlled by software that simulates on-orbit phases.

SIL is an off-line simulation developed in virtual environments (Matlab – Simulink, LabView, RobotStudio), used to perform the code generation and downloaded on target platform running in Rapid operating system or ForceSeat.

HIL is a real-time simulation being the most suitable method for checking, testing and validation of complex and encapsulated "real-time" systems as identified in the proposed system, involving real components in this process ("Plant Simulation"). By using this concept it is possible to test hardware before implementing it in a real process. HIL architectures allow partial or complete simulations in virtual environments preceding simulations in real-environments.

3. Facility Description

"SpaceSysLab" consists of a virtual platform (VP) based on GNC system (guidance, navigation, and control) and an experimental platform (EP) based on a robotic space system. EP is mainly made up of two subsystems: robotic system with two ABB IRB 7600/4600 robots with running rail path (over 20 meter) and Stewart platform for R&D processes and Air Cushion Robots for simulating the anti-gravitational effect (see Figure no. 1).

VP+EP test system is a hybrid simulator, designed to simulate simultaneously the relative dynamics of two motion bodies on relatively short distances in meeting/coupling maneuvers (rendezvous, proximity, and docking – RP&D). The facility allows operator's intervention (crew-in-the-loop) in the system for analyzing various space missions and advanced programs in real time.

3.1. Hardware Overview

The SpaceSysLab facility has the following hardware elements:

– A 7600 IRB ABB robot system (UAV relative motion) with running rail path (over 20m) and maximum load on the last axis – 500 kg.

– A 4600 IRB ABB robot system with maximum load on the last axis – 60 kg.

– A Stewart CKAS "W" – 6DOF Motion Platform.

– An ARRI Max 12/18 used as Sun simulator.

– A computer-based MCS system.

There is also a buffer zone around the robots and the rail system. A typical setup for the R&D process is as follow: one of the robots transports a client-vehicle module which can be a satellite, a drone, etc., simulating the 6DoF movement of the client-vehicle. The rendezvous vehicle module, which can be a space vehicle, a ship, an oil rig, a road vehicle, etc., is transported by the other robot.

A specific computer system controls the whole simulation process in real time. Software can simulate and calculate the first part of the simulation, such as orbit dynamics or autonomous landing. If we refer to VN (visual navigation) using optical sensors, such as the client module of the camera, it is usually illuminated so that the test lighting conditions are as similar as possible to those in the operating area. In addition, different lighting directions can be simulated, such as front, side or back lighting from the sun.

3.2. Control, Sensor, and Monitoring System

The plant has a dedicated automated control and surveillance system. An insight into the surveillance system shows three different levels of control:

– The local robot control (LRC). All robots are individually controlled in real-time by their dedicated LRC unit. (RobotWare software for IBB ABB robots and ForceSeat software for the Stewart platform).

– The control and monitoring system (CMS) which is a real-time tracking system for the overall installation. The CMS will implement two ways of monitoring the R&D process: control through the previously established corrective procedures manual and control by automat management.

– The application control system (ACS). The models of airspace vehicle dynamics and different phases can be executed in MATLAB – Simulink. The Matlab – Simulink code is transferred to LabVIEW, RobotStudio (IRC ABB) and C++ environments and real-time executable is sent via CMS.

For R&D simulation control each vehicle module (Chaser, Target) is equipped with different hardware: control unit sensors such as rendezvous sensor (LIDAR, IMU, GPSi, camera, radar altimeter) associated with specific software and interfaces.

The complete control of the vehicle module consists of the following functions:

– Reproducing a trajectory according to a predefined scenario.

– Defining and optimizing the trajectory in terms of real-time events.

– Autonomous navigation control.

The radio subsystem provides measurement of linear and angular distances in relation to the Target vehicle. The laser position subsystem provides linear and angular measuring distances relative to the Target vehicle in relation with the inertial reference system, being used at the same time with the deviations correction from the IMU. The video camera subsystem provides measurement of linear and angular distances in relation to the Target vehicle. Additionally, sunlight simulation system has an important role in generating realistic conditions of sunlight (as in space), especially for imitation of the sunlight space flight disruptions (intensity and radiation) in the visible spectrum.

The GNC software running for controlling the unit is developed using

Matlab – Simulink, RobotStudio environments. Once developed, the models are automatically coded using the Labview, Rapid or C++ programs. To facilitate the transfer from the Matlab – Simulink codes to Labview and C++ environments, a conversion that is done in-house is used.

Since UAV approach/landing modules or operational proximity guidance of air-cushion robots is the main research focus of GNS, usually only the guidance block is modified and a set of predefined standard navigation and control subsystems is used.

At the CMS level in the laboratory, the entire simulation is controlled and monitored. The CMS is a Windows computer, representing the interface between the operator and the robotic system. A simulation can be run either in real hardware or in off-line simulation mode (RobotStudio).

In addition to the simulation, the operator must continuously check the safety status of the robotic system during the simulation.

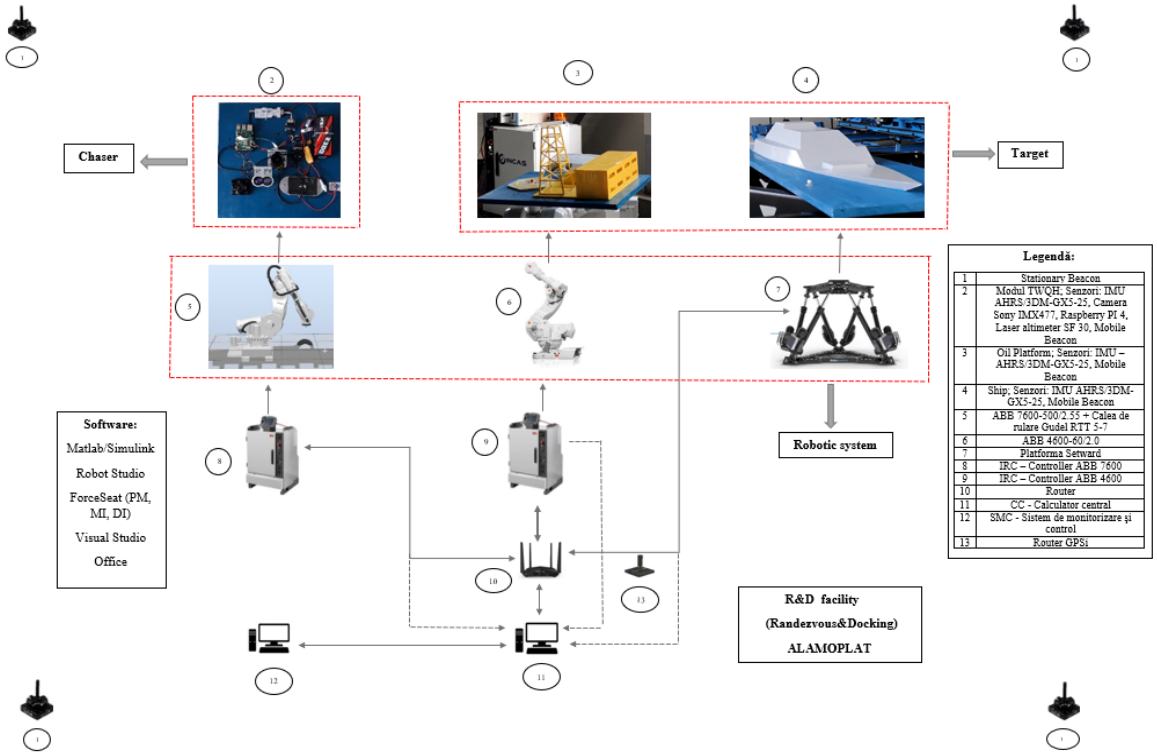


Figure no. 1: *Rendezvous and docking facility*
(Source: Automatic Landing on Mobile Platform/ALAMOPLAT)

4. Results

4.1. Software-in-the-Loop Simulation

4.1.1. Virtual Simulation of Hybrid UAV

The model of the hybrid drone is presented in detail in (UAV platforms, 2019).

The controller design, developed for guidance and control for full rendezvous at the landing point (Integral Backstepping method – robustness to external disturbances and uncertainty), uses Matlab – Simulink environment.

The modelling of the dynamic behaviour of the hybrid UAV (Tandem Wing Quadrotor H) model under the conditions of airflow present around a ship or a mobile ground vehicle platform considers:

– Aerodynamic contribution of the tandem wing, nonlinear effects of cross-coupling kinematics, actuator saturation and rate limits.

– External condition such as sea states and wind profiles.

– Airworthiness requirements: STANAG 4703, MIL F 8785 ASG, ADS 33 E PRF (RTO-AVT UAV Design Processes and Criteria Structural Design Aspects and Criteria for Military UAV).

The main objectives of the experiments are:

– To identify key factors for safe landing trajectory.

– To analyze external condition such as sea states and wind profiles.

– To investigate how automatic operations are executed for landing on the deck of the ship.

– To define the envelope of operability and limits for the floating platform.

SIL (Software-in-the-Loop) simulation was performed using Matlab and RobotStudio software.

4.1.2. Aircushion Robots' Off-line Simulation

A general model of the two-dimensional motion of air-cushioned robots with three degrees-of-freedom (of which two for displacement and one for rotation) dynamics is presented below to simulate a rendezvous process between the Target and the Chaser in the two-dimensional plane. The relative equations for the translational motion between Target and Chaser are presented by Ioniță et al. (2019).

Considering the maneuver of rendezvous between two spacecrafts, a PID control was adopted to guaranty the stability of the robot motion on the air cushion, taking in account the possible uncertainties representing the unmodeled dynamics and neglecting the nonlinearities.

The scenarios of the close-proximity operations are performed using multiple two-impulse transfers to represent each phase maneuver as essentially "finite".

Simulations were performed using three methods:

– Integration of proposed equations.

– Calculation of the position and velocities (by deriving the functions of displacement in the local frame).

– Calculation of position and velocity of the Chaser.

The GNC software running on real-time code is developed using the Matlab - Simulink software (Nguyen, Bordei, Nguyen & Ioniţă, 2019).

4.2. Hardware-in the-Loop Simulation

4.2.1. Development of Automatic Approach/Landing Technique of Hybrid UAV

Real time simulation of autonomous landing (searching, tracking, observation, docking modes) and validation of proposed UAV on ground platform (ship) are developed separately in two steps: one is for approach and second for landing (see Figure no. 2). Experimental validation of successive landing in multiple trials is tested at different speed (Apostolescu, Savu, Guţă & Ioniță, 2019; Costache, Nichifor, Apostolescu, Costea & Ioniță, 2021).

Entire experiment includes the following steps:

– Preparing for landing, capturing the initial point of a glide path for landing.

– Identifying landing reference (markers), estimating their position, calculating necessary landing parameters on the ship deck.

– RTKGPS (real time kinematic global position system) provides an accurate position.

– Vision system included for final approach (FA).

– Controller switching at selected distance, vertical control.



(a) HIL approach on ship platform *(b) HIL landing on oil platform*

Figure no. 2: *Approach/Landing test bench*
(Source: Automatic Landing on Mobile Platform/ALAMOPLAT)

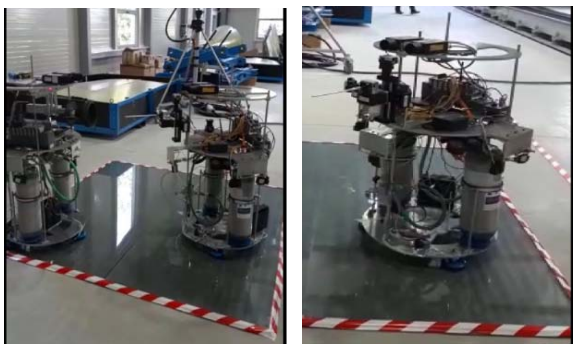
4.2.2. Aircushion Robots Closed R&D Simulation

Since proximity-operated guidance of the air-cushion robot is the main research focus of the air-cushion robot system, typically it is only the guiding block that is altered and a set of preconfigured standard subsystems for navigation and control are used (Fehse, 2003; Ankersen, 2010; Ioniță & Popescu, 2016).

The GNC software running on real-time code is implemented in Matlab – Simulink environment. Once they have been generated, the Simulink models are self-encoding using the Labview program. To facilitate the transfer from the Matlab – Simulink code to Labview environment, a conversion done in-house is used. The software architecture ensures that the superimposed GNC software operating on board reacts to the inputs of the sensors and delivers the corresponding actuator outputs in a precise, preset time interval.

The software is designed so that the user can define the navigation, control and guidance subsystems, thus facilitating research in any of these areas. Each robot has a control subsystem consisting of the thruster mapping and modulation software. Thruster mapping aims to select the thrusters required to generate the desired control input, force and torque. For each 3DoFs (see Figure no. 3) a PID control logic is used to calculate the required impulse.

While simulating flight conditions, the GNC software offers the possibility to verify the guidance, navigation and control algorithms. Vehicles "float" on an air cushion on a very flat surface, faithfully reproducing two-dimensional motion with three degrees-of-freedom. The Target vehicle is assumed to be fixed or moved after the known trauma, while the Chaser vehicle has complete maneuvering capabilities. Manoeuvring is powered with gas engines.



(a) *(b)*

Figure no. 3: *Air floating test bench*
(Source: CONtrol TECHnologies for SATellite Systems/CONTECHSAT)

5. Conclusions

A detailed description of INCAS SIL+HIL (Software-in-the-Loop+Hard-in-the-Loop) simulator has been presented. The test bench is used to verify a GNC process for spacecraft proximity operations and approach/landing of UAV. The GNS code, which was tested, developed and validated under laboratory conditions, can be implemented in control systems and embedded on aerospace vehicles.

Last section shows the Hard-in-the-Loop experiment to demonstrate the potential capabilities of the R&D robots and to show the functionality of the sensors.

The on-going efforts of INCAS to develop a SIL/HIL simulating capability for the new research area have been presented. This facility opens a new way in which the robot system delivering the relative motion of two aerospace vehicles performs the R&D missions.

To meet the requirements for HIL simulation, two robots must be properly controlled using robot control technology.

However, it is found that many of the advanced robots control techniques cannot be implemented because the laboratory does not have a floating floor surface with planar/flat and horizontal levelling accuracy in the "SpaceSysLab" facility for the moment. To solve this problem, a proposed alternative will be chosen.

The GNC algorithm of the Chaser was tested in a simulation environment where the dynamic model and sensors performances were estimated. The GNC algorithm was implemented on the Chaser controller in order to verify the functionality of the sensors.

This work/paper reported the current status of the new R&D "SpaceSysLab" facility. This has demonstrated that the facility is ready for HIL rendezvous and docking simulation and the overall simulation structure is in place. In the future, this simulation structure will be used in a research that will focus on the detailed development of its components.

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