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Air Cushion Robots Ground Testing Bed Experiments and Control Algorithm for Autonomous Rendezvous and Docking

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***Abstract*—This article presents a detailed technical description of "SpaceSysLab" simulator ACRS, located at INCAS South – Muntenia Region, Prahova, Maneciu, Romania. It is a robotic test bench for tests, verification and validation of R&D systems. Both open loop and closed loop tests can be performed at "SpaceSysLab", where the facility supports different applications. Also the work gives an overview GNC computational algorithms for real time applications in R&D motion. The research of the air cold thruster measurement was to estimate the thrust force of the proposed model for ACRS in laboratory environment. We also designed and manufactured the thruster devices that included the thruster calibration on air cushion robots.**

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

***Index Terms*—Air bearing test bench, air cushion robot, GNC software, HIL.**

I. INTRODUCTION

Rendezvous and docking maneuvers of two autonomous space vehicles have been extensively studied over the past decades. Advanced in autonomous on-board guidance, navigation and control seem to be essential in order to prepare a large variety of next mission. To achieve this objective the last results, show that development of GNC algorithms needs to occur in parallel with new architecture, hardware and software. The rendezvous phase consists of different controlled orbital maneuver in which an active space vehicle (named chaser) approaches a passive space vehicle (named target) in its low orbit. A critical phase for such mission is the successful docking to the target vehicle.

In the past years, numerous missions have been proposed and attempted exploring various techniques for safely conducting rendezvous and docking operation [1]. In order to ensure safe on-orbit operation, many ground testing must be performed to demonstrate that the GNC algorithm meets performance requirements. The ground-based demonstration system can provide suitable fidelity to verify and validate GNC algorithms.

A survey of relevant test bed has been presented exhaustively in [1]. Of these test beds a few research centers utilize a three degree of freedom (3 DoF) translational air bearing which translate on an epoxy, granite or glass surfaces. Two different test beds mentioned here are a 3 DoF's test bed in Naval Postgraduate School (NPS) of Montery [1] and are a 3 DoF's test bed in Thales Alenia Space Turin [2] due to fact that both test beds can analyses only the proximity maneuvers. INCAS has been implementing last two years an experimental infrastructure "SpaceSysLab". This research capacity is developed on South – Muntenia Region, Prahova, Maneciu district which includes a virtual platform and an experimental platform destinated to space applications.

The aim of present work is to present: air cushion test bench, thruster development for air bearing robots motion, software architecture for test bench simulator, simulation results in Matlab/Simulink environment. Last section shows the Hard in the Loop experiment on air cushion test bench to demonstrate the potential capabilities of the R&D robots and to show the functionality of the sensors.

II. EXPERIMENTAL TEST BENCH

"SpaceSysLab" Air Cushion Robot Simulator (SSL – ACRS) is composed by three main elements: a glass floor floating surface, two air cushion robots (chaser and target) and a laboratory measurement system.

The air cushion robots consist of a chaser and target vehicles. The chaser and the target are similar except for docking mechanism and navigation equipment that differs according to their specific roles (Fig 1, 2). The chaser has full maneuver capabilities while the target is assumed to be fixed and moving only docking mechanism. Three flat round 100 mm diameter air bearing are used by ACRS to achieve quasi-frictionless motion on the top of the glass floor. The air bearings use compressed air to lift the ACRS approximately 5µm, creating an air film between robots and the glass floor that eliminate their direct contact.

Both chaser and target are all equipped with 6 thrusters mounted in the patern shown (see Fig. 1, 2). Each thruster unit includes a fast response solenoid valve and it provides a nominal thrust force between 0.2 – 1.5 N (see Fig. 8). Maintain the attitude of spacecraft precisely aligned to a given orientation is a crucial for space missions. The problem became challenging when on/off thrusters for robot's precision pointing calls (for) a switching controller delivering some kind of pulse modulation in order to comply with the

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minimum firing time of thrusters. In this way a switching frequency of actuators must be estimated.

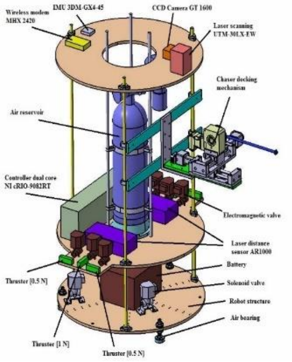


Fig. 1. Robot chasseur

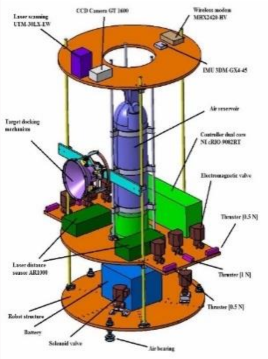


Fig. 2. Robot target

The chaser is equipped with 4 sensors: radio finders, laser position finders and a camera that provides linear and angular measurements with respect to the target vehicle and with an IMU that provides linear and angular measurements with respect to the test-bed reference frame considered inertial. Moreover, the laser position finder can perform measurements w.r.t. the inertial reference frame and it's used also to correct IMU's drift.

Unlike the chaser, the target doesn't need a relative navigation system and it just has to carry the transmitter of the radio finder system and the optical marker for the camera that the chaser requires for its navigation sensors. Then the target moves w.r.t. the inertial reference frame system by using only an IMU and the laser position finders.

Cold gas propulsion system play a main role while considering air cushion robots for a wide range of plan paralell trajectories. The system mainly consists compressed air tank, solenoid valves, thrusters, flat round air bearings, tubing and fittings (Fig. 3). From design point of view three important components of cold gas propulsion system including compressed air tank, flat round air bearings and cold gas thrusters play an important role. The compressed air, supplied at 6 bars is delivered from two on-board tanks holding 6.8 liters of compressed air at 300 bars, separated appropriately for air bearings (6 bars) and for thrusters (10 bars). A solenoid valve controls the flow towards the air bearings and thrusters and an air filter prevents any contamination and forcing materials from damaging to the delicate air bearings components.

The glass floor surface with 1m by 2 m dimension and 10 mm thick is primary choice only to test air cushion robots. The air cushion robots (chaser and target) are equipped with four sensors: a laser position finders (MHX 2420), a camera (Prosilica GT 1600C) and IMU (3DM-GXU-45) that provides linear and angular measurement with respect to the test bench reference frame considered inertial. Also the chaser and the target are separately equipped with MCU – main control unit (Controller dual core NicRIO – 9082RT).

The laboratory measurement system includes a Monitoring Control System based on an external computer PXI 8880.

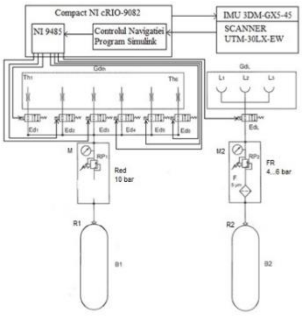


Fig. 3. Schematic of compressed air propulsion system

III. THRUSTER DESIGN, MANUFACTURING AND TESTING

The present part focuses in a way on cold gas thruster design, manufacturing and its experimental testing in laboratory conditions. The thrusters are the convergent – divergent nozzles that provide desired amount of thrust to perform motion of air cushion robos on the plane [3]-[4].

Design model A thruster model has been manufacturing with convergent-divergent angles close to 56 degree. Divergence loss is an important criteria to check for, regarding the nozzle performance. The nozzle area diameter has been dimensioned at 0.09, 0.5, 1.0 and 4.0 mm respectively.

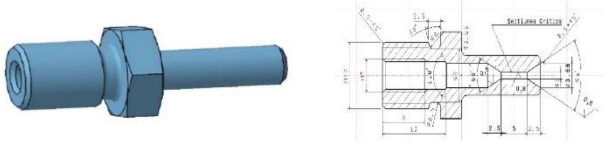

(a) (b)

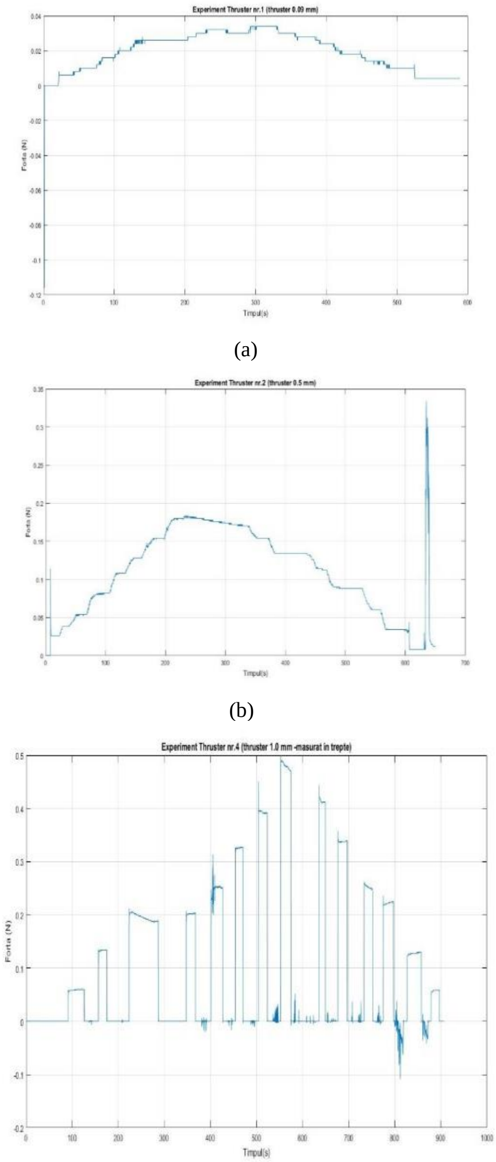
Fig. 4. Thruster technical drawing.

A. Lab Testing

For the firing process, the thruster was mounted on a stand using an adaptor (Fig. 5). A detailed thrust force measurement was carried out with a variation of input pressure for different mass flow conditions and different exit nozzles.

Fig. 5. Experimental setup for thruster static force measurement

A SAUTER FH-S force sensor is used to measure static force of the thruster device. Thrust values of 34 mN to 480 mN at 6 bar presure difference were reported for laboratory testing. All the data were recorded and presented below (fig. 6(a),6(b),6(c),7).



(a)

(b)

(c)

Fig. 6. Variation of thrust force versus time.

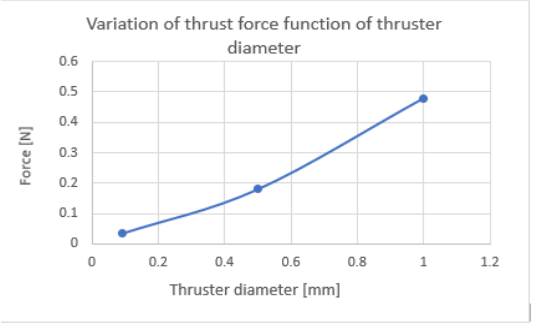


Fig. 7. Variation of thrust force with nozzle aria diameter

The test bench used for verifying translational and rotational motion of robots is a floating surface with 1m x 2m glass floor. Because the planar accuracy and the horizontal leveling accuracy could not be estimated, the thruster device used for experimental models of robots has the 5 mm nozzle diameter. The parameter like pressure difference, temeperature and thrust force are studied and reported for different cases of thrust values ranging from 0.2 bar pressure difference to 9.5 bar pressure difference respectively, in laboratory environment. The thrust force variation versus pressure diference is presented bellow.

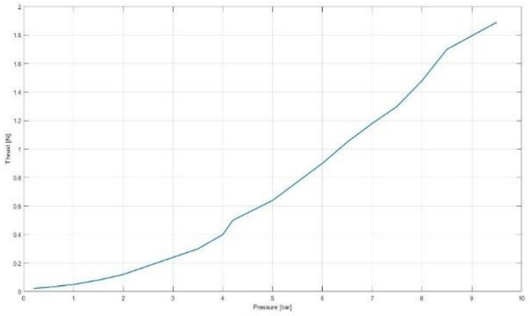


Fig. 8. Variation of thrust force with pressure difference tested on air cistern chaser

IV. DYNAMIC MODEL

A general model 3-DOF is presented below to simulate a rendezvous process of the Target and Chaser in the plane *OXZ*. According to CW equations [5]-[8], the relative equations for translational motion between Target and Chaser are written as:

$$\ddot{x} - 2\omega\dot{z} = \frac{1}{m}F_x \tag{1}$$

$$\ddot{z} + 2\omega\dot{x} - 3\omega^2 z = \frac{1}{m}F_z \tag{2}$$

and the attitude dynamics is expressed by using Euler equation:

$$I\ddot{\theta} = M \tag{3}$$

$$\dot{\theta} = \omega + \omega_c \tag{4}$$

$$\omega = \sqrt{\frac{\mu_0}{r^3}} \tag{5}$$

$$F_x = (F_1 - F2) + F_{xf} \tag{6}$$

$$F_y = [(F_3 + F_4) - (F_5 + F_6)] + F_{yf} \tag{7}$$

$$M = [(F_3 + F_6) - (F_4 + F_5)]a + M_f \tag{8}$$

$$F_{yf} = F_{xf} = F_f \tag{9}$$

$$F_f = \mu mg \tag{10}$$

$$M_f = \frac{2}{3}\mu mgR = \frac{2}{3}RF_f \tag{11}$$

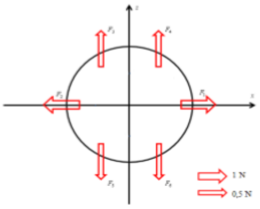


Fig. 9. Thrust mapping.

V. DEVELOPMENT OF TEST BENCH SIMULATOR USING SOFTWARE TOOLS

In order to simplify the algorithm development and subsequent implementation on the ACRS, a development simulator and an ACRS software template were created using a common custom library. The library contains common software navigation and control subsystems that are used in both the simulator and later in the ACRS onboard software. The simulator uses simulated sensors and actuators and also simulates the ACRS response, while the ACRS software templates uses the interfaces to the onboard sensors and actuator.

The purpose of the development simulator is to create an environment which accurate represents the tests bench allowing for rapid development of guidance algorithm as a ‘virtual’ test bench. Except for the interfaces from sensors and control actuator the development simulator utilizes the same supporting software (Matlab/Simulink) such as navigation filters, actuator control logic and rate transition in order to achieve the goal. The layout simplifies the transition from the development environment to the running the software onboard the ACRS. ACRS Simulator means the modeling of test-bench dynamics in the Matlab/Simulink environment, in which it is possible to test the behavior of GNC system without the hardware in the loop. The ACRS is comprised of three main subsystems that emulate the real test-bench’s functions to:

Dynamic block – it’s the 3 DoFs dynamic model of two rigid bodies with constant mass in relative motion.

Actuator model – takes in account of the on/off thruster switching time and the uncertainty of the thruster’s position on the vehicle. Sensor model: implement the disturbance and the errors of the sensors.

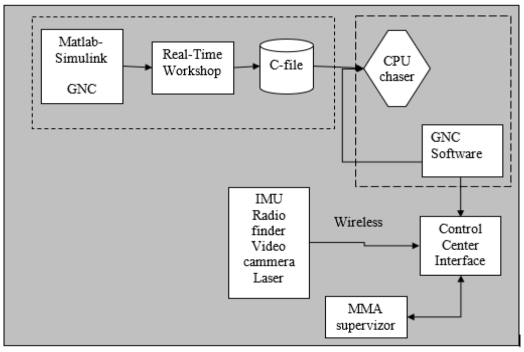


Fig. 10. Block diagram for a robotic based R&D simulator with various software elements.

The ACRS allows verification of guidance, navigation and control algorithms by simulating flight conditions. Vehicles "float" on an air cushion on a very flat surface, faithfully reproducing two-dimensional motion with three degrees of freedom (two for pitch and one for rotation). Target and chaser vehicles are similar. The target vehicle is assumed to be fixed or moved after the known trauma, while the chaser vehicle has all the maneuvering capabilities. The maneuvers are secured by gas engines.

Three reference systems will be used:

- Fixed reference system coinciding with the support (the mass on which the vehicles are moving);
- Reference system related to the object; and
- The relative reference system centered on the CoM target.

For the scenarios, the equations presented in the general model for air cushion robots were used.

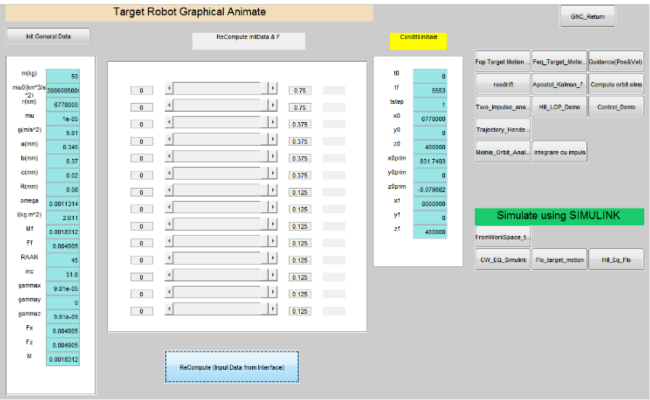
In this scenario the close-proximity operations along the V-Bar are performed using multiple two-impulse transfers in order to represent each maneuver of the phase as essentially “finite”. This scenario more closely represents a motion strictly along V/R-Bar directions.

Simulations were performed using three methods:

Integration of proposed equations in [5];

Calculating the position and velocities (by derivating the functions of $x\ (t), z\ (t)$ in the local frame [5];

Calculation of position and velocity like in [9].



m(kg) 50
miu0(km^3/s^2) 39860050000
r(km) 6778000
miu 1e-05
g(m/s^2) 9.81
a(mm) 0.345
b(mm) 0.37
c(mm) 0.02
R(mm) 0.56
omega 0.0011314
I(kg.m^2) 2.611
Mf 0.0018312
Ff 0.004905
RAAN 45
inc 51.6
gammax 9.81e-05
gammay 0
gammaz 9.81e-05
Fx 0.004905
Fz 0.004905
M 0.0018312

0 0.75
0 0.75
0 0.375
0 0.375
0 0.375
0 0.375
0 0.125
0 0.125
0 0.125
0 0.125
0 0.125
0 0.125
0 0.125
0 0.125

t0 0
tf 5553
tstep 1
x0 6778000
y0 0
z0 400000
x0prim 831.7493
y0prim 0
z0prim -0.079682
xf 8000000
yf 0
zf 400000

Fig. 11. Interface for the three methods

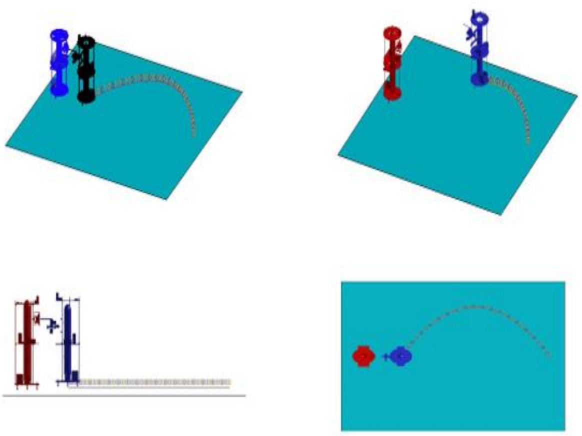


Fig. 12. Matlab/Simulink Simulation of R&D process.

VI. CONTROL DYNAMIC SIMULATION USING MATLAB/SIMULINK ENVIRONMENT – CASE STUDY

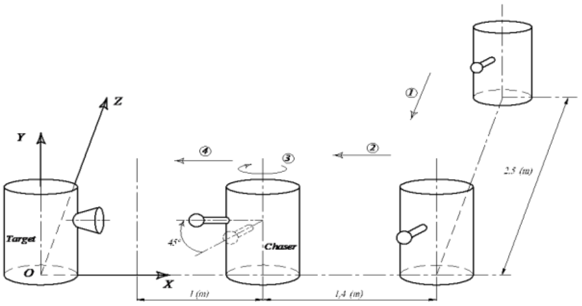


Fig. 13. Rendezvous of Chaser and Target in plane OXZ

For purpose of illustrating rendezvous process, let’s consider one example:

Control the Chaser shown in fig. 13 to approach the Target on the desired trajectory as:

- The stage 1: The Chaser moves along Z direction with a distance of 2, 5 (m).

- The stage 2: The Chaser moves along X direction with a distance of 1,4 (m).
- The stage 3: The Chaser rotates around Y axis attached to the Chaser with an angle of 45o.
- The stage 4: The Chaser continues to move along X direction with a distance of 1 (m) to approach the Target.

With the initial position of Chaser is (3,993; 2,5) (m), and for the Target is (0; 0) (m) in the plane OXZ.

For solving this issue, we will use PID Controllers to produce appropriate forces to control the Chaser to follow the specified trajectory. By using MATLAB Simulink, the controlling model will be simulated. For that purpose, let's give our system some data as:

$$m = 50kg \;;\; \mu_0 = 398600{,}5 \cdot 10^9 \,\frac{m^3}{s^2} \;;\; r = (6378 + 400)km;\ \mu = 10^{-5};\ g = 9{,}81\,\frac{m}{s^2};$$

$$I = 2{,}611\ kg \cdot m^2 \;;\; a = 345\ mm \;;\; b = 370\ mm \;;\; c = 20\ mm;\ R = 560\ mm;\ \omega = 0{,}0011\,\frac{rad}{s}$$

The initial states of the system are:

$$x(t_0) = 3.993\ (m);\quad \dot{x}(t_0) = 0\ (m/s);\quad z(t_0) = 2{,}5\ (m);$$

$$\dot{z}(t_0) = 0\ (m/s); \theta(t_0) = \frac{-3\pi}{4}\ (rad);\quad \dot{\theta}(t_0) = 0\ (rad/s);$$

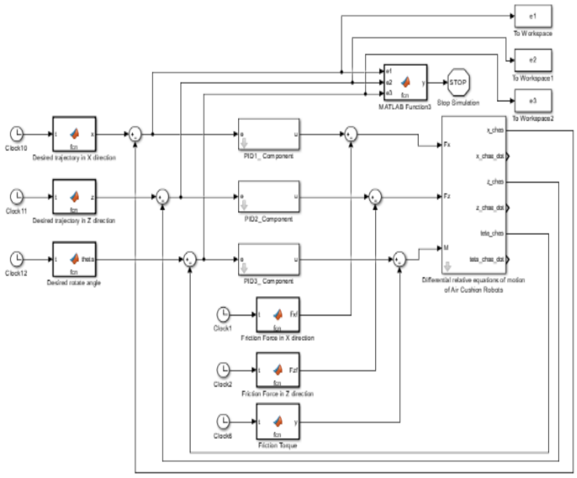


Fig. 14. Simulink model for controlling air cushion robots.

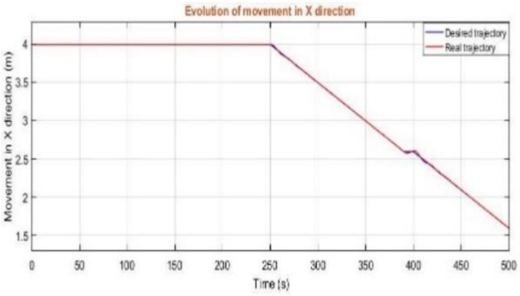


Fig. 15. Movement of Air Cushion in X direction versus time.

And by applying the Genetic Algorithm for tuning PID controller parameters in our system, the values of K_{Pi}, K_{Ii}, K_{Di} (i = 1, 2, 3) are determined as:

$$K_{P1} = 7.8500;\ K_{I1} = 0{,}1900;\ K_{D1} = 7{,}7500;$$
$$K_{P2} = 8{,}9700;\ K_{I2} = 0{,}1600;\ K_{D2} = 6{,}7700;$$
$$K_{P3} = 74{,}78;\ K_{I3} = 29{,}95;\ K_{D3} = 50{,}97.$$

The results obtained from Simulink model are shown in figures as following:

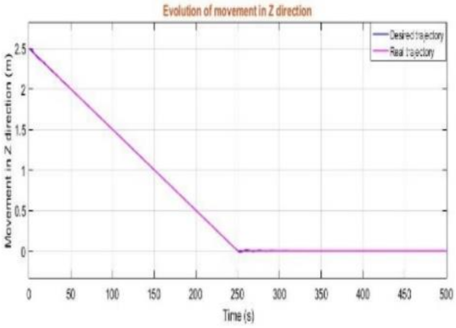


Fig. 16. Movement of air cushion in Z direction versus time.

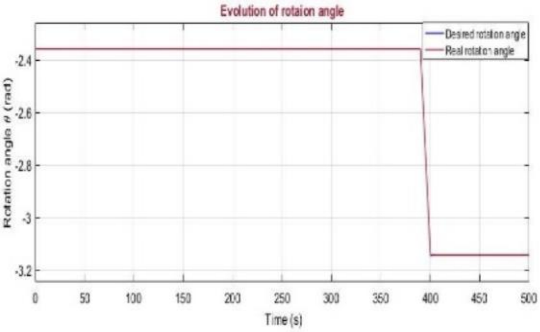


Fig. 17. Angle rotation versus time.

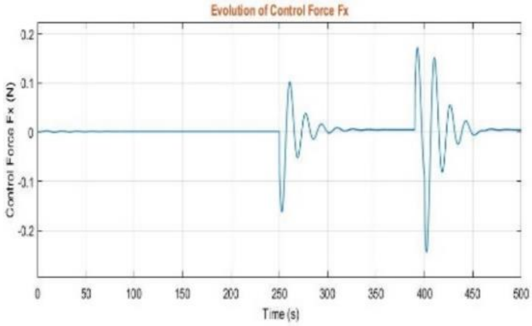


Fig. 18. Variation of control force Fx versus time.

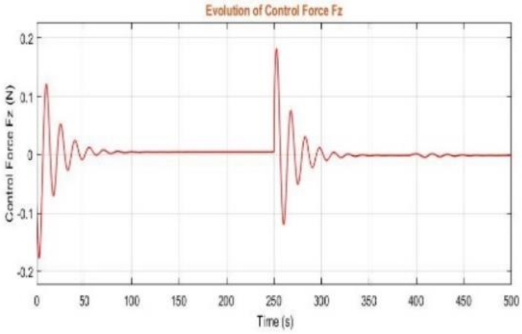


Fig. 19. Variation of control force Fy versus time.

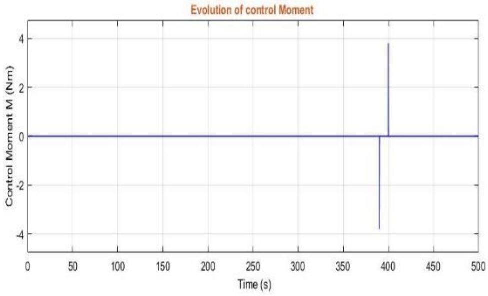


Fig. 20. Variation of control force Fz versus time.

For evaluating how well the PID controller system perform the given task, we will consider the errors between desired coordinates and real coordinates as formulas below:

$$e_x = x_{des} - x_{re} \quad (12)$$

$$e_z = z_{des} - z_{re} \quad (13)$$

$$\theta_x = \theta_{des} - \theta_{re} \quad (14)$$

where $x_{des}, z_{des,} \theta_{des}$ are desired coordinates of Air Cushion robot, $x_{re}, z_{re,} \theta_{re}$ are real coordinates of Air Cushion robot.

Then for observing visually, let's use the results shown in the following figures:

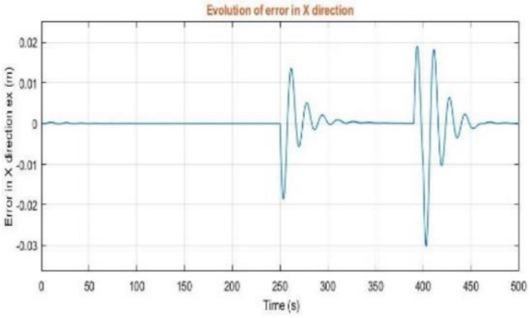


Fig. 21. Variation of error in X direction versus time.

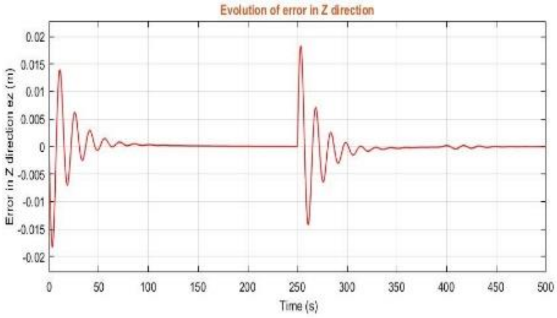


Fig. 22. Variation of error in Z direction versus time.

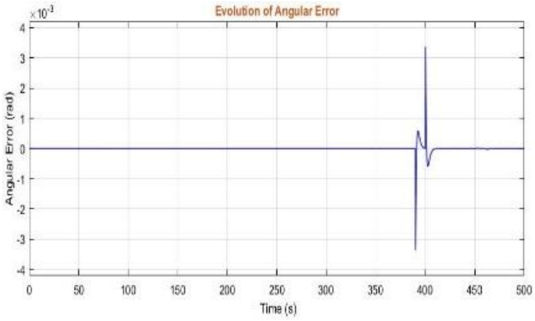


Fig. 23. Variation of angular error versus time.

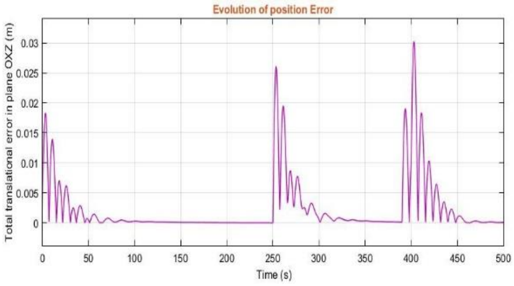


Fig. 24. Variation of total translational error versus time

And for having overall view about error, we should examine the total translation error, which is computed in the expression as:

$$e_{tot} = \sqrt{(x_{des} - x_{re})^2 + (z_{des} - z_{re})^2} \quad (15)$$

Then the result is shown in Fig. 24.

VII. HARDWARE IN THE LOOP R&D TESTS

As aircushion robot proximity operating guidance is the primary research focus of ACRS, only the guidance block is usually modified and a set of standard predeveloped navigation and control subsystems is used.

The GNC software running on RT-OS is developed using the Matlab / Simulink environment once developed the Simulink models are autocoded using the Labview program. To facilitate the transfer from the Matlab-Simulink code to Labview environment is used a conversion that is made at the home.

At the core of the ACRS software architecture is a Real Time Operating System (RT-OS) which ensures the overlying GNC software running on-board responds to sensor inputs and generates the appropriate actuator outputs within a strict and predefined time span. For achieving the desired real-time requirement two main control unit NicRIO – 9082RT(OS) have been chosen. As illustrated in Fig. 25 the GNC block first samples the on-board sensors and the actuator states to produce an inertial state estimation. The standard control subsystem, which is comprised of the steering logic and converts the guided-desired actuator input to the required low-level signals to drive the different onboard actuators in fig 26. The software is development in such a manner that the navigation, guidance and control subsystems can be user-defined allowing to perform research focused on any of these areas.

The control subsystem of every ACRS consists of thruster mapping and thruster modulation software. The purpose of thruster mapping is to select the appropriate thruster to fire in order to generate the desired control input including force and torque. Additionally since the thruster operate in on/off mode a modulation scheme is developed in order to realize the desired force for each thruster (Fig. 25).

The impulse required is calculated using a PID control logic for each 3DoFs. The control logic is activated only if the error on position and/or attitude and/or velocity is outside of dead band. A PWM control generates the on/off commands for the electro-valves at the time interval of 0.05 sec. The saturation is reached during acceleration and deceleration transient.

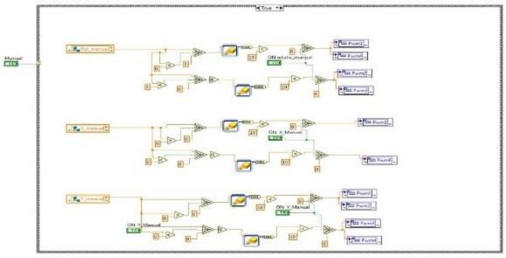
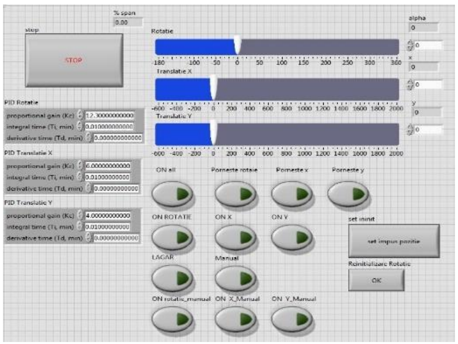


Fig. 25. Labview scheme of R&D process.



PID Rotatie
proportional gain (Kc) 12.3000000000
integral time (Ti, min) 0.010000000000
derivative time (Td, min) 0.000000000000

PID Translatie X
proportional gain (Kc) 6.00000000000
integral time (Ti, min) 0.01000000000
derivative time (Td, min) 0.00000000000

PID Translatie Y
proportional gain (Kc) 4.00000000000
integral time (Ti, min) 0.01000000000
derivative time (Td, min) 0.00000000000

Fig. 26. Control panel for R&D test bench.

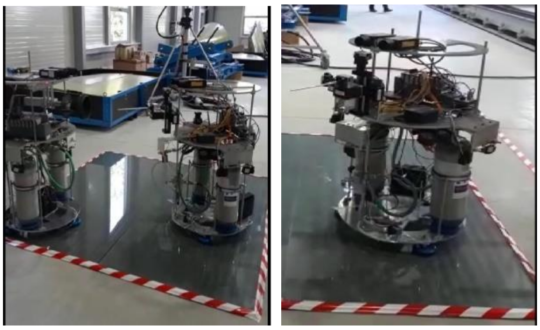

(a) (b)

Fig. 27. Air floating test bench at INCAS, spacesys lab".

VIII. CONCLUSION AND NEXT STEPS

This work presented a numerical and experimental investigation of the INCAS "SpaceSysLab" ACRS Hard in the Loop simulator for proximity operations.

The on-going efforts of INCAS to develop a HIL/HMI simulating capability for the new research area was presented. This facility opens a new way in the 3DoF air bearings robots to deliver the relative motion of two space vehicles which perform the R&D missions. To meet the requirements for HIL simulation, two robots have to be properly controlled with robots control technology. However, it is found that many advanced robots control techniques cannot be implemented because the laboratory do not have a floor floating surface with planar and horizontal leveling accuracies on "SpaceSysLab" facility this time. To solve the problem a proposed alternative will be chosen.

The main scope of the air cold thruster measurement was used to estimate the thrust force of the proposed model for ACRS in laboratory environment. We also designed and manufactured the thruster devices that include the thruster calibration on air cushion robots. The GNC algorithm of the chaser tested inside simulation environment in which the dynamic model and sensors performances has been estimated. The GNC algorithm has been implemented on Chaser CPU in order to verify sensor functionality. This work reported the current status of the new R&D facility SpaceSysLab". A detailed overview of ACRS is given including all upgrades made in the last year. Moreover, the paper presents implementation of a closed loop scenario based on camera sensor which is a first rendezvous application using ACRS facility. It has been showing that the facility is ready for HIL rendezvous and docking simulation and the overall simulation structure has been established. Forthcoming researches will use this existing simulation structure and focus on detailed component development.

Considering the maneuver of rendezvous between two spacecrafts a PID control has been adopted to guaranty the stability of the air cushion robot motion, taking in account possible uncertainty representing unmodeled dynamics and neglecting nonlinearities. A detailed description of INCAS ACRS (air cushion robots) Hard in the Loop (HIL) simulator has been presented. The test bench can be used to develop and experimentally demonstrate a GNC process for spacecraft proximity operations. With an available ACRS and extensive software GNC tools for real time on-board operations the test of air cushion robots can be quickly and easily developed.

NOTATION

$\mu_0 -$ gravitational constant of Earth (m^3/s^2)
$\mu -$ friction coefficient
$\omega -$ mean motion (1/sec)
$F_i -$ thrust force (N)
$F_f -$ friction force (N)
$F_x -$ force component on the Ox axis (N)
$F_y -$ force component on the Oy axis (N)
$F_z -$ force component on the Oz axis (N)
$M -$ moment (Nm)
$M_f -$ friction torque (Nm)
$m -$ mass (kg)
$g -$ gravitational acceleration (g/s^2)
$r -$ radius (km)
$I -$ moment of inertia (kgm^2)

ABBREVIATIONS

HIL	Hardware-In-the-Loop
DOF	Degrees Of Freedom
w.r.t.	With Respect To
CoM	Center of Mass
MOI	Moment Of Inertia
ODE	Ordinary Defferential Equation
LVLH	Local Vertical / Local Horizontal
CW	Clohessy and Wiltshire
PID	Proportional Integral Derivative
ACRS	Air Cushion Robot Simulator
V/R bar	Approaches of spacecraft toward to target
RT-OS	Real Time Operating System
HMI	Human Machine Interface
CPU	Central Processing Unit

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