Facility for validating technologies for the autonomous space rendezvous and docking to uncooperative targets

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Abstract. We present the latest advancements in the air-bearing facility installed at La Sapienza's GN Lab in the School of Aerospace Engineering. This facility has been utilized in recent times to validate robust control laws for simultaneous attitude control and vibration active damping. The instrumentation and testbed have been restructured and enhanced to enable simulations of close proximity operations. Relative pose determination, accomplished through visual navigation as either an auxiliary or standalone system, is the first building block. Leveraging the acquired knowledge, optimal guidance and control algorithms can be tested for contactless operations (e.g. on-orbit inspection), as well as berthing and docking tasks.

Introduction

Rendezvous and docking maneuvers have been successfully performed since the early days of spaceflight, but still pose challenges due to the increasing complexity of the mission scenario. From the early missions that required a human pilot, the goal of autonomous operations has already been achieved with notable examples in the ISS cargo resupply.

The current state of the art in proximity operations still involves some form of cooperation between the maneuvering satellite (the Chaser) and the Target satellite in the form of aids to relative navigation or in the form of mechanical interfaces to facilitate the docking phase. In either case, the Target satellite is usually controlled and fully operational. Much research is being done to extend these operations to a larger class of objects that are noncooperative and uncontrolled. Applications range from debris removal (see [1]) to orbital maintenance operations to repair or extend the operational life of a satellite.

Several missions have been developed to demonstrate the technology required for rendezvous and proximity operations (see the AVANTI demonstration [2] or the ELSA -D mission [3]).

A fundamental step in increasing the TRL of the required technologies is to conduct ground experiments to validate the components in a laboratory environment (typically TRL 4/5). For example, the work in[4] focuses on experimental verification by implementing and comparing real-time guidance algorithms on the Floating Spacecraft Simulator (FSS) testbed; a similar air-bearing testbed is used in [5] to validate the effectiveness of relative pose measurement systems. Various experimental approaches (e.g., using drones) can be used to test guidance and navigation subsystems (see [6]).

One of the most critical technologies to consolidate for successful close-proximity operations is the ability of an active spacecraft to accurately estimate its relative position and attitude (pose) with respect to an active/inactive Target (see [7]).

At the Guidance and Navigation Laboratory (GN Lab) of the School of Aerospace Engineering at La Sapienza, University of Rome, we have developed over the last decade a test bed consisting of a free-floating platform that can maneuver in a frictionless environment thanks to ON-OFF thrusters. The test bed, now in its second stage of development, has been used in the recent past to validate the active robust control system for attitude control of large flexible satellites as part of an ESA ITT study.

This paper shows the current equipment of the facility, consisting of two free-floating platforms (with a fleet to be expanded in the near future), a very accurate external measurement system (providing position and attitude measurements of the platforms with an accuracy of 0.1 mm and 0.01 degrees, respectively), and large screens for the projection of simulated orbital views that are changed in real time according to the motion of the platform.

With this configuration, it is now possible to validate critical short-range subsystems, such as visual navigation to determine the position of an uncooperative target in difficult lighting conditions and with limited computing power. Different algorithms can be tested for long-range (in which case a simple angle algorithm can be used) and short-range scenarios (feature-based algorithms or AI techniques are viable options). Maneuvers based on this information can eventually lead to docking, a phase where experimental validation of the behavior of the mechanisms and platforms during contact dynamics in a reactionless environment is critical. Successful validation of the critical aspects of GNC in a laboratory environment will pave the way for the realization of space-based enablers using microsatellites.

The first platform: early development of PINOCCHIO

The GN Lab has been developing a free-floating platform since 2012 (see [8]). In its first version, the platform, named PINOCCHIO (Platform Integrating Navigation and Orbital Control Capabilities Hosting Intelligence Onboard), was a 10-kg class platform, that utilized low-pressure air (10 atm) stored in an onboard tank for generating a thin film of air removing the friction between the air-bearings and the working table. It incorporated a second onboard tank supplying eight nozzles, serving as cold gas thrusters to enable horizontal movement and rotation around the vertical axis (yaw). Originally, a glass table (Fig. 1 - left) was used, but it was later upgraded to a black granite table due to its improved dimensional stability and operational workspace. PINOCCHIO operated autonomously, with its onboard computer managing all functions. The modular architecture allowed for the integration of various avionics components, including accelerometers, gyros, cameras, and lab star sensors, to instrument the guidance and control systems for both position and attitude. The platform's bus, which closely resembled the size and mass properties of a real microsatellite, proved instrumental in numerous studies conducted by the Sapienza team in recent years, as referenced in [9][10][11]. These studies encompassed areas such as rendezvous and docking guidance, optical navigation, and combined control of the platform's attitude during robotic arm motion (as depicted in Fig. 1). Additionally, the team explored the effects of flexibility in attitude control resulting from elastic appendages.

The need to further investigate the research field of attitude control of very large and flexible satellites using a multi-input multi-output control with attitude and elastic sensors and actuators, in the framework of the ESA ITT EXPRO-PLUS project “ACACLAS” (Advanced Collocated Active Control of Large Antenna Structures), called for the design, realization and characterization of a new platform to increase the performance and the capabilities of the test rig.

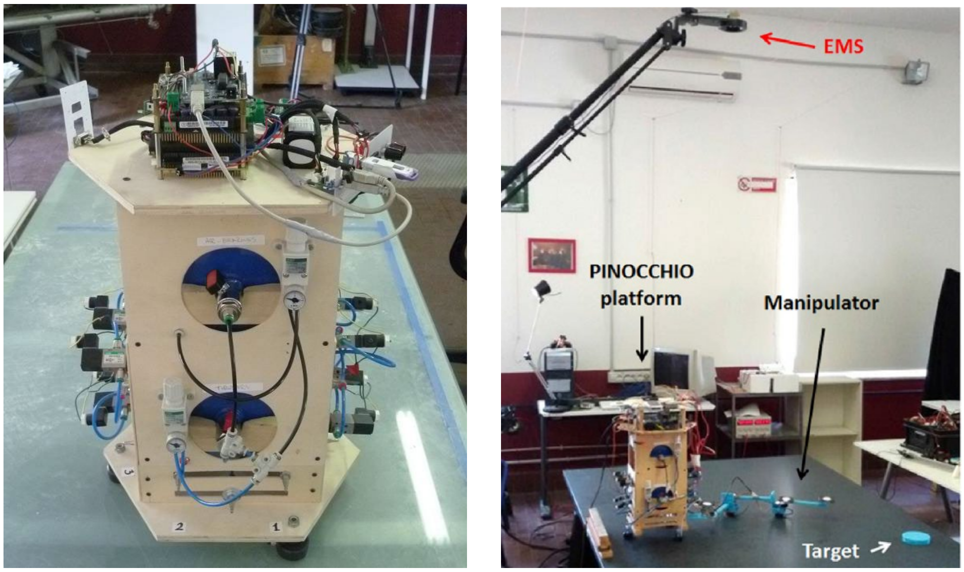

Fig. 1 The first version of the floating platform (left) and one of the experiments focused on the use of space robotic manipulators (right)

The second platform: a special focus on attitude control of highly flexible satellites

A new platform has been developed to enhance the performance of the initial platform in several aspects:

(a) Increasing the bus rigidity
(b) Extending the duration of experiments
(c) Including a dedicated electronics module for the payload
(d) Equipping the test rig with a high-accuracy metrology system.

The floating platform's structure has been completely redesigned using an Aluminum alloy (UNI 6060). It has overall dimensions of 300 mm × 350 mm × 480 mm (height) and consists of three compartments, which can be expanded due to its modular design, catering to specific purposes. The lower compartment houses the pneumatic system, while the second floor (300 mm × 350 mm × 100 mm) accommodates the electronics, including sensors, microcontrollers, power supplies, and wiring (see Fig. 2 - left). To achieve the required long experiment duration, a high-pressure tank with an operational pressure of 200 atm is used (see Fig. 2 - right). The third floor provides additional modules for specific missions. Currently, it houses the electronics required to control flexible appendages, such as solar panels and antennas (see Fig. 3 - left). These structures can be easily attached when experiments necessitate active control of flexible appendages. In such cases, a smaller, more precise working table is utilized since attitude maneuvers are typically the main focus (see Fig. 3 - right).

For accurate measurements of the structure's attitude and elastic displacement, a VICON system is employed. This technique utilizes retroreflective markers that are tracked by six infrared cameras. A detailed characterization of the platform can be found in reference [13], demonstrating navigation accuracy below 100 µm for position and 0.003 deg for attitude.

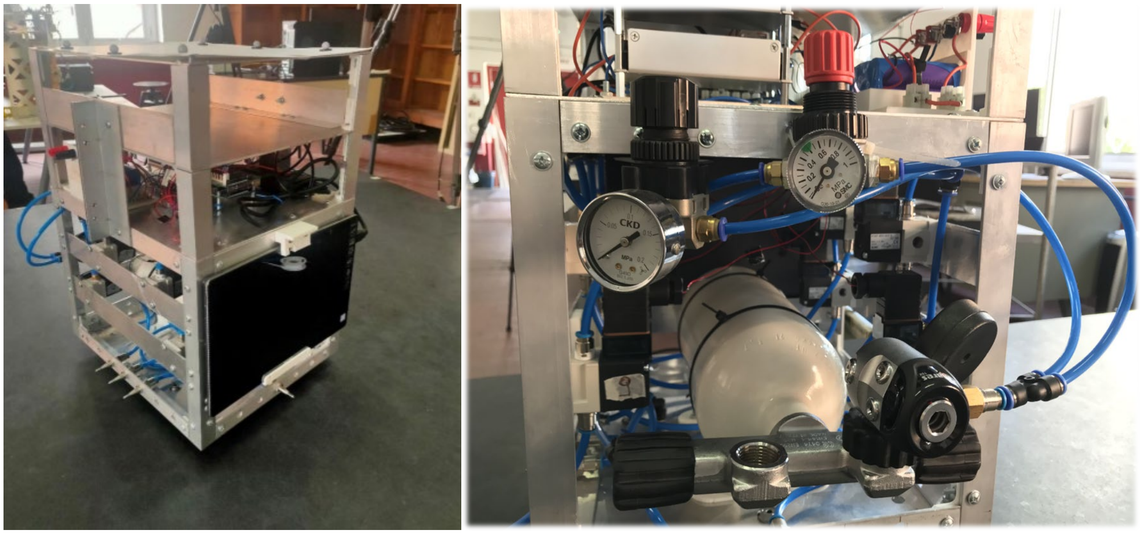

Fig. 2 The new version of the floating platform (left) with the high-pressure systems for air-bearings and thrusters (right).

Fig. 3 Electronics compartment (left) used for vibration sensing and control of the highly flexible appendages (right).

A testbed for autonomous rendezvous and docking

The two platforms and the external metrology system have been now repurposed at the scope of testing guidance, control and, more specifically, optical navigation for the determination of the relative pose of a Chaser satellite with respect to a Target satellites. Active electro-optics systems can be used and tested, showing a promising performance (see [12]); these systems can be aided or partially substituted by vision systems (monocular or stereovision). For a hardware-in-the-loop test, the orbital environment should be reconstructed also from a visual point of view. To achieve this, an array of screens has been arranged to project realistic potential background images (Fig. 4 - left depicts the currently installed first screen). This allows the Chaser satellite's acquired image to include not only relevant Target satellite features but also various potential sources of visual disturbance, such as Earth landscapes, clouds, or stars (see Fig. 4 - right). Additionally, a lamp simulating the sun's position can be used to account for the constraint of avoiding blinding of the Chaser's cameras.

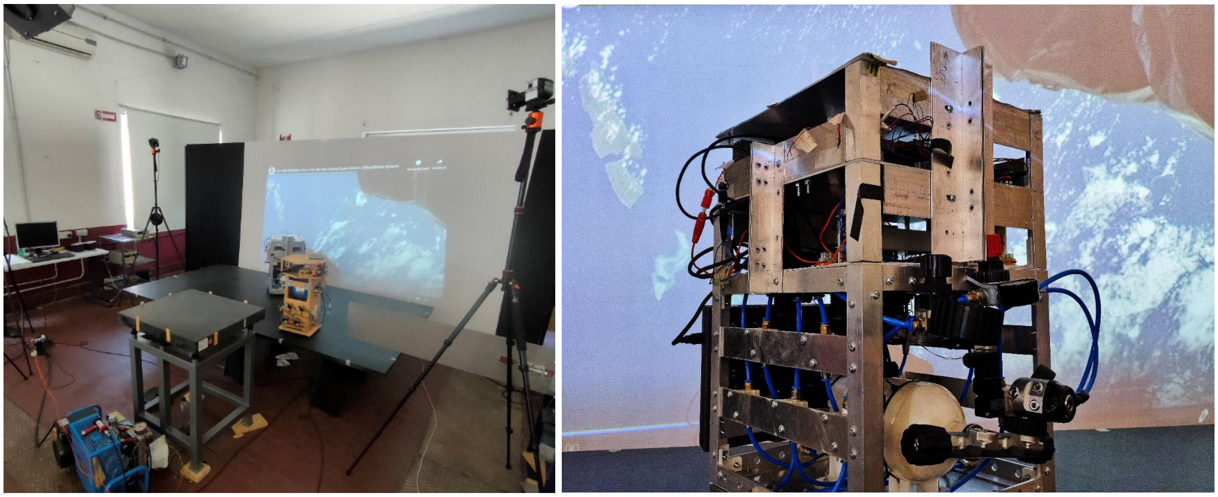

Fig. 4 First installed white screen with the two floating platforms (left) and a snapshot acquired by the navigation systems on board the Chaser satellite (right).

The onboard navigation systems provide relative pose measurements that must be validated thanks to benchmark metrology systems. The VICON system already mentioned in the previous section is a powerful mean in this sense. The inertial position of both platforms can be computed in real-time with a maximum frequency of 300 Hz, and with an accuracy which is much better than what achievable with the onboard systems. Fig. 5 reports an example of the visualization and the stream of data available with such a system, where each platform is identified by a different pattern of reflective markers.

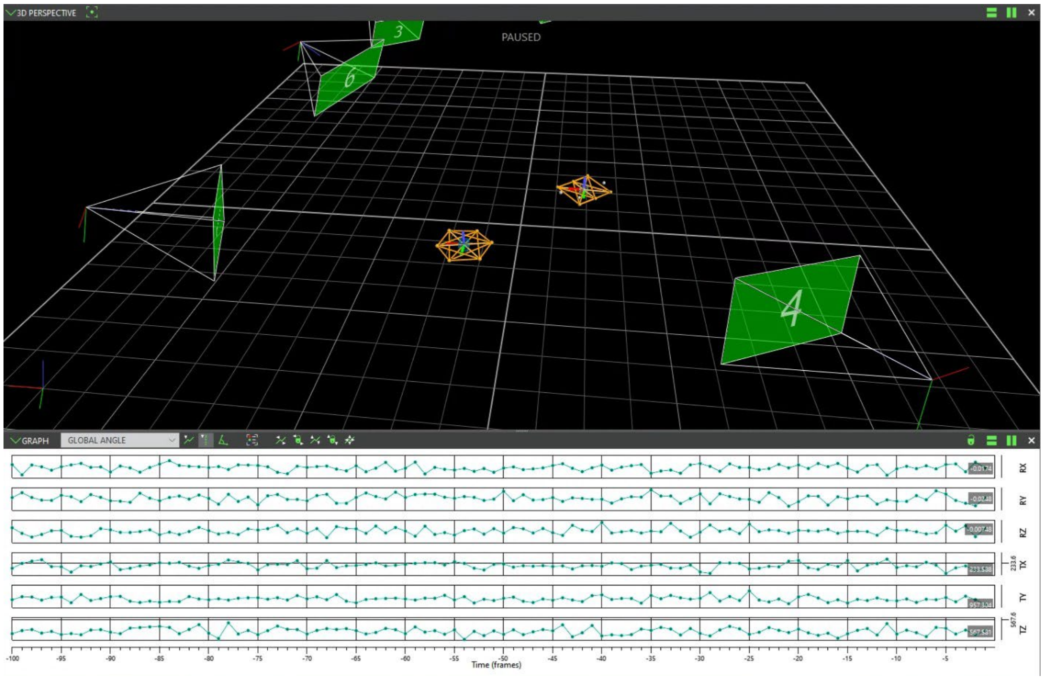

Fig. 5 Chaser and Target platforms acquired by the external metrology system

This set up can be used not only for visual based navigation, but also for testing range finders (LIDAR or radio frequency) and systems emulating differential GPS measurements. Relative pose determination is one of the building blocks of the autonomous rendezvous and docking operations. While it can be also tested using robotic arms (see [14]), with the air-bearing approach also the guidance and control algorithms can be tested in closed loop, including the contact forces and the post contact dynamics which are among the most difficult phases to simulate. The position and attitude control of the single platforms are accurate enough (see Fig. 6 for an example of an attitude slew maneuvers of 30 deg, with stationary error of 0.1 deg) to allow for a complete docking, including the validation of the performance of mechanical hardware.

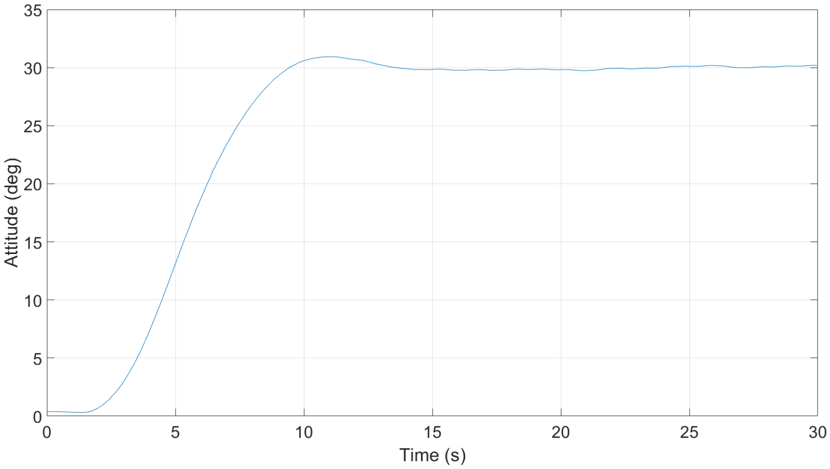

Fig. 6 Example of an attitude slew maneuver

Conclusions

We have showcased the key features and performance of an experimental testbed that has played a crucial role in validating attitude control algorithms for highly flexible spacecraft. Currently, we are expanding its capabilities to facilitate testing of space proximity operations, specifically focusing on control and relative navigation. We encourage the academic community to explore this platform for validating and testing various building blocks of the autonomous formation flying guidance, navigation, and control architecture, in the framework of future fruitful collaborations.

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