

Implementation of a Federated Laboratories Network for Testing Formation Flying Technologies

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Abstract

Formations of microsatellites are a highly attractive solution for achieving responsive space missions focused on Earth observation and communication support, due to their low cost and mass. However, operating these formations is challenging and requires extensive testing, which can be difficult to carry out due to the need for multiple platforms and large testing spaces. This paper presents the first concept and the first steps of a research program funded by NATO in the framework of the Science for Peace and Security program, with the specific purpose to develop and evaluate the necessary infrastructure for establishing a virtual, multi-platform distributed laboratory network comprised of laboratories from Sapienza, Lulea and Cranfield Universities. The value of this network will be increased by sharing resources, equipment, and expertise among the participating laboratories.

Keywords: Formation Flying; free floating testbeds; coordinated experiments

1. Introduction to the project

The capability of accessing information relevant to unreachable regions can be fundamental in many scenarios, such as natural disasters (floods, earthquakes, volcano eruptions) or war scenarios. A fast response in those situations is the critical factor. Of course, this could be in principle done with already existing remote sensing or communication satellites; unfortunately, their orbital configuration does not allow for fast revisiting time all over the world, since they have originally been designed for specific regional coverage.

An alternative solution that has been increasingly considered is the possibility to deploy ad hoc satellites for a specific, time limited scope. Because of the long design and production phase of a traditional satellite, together with its large cost and limited launch opportunities, the attention has been rather focused on the microsatellites class. These are platforms of very limited dimensions and weight (in the range of tens of kilograms) and often equipped with COTS (Commercial -off-the-shelf) components. Due to these characteristics, their production and launch cost is very low, and the launch possibility are much larger, including very small launchers or even air-to-orbit systems.

The drawback of microsatellites is their reduced (and in some cases uncertain) performance. The payload that can be equipped onboard is constrained by the limited available volume, mass, and power. Therefore, the performance of a single microsatellite is expected to be lower than that of traditional, larger satellites. However, the situation changes when a fleet, or formation, of

microsatellites is deployed instead of a single microsatellite. If the members of the formation are controlled in such a way that their relative attitude and position are accurately controlled, coordinated, and synchronized, they can create virtual structures of huge dimensions (ranging from a few meters to tens of kilometers), which enables them to achieve performance that is similar or even larger than traditional satellites by combining data from the individual platform.

The technical challenge in this scenario lies in the Guidance, Navigation, and Control (GNC) system of the microsatellites. The close proximity of the satellites, combined with the strict requirements for attitude and relative position accuracy, calls for a degree of autonomy in the microsatellites, which is still an immature technology in space activities. The simplified onboard hardware of the microsatellites further increases this challenge.

An extensive experimental activity is required in order to rise the technological readiness level of the GNC system of the microsatellites in order to perform responsive formation missions.

Experimental verification of space systems, in particular concerning GNC aspects, calls for a zero-gravity or microgravity environment. This condition cannot be rigorously achieved in terrestrial laboratories, and different approaches have been followed to reach an acceptable approximation of the space environment. Some of them allow 6 degrees of freedom (DOF) for the platform, but they are limited to short time operations: in this category we find parabolic flight and drop towers. Different approaches aim at fighting the gravity forces by

using suspension wires or large pools for neutral buoyancy vehicles. Problems in these cases are connected to the complex balancing that is needed (in the suspension wires case) and in the need to work in a submarine environment, with increased costs and the presence of a non-negligible friction.

The strategy that is currently the most developed consists in using platforms that can move frictionless on a flat working surface thanks to air-bearings. In its basic configuration, only three DOFs are available for motion control in space-like environment: two planar translations and one rotation about the vertical axis. More complex solutions also enable two additional rotations, by including a spherical air bearing as a support for the experimental platform, that at this point can be considered a 5 DOFs test-rig: this advanced configuration is appealing for the full simulation of a satellite motion, but from a practical point of view it presents hard challenges in balancing the system with dummy masses. As a consequence, most of the laboratory free floating testbeds usually choose the basic 3 DOFs configuration, as in the case of the platforms developed in the laboratories involved in the proposed research.

The need of testing formations of satellites increases the level of complexity of the required facility. One of the strictest constraints is relevant to the availability of a very flat and horizontal worktable. The presence of many floating platforms could push the dimensions of the worktable beyond technical limits. As an example, granite tables are often used; if the dimensions have to be increased, one solution is to use piecewise construction, with the difficulty of realizing a nearly zero discontinuity between the table patches. Also the perfect levelling of a worktable is quite easy for small dimensions, while it becomes soon very complex for large dimensions. At the same time, the relevant dimensions of the hosting laboratory should consequently increase. As a final trivial consideration, building multiple platforms and multiplying the required hardware involves a cost that linearly grows with the number of involved platforms. This makes the testing of formations of satellites an activity that is beyond the possibilities of usual academic and industrial laboratories.

The proposed solution consists in exploiting the capabilities of different laboratories, even in different Countries, in order to experimentally test GNC system for formation of satellites in an approach here called “Federated Laboratories”.

This research, developed in the framework of the NATO Science and Peace for Security program, proposes developing an infrastructure for distributing the experimental activity over a network of federated laboratories hosted in three Universities: Sapienza University of Rome, Cranfield University and Lulea Tekniska Universitet. Just like in the satellites’ formation case, also in the federated laboratories case the result is

obtained by sharing the technological capabilities of the single laboratory, with other similar (but not identical) laboratories spread over different countries or NATO partners. The advantages are clear: each laboratory can use its own capabilities originally thought for the test of the single satellite, and transform them in a satellite formation test rig. Each laboratory has been developing its own platform and relevant technologies independently, and this should not be considered a limitation, but rather a strength. In this way the different capabilities (for example: different sensors, vision-based systems, navigation systems and so on) can be of use to all the other connected platforms. This can be achieved by realizing first a communication architecture among the laboratories. UDP internet protocols are one of the candidate technologies for the scope. Communication delays among distance countries are a challenge that replicate the inter-satellite communication latency in space.

The different laboratories have been developed independently, and with different design philosophy and goals. Therefore, some upgrades must be designed and implemented to make all the facilities compliant with the federated laboratory experiment. Also the simulation of a specific mission can demand for add-ons to the current laboratory equipment.

In fact, two main activities will be performed in this research, a first one relevant to the design of a meaningful responsive mission scenario for a formation of microsattellites, with the relevant development of the GNC requirements and possible solutions (to be numerically validated), and a second one relevant to the laboratory upgrades, interconnection and finally the GNC system tests. Of course, the laboratory activity also depends on the designed mission. A first hypothesis consists in a formation of microsattellites deployed to identify and observe predefined Earth regions. At the scope, one (or all) the facilities should be equipped with a vision system for the projection of Earth images such that the platform can acquire and process them with onboard dedicated hardware (cameras and processor). The attitude of the single satellite is determined by the requirement of observing the region and, at the same time, being synchronized with the other platforms in the different laboratories (that could be observing – or not – the same Earth images). A consensus-based algorithm will finally drive the platform attitude to point all at the desired direction, by sharing the information and optimizing the two different drivers. Similar missions can be designed involving the relative position, when precise formation configuration is required. In both cases (attitude or position requirements) the definition of common virtual reference frames will be a fundamental preliminary activity. The experimental platforms will provide an ideal setting for re-creating eventual orbital-like conditions so that Artificial Intelligence-based

algorithms can be trained through the exploitation of the experiment-derived datasets.

The proposed research aims, from one side, at experimentally validating GNC algorithms for specific missions of interest, and, at the same time, providing a general demonstration of the capability offered by such an infrastructure, enabling to design experiment with a virtual very large laboratory, that could be otherwise impossible with single isolated laboratories.

The remainder of the this paper is organized as follows: in Section 2 the research organization is outlined; in Section 3 a brief overview of the possible mission objectives that can be simulated with the federated labs is reported; in Section 4 the solutions for free floating platforms adopted in the other Universities or research centers are reviewed, serving as input for the upgrade of the current facilities (described in Section 5). Some information of the previous activities performed in the framework of the federated laboratories can be found in Section 6, while final remarks are reported in Section 7.

2. Research group and organization

The research group (Fig. 1) that has been awarded the grant for the realization of the network of laboratories for formation flying tests is lead by the School of Aerospace Engineering of Sapienza University of Rome (Italy), the University of Cranfield as co-director from a NATO country, and the Lulea Tekniska Universitet from Sweden, as a NATO partner country.



Fig. 1 Research group composition

2.1 Project organization

The research is roughly divided in two main phases: a first phase in which the GNC for the relative configuration acquisition and keeping is designed and tested in the framework of a high-fidelity numerical propagator, and a second phase in which the facilities will be upgraded and completed in order to test a scaled version of the formation flying algorithms. In detail, the project is organized in 10 main tasks, that, in two years, will lead to the realization of the network of laboratories.

Task 1: Review of existing free-floating facilities (Months 0 – 3)

Task 2: Definition of formation flying mission objectives (Months 0 – 4)

Task 3: Definition of Navigation and Control architecture (Months 6 – 10)

Task 4: Formation dynamic model simulator (Months 4 – 7)

Task 5: Numerical validation and verification of GNC algorithms (Months 10 – 12)

Task 6 Design and implementation of the facilities upgrade (Months 10 – 15)

Task 7: Scaling of Navigation and Control algorithm for the testrig (Months 15 – 18)

Task 8: Characterization and testing of the upgraded facilities (Months 15 – 18)

Task 9: Inter-laboratory communication protocols design and tests (Months 16 – 18)

Task 10 Formation flying synchronization experiments (Months 18 – 24)

3. Mission objective selection

The formation flying mission objectives must be defined in order to focus on specific requirements and objectives when developing the GNC system. Remote sensing, communication and navigation tasks performed by a formation of microsatellite have been investigated. Orbital configuration and onboard payload, together with the expected performance should be qualitatively assessed. The GNC system overall requirements, their achievability and most critical aspects to be verified will be assessed.

The resulting output is consisting of the mission objectives and the GNC requirements.

3.1 Earth observation missions

Among the analysed missions, the Harmony mission [1]. is used as the example for further development of mission objectives.

The Harmony constellation mission is a candidate for the Earth Explorer 10 program by the European Space Agency (ESA), has multifaceted objectives. It aims to observe land, ice, and ocean surface dynamics using advanced technologies such as synthetic aperture radar and remote sensing. The mission seeks to enhance monitoring capabilities for various Earth surface dynamics by deploying a constellation of satellites. The primary objectives of the Harmony constellation mission include maximizing observation data, minimizing latency, and autonomously adapting to unexpected events [2].

Each Harmony satellite will be equipped with a passive SAR (Synthetic Aperture Radar) instrument as its

main payload. This instrument will capture reflections of signals transmitted by Sentinel-1 to Earth. Additionally, each satellite will carry a multibeam thermal infrared camera to measure the height and motion of clouds. By interacting with the other two satellites, Harmony will measure the deformation of Earth's surface in three dimensions and determine ocean current speeds with an accuracy of 0.2 m/s.

The constellation geometry of Harmony mission is designed to optimize satellite constellations for efficient data collection and monitoring. Studies have shown that reconfigurable satellite constellation designs can be optimized for disaster monitoring using physical programming techniques [3]. The Harmony satellites can orbit in two different formations, stereo and cross-track. In stereo formation, Harmony A will trail the Sentinel-1 satellite by 350 km, while Harmony B will lead it by 350 km. In cross-track formation, the Harmony satellites will orbit side by side, 200 to 500 meters apart, and 350 km behind the Sentinel-1 satellite. The choice of formation depends on the specific observational needs.

The GNC requirements for the proposed formation flying Earth observation mission are:

- Satellites must be in synchronized orbits to capture images of the same area within a short time frame. This synchronization helps minimize changes in lighting and atmospheric conditions.
- The orbit determination accuracy should be within 10 meters.
- The orbital velocity measurement accuracy should be between 10 and 100 cm per second.
- The satellites will require precise 3-axis stabilization with an accuracy of at least 0.1 degrees to maintain their orientation and ensure the instruments are correctly aligned for optimal data capture.
- The slew rate of the satellites should be at least 2 degrees per second in pitch and roll at least.
- The satellites should have angular jitter of less than 0.1 degrees during imaging mode.



Fig. 2 Illustration of Harmony's mission concept showing the two formation flying (From [1])

3.2 Inter-satellite Communications

Optical wireless communications in outdoor environments, known as free space optics (FSO), involve transmitting an optical signal from a transmitter to a receiver over the atmosphere or space, requiring a clear line of sight. FSO links can be terrestrial, non terrestrial (aerial), space, or deep space. Satellite-to-satellite FSO links, referred to as laser inter-satellite links (LISLs), offer advantages over radio frequency-based links, including higher data rates, smaller antenna sizes, reduced interference, and lower power requirements [9].

Based on the analysed missions the Starlink mission is used as the example for further development of mission objectives.

The Starlink Constellation with Laser Intersatellite Links (LISL) is one such mission that aims to establish efficient communication networks through the deployment of LISLs between satellites within the constellation. This mission is designed to enhance data transfer speeds, communication reliability, and network performance. The mission prioritizes optimizing the visibility and topology of LISLs within the mega constellation to ensure seamless communication and connectivity between satellites in different orbital planes. Additionally, precise orbit determination and baseline establishment using high-precision GPS receivers are key components to facilitate accurate communication and coordination among satellites [9][17].

A LEO (Low Earth Orbit) or VLEO (Very Low Earth Orbit) satellite constellation typically consists of multiple orbital planes, each containing numerous satellites. These satellites can be connected via Laser Inter-Satellite Links (LISLs), which are classified based on their location within the constellation.

The GNC requirements for the proposed formation flying LSIL mission are:

- The LISL satellites should have high attitude accuracy of around 0.01 deg
- The orbit determination accuracy should be between 1 and 2 meters.
- The orbital velocity measurement accuracy should be around 10 cm per second.
- The slew rate of satellite about yaw axis should be between 5 and 10 degrees per second depending on the constellation geometry to enable quick alignment with the neighbouring satellite and minimize latency.
- The slew rate about pitch and roll axes should be at least 2 degrees per second.

- The maximum angular jitter should be 0.01 degrees during inter-satellite communication for a stable optical link.

4. Survey of air bearing testbeds

4.1 Air bearing testbeds survey

The aim of this section is to summarise the available literature of scientific international journals and general information from the internet in order to identify the laboratories currently involved in testing GNC systems of satellites and formation flying of satellites, highlighting the specific technical choices, resulting performance and limitations. This survey will serve as benchmark for the upgrade of the facilities of the proponent group.

Most of the tests for formation flying are carried out by using air bearing testbeds. These testbeds can be categorized by various qualities of their surface and various qualities of the platform that operates within the testbed. A summative characterization of the state of art of the facilities has been carried out based on surface materials, in section 4.2, and number of degrees of freedom associated to the floating platforms, in section 4.3. Within the literature review, 17 laboratories are reviewed, however, some laboratories have multiple testbeds and so the overview graphs will add up to greater than 17.

4.2 Surface materials

Four different materials have been used to create air bearing testbeds across the world: Granite, Glass, Epoxy and Aluminium. An overview of how many testbeds are made from which material are shown in Fig. 3. Of the materials reviewed, epoxy had the lowest roughness at $RZ = 1.8 \mu\text{m}$ while the roughest seems to be aluminium, however no number is given to this roughness [4]. Granite is the flattest material by a significant margin, the flattest granite measuring within 0.0003° of the horizontal, while the least flat material is Epoxy, measuring within 0.4° of the horizontal.

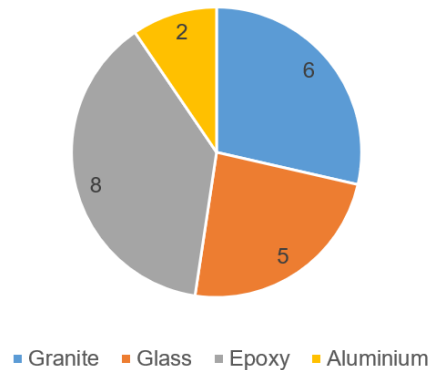


Fig. 3 Pie chart showing materials used in different testbeds

Epoxy allows for the largest continuous installations of a testbed surface as it can be poured, with the maximum surface area found during the literature review of 350 m^2 [6]. However, it isn't as scratch resistant as granite and thus could need more maintenance during its lifetime [7].

Glass is a scratch resistant material that is relatively cheap in comparison to granite, with the added benefit of it being transparent, allowing images to be placed underneath the surface which can be used for navigation. However, due to the flexibility of glass, thick sheets are needed to support the weight of platforms that operate on top of it, meaning only small areas of glass are used in the testbeds, with the largest piece found having a surface area of 23.8 m^2 [8][9].

Granite is the most flat, as shown in first paragraph of this section. However, it is expensive, heavy and limited to smaller sizes than epoxy, meaning it requires multiple surfaces to achieve a large area which leads to discontinuities between the surfaces that needs to be minimized [8][10].

Aluminium is not used and the author could not find information about its benefits within an air bearing testbed. One drawback of this material that is known is has a rougher surface finish than granite, as discussed in the first paragraph of this section, leading to larger air bearings needed by the platforms [5].

Fig. 5, Fig. 6 and Fig. 7 show three examples of the different most common materials: glass, epoxy and granite.

4.3 Platforms' DoF

Each air bearing platform found during the literature review fell into 1 of 4 categories: 2 DoF, 3 DoF, 5 DoF and 6 DoF. The distribution of different types of air bearing platforms can be seen Fig. 4.

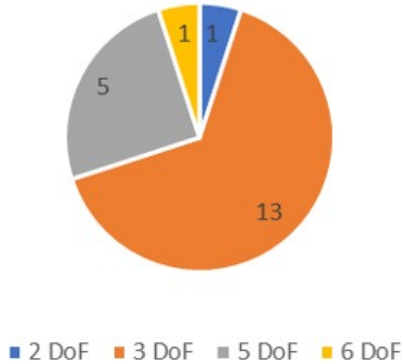


Fig. 4 Pie chart showing the distribution of different DoF of platforms used in different testbeds

The 2 DoF system found in the literature is quite specific and it is outside the interest of the present research.

The 3 DoF air bearing platforms with linear air bearings only, allowing for 2 translational DoF parallel to the surface it operates on as well as an unconstrained yaw rotation, providing an additional rotational DoF. The total mass of the 3 DoF platforms found in the literature review varied between 10 kg and 154 kg.

The 5 DoF systems are built on top of the 3 DoF platform architecture. The 5 DoF system adds a spherical air bearing to the 3 DoF system, allowing for 2 additional, constrained, rotational DoF in the pitch and roll axis. The total mass of the 5 DoF platforms found in the literature review varied between 45 kg and 150 kg.

The 6 DoF systems are then built further on top of the 5 DoF platform architecture. An air bearing pulley system with a counterweight is added to the 5 DoF platform, this allows for the mass of the system being tested to be balanced and minimal friction in the pulley system. This allows for an additional translational DoF perpendicular to the surface.

Each of the previously mentioned platforms can either be fed gas by an external tube or have an independent gas supply mounted on board. An independent gas supply negates any disturbances from an external gas tube however they have a limited run time, while the external tube allows for unlimited run times.

Table 1, reported in Appendix, shows a summative overview of the above-presented testbeds, highlighting

the key technical characteristics and specifications alongside with main equipment used for motion tracking.



Fig. 5 Left: ORGL epoxy floor. Right: ACROBAT platform (from [4])

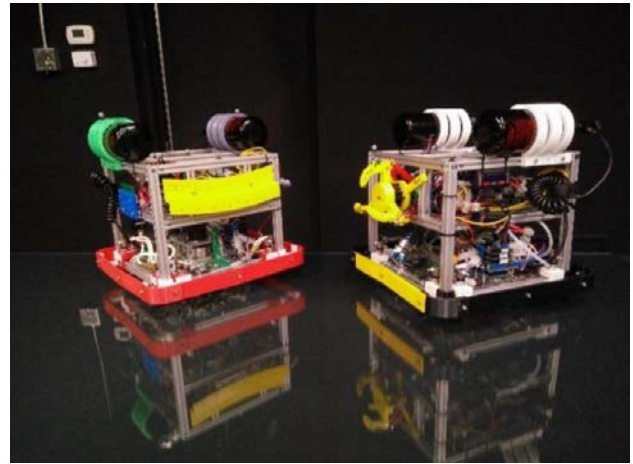


Fig. 6 The Two smaller 3DoF platforms on the glass testbed (from [12]).



Fig. 7 – Left: FSS on top of the granite table at the Naval Postgraduate School. Right: FSS with labelled components (from [13])

5 Current status of the FedLabs network

In order to realize the first example of federated laboratory network, the current facilities involved in the project must be updated to reach the required technological level. Once all involved laboratories have

been prepared, together with a robust communication link, experiments will be run to assess the achievable performance. Attitude synchronization based on consensus concept is a good example of the possible activities that can be performed. Earth observation capabilities can be simulated on one of the platforms thanks to a vision-based system relying on the observation of projected images of the Earth; image processing can happen on board the same satellite, or the computation load can be shared with the other platforms by sending the relevant data. Once the target area on the Earth surface has been recognized, all the platforms can perform attitude reconfiguration in order to point at the same region, each one with its own payload. Resulting dataset is finally gathered by one of the satellites and sent to a virtual ground station.

The development of such testing facilities and the development and testing of such GNC technologies has a direct impact on the new key activities that are characterizing the New Space Economy. In fact, many new industrial actors are starting to be interested in the capabilities of formation of microsatellites; their still immature technology level call for extensive experimental campaigns that are slowing the realization of such missions. The availability of the proposed Federated Laboratories could foster the design of this new, more agile and responsive space missions.

The three research groups are already developing facilities for test of satellites using free-floating platforms, at different levels of maturity and readiness.

- The School of Aerospace Engineering of Sapienza has been continuously developing since 2011 the PINOCCHIO (Platform Integrating Navigation and Orbital Cooperative Control Housing Intelligence Onboard Testbed) experimental platform. It is a floating platform built to replicate the dynamic behavior of a satellite in order to study and test autonomous operations in space. It can also be used for simulation and testing of attitude and position control laws on very flexible satellites.

The free-floating platform is made with an air suspension system that allows testing (limited to the horizontal plane) of complex space operations, such as rendezvous and docking. The platform is powered by cold gas thrusters. Navigation is accomplished by an on-board Inertial Measurement Unit (IMU), and by an external metrology system, realized by six VICON infrared cameras. The platform produces a low-friction environment by expelling air from three planar bearings to generate a layer of air between the worktable and the test platform. This allows the platform to move in three DOFs, two linear translations and one rotation about the vertical axis, with minimal friction on a flat floor. The platform frame is modularly designed so that it can be reconfigured as the objectives of the experiment change.

The structure of the floating platform is made of aluminium alloy. The overall dimensions of the structure are 300mm x 350mm x 480mm. The principle that guided the design is the idea of modularity: the structure consists of three compartments, each of which can be used for a specific purpose. The lower compartment (300mm x 350mm x 280mm) houses the pneumatic system, while the second floor (300mm x 350mm x 100mm) houses the electronics: sensors, Arduino boards, and wiring. The third floor will house the electronics needed to operate actuators and sensors to control the aerodynamic appendages for the proposed study. The total weight of the platform is currently 22 kg and the measured moment of inertia is 0.47 kg m² (around the vertical axis, perpendicular to the table passing through the center of mass). As recently done for ESA's ITT "ACACLAS - Advanced Collocated Active Control of Large Antenna Structures"), the platform can be modified to allocate even large panels (see Fig. 8), thus allowing for reproducing the complex attitude dynamics when disturbed by the elastic dynamics of solar panels or antennas, increasing the reliability of the experiment ([14]).



Fig. 8 Experimental platform configuration with a central bus plus four large panels.

The external metrology system allows for very precise measurement of both the attitude of the bus and its mobile appendages, if any. The Vicon system consists of a set of six infrared cameras arranged around the worktable and tracks the optical markers connected to the moving platform. The data are collected at a frequency that can be set up to 300 Hz and recorded directly on a computer at the ground station and sent wirelessly to the floating platform for use in the control loop. Although the angular and positional accuracy of the Vicon is highly dependent on the configuration of the setup, including the number of cameras, the way the cameras are positioned, and the number of optical markers on the platform, the Vicon system still offers far superior performance compared to the IMU device. This system is currently used to determine the real-time position and attitude of the floating platform, which is necessary for the control and navigation algorithm. In fact, VICON thermal imaging cameras can determine the position of reflective

markers with an accuracy of at least a tenth of a millimeter. This leads to an accuracy in attitude determination on the order of 0.01 degrees. The platform controlled using thrusters, based on VICON and IMU measurements, is able to acquire a desired attitude with accuracies of up to 0.066 degrees (3 sigma), depending on the thruster feed pressure values (Fig. 9).

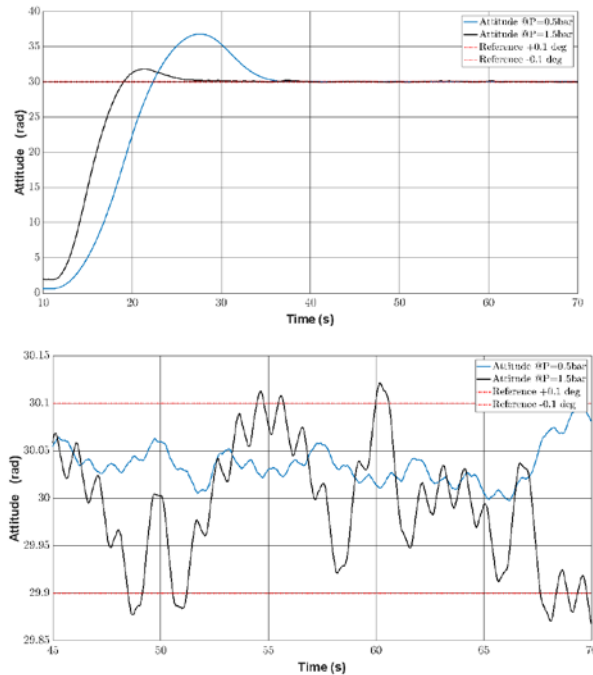


Fig. 9 Example of attitude maneuver carried out with the floating platform, feeding thrusters at various pressure levels.

- KNATTE is a frictionless vehicle that has been developed as a joint project between LTU and the University of Rome La Sapienza. Together with a frictionless table, it serves as the foundation of a multi-purpose platform, located at the Space Avionics Laboratory at LTU in Kiruna, Sweden. The Space Avionics Laboratory is shown in Fig. 10. The platform can emulate spacecraft behaviour in orbit for validating various guidance, navigation, and control algorithms, and acts as a testbed for performing hardware-in-the-loop simulation experiments with real and analogous small-satellite components.

The KNATTE platform is composed of three main subsystems: the mechanical subsystem, the pneumatic subsystem, and the electronic subsystem. The mechanical subsystem comprises the structural elements of the vehicle and consists of a cubic structure, measuring 300 mm per side, made of extruded aluminium beams. The pneumatic subsystem accommodates a 1.1-litre tank of compressed air. It generates a frictionless effect between KNATTE and the table surface by feeding the compressed air to three equilaterally distributed air-

bearings at the bottom of the vehicle. Secondly, it allows for actuation of translational and rotational motion by feeding air to eight nozzles, symmetrically distributed along the sides of the vehicle. The nozzle pressure equates to a maximum thrust of 0.64 N and a maximum torque of 0.102 N m and allows for approximately ten minutes of operation with a medium use of the thrusters. Finally, the electronic subsystem is responsible for providing power supply to the other components, as well as control actuation, data handling and wireless communications. An on-board computer running Matlab and Simulink handles commands and generates control signals that are digitised and distributed to the thrusters. In addition, the subsystem features an IMU providing position and orientation data utilised by the navigation system. With the tank fully pressurised, the combined system has a total weight of 9986 g and a moment of inertia about the vertical axis equal to 0.160 kg m².

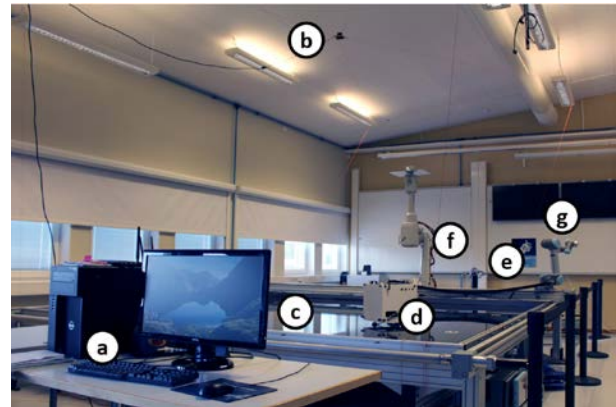


Fig. 10 Overall layout of KNATTE: (a) simulation computer, (b) camera, (c) frictionless table, (d) frictionless vehicle, (e) frictionless attitude stand, (f) fixed-base robot manipulator and, (g) moving-base robot manipulator.

The frictionless table consists of an epoxy coated surface, elevated on top of a metallic structure with 20 adjustable feet, and allows KNATTE to operate within a virtually frictionless environment. The overall dimensions of the surface measure 3515 mm × 3780 mm, however, due to limitations in the field of view of the Computer Vision System, the effective area of operation is limited to a sub-region measuring approximately 3.0 m × 1.7 m.

Even considering that the frictionless table has been constructed for rigidity it tends to deform over time. Such deformations are difficult to measure with common instruments but are really apparent during simulations because such deformations induce forces on the frictionless vehicle during the experiments. Hence the frictionless table needs to be calibrated regularly. It may be useful to find faster, more precise, and more reliable calibration methods.

The Computer Vision System (CVS) provides tracking data, in the form of horizontal position and heading measurements, at 20 samples per second. The system consists of a generic webcam, suspended from the laboratory ceiling by four cords and connected to the simulation computer via USB. An image processing algorithm, coded in Matlab and implemented on the simulation computer, handles the observations from the sensor and translates the images into position and orientation values. To facilitate transformation between the camera and navigation coordinate frames, KNATTE and the frictionless table have been equipped with a set of fiducial markers, one in each corner of the camera's field of view and one on top of the vehicle itself. This allows precise tracking of the position and orientation of KNATTE with accuracies of approximately 6 mm and 0.22° .

Despite its high precision under nominal conditions, the performance of the CVS is highly sensitive to any lighting variations within the laboratory and has to be calibrated before each simulation. Such perturbing effects can to some extent be attributed to natural variations in the ambient light, but even more so to the direct glare from light fixtures in the ceiling. This light reflects in the glossy surface of the epoxy and the white regions of the fiducial markers and induces a bloom effect in the captured images. As the fiducial marker on top of KNATTE passes through these regions, such visual artefacts may lead to misreadings of the vehicle's position and orientation.

Overall, the simulation environment has demonstrated to offer the adaptability that is required for the agile development of space missions. Such an environment has been used as a platform to create various subsystems, from the testing of real hardware prototypes to the simulation of physical models.

- Cranfield University is building a facility for developing and testing guidance, navigation and control algorithms for spacecraft formation flying, in-orbit operations and space robotics applications. The plan is to have a versatile testing facility that can be used for simulating space-like conditions (e.g., frictionless, illumination, gravity, etc.) for developing technologies and capabilities for future in-orbit operations.

The on-going works for the realizations of the testing facility are shown in Fig. 11. The surface is made by a reduced roughness epoxy-based layer where floating platforms could move in a reduced-friction condition. The current plans foresee that the working surface will have dimensions of 350×400 cm, with the possibility of extension up to 350×600 cm. To reproduce space-like lighting conditions, the boundaries of the entire testing area are painted in black and eventually, star and celestial maps will be projected on the walls. Different sunlight conditions will be simulated via a lamp held by the end

effector of one of the robotic arms in the test area. The floating platforms, which eventually simulate the prototype of spacecraft flying in formation, will be equipped with an autonomous pneumatic system and flat air bearings that guarantee enough lift to obtain reduced friction with the table. The motion of the platform will be monitored and tracked via a high-precision motion-tracking system using 6 to 8 cameras.



Fig. 11 Making of the test facility in Cranfield University

This particular setup will be better suited for testing the eventual image-based navigation algorithms. Cranfield university has experience developing image-based visual servoing controls for spacecraft formation flying and space robotics applications. An example is provided in Fig. 12, where a visual servoing control strategy was applied to the specific case of a robotic manipulator performing in-orbit servicing. The applicability of such algorithms was tested and assessed via numerical simulations but a proper characterization of the performances and robustness by experimentation is required.

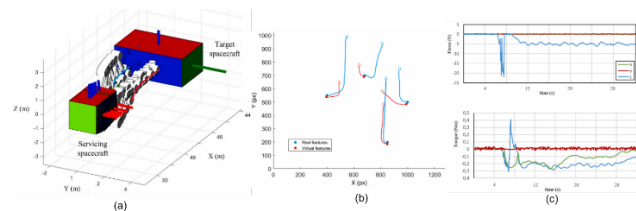


Fig. 12 Image-based visual servoing in orbit servicing manoeuvre1. (a) 3d visualization of the manipulator's trajectory; (b) Evolution of the visual feature trajectories during the servicing manoeuvre; (c) Contact forces and torques at the end effector of the manipulator

A manipulator system will be developed using two robotic arms appended on gantry systems. Both robotic arms will be able to interact with floating platforms and each other. The robotic arm will have six degrees-of-freedom with adaptive end-effector components such as gripper, and it can reach any location in the coverage area. The robotics arms will be also used for developing contact dynamics and haptic-based approaches for effective contact operations in space and free-floating conditions. This gentry system will be also used to simulate the proximity dynamics of two or more spacecraft performing in-orbit operations such as docking and berthing, for example, holding ad-hoc build target mockup that will be chased by the floating platforms.

The floating platform together with reduced friction table and manipulator system will be useful in simulating in-space robotic manipulation, spacecraft/satellite contact, and proximity operations (e.g., debris removal, capturing, etc.), and validating respective GNC algorithms such as the visual based navigation algorithms already developed by Cranfield up to TRL 5.

6. A FedLab precursor

In 2021 [15] an approach for conducting coordinated experiments between floating platforms at two remote laboratories has been investigated. Two independently designed platforms, one at Luleå University of Technology and the other at La Sapienza University of Rome, were established for this purpose. A synchronization method based on the Simple Network Time Protocol was created, allowing the offset and delay between the agents to be measured (Fig. 13). Both platforms exchange data about their measured time and pose through a UDP/IP protocol over the internet. This approach was validated with the execution of simulated operations. A first demonstrative experiment was also performed showing the possibility to realize leader/follower coordinated operations. The results of the simulations and experiments showed communication delays on the order of tens of milliseconds with no significant impact on the control performance. Consequently, the suggested protocol was proven to be adequate for conducting coordinated experiments in real time between remote laboratories. In fact, it was found that the long distance separating the platforms (~3900 km) did not affect the experiment results.

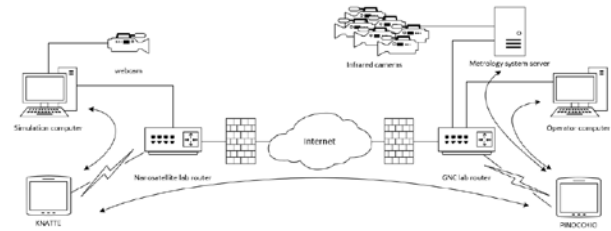


Fig. 13 Network Setup between the labs in Kiruna and in Rome

7. Conclusions

In this paper we have presented the rationale, the objectives and the organization of a joint research under development in the framework of the NATO SPS program. The final goal is to realize a virtual international laboratory performing tests for the GNC of formation flying satellites. At the scope three laboratories at the School of Aerospace Engineering of Sapienza University of Rome, Luleå University of Technology and Cranfield University have been re-designed and upgraded to be a node of this academic network.

The free floating facility will be ready in the next months to perform coordinated attitude and close proximity operations simultaneously in the three locations thanks to a communication protocol purposely developed to synchronize the experiments.

This approach will be useful for each research partner to increase its own capability, and will pave the way to a future increase in the number of participants, increasing in this way the shared hardware and algorithmic capabilities.

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Table 1 - Summative table of air bearing testbeds

Institution	Surface Material	Floor Dimensions	DoF of Platform	Mass of Platform	Measurement system & accuracy
ADAMUS Laboratory [16]	Epoxy	18.1m ² , 3.96m by 4.57m	6	Unknown	PhaseSpace Impulse system (8ms latency, 1-5mm accuracy)
DLR Bremen [17]	Granite	20m ² , two 4m by 2.5m tables	5	Unknown	Six infrared cameras with retroreflective markers
ESTEC, ESA [4]	Epoxy	45m ² , 5m by 9m	3 (all)	ACROBAT: 129kg, ACROBAT w/Satsim: 154kg MANTIS: 28kg	12 Vicon Bonita B10 cameras
Florida Institute of Technology [12]	Epoxy & Glass	Epoxy: 21.6m ² , 6m by 3.6m Glass: 5.75m ² , 1.6m by 3.6m	3 (on epoxy/glass) 4 (on rail)	15kg (on glass) 20kg (payload on rail)	12 OptiTrack Prime 17W cameras & Microsoft Kinect sensor
Georgia Tech [18]	Epoxy	13.4m ² , 3.66m by 3.66m	5	Unknown	NorthStar system, Two axis star sensor, Three axis magnetometer (0.0006 Gauss accuracy), Three axis rate gyro (0.029°/s accuracy), IMU
Luleå University of Technology [7]	Epoxy	9.1m ² , 3.02m by 3.015m	3	9.986kg	IMU (0.001g accuracy), Gyroscope (0.0625°/s accuracy), Magnetometer (0.076μT accuracy)

NASA JPL [19]	Aluminium + Glass (FCT) Granite (SSDT)	137.8m ² , multiple small glass/aluminium panels (FCT) 0.36m ² , 0.6m by 0.6m (SSDT)	5 (FCT) 3 (SSDT)	14.5 kg with 30kg payload (SSDT)	Celestial sensor, Formation flying sensor, Crossbow IMU 400 (FCT) KVH 1750 IMU, Vicon motion tracker (SSDT)
NASA MSC [6]	Epoxy	350m ² , 14.41m by 26.21m	3 8 (DOTS)	225kg (DOTS)	Leica Laser Tracker LTD800 (0.03-0.015mm accuracy)
NTUA [20]	Granite	3.9m ² , 2.2m by 1.8m	3	Unknown	Overhead camera, Optical sensors
Naval Postgraduate School USA [13]	Granite	16m ² , 4m by 4m	3	Unknown	10 Vicon motion capture cameras (sub millimetre accuracy), Fiber-optic gyroscope
Sapienza – Università di Roma [14]	Granite	0.4m ² , 0.63m by 0.63m	3	Unknown	6 Vicon motion capture cameras, IMU
CPKPAN [21]	Granite	6m ² , 2m by 3m	2	18.9kg	Visual pose estimation system
University of Luxembourg [22]	Epoxy	15m ² , 5m by 3m	3	300kg (max for floor)	OptiTrack motion capture system (sub millimetre accuracy), FLIR Blackfly S BFS-U3-16S2C camera
University of Padova [10]	Glass	6m ² , 2m by 3m	5	45kg	Three Quadrature Encoders optical flow sensors, IMU

USC [23]	Epoxy	210m ² , 15m by 14m	3	25kg with 50kg payload	Evolution Robotics' NorthStar system (2.5cm, 3° accuracy), SHARP GPY0A02YK proximity Sensor
University of Würzburg [9]	Glass (Both)	4m ² , 2m by 2m	3	Unknown	Star tracker
Yonsei University [5]	Aluminium	18m ² , four 3m by 1.5m pieces	5	150kg	Ultrasonic triangulation system (10mm accuracy), OptiTrack motion capture system (0.02mm accuracy)



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