IAC-18,B6,3,7,x43656

Dance: a Frictionless 5 DOF Facility For GNC Proximity Maneuvering Experimental Testing And Validation

Pierluigi Visconti[a]*, Stefano Silvestrini[a], Michèle Lavagna[a]

[a] *Department of Aerospace Engineering, Politecnico di Milano, Via La Masa, 34, 20156 Milan, Italy, pierluigi.visconti@mail.polimi.it*
* Corresponding Author

Abstract

In the last decade, the different space agencies, such as NASA and ESA, have shown serious interest in considering new mission scenarios exploiting a swarm of satellites flying in formation (i.e., Formation Flying). Simultaneously, the growing trend of miniaturization perfectly fits this perspective, providing even more flexibility to the mission. Having a swarm of small spacecrafts, distributed over a large volume, can be used to achieve various capabilities and functions. It can be exploited for a three-dimensional mapping of the space, providing much more information with respect to the large and singular satellite. Moreover, the risk at the launch site can be mitigated using different launchers and launch dates. Even the robustness of the entire mission would be intensely incremented, spreading the redundancies across the formation rather than across the same monolithic spacecraft. Finally, the overall mission cost can be reduced exploiting a mass-production technique for the different satellites. Therefore, Formation Flying introduces new possibilities for the space engineering, but it obviously also poses new challenges due to the low level of maturity of such technologies. Here comes the need of new test campaigns able to rise the Technology Readiness Level (TRL) of this innovative hardware and software.

In this context, this paper presents the design, the modelling and the setup of a new frictionless facility at the Aerospace Science and Technology Department of Politecnico di Milano for on-ground testing and validation of spacecrafts relative GNC maneuvering. It will serve as a testbed for experimental verification of innovative software, such as artificial intelligence in the control logic, as well as testing new hardware-in-the-loop. The force-less and torque-less environment is achieved using a set of linear and hemispherical air bearings. In this way, each vehicle has five degrees of freedom (DOFs): two translations and three rotations. This also follows the trend of the state of the art, being it a common architecture adopted for on-ground spacecraft simulators.

Keywords: GNC, on-ground testbed, spacecraft, proximity, frictionless

Nomenclature

q_i	Generalized Coordinate
Q_{q_i}	Generalized Non-Conservative Force
L	Lagrangian
T	Kinetic Energy
V	Potential Energy
X_D, Y_D, Z_D	DANCER Position
φ, θ, ψ	Attitude Platform Euler Angles
ψ_{TP}	Translational Platform Angle
θ_{RWi}	Reaction Wheel Angle
$\dot{X}_D, \dot{Y}_D, \dot{Z}_D$	DANCER Velocities
$\boldsymbol{\omega}_{AP}$	Attitude Platform Angular Velocities
ω_{TP}	Translational Platform Angular Velocity
$\boldsymbol{\omega}_{RW}$	Reaction Wheels Angular Velocities
M_D	DANCER Total Mass
M_{TP}	Translational Platform Mass
M_{AP}	Attitude Platform Mass
J_{TP}	Translational Platform Moment of Inertia
$\boldsymbol{J}_{AP}$	Attitude Platform Moment of Inertia
$\boldsymbol{A}_{RW}$	Reaction Wheels Configuration
$\boldsymbol{I}_{RW}$	Reaction Wheels Inertia Matrix
$\boldsymbol{\rho}_{CM_{TP}}$	Translational Platform Centre of Mass Position
$\boldsymbol{\rho}_{CM_{AP}}$	Attitude Platform Centre of Mass Position
$\boldsymbol{g}$	Gravitational Acceleration
$\boldsymbol{f}_{kn}$	Cold Gas Thruster Force
$\boldsymbol{l}_{kn}$	Cold gas Thruster Position
$\odot$	Element-wise Dot Product
$\otimes$	Column-wise Cross Product
$\boldsymbol{A}_{B/N}$	Direction Cosine Matrix
$\boldsymbol{F}_T$	CGT Total Force Vector
$\boldsymbol{M}_T$	CGT Total Torque Vector
$\boldsymbol{B}_N$	CGT Direction Matrix in Inertial Frame
$\boldsymbol{B}_B$	CGT Direction Matrix in Body Frame
$\boldsymbol{L}$	CGT Configuration Matrix
$\boldsymbol{u}_M$	Desired Controlling Torques
$\hat{}$	Hat Operator
$\boldsymbol{A}_e$	Attitude Error Matrix
$\boldsymbol{A}_d$	Desired Attitude Matrix
$\boldsymbol{e}_A$	Attitude Error Vector
$\boldsymbol{\omega}_e$	Angular Velocities Errors
K_ω, K_A	Attitude Controller Gains
$\boldsymbol{u}_F$	Desired Controlling Forces
$\boldsymbol{e}_r$	Position Error
$\boldsymbol{e}_v$	Velocity Error
K_P,K_I,K_D	Translational Controller Gains

Acronyms/Abbreviations

DOF	Degree Of Freedom
TRL	Technology Readiness Level
DAER	Aerospace Science and Technology Departmet
FCT	Formation Control Testbed
JPL	Jet Propulsion Laboratory
TEAMS	Test Environment for Applications of Multiple Spacecraft
DANCE	Device for Autonomous guidance Navigation & Control Experiments
DANCERS	Device for Autonomous guidance Navigation & Control Experiments on Relatively moving Spacecrafts
IR	Infrared
TP	Translational Platform
AP	Attitude Platform
CM	Centre of Mass
CR	Centre of Rotations
BSP	Board Support Package
OBC	On-Board Computer
SBC	Single Board Computer
RTOS	Real-Time operative System
CFRP	Carbon Fibre Reinforced Polymer
FEA	Finite Element Analysis
PWPF	Pulse Width Pulse Frequency
VRT	Virtual Reality Toolbox
PIL	Processor-In-the-Loop

1. Introduction

On October 4, 1957 the Soviet Union successfully launched Sputnik-1. After almost 4 months, on January 31, 1958 the United States launched Explorer-1. If the former marked the start of the Space Age, the latter marked the start of the Space Race [1], fostering the use of innovative technologies in the space engineering. Soon arose the need of larger and bigger spacecrafts, as well as automatic control, in order to fulfil new mission scenarios. However, in the last decade, the various space agencies have shown serious interest considering new mission scenarios exploiting a swarm of small satellites flying in formation (i.e., Formation Flying). This introduces new possibilities for the space engineering, but it obviously also poses new challenges due to the low level of maturity of such technology. Here comes the need of new test campaigns able to rise the Technology Readiness Level (TRL) of this new hardware and software.

1.1 Formation Flying in Space

The formation flying satellites are going to revolutionize the space engineering. In fact, the use of a cluster of satellites can bring many different advantages, from the launch up to the disposal. But, first of all, it is important to delineate what formation flying means. Wang, Wu, and Poh, in the book Satellite Formation Flying, define formation flying as "a set of more than one satellite whose dynamic states are coupled through a common control law. In particular, at least one member of the set must (1) track a desired state relative to another member, and (2) the tracking control law must make use of the state of at least one of other members" [2]. This means that, despite being both distributed systems, constellations and formation flying satellites completely differ in the control strategy. The former consist of a number of satellites, each one controlled uniquely with respect to its position and velocity. On the contrary, formation flying satellites are controlled in order to maintain a relative position, separation or orientation. For these reasons, having a swarm of spacecrafts distributed over a large volume can provide many advantages: the three-dimensional mapping of the space, the reduction of the risk at the launch site, the reduction of the overall mission cost and even the increase in mission robustness.

For all these benefits and many more, the different space agencies, such as NASA and ESA, are continuously exploiting this architecture in many different new mission proposals. Moreover, the always stronger trend of miniaturization perfectly fits the formation flying scenario, providing even more flexibility to the mission. A recent review of existing formation flying and constellation missions using nanosatellites [3], counts almost forty missions that employ multi-satellites with mass smaller than 10 kg.

Just like in every engineering field, also in space engineering it is very important to test and validate new technologies before introducing them in the real environment. However, in-orbit testing can be very expensive and time consuming. For this reason, it is important to be able to simulate the space scenario on ground. In this context, this dissertation aims to present the design, the modelling and the setup of a frictionless facility at the Aerospace Science and Technology Department (DAER) of Politecnico di Milano for on-ground testing and validation of spacecraft relative GNC maneuvering. It will serve as a testbed for experimental verification of innovative software, such as artificial intelligence in the control logic, as well as testing some new hardware-in-the-loop.

1.2 Spacecraft Simulators Architectures

Since the beginning of the space exploration, the need of simulating the space environment on ground was evident. No hardware can be launched without a series of tests and verification. And the same holds for any part of a satellite software. However, every component of a spacecraft works in a specific way, meaning that many different simulators must be employed. This is probably the main reason for the well-known slowness in the technological development of the space industry.

In order to recreate the space environment on ground, it is important to simulate the condition of microgravity.

Only in this way, it would be possible to test attitude and translational dynamics in a very representative and effective way. For this reason, several studies have been carried out in developing systems able to simulate weightlessness. Possible solutions for this problem are the drop towers and aircraft parabolic flights. However, they can provide only few seconds of simulations. Also underwater test tank can compensate gravity by buoyancy forces, even though it can be very challenging to submerge the satellite in water. Another possibility is to create a force-free and torque-free environment where the spacecraft dynamics can be unperturbed. Many solutions can be adopted such as magnetic levitation or gravity offloading systems. However, the most adopted solution for recreating a space-like environment on ground is thanks to air bearings.

An air bearing is a mechanical device able to create a thin film of air between two surfaces in relative motion. Therefore, the pressurized air injected in the system acts as a lubricant and avoids contact between the two surfaces, reducing the friction of several orders of magnitude. This architecture for an on-ground spacecraft simulator has been patented and implemented for the first time in the 1960 by NASA [4]. However, because of its several advantages against all the other systems, several other universities and industries soon adopted this configuration as well. Moreover, this system can be adopted both for orbital dynamics simulations as well as for attitude dynamics simulations. In fact, using a planar system with linear air bearings, it can provide a force-free environment for planar motion. On the contrary, using a rotational air bearing it is possible to create a torque-free environment. The use in conjunction of linear and rotational bearings provide a 5-DOF environment suitable for relative GNC testing and maneuvering.

1.3 Existing Facility Survey

One of the most import on-ground spacecrafts simulators is the Formation Control Testbed (FCT) at the Jet Propulsion Laboratory (JPL). It is a multi-robot, flight-like, system-level testbed for ground validation of formation GNC architectures and algorithms [5]. Figure 1 shows the selected architecture for the vehicles: a combined system made of two main platforms. Each robot is 1.6 m tall and has a diameter of 1.5 m. The lower platform weights about 80 kg and it hosts three linear air bearings for translational motion, a spherical air bearing for rotational motion and a linear actuator for the vertical translation. Four composite vessels are employed on the lower platform for the air storage. The upper platform, on the contrary, weights 170 kg and it exploits sixteen 1 N cold gas thrusters and three orthogonally-mounted reaction wheels for the dynamics control. The facility floor is made of fourteen metal panels for a total area of 7.3 m-by-8.5 m.

Moving to Europe, it's worth mentioning the Test Environment for Applications of Multiple Spacecraft (TEAMS). It is a test facility developed and built up at the Institute of Space Systems of the DLR in Bremen, Germany [6]. It consists of two vehicles, called TEAMS_5D, with 5 DOFs and four smaller vehicles, called TEAMS_3D, with only 3 DOFs (i.e. planar motion). If the latter are based only on linear air bearings, the former employ configuration with two platforms connected by a spherical air bearing. The TEAMS_5Ds are fully controllable in attitude as well as in translations, in fact, they are equipped with sixteen cold gas thrusters of 0.06 N and three reaction wheels. The total mass of the vehicle is smaller than 100 kg, being therefore smaller with respect to the previous facility. However, also the test arena is smaller, in fact, it is made of two granite tables of 4 m-by-2.5 m each. Figure 2 shows the TEAMS facility with the different vehicles.

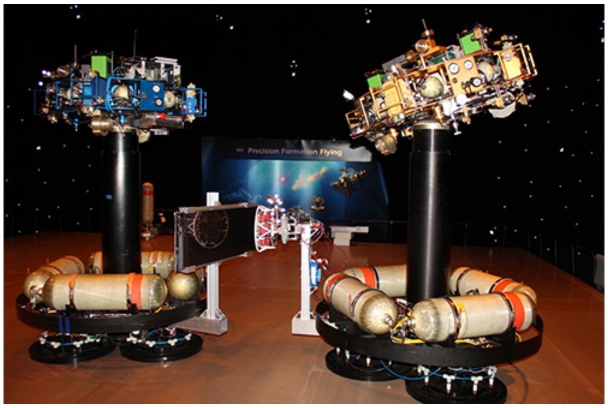


Fig. 1 The Formation Control Testbed - JPL [5]

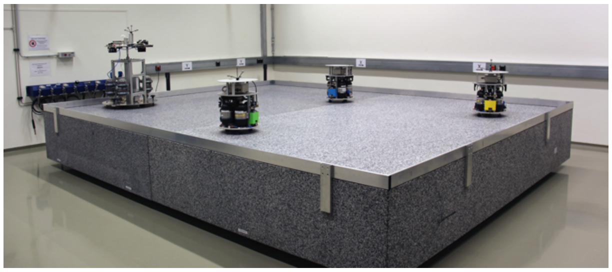


Fig. 2 The Test Environment for Applications of Multiple Spacecraft - DLR Bremen, Germany [6]

2. Facility Design

Formation flying is going to innovate completely the space industry, however, it will cross the chasm only when the TRL of the relative technologies, both hardware and software, will be raised to the maturity level. This implies the testing and the verification of such technologies. But the only way to cut the costs and shorten the process duration is thanks to on-ground facilities. For this reason, this project wants to provide the Politecnico di Milano with a cutting-edge testbed for experimental tests and simulations of relative attitude and orbital dynamics.

A frictionless facility already exists at DAER laboratories, however, it is affected by few flaws. For this reason, the aim of this paper is to design a completely new simulator able to demonstrate both attitude and orbital dynamics for internal as well as external projects. The name of this new facility is **DANCE**: **D**evice for **A**utonomous guidance **N**avigation & **C**ontrol **E**xperiments. Analogously, the related vehicles will be called **DANCERS**: **D**evice for **A**utonomous guidance **N**avigation & **C**ontrol **E**xperiments on **R**elatively moving **S**pacecrafts. It follows a brief description of the testbed arena as well as of the vehicles.

2.1 DANCE Test Environment

Following the work done by Carlini and Marcuccio in [7], the idea is to employ a glass plate, 10 mm thick and 3 m-by-3 m large, as testbed floor for DANCE facility. Even if the crystal has a very high elastic modulus, an uniform supporting structure made of self-levelling epoxy resin is employed to ensure system rigidity. Moreover, in order not to introduce relevant perturbing forces to the vehicles, the maximum allowable floor slope is computed to be only 0.38 mrad.

Another important aspect is the facility tracking system, able to provide an absolute measurement of the vehicles position and attitude. It has to meet very strict requirements in terms of accuracy. In fact, the selected system employs a set of four infrared (IR) cameras and different markers on the vehicles: in this way it is able to provide DANCERS position within few millimetres and their attitude within 0.4°.

Finally, an air filling system is employed to refill the vessels for the vehicles on-board air storage and a control room provides the user with all the different tools and supporting hardware in order to conduct and monitor the entire simulation.

2.2 DANCERS

In order to test and validate relative GNC maneuvering, the facility employs two vehicles able to recreate a torque-free and force-free environment in 5 DOFs. At this purpose, each vehicle mounts three linear air bearings for the planar motion and a hemispherical air bearing for the rotational motion. Thus, DANCER can be seen as made of two distinct platforms: the Translational Platform (TP) on the bottom of the robot and the Attitude Platform (AP) on top. The former has to provide the frictionless environment for the latter, which, on the contrary, can be seen as the actual spacecraft able to host a possible payload.

2.2.1 Attitude Platform

In order to perform relative dynamical tests, it is important to have full controllability of DANCERS attitude and translational dynamics. Therefore, the upper platform hosts a set of 12 cold gas thrusters able to provide a thrust of 1.1 N each, modulated at a very high frequency (1000Hz). The nozzles are placed in such a way so to roughly control both translations and rotations of the AP. Moreover, two vessels of 2 L each are employed for the on-board storage of pressurized air at 200 bar, ensuring 30 minutes of simulations.

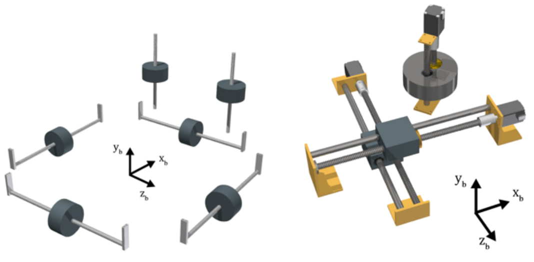
The fine control of the attitude dynamics is in charge of a set of three reaction wheels, orthogonally-mounted, able to provide a maximum torque of 55 mNm. All the actuation system is custom-made at DAER laboratories.

However, having the air bearings and a system of actuators does not ensure the capability of simulating the microgravity environment. In fact, any static or dynamic unbalance of the AP would imply a relevant perturbing torque on the system. The only way to reduce as much as possible these torques is by placing the centre of mass (CM) of the upper platform as close as possible to the centre of rotations (CR) of the hemispherical bearing. On the other hand, asking for a maximum drift of 5° in one minute, it implies a maximum error between CM and CR of 10^{-7} m, and this is not achievable merely by a well-designed configuration.

Therefore, a complex system of masses is used as balancing system for the entire platform. Moreover, the potential on-board payload could introduce dynamical unbalance. Thus, the balancing system consists of a static balancing system (Fig. 3-a) for gross and manual corrections and a dynamic balancing system (Fig. 3-b) for automated and precise offset compensation during the entire simulation. Adopting a system with three orthogonally-mounted lead-screws with a very small pitch, it is possible to finely move three masses so to fulfil the balancing requirements.

DANCER vehicles have to perform dynamics control autonomously, employing the on-board hardware. This implies that all the sensors, especially those concerning attitude dynamics and translational dynamics must be able to provide a state estimation without relying on external systems. Therefore, an Inertial Measurement Unit (IMU) is employed together with a compass sensor, in order to have absolute reference knowledge. Moreover, an optical camera is used for relative state estimation between the two vehicles.

For what concerns the avionics, the key points for the selection are: cost, mass, volume, performances and availability of the board support packages (BSP) for Matlab® and Simulink® environment. This last point is important because, nowadays, the MathWorks® Suite has become a very powerful tool for engineering and it is important to provide the facility of complete Matlab and Simulink support. In this way, it will be possible, thanks to the embedded coder, to easily convert Simulink blocks into equivalent code to be quickly uploaded on the vehicle on-board computer (OBC). Accordingly, the baseline architecture uses an ARM®-based single board computer (SBC) as main OBC working side by side with a microcontroller from Texas Instrument. On one hand, the SBC will have a real-time operative system (RTOS) able to run high-level algorithms such as control laws, optical navigation, artificial intelligence and other complicated software. On the other hand, the microcontroller will serve as intermediary between OBC and hardware.



(a) (b)

Fig. 3 DANCERS Static Balancing System (a) and Dynamic Balancing System (b)

The communication between the two DANCERS and the control room is performed using an RF link, in order to resemble as much as possible a real intersatellite-link. Thus, a 100mW RF transceiver at 433 MHz is used to transfer more than 50 state variable, 2 bytes each, at a frequency of 100 Hz.

An electric power system has to provide power to all the actuators and the avionics on board. However, the vehicles cannot have any mechanical interface with the external world because it would perturb its dynamics. For this reason, a system of batteries is used to store energy on board. Considering the power budget of the vehicle (Tab. 1), the battery pack uses 16 cells of 3,7 V each, arranged in such a way so to obtain a capacity of 6000 mAh, a sufficient amount of energy to cover the entire duration of the simulation.

Subsystem	**Power [W] (20% margined)**
Actuators	217.2
Balancing System	16.8
Sensors	5.9
Avionics	23.0
Total	262.9
Total + 10%	289.2

Tab. 1 DANCER Power Budget

2.2.2 Translational Platform

One of the most important parts of DANCERS vehicles is the floating system, which will ensure the frictionless capabilities. In fact, it shall be able to reproduce a force-free and torque-free environment in the planar motion as well as in the three attitude rotations. The solution adopts three linear air bearings and a hemispherical air bearing. The former are flat pads equipped with small holes where pressurized air flows, creating an air cushion on which the system translates. They are selected having in mind the total mass of DANCER vehicle. On the contrary, the latter consists of a pair of concave-convex hemispheres perfectly lapped. The concave base is made by a porous material where air flows, creating the air cushion. It is selected considering its load capacity since it has to withstand the weight of the attitude platform. Moreover, a pneumatic circuit is employed in order to provide air to the floating system for the entire duration of the simulation. At this purpose, two carbon-fibre vessels of 3 L each are used to store on board 1200 L of dry air.

The last component of DANCERS, and perhaps the most important, is the structure, which has to accommodate all the aforementioned components in an optimal configuration. Having in mind the main driver that is rigidity, the structure is designed starting from its main elements. In fact, the key elements to be considered are:

- it has to mount the three linear air pads on the very bottom, offloading all the vehicle weight on them and keeping the CM at the centre of the contact points;
- it has to mount the hemispherical air bearing to enable free rotations of the system, therefore, a pedestal structure is needed in order to avoid any possible obstruction of the free-floating platform movements;
- the free-floating platform has to host all the different components, trying to keep the CM and the CR as close as possible.

Here comes the need of two distinct platforms: the TP able to host the floating system and the AP where all the other subsystems are placed. Moreover, to align as much as possible CM with CR, AP can be subdivided into two other parts. Placing the massive actuators below the centre of rotations and the avionics, with the electronics and the payload, above it, it is possible to balance the entire system.

All the structure will be made in-house using the carbon fiber reinforced polymer (CFRP). In this way it is possible to save mass, gaining in strength and rigidity. In fact, the vehicle structure has to withstand the weight of all the subsystems, trying to minimize the deflections due to system dynamics. Considering DANCERS mass budget (Tab. 2) and the relative configuration of the different subsystems (Fig. 4), the structure sizing has been performed using a Finite Element Analysis (FEA) in order to assess the stress conditions of the different structural components.

Subsystem	Mass [W] (20% margined)
(1) Floating System	9.4
(2) Actuators	10.9
(3) Balancing System	9.9
(4) Sensors	0.3
(5) Avionics	0.1
(6) Electric Power System	3.1
(7) Structure	5.9
(8) Payload	2
Total	41.6
Total + 20%	49.9

Tab. 2 DANCER Mass Budget

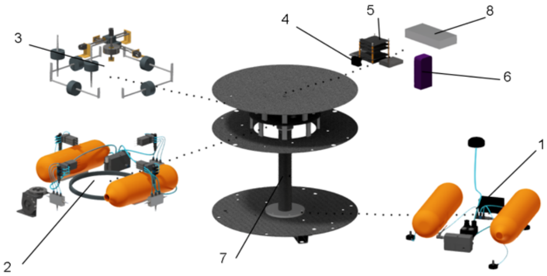


Fig. 4 DANCER Configuration

3. Dynamical Model

The DANCE facility will serve as a simulator for relative dynamics, both translational and rotational. Therefore, dynamical models of the two vehicles on the platform will be fundamental. Only in this way, it will be possible to predict and control in the right way the DANCERS dynamics and accomplish the simulation goals.

However, before starting with relative dynamics, it is important to set-up the entire facility. Actuators have to be characterized, sensors have to be calibrated, control laws have to be tuned. All the components of the system will have to be tested and validated. For these reasons, before developing a relative dynamical model, it is important to derive the model of the single robot with all its main components. It will serve for initial numerical tests, for the tuning of the control laws and also as visualization tool. Then, in a second stage, it will be used as fundamental brick for the development of a refined relative dynamical model of the facility.

3.1 Equations of Motion

In order to derive the equations of motion describing the vehicle dynamics, it is important to make few assumptions:

- DANCER is considered as made by discrete rigid bodies, in particular the translational platform, the attitude platform and the reaction wheels;
- CM and CR of the attitude platform precisely coincide for the entire duration of the simulation;
- No friction is present;
- The testbed arena is exactly flat and horizontal.

The set of differential equations describing the attitude dynamics and the translational dynamics of the vehicle can be derived exploiting the Euler-Lagrange equations. The generic form for a set of generalized coordinates q_i, in the presence of non-conservative forces Q_{q_i}, is:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = Q_{q_1} \quad \forall \quad i = 1, \dots, n \qquad (1)$$

where L is the Lagrangian, made as:

$$L = T - V \qquad (2)$$

T and V are the kinetic energy and the potential energy of the system, respectively. On the other hand, the generalized coordinates q_i can be identified considering the degrees of freedom of the entire system, which are:

- X_D, Y_D and Z_D are the translations of the TP and of the AP;
- φ, θ and ψ are the euler angles for the AP;
- ψ_{TP} is the rotation of the TP around the vertical axis;
- θ_{RW1}, θ_{RW2} and θ_{RW3} are the angles of the three reaction wheels.

These coordinates are state variables of the system, together with:

- $\dot{X}_D$, $\dot{Y}_D$ and $\dot{Z}_D$ are the velocities of the TP and of the AP;
- $\boldsymbol{\omega}_{AP}$ is the vector of the angular velocities of the AP;
- ω_{TP} is the angular velocity of the TP around the vertical axis;
- $\boldsymbol{\omega}_{RW}$ is the vector of the angular velocities of the three reaction wheels.

The total kinetic energy of the entire robot can be seen as the sum of the kinetic energies of the different components of DANCER, which are considered as rigid bodies. Therefore, under the aforementioned assumptions, the kinetic energy can be computed as:

$$T = \frac{1}{2} M_D \left(\frac{d\boldsymbol{r}_D}{dt}\right) \cdot \left(\frac{d\boldsymbol{r}_D}{dt}\right) + \frac{1}{2} J_{TP} \omega_{TP}^2 + \frac{1}{2} \boldsymbol{\omega}_{AP} \cdot \boldsymbol{J}_{AP} \boldsymbol{\omega}_{AP} + \frac{1}{2} \boldsymbol{\omega}_{RW} \cdot \boldsymbol{A}_{RW} \boldsymbol{I}_{RW} \boldsymbol{\omega}_{RW} + \boldsymbol{\omega}_{AP} \cdot \boldsymbol{A}_{RW} \boldsymbol{I}_{RW} \boldsymbol{\omega}_{RW} \qquad (3)$$

where M_D, J_{TP} and $\boldsymbol{J}_{AP}$ are respectively the total mass, the moment of inertia of the translational platform and the inertia matrix of the attitude platform in principal axes of inertia. The matrix $\boldsymbol{A}_{RW}$ is introduced to take care of the reaction wheels orientation and, in this case, having them aligned with the body reference frame, it is equal to the identity matrix. On the contrary, $\boldsymbol{I}_{RW}$ contains, on its diagonal, the moments of inertia of the three wheels.

Having a system of rigid bodies, the only potential energy is the gravitational energy. It can be computed considering the vectors $\boldsymbol{\rho}_{\boldsymbol{CM}_{TP}}$ and $\boldsymbol{\rho}_{CM_{AP}}$ describing the position of the centers of mass with respect to the center of rotation. Therefore:

$$V = M_{TP}\boldsymbol{g} \cdot \left(\boldsymbol{r}_D - \boldsymbol{\rho}_{CM_{TP}}\right) + M_{AP}\boldsymbol{g} \cdot \left(\boldsymbol{r}_D - \boldsymbol{\rho}_{CM_{AP}}\right) \tag{4}$$

where $\boldsymbol{g}$ is the vector of the gravitational acceleration. Considering the assumptions, it is possible to demonstrate that potential energy is constant.

For what concern non-conservative forces, no friction terms are involved in DANCERS dynamics because of the air bearings. However, they employ a set of cold gas thrusters which generates non-conservative forces and torques on the robots. It is possible to write their contribution considering the four cluster:

$$\boldsymbol{F}_T = \sum_{k=1}^{4} \sum_{n=1}^{3} \boldsymbol{f}_{kn} \tag{4}$$

$$\boldsymbol{M}_T = \sum_{k=1}^{4} \left(\sum_{n=1}^{3} \boldsymbol{l}_{kn} \times \boldsymbol{f}_{kn}\right) \tag{5}$$

where $\boldsymbol{f}_{kn}$ is the vector of the force exerted by the n-th thruster on the k-th cluster, while $\boldsymbol{l}_{kn}$ is the position vector of the n-th thruster on the k-th cluster in body frame. These equations can be simplified adopting a matrix notation:

$$\boldsymbol{F}_T = \boldsymbol{B}_N \boldsymbol{f}_T \tag{6}$$

$$\boldsymbol{M}_T = \boldsymbol{L} \otimes (\boldsymbol{B}_B \odot \boldsymbol{f}_T) \tag{7}$$

where the operator $\odot$ represents the element-wise dot product while $\otimes$ represents the column-wise cross product. These two operations are fast and easy to handle on numerical software such as Matlab.
Manipulating all the previous equations it is possible to obtain the equations of motion for the DANCER vehicle:

$$\boldsymbol{J}_{AP}\dot{\boldsymbol{\omega}}_{AP} + \boldsymbol{\omega}_{AP} \times \boldsymbol{J}_{AP}\boldsymbol{\omega}_{AP} = \boldsymbol{A}_{RW}\boldsymbol{I}_{RW}\boldsymbol{\omega}_{RW} \times \boldsymbol{\omega}_{AP} - \boldsymbol{A}_{RW}\boldsymbol{I}_{RW}\dot{\boldsymbol{\omega}}_{RW} + \boldsymbol{L} \otimes (\boldsymbol{B}_B \odot \boldsymbol{f}_T) \tag{8}$$

$$M_D \frac{d^2\boldsymbol{r}_D}{dt^2} = \boldsymbol{A}_{B/N}^T \boldsymbol{B}_B \boldsymbol{f}_T \tag{9}$$

where $\boldsymbol{A}_{B/N}$ is the direction cosine matrix used to rotate a vector from inertial reference frame to body reference frame. The constraint equations are obtained as well:

$$\omega_{TP} = 0 \quad \rightarrow \quad \psi_{TP} = const \tag{10}$$

$$\dot{Y}_D = 0 \quad \rightarrow \quad Y_D = const \tag{11}$$

These equations can be solved thanks to a numerical computation software, starting by a set of initial conditions and using a controller to provide system stability.

3.2 Numerical Model

The behaviour of the cold gas thrusters is highly non-linear and non-conservative. Consequently, a computational software has to be employed for the solution of the problem. With this aim, the Mathworks® suite is exploited, especially Matlab® and Simulink®. The entire model of DANCER is implemented in the software, trying to simulate its dynamics. Equations of motion, actuators and sensors are introduced as blocks.

The direction cosine matrix is employed to describe the vehicle kinematics. In fact, it is the most powerful attitude representation because it is global and unique. Moreover, it is important to introduce a controller able to command the thrusters and the reaction wheels in order to reach a desired dynamic. For what concern the attitude dynamics, a non-linear controller is derived using the Lyapunov's direct method on a function of the energy of the system. It has the following form:

$$\boldsymbol{u}_M = -K_\omega \boldsymbol{J}_{AP}\boldsymbol{\omega}_e - K_A\boldsymbol{e}_A + \boldsymbol{\omega}_{AP} \times \boldsymbol{J}_{AP}\boldsymbol{\omega}_P - \boldsymbol{J}_{AP}[\boldsymbol{\omega}_e]\hat{}\,\boldsymbol{A}_e\boldsymbol{\omega}_d \tag{12}$$

where the symbol ˆ represent the hat operator used to obtain a matrix from a column vector, $\boldsymbol{A}_e$ is the error matrix and it is equal to the identity matrix only when $\boldsymbol{A}_{B/N}$ is equal to the desired $\boldsymbol{A}_d$. $\boldsymbol{e}_A$ is the attitude error computed from $\boldsymbol{A}_e$ using the inverse hat operator. The vector $\boldsymbol{\omega}_e$, instead, contains the errors in the angular velocities with respect to the desired $\boldsymbol{\omega}_d$. Finally, $\boldsymbol{u}_M$ is the vector containing the desired torques while K_ω and K_A are the two gains used to tune the system response for what concern the attitude dynamics.
On the other hand, for what concern the translational dynamics, a simple PID controller is adopted and the desired forces $\boldsymbol{u}_F$ can be computed as follows:

$$\boldsymbol{u}_F = K_P\boldsymbol{e}_r + K_I\int_0^t \boldsymbol{e}_r\,(t')dt' + K_D\boldsymbol{e}_v \tag{13}$$

where $\boldsymbol{e}_r$ is the error with respect to the desired position and $\boldsymbol{e}_v$ is the error with respect to the desired velocity. The gains K_P, K_I and K_D can be tuned in order to optimize the system response.

It is also important to implement in the model the behaviour of the actuators. The term in equation 8 related with the reaction wheels represents their torque and it has to be limited in order to represent the real system capabilities. On the other hand, the cold gas thrusters are jets of pressurized air controlled by fast electrovalves. Therefore, there is no way to control the amount of force they can exert. The only way to achieve some flexibility is adopting a modulation scheme which is able to provide a sort of throttleability to the system. In this model, a Pulse-Width-Pulse-Frequency (PWPF) modulation scheme is adopted because of its benefits with respect to other algorithms. In fact, it is able to save propellant mass, providing a smoother actuation with a close-to-linear behaviour. More information on thrusters PWPF modulation can be found in the work of Agrawal, Mcclelland, and Song [8]. Another important aspect of this subsystem is how to implement the thruster selection algorithm. Lately, a lot of research has been done in this field, trying to find the most efficient way to select the right thrusters in order to reduce the propellant consumption. However, this is at odds with computational cost, therefore, a trade-off is necessary. The baseline is to adopt a jet selection by look-up table. This is a very fast and easy algorithm, which can be optimized employing an efficient reference catalogue.

Finally, the external constraints have to be applied on the equations of motion. In fact, the vehicle position and attitude are not completely unconstrained. The platform has a finite area of 3 m-by-3 m. On the other hand, the hemispherical air bearing is not able to provide full rotations in pitch and roll. This can be achieved modelling a damper-spring system on the border of the arena as well as at the limits of the bearing.

Thanks to all the different aforementioned blocks, the entire model of the DANCER dynamics is built. The model can be numerically solved starting from a set of initial conditions and adopting the right solver. In fact, it is important to consider that the resulting system of differential equations is stiff because the dynamics of the vehicle is much slower with respect to the dynamics of the thrusters, for example. Therefore, a fixed-step third-order method is employed for the numerical integration of the entire model. The resulting numerical model has been exploited for the sizing of the major components of each subsystem of the DANCER vehicles. It has also been used for the initial characterization of the system performances. Moreover, it will serve as starting point for the implementation of the DANCER software.

In order to visualize the complex dynamics of the DANCER vehicle, it is possible to exploit the Virtual Reality Toolbox (VRT) which allows to create animated three-dimensional scenes driven from the Matlab and Simulink environment. A screen-shot is reported in figure 5 as example.

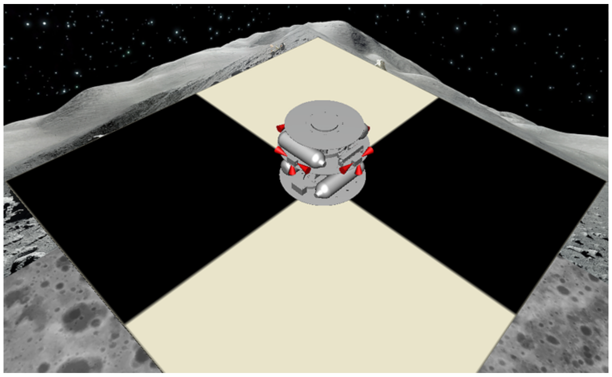


Fig. 5 VRT DANCER graphical model

4. Facility Integration: Current Status

The following section describes the current status of the implementation of the DANCE test-bed. In particular, the structure, the propulsion system and pneumatic management system are being developed and manufactured. The Microcontroller tests are focused on assessing the most effective approach for fast prototyping and translation of control algorithms from numerical simulations to hardware implementation.

4.1 Primary Structure

In order to save mass in the primary structure, the composite carbon fiber material is selected for massive components. A pre-impregnated carbon-epoxy material is utilized for manufacturing at the Department of Aerospace Science and Technology laboratory (DAER) at Politecnico di Milano. In particular, the selected product is a 300 mm unidirectional tape from HEXCEL. The lamination sequence is a composition of plies orientation 0°, 90°, -45° and 45°. The laminated plates have been cured in the autoclave following the desired cycle of pressure and temperature. **Errore. L'origine riferimento non è stata trovata.**Figure 6 and 7 show the different stages of the manufacturing process: the plies lamination and the subsequent autoclave curing at DAER.

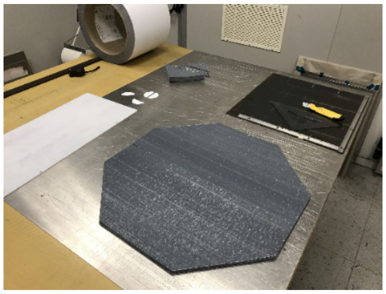


Fig. 6 Plies lamination

Fig. 7 Autoclave curing

The plates have been cut using a water jet machine shaping the external circumference and the big-sized holes. Figure 8 shows the base reinforcement plate after the water jet cut.

Fig. 8 Base reinforcement plate after water jet cut.

Due to the risk of delamination, the smaller holes were drilled using drill bits provided by SANDVIK®. Figure 9 shows the Middle Plate with all the holes drilled at DAER.

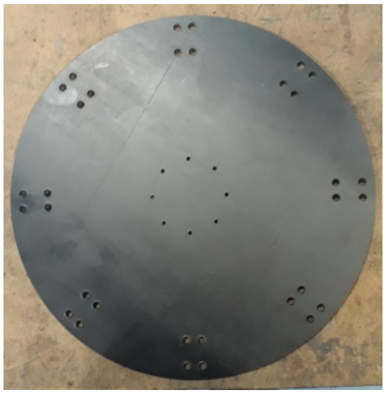


Fig. 9 Middle Plate after drilling

The last component of the DANCER primary structure made by a composite material is the pedestal body, shown in **Errore. L'origine riferimento non è stata trovata.** 10.

Fig. 10 Pedestal

4.2 Propulsion System

The propulsion system is composed of cold-gas thrusters, operating with compressed air. Given the on-ground application, it is unnecessary to buy space-qualified hardware; hence, the thrusters' assemblies are manufactured and assembled in-house. In order to obtain thrust from a compressed fluid in an efficient way, it is important to adopt a nozzle. A commercial nozzle has been chosen for the implementation in order to deliver a nominal thrust of 1.1 N at a nominal pressure of 6 bar.
The single thruster assembly, shown in figure 11**Errore. L'origine riferimento non è stata trovata.**, is composed by three nozzles mounted on the aluminium housing. The aluminium housing provides the fluidic connection between the nozzles and the pneumatic management system.

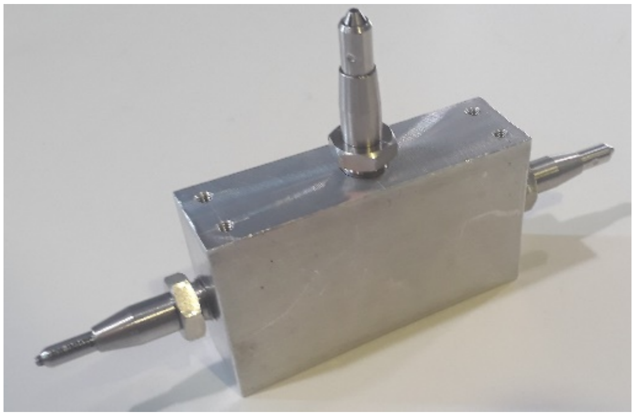


Fig. 11 Thruster assembly

The aluminium housing is secured to the structure by four screws and the pneumatic line interface is made of three channels connecting the fluidic fittings to the nozzles. The complete propulsion system comprises four assemblies, yielding a total of 12 thrusters, placed orthogonally on the *xy-plane* of the attitude platform, in order to provide controllability along every axis, both rotationally and translationally.

4.3 Pneumatic Management System

The pneumatic management system concerning pressures below 10 bar completely relies on components by FESTO®. Two separated assemblies are integrated, namely one for the Attitude Platform and one for the Translational Platform. The former is in charge of delivering compressed air to the linear and the hemispherical bearings, with a nominal pressure of 5.5 bar; the latter is dedicated to the feeding of the propulsion system. The microcontroller, which is responsible for the low-level control architecture, handles part of the actuation, e.g. electrovalves.

- **Translational Platform:** the TP pneumatic management system, shown in figure 12**Errore. L'origine riferimento non è stata trovata.**, comprises a proportional pressure regulator, 6-mm fluidic tubing connections and two directly actuated solenoid valves, together with generic fluidic fittings. One pneumatic line is dedicated to the hemispherical bearing, whereas a single valve controls the flow through the three linear bearings.

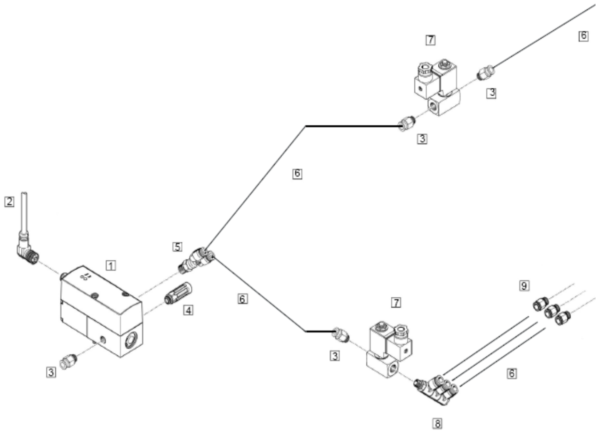


Fig. 12 Pneumatic management system on the Lower Platform

- **Attitude Platform:** the AP pneumatic management system, shown in figure 13**Errore. L'origine riferimento non è stata trovata.**, comprises a proportional pressure regulator, 6-mm fluidic tubing connections and 12 in-line fast switching electrovalves (1000 Hz), each one controlling the flow through one single nozzle.

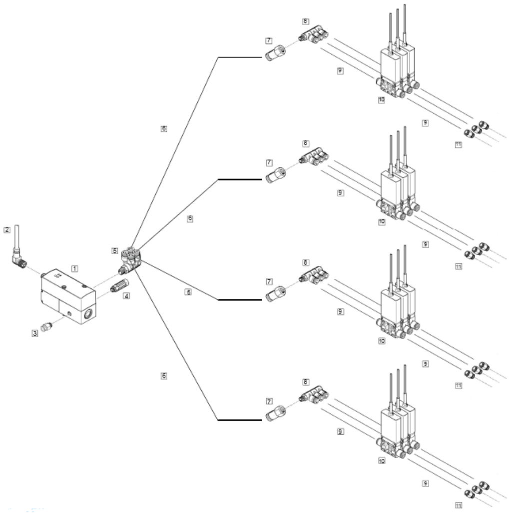


Fig. 13 Pneumatic management system on the Upper Platform

The integration between the pneumatic circuit and the primary structure is currently being performed.

4.4 MCU/SBC Testing

The DANCER on-board computing process is split into two hierarchical levels. As mentioned, DANCER is equipped with a BeagleBone Black Wireless with onboard 802.11 b/g/n 2.4GHz WiFi and Bluetooth mounting a Octavo Systems OSD3358 1GHz ARM® Cortex-A8 processor as Single Board Computer in charge of handling high-level task, data processing and control algorithms.

The low-level controller is a C2000 Delfino MCUs F28379D, which is in charge of controlling the hardware. For instance, the MCU unit manages the electrovalves actuation, RW speed/torque control and dynamic balancing. The control algorithms are developed in Matlab/Simulink® environment and transferred into the boards using the dedicated coder. This approach is adopted to ease the process of algorithm implementation for fast prototyping as well as to increase the standardization for third parties interface.

Figure 14 shows the result of a Processor-in-the-loop (PIL) simulation in which the DANCE control algorithm is deployed to the board and run in parallel with a Desktop-PC equipped with Intel® Core™ i5-3470 CPU@3.20GHz 8GB RAM.

As shown in figure 14, the discrepancies are $<10^{-6}\%$, meaning that the board is suitable to process the low-level control scheme.

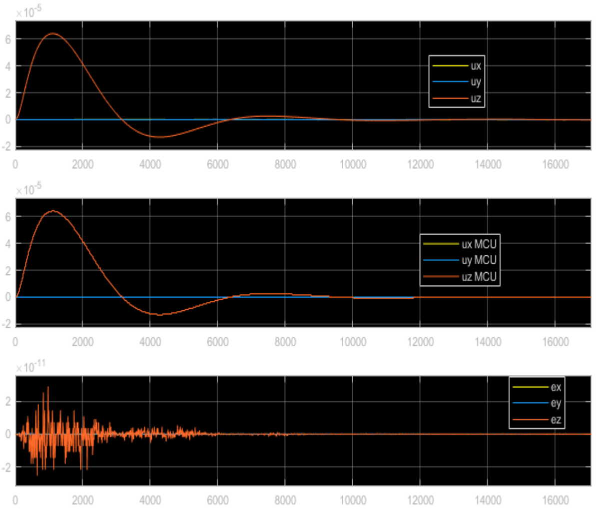


Fig. 14 Processor-in-the-loop (PIL) simulation of the control algorithm. The code is deployed to the board after translation from Simulink model.

5. Conclusions and Future Steps

The design and integration of a frictionless 5-DOF facility for GNC proximity manoeuvring experimental testing and validation have been thoroughly presented in this paper. The DANCE facility will be an essential tool for testing and validating a variety of possible hardware and software. Different configurations will be available, involving relative dynamics experiments but also absolute dynamics in force-free and torque-free environment. Formation flying, in fact, is only one possible scenario that DANCE platform will be able to provide. In this way, DAER will benefits of a competitive and outstanding tool. Starting from the overall requirements and goals, the different subsystems of the DANCERS vehicles, as well as of the testbed arena, have been designed, trading-off various aspects. Several difficulties have been faced during this process, because of the complex systems involved and because of the several interconnections within the distinct components.

However, in order to deal with the aforementioned problems, a series of numerical tests have been performed, employing the derived dynamical model. Indeed, despite necessary assumptions, the DANCER model can be accurate enough for the characterization of several aspects of the vehicles.

After all the iterations and the trade-offs, the resulting vehicles are small and light, but they still provide all the necessary capabilities required for the facility. In fact, comparing DANCERS with other 5 DOFs vehicles, the former are five time lighter than the latter, but they provide similar performances in term of experiment duration and accuracy.

In order to obtain a fully functional facility some actions need to be taken in the immediate future, mostly regarding the manufacturing and integration of the facility itself.

- Functional tests of all the subsystems
- Integration of the secondary subsystems on the primary structure
- Integration of DANCE test environment: the resin basement for the arena floor has to be realized to fix alignment issues.
- Tracking system installation: for absolute navigation of DANCER.

Acknowledgements

The authors would like to thank FESTO, SANDVIK for the support to the project.

References

[1] Macdonald, Malcolm and Badescu, Viorel, The international handbook of space technology, Springer, 2014.

[2] Wang, Danwei, Wu, Baolin, and Poh, Satellite Formation Flying. Vol. 87. Jan. 2017.

[3] Bandyopadhyay, Saptarshi et al, Review of Formation Flying and Constellation Missions Using Nanosatellites, In: 53 (Mar. 2016), pp. 1–12.

[4] L, H.A. and W. Haeussermann, Satellite motion simulator, US Patent 3,092,918. 1963, https://www.google.com/patents/US3092918.

[5] Regehr, M. W. et al, The Formation Control Testbed. In: *2004 IEEE Aerospace Conference Proceedings (IEEE Cat. No.04TH8720)*. Vol. 1. 2004, 564 Vol.1.

[6] Daitx, Henrique et al. Development of a Combined Attitude and Position Controller for a Satellite Simulator. Sept. 2016.

[7] Carlini, Alessandro and Marcuccio, Mirna. Apparato sperimentale per la simulazione dinamica di un mini-robot flottante con applicazione spaziale. Anno Accademico 2002-2003. MA thesis. Politecnico di Milano.

[8] Agrawal, Brij N, Mcclelland, RS, and Song, Gangbing. Attitude control of flexible spacecraft using pulse-width pulse-frequency modulated thrusters. In: *Space Technology- Kedlington* 17.1 (1997), pp. 15–34.