Mechanical and pneumatic design and testing of a floating module for zero-gravity motion simulation

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Abstract Close proximity operations demand an accurate control in a micro-gravity environment, hence they must be reproduced and simulated systematically. Consequently, laboratory tests are a crucial aspect to validate the performances of space systems. This paper presents the development of a floating pneumatic module, whose dimensions and mass are representative of a 12U CubeSat. The vehicle has been designed to perform planar low friction motion over a levelled table for docking experiments. The paper focuses on the pneumatic and mechanical designs and on the laboratory tests of the module. The pneumatic design regards the air-compressed pneumatic system. The major specifics have been determined by the requirement of performing a docking procedure by starting from a distance of 500 mm. The mechanical design has been guided by two main requirements. The first is the possibility to accommodate different docking systems (e.g.: docking port). The second is the possibility to control the position of the centre of mass of the module. Several tests have been performed to verify the capabilities of the vehicle, such as: (1) pneumatic tests to evaluate the thrust of the propulsion system through the execution of linear motions and (2) mechanical measurements with dedicated setups to improve the estimation of the position of the centre of mass from the CAD model of the system.

Introduction

A Close Proximity Operation (CPO) of an on-orbit spacecraft can be defined as a manoeuvre of one spacecraft (chaser) in a relative orbit with respect to another spacecraft (target) [1]. These operations are performed in micro-gravity conditions and include docking manoeuvres which require a systematic characterization of the forces and torques arising from the interaction of the chaser and the target. Therefore, laboratory tests and the realization of dedicated facilities are a critical aspect to validate the performances of docking mechanisms.

Among various microgravity simulation methods, such as parabolic flights, drop towers or robotic manipulators, an achievable solution for a laboratory environment is the use of planar Air-Bearings (ABs), which allows floating of tested devices [2] with the creation of a thin film of pressured gas between an internal porous structure and a surface. Thus, a planar 3 DoF motion can be achieved in a quasi-frictionless condition. Although a reduced number of DoF is obtained compared to the 6 DoF of an on-orbit motion, planar ABs are usually used as a support for dedicated vehicles which are equipped with thrusters and/or reaction wheels to simulate a satellite for CPOs and, specifically, docking manoeuvres experiments [2].

This paper presents the development of a floating pneumatic module, which has been designed to perform 3 DoF low-friction planar motion with three ABs over a levelled table. The module has a volume of 330x224x224 mm^3 with a mass of approximately 12 kg, so that it represents the mass properties of a 12U CubeSat.

With a dedicated propulsion system, the main goal of the vehicle is to simulate docking manoeuvres starting from a distance of 500 mm. The vehicle can operate both as a chaser, active mode, and as a target, passive mode, and it can accommodate different docking systems.

Pneumatic design

The pneumatic system has been designed to allow the vehicle to float with three round ABs and perform translational and rotational manoeuvres over a levelled table with a compressed air propulsion system.

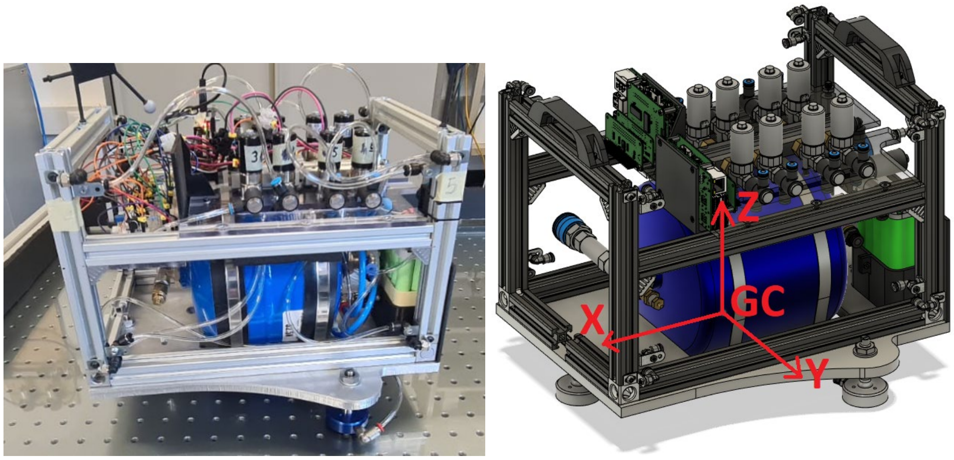
Furthermore, the pneumatic system has been realized to satisfy the following requirements: (1) motion is provided by 8 thrusters (2 thrusts for each corner of the vehicle); (2) each thruster is activated by one Electro-Valve (EV); (3) the pneumatic circuit ensures a total floating time of 3 min and performs an acceleration of 50 mm/s^2.

Requirements (2) and (3) have led to the following specifications: (a) the three ABs with a diameter of 40 mm are able to lift a total weight of approximately 68 kg at an input pressure of 3.9 bar; (b) each thrust is composed by two nozzles with a throat diameter of 1.3 mm to improve the produced force and reduce the working pressure; (c) the total air volume should be at least 2 L at 10 bar. Therefore, the pneumatic circuit has been realized with a 2.5 L tank and a single pressure regulator to control ABs and thrusters at the same pressure.

Mechanical design

The mechanical design has revolved around the positioning and sizing of components, so that they would fit inside the total volume of the module. The mechanical design has been guided by three main requirements: (1) the module accommodates different docking systems with a dedicated volume of 100x224x224 mm^3 in the front part; (2) the three ABs are positioned in an equilateral triangular configuration and the Centre of Mass (CoM) of the module is controlled to be coincident (with an error of 1 mm) with the centroid of the ABs to guarantee uniform floating of the vehicle; (3) the centroid of the thrusters is aligned with the CoM of the system to allow pure rotational motions. Additionally, the centroid of the ABs coincides with the Geometrical Centre (GC) of the 330x224x224 mm^3 volume of the system.

Figure 1 shows (a) the CAD model of the vehicle with the reference frame at the GC used to refer the position of the CoM and (b) the assembled module.



(a) (b)

Figure 1: (a) CAD model of the vehicle (b) Assembled module

An estimation of the position of the CoM has been obtained from the complete CAD model. With a total estimated mass of 8.2 kg with no payload, the CoM has been placed at -27.4 mm along the X axis and -0.9 mm along the Y axis with respect to the GC (Figure 1a). Moreover, the fully assembled module of Figure 2b has a greater total mass of 8.4 kg, because it includes electrical components and wiring which have not been considered in the CAD model.

A possible solution to control the position of the CoM of a system is the realization of custom masses which can be moved either automatically with motors [3] or manually [4]. For this reason and to get closer to the goal of a total mass of 12 kg, a group of manually movable steel masses has been designed and their masses have been determined from the CAD estimation.

In particular, three sets of masses have been designed: (1) a set of fixed masses (total mass of 620 g) to be mounted on the front part of the system to bring the CoM closer to the GC; (2) a couple of movable masses of 687 g each to control the X coordinate of the CoM; (3) a movable mass of 240 g to control the Y coordinate of the CoM.

Furthermore, considering a mass of 1 kg to represent a generic payload, by acting on the moving masses, it is possible to shift the X and Y coordinates of the CoM in a ±5 mm and ±2 mm ranges which contain the centroid of the ABs.

Tests on the pneumatic system

The tests on the pneumatic system have involved the execution of linear motions over the levelled table to estimate the provided thrust. The position of the module has been measured by a motion capture system (OptiTrack Prime^x 13 with an accuracy of ±0.2 mm). Figure 2 shows the setup for the tests on the pneumatic system.

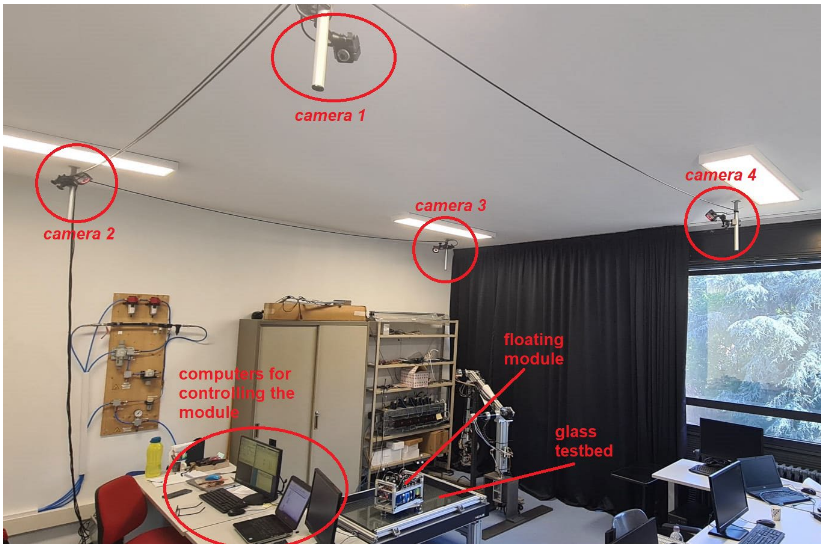


Figure 2: Main setup for the tests on the pneumatic systems

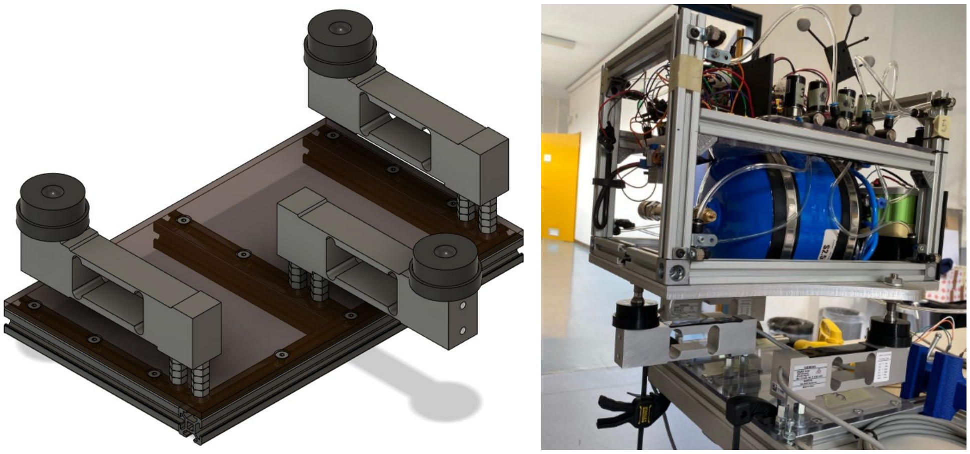
By commanding an impulse of 1 s to the EVs, two linear trajectories along the X and Y axes have been performed. By analysing the data of the measured position, the resulting thrusts have been estimated to be 1.541 N along the X axis and 1.531 N along the Y axis. The expected thrust has been calculated to be 2.225 N: the discrepancy could be related to the localized pressure losses in the pneumatic system.

Measurement of the position of the centre of mass

Mechanical measurements have been performed to estimate and balance the position of the CoM of the module. The position of the CoM has been measured with a setup of three load cells (rated load of 10 kg with an output of 2 ± 0.2 mV/V) placed under the supports of the three ABs. Figure

3 presents (a) the CAD model of the setup of the load cells and (b) the assembled setup with the module placed on top.

A Matlab algorithm has taken the three outputs of the load cells as inputs and converted them into mass values to compute the position of the CoM. With no payload and no fixed or movable masses (total mass of 8.4 kg), ten measurements have been acquired to account for the noise of the load cells. With an uncertainty of ±1 mm (~0.4% of the dimensions of the module), the mean value of the ten positions has placed the CoM at -25.6 mm and -3.1 mm along the X and Y axes with respect to the GC. The discrepancy from the CAD estimation is approximately 0.7%.
By mounting and acting on the moving masses, the CoM can be aligned with the GC within a ±1 mm range.



(a) *(b)*

Figure 3: (a) CAD model of the load cells setup – (b) Assembled load cells setup with module

Conclusions

This paper presents an overview of the pneumatic and mechanical designs and the performed tests and measurements of a floating pneumatic module which has been designed to execute 3 DoF planar low friction motion.

The thrust provided by the propulsion system has been quantified and the capability of the module to perform simple linear trajectories proven.

The position of the CoM has been measured with an uncertainty of ±1 mm, through a dedicated measuring setup.

The next steps of the development will involve the execution of rotational motions around the main axis over the levelled table to estimate the inertia of the module.

References

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