AIAA Guidance, Navigation, and Control Conference
08 - 11 August 2011, Portland, Oregon

AIAA 2011-6591

Advances on a 6 Degrees of Freedom Testbed for Autonomous Satellites Operations

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This paper presents recent developments in designing a novel 6 degrees of freedom (DOF) experimental testbed for validation of guidance, navigation and control algorithms for nano-satellites. The main catalyst for this research is the desire to experimentally test these algorithms in a 1g laboratory environment, in order to increase system reliability while reducing time-to-launch and development costs. The system stands out among the existing experimental platforms because all degrees of freedom of motion are dynamically reproduced. The majority of the existing platforms guarantee at the most 5 DOF force-free motion, excluding the vertical motion. The sixth DOF, when considered, is reproduced only from a kinematic point of view, by using an electrical motor. The presented testbed achieves 6 DOF dynamical motion by using 12 cold gas thrusters. A condition of almost frictionless motion along the 6 DOF is realized using 3 sets of air bearings: linear air bearings for the planar translational motion of the platform over an epoxy floor, air bearing pulleys embedded in a mass balancing system for the gravity-free vertical motion, and a spherical air bearing providing the additional 3 rotational DOF. The challenges of near gravity-free vertical translation in a 1g field are addressed using a unique counterbalancing system.

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Nomenclature

ADAMUS	=	ADvanced Autonomous MUltiple Spacecraft
MP	=	Moving Platform
AS	=	Attitude Stage
TS	=	Translational Stage
GNC	=	Guidance Navigation and Control
DOF	=	Degree of Freedom
BP	=	Balancing Platform

I. Introduction

Air-bearing based spacecraft simulators are used to experimentally test guidance navigation and control (GNC) algorithms that will be used on satellites for autonomous operations. Air bearing-based technology provides near frictionless rotational and translational motion, bringing the 1g laboratory conditions close enough to the micro-gravity operating ones. In accordance with the classification of [1], it is possible to divide the simulators into 3 main categories, based on the degrees of freedom that they provide:

1) the *planar systems* allow planar motion and (but not necessarily) vertical spin motion. These systems generally carry their own compressed air in tanks and create an air cushion, which provides almost frictionless planar sliding motion on a smooth flat surface. The vertical spin motion is generally reached either using a reaction wheel or compressed air thrusters. These systems can be used, for example, to test docking and rendezvous operations, as in the case of the MIT Field and Space Robotic Laboratory (FSRL) experimental platform [2]. The MIT FSRL platform consists of a team of two robots capable of planar motion and vertical spin on a granitic smooth surface. The goal of these robots is to collaborate, in order to build large flexible structures in space. They carry their own compressed air, and have manipulating arms. A laser system is used for tracking purposes. Another example of planar system is the autonomous docking test bed at the Naval Postgraduate School Space Robotics Laboratory [3]. In this apparatus, autonomous approach and docking operations of a chaser spacecraft to a target spacecraft of similar mass are tested. The platform can float over an epoxy smooth surface; translational motion is achieved by using cold-gas thrusters while spin is achieved by thruster couples, or by using a reaction wheel. Other examples of planar systems developed by companies and universities can be found in [4]-[10];

2) the *rotational systems* allow the dynamic simulation of satellite's attitude motion. Depending on the geometry of the platform, the pitch, yaw or roll rotations may be limited. According to which rotation has full freedom, rotational systems are divided into “tabletop” systems, “umbrella” systems and “dumbbell” systems. The first two types guarantee a full freedom yaw rotation (and pitch and roll rotations limited by the geometry). The main difference is in their geometry. The first type is basically a table attached to a spherical air bearing while the second type has a cylindrical bar connecting the table to the spherical bearing. The dumbbell systems guarantee full freedom yaw and roll rotations. Fig. 1 shows the three rotational systems configurations.

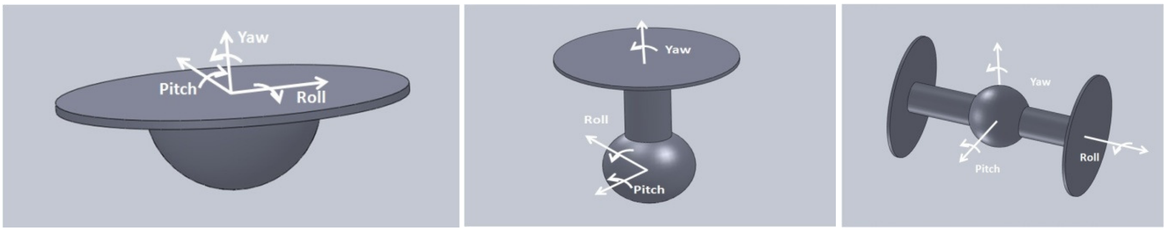

Fig. 1 a) Tabletop System, b) Umbrella System, c) Dumbbell System

Examples of rotational system of the first and second type are the Naval Postgraduate School's Three Axis Attitude Dynamics and Control Simulator [11], which provides full freedom in yaw and ± 45° in pitch and roll and the Georgia Tech’s School of Aerospace Engineering simulator, which provides full freedom in yaw and ± 30° in pitch and roll [12]. The University of Michigan's Triaxial Air Bearing Testbed [13], [14] is a dumbbell rotational system. This system provides full freedom for yaw and roll and ± 45° in pitch;

3) the *combination systems* are simulators which integrate the capabilities of planar systems and rotational systems. These devices can have 5 to 6 degrees of freedom, combining translation and attitude stages. The Marshall Space Flight Center's Flight Robotics Laboratory has one of the most developed simulation platforms in the world [15]. This test bed provides 6 DOF motion on a flat surface of 44 ft x 66 ft. The vertical motion is provided by a cylindrical lift and not by thrusters. A 5 DOF simulator has been developed by the Lawrence Livermore National Laboratory [16]. It combines a platform with full freedom yaw, ± 15° pitch and ± 30° roll on a dynamic air bearing vehicle. In this device there is no vertical degree of freedom. More recent research related to 5 DOF simulators has been done by Georgia Institute of Technology and Harbin Institute of Technology. Both projects combine a lower platform guaranteeing 2 translational DOF with an upper platform, connected with a spherical air bearing, which gives the additional 3 rotational DOF [17], [18]. An interesting example of 6 DOF testbed is the MIT “SPHERES”

project [19], [20]. This testbed can reach full 6 DOF when used in the International Space Station (ISS)'s micro-gravity environment. Another 6 DOF platform has been developed by the NASA Jet Propulsion Laboratory. In this case the vertical motion, giving the 6th degree of freedom is provided by a powered vertical stage, actively controlled to provide a simulated zero-g environment for the attitude platform [21].

The main goal of this paper is to present the advances on the development of a unique 6 DOF test bed at the Advanced Autonomous Multiple Spacecraft (ADAMUS) laboratory. The test bed differs from the existing 6 DOF systems because it guarantees dynamical reproduction of motion along/about the full 6 degrees of freedom. The resulting behavior of the system will be much closer to the actual dynamics that satellites present when operated on the field, as compared to systems that use linear motors or other kinematical solutions. An important problem when dealing with attitude spacecraft simulators is the mass balancing system. In fact, in order to effectively operate the simulators without undesired gravitational torques, the center of mass of the attitude stage has to be coincident with the center of rotation, located in the rotational air bearing. In order to align the center of mass with the center of rotation, additional moveable masses are often used. Using adaptive methods, the masses are moved until the equilibrium position is reached, with the center of mass aligned to the center of rotation of the joint [22], [23]. The ADAMUS testbed attitude stage uses a Balancing Platform (BP) for equilibrium purposes. The BP is connected to the attitude stage with a linear motor that allows changing the distance of the BP with respect to the attitude stage along the vertical axis. The BP also hosts two linear motors that can move along the two remaining axes. The movement of the whole BP mass along the vertical axis and the movement of the two motors along the other two axes provoke a change in the position of the global center of mass of the attitude stage. By fine calibrations and tuning of the position of the three linear motors it is possible to move the global center of mass, aligning it with the center of rotation. The unique design of the ADAMUS platform will potentially allow for different spacecrafts testing by simply switching out the attitude stage. Fig. 2 shows the interchangeable attitude stage, connected to the testbed base through the spherical air bearing while Fig. 3 is a detailed view of the BP. Another important feature of the ADAMUS testbed is how directly it addresses the challenges of near gravity-free vertical translation in a 1g field. This is accomplished using a unique counterbalance method that employs a matched variable-mass counterbalance and near-frictionless air bearing pullies to allow close to gravity-free motion along the local gravity vector. The testbed is moved by compressed air thrusters only and, during the experiments, due to air consumption, there will be a constant variation of the attitude stage mass. This mass variation does not produce a change in the position of the global center of mass since the air is stored in two identical tanks, mounted symmetrically on the attitude stage, having their center of mass coincident with the center of rotation along the vertical axis. The pneumatic connections are made such that the air consumption is the same for both the tanks so that the amount of air in the tanks is the same at any time.

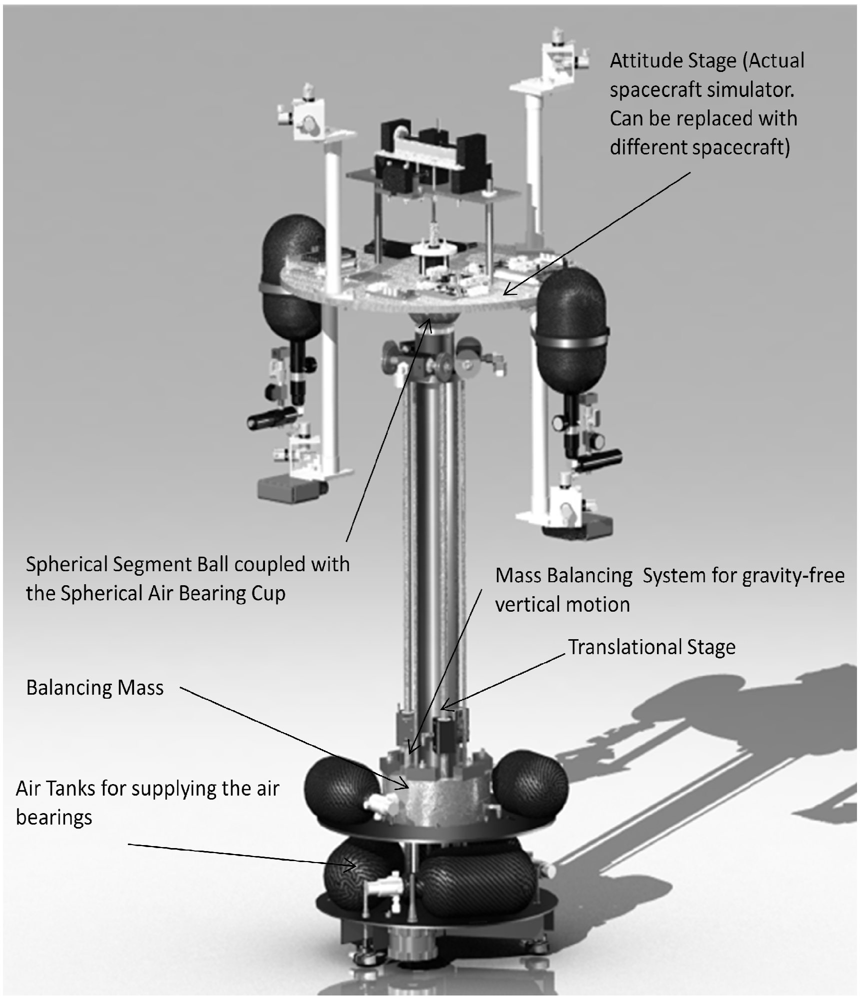

Fig. 2 Interchangeable Attitude Stage connected to the Translational Stage through a spherical air bearing

The overall system represented in Fig. 2 will be operated on a flat epoxy surface. The position and attitude of the robotic simulator will be provided in real time by the PhaseSpace Impulse System®, which will stream tracking data to the simulator's onboard computer.

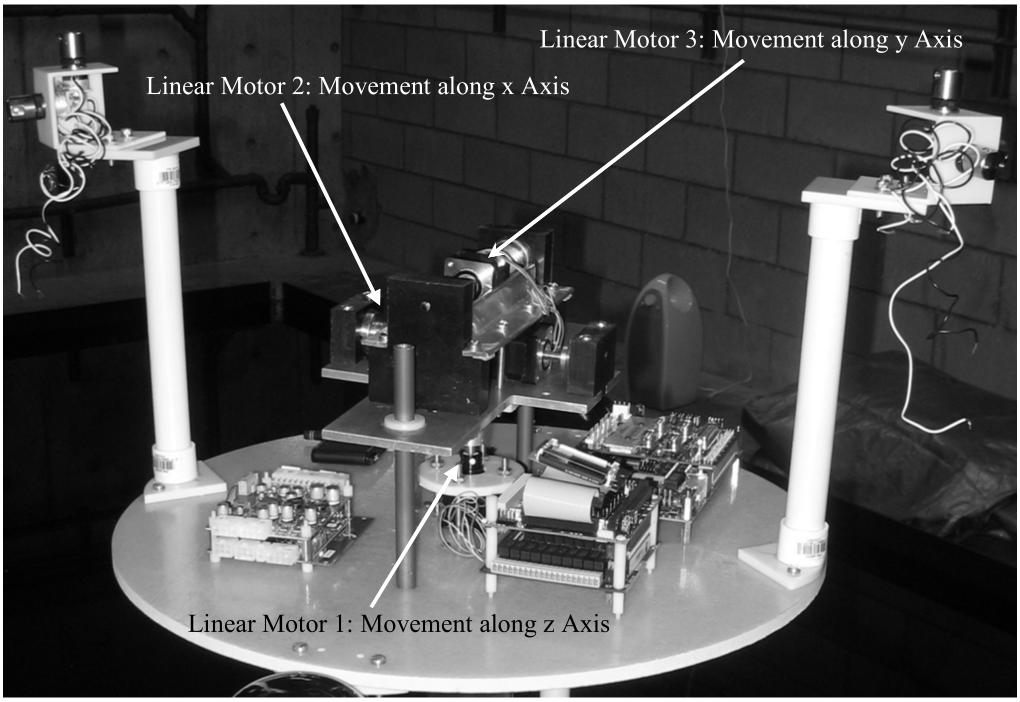

Fig. 3: Magnified view of the Balancing Platform connected to the Attitude Stage through Linear Motor 1

The paper is organized as follows: in Section II (System Configuration) an overview of the system is given, with a detailed list of all subsystems and an explanation of their interactions. Section III describes the envisioned preliminary experiments that the team is planning, while in section IV, the conclusions and the future work are discussed.

II. System Configuration

A. General Overview

The simulator, or moving platform (MP) shown in Fig. 2, will be composed by a Translational Stage (TS) (Fig. 4 and Fig. 5) built by Guidance Dynamics Corporation® (GDC) and by an Attitude Stage (AS) (Fig. 6 and Fig. 7) designed and built by the ADAMUS lab.. The TS will move virtually without friction over a 13 ft x 15 ft epoxy floor built by Precision Epoxy Products, a division of Rock Art, Ltd, via 3 linear air bearings that will create an air cushion between the TS and the floor. The AS will be the actual satellite simulator. 12 cold gas thrusters will be distributed about the AS in order to provide translational and rotational motion in and around the 3 axes. The AS will be connected to the TS through a spherical segment air bearing. A system of air pulleys on the TS will allow gravity-free vertical motion of the AS. On the AS there will be the onboard computer, which will determine which thrusters to actuate according to different sets of GNC algorithms to be tested and the dynamics information streamed by PhaseSpace Impulse System®, comparing it with desired trajectories and maneuvers stored on the computer. The PhaseSpace Impulse System® will track the position and the attitude of the AS using a set of LEDs properly distributed on it and a set of cameras mounted around the experimental area. The required compressed air for the thrusters will be provided by two tanks attached to the two lower arms of the AS, while the compressed air for the air bearings comes from tanks on the TS. The electrical power to run the Moving Platform (MP) subsystems will be provided by two Lithium-ions batteries connected to a power management system which will be located as well on the AS. A balancing platform (BP) will be connected to the AS in order to get precise alignment of the global center of mass with the center of rotation. The motors that are located on the BP will be connected to a set of motor drives and to a controller card which will be driven by the onboard computer in a closed loop control fashion. Table 1 lists the main components of the testbed, and the companies they have been purchased from. See also Fig. 6 for the localization of the components.

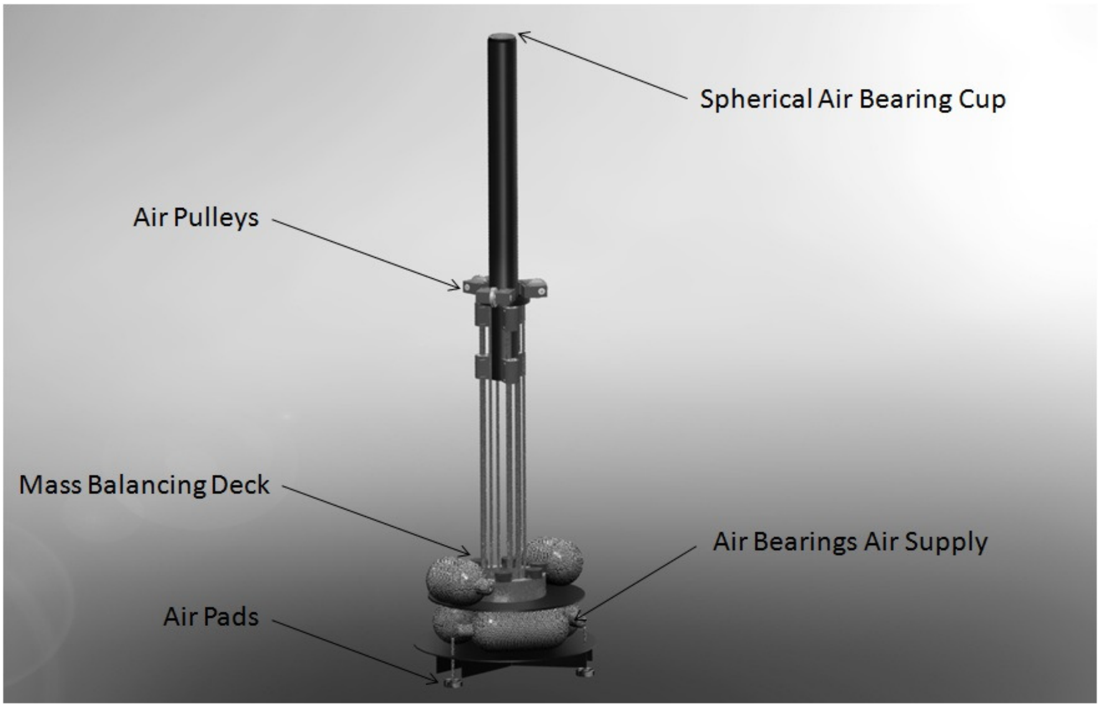

Fig. 4 Rendering of the Translational Stage

Fig. 5: Translational Stage

Table 1: Testbed Main Components

Element	Assembly	Components	Model	Company
Moving Platform	Translational Stage	-	-	Guidance Dynamics Corporation
	Attitude Stage	Thrusters, 12x	EH2012	Gems Sensors and Controls
		Battery Management System	MP-04R	OceanServer Technology Inc.
		Dc-Dc Converter	DC123R	OceanServer Technology Inc.
		Li-ion Batteries, 2x	ND2054	Inspired Energy®
		Tracking System (LEDs and Puck)	PhaseSpace Impulse System	PhseSpace Inc.
		Compressed Air Tanks, 2x	Ninja 4550	Ninja Paintball
		Relays Module	IR104-PBF	Diamonds Systems
		Wireless Receiver	DWL-G730AP	D-Link
		Onboard Computer	ADLS15PC	Advanced Digital Logic
		Motor Controller Card	DCM-2133	Galil Motion Control
		Motor Drives	SDM-20242	Galil Motion Control
		Non-Captive Motor (2)	35F4N-2.33-024	Haydon Kerk
		Captive Motor	35H4N-2.33-049	Haydon Kerk
Epoxy Floor	-	-	-	Precision Epoxy Products
Tracking Apparatus	-	Camera, Server, Wireless devices	PhaseSpace Impulse System	PhaseSpace Inc.

B. Translational Stage

The TS is being custom built by Guidance Dynamics Corporation®, according to the ADAMUS laboratory team's specifications. Fig. 4 and Fig. 5 show the rendering and the actual TS. The TS contains the linear air bearings necessary to create the air cushion that separates the structure from the floor and the mass balancing system, based on air pulleys, necessary for near gravity-free vertical motion of the AS. The TS terminates with a spherical air bearing cup, and the mating spherical segment ball which will be attached to the AS. The TS also carries the compressed air tanks and interconnected pneumatics that store and distribute the air used by all the air bearings of the platform.

C. Attitude Stage

The attitude stage (AS) is composed of a disc connected to the spherical air bearing. Attached to the AS are four arms. Two arms extend upwards while the other two arms extend downwards. The arms are attached symmetrically to the disc, in order to ensure mass balancing and proper propulsion when the thrusters are activated. There are three thrusters per arm mounted along its edge. Using the proper combination of active thrusters it is possible to obtain translational or rotational yaw, pitch or roll motions. The AS provides full 360° of yaw freedom and ± 45° about the pitch and roll axes. The thrusters and the air bearings are fed with compressed air, which is stored in carbon fiber tanks attached to the AS. During the simulation operations there will be a constant mass loss due to the compressed air usage. For balancing reasons the tanks are placed having their combined center of mass coincident with the center of rotation of the attitude stage. The flat disk of the AS also supports the power management system, the onboard computer and the puck, a device used by the PhaseSpace Impulse System for controlling the proper flashing frequency for each LED so that the cameras system will recognize their position. A total of 6 LEDs are positioned on the edges of the arms and on the middle of the upper platform. The batteries needed to power the system are located on the lower arms in order to lower the center of mass position. Fig. 6 and Fig. 7 show the AS connected to the air bearing but detached from the translational stage in a render and actual view respectively. Wiring and pneumatic connections are not shown in the pictures for clarity reasons.

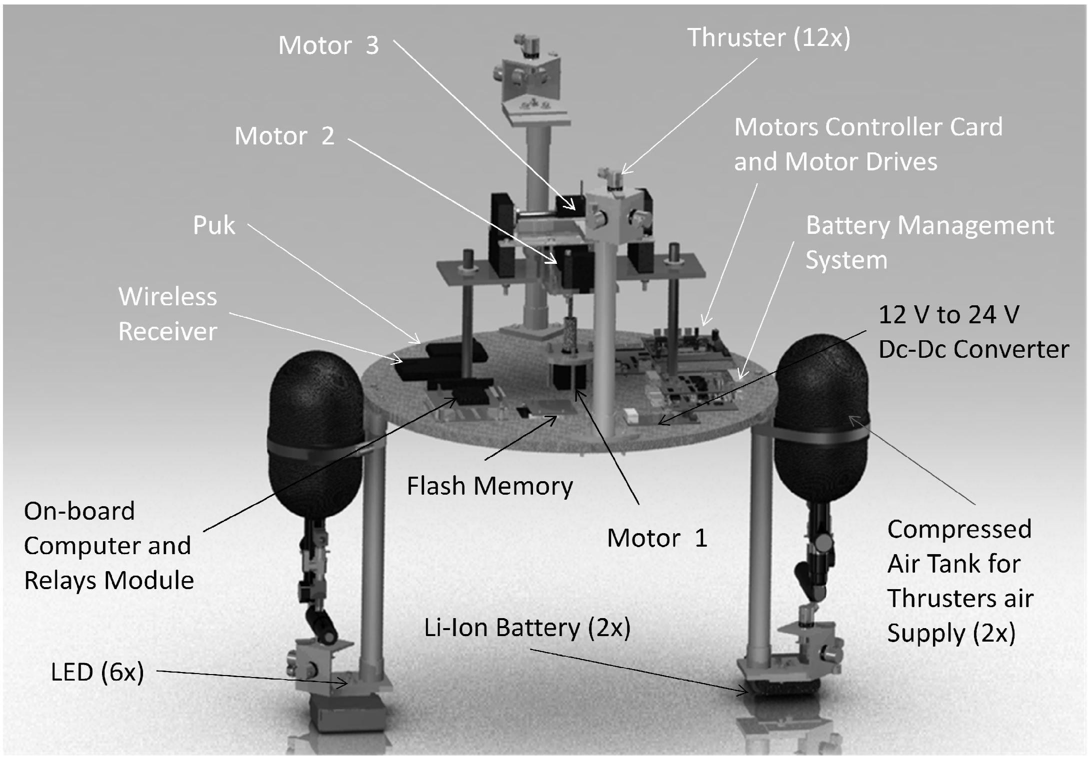

Fig. 6: Rendering of the Attitude Stage

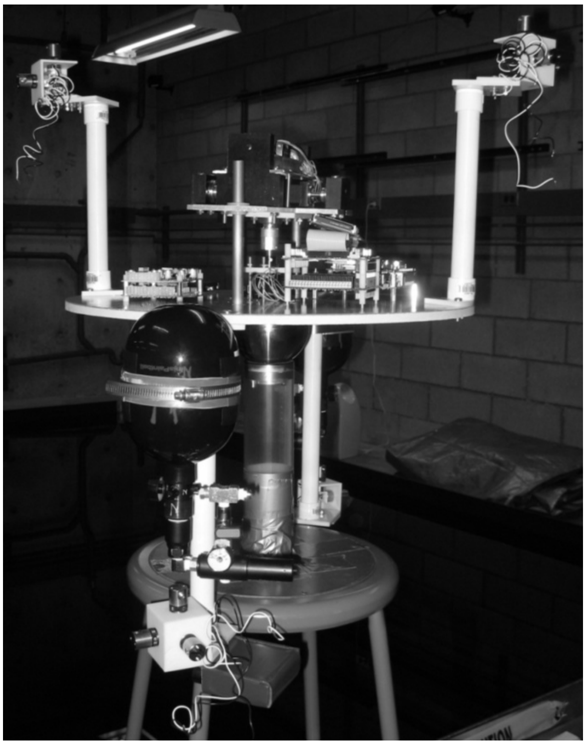

Fig. 7: Attitude Stage

The AS also hosts the Motors drives and controller card. They are connected to the onboard computer that will generate the control algorithm in order to keep the stage as balanced as possible, meaning aligning the global center of mass of the AS with the center of rotation with the highest possible precision, in order to eliminate any possible gravity torque.

D. Power and Data Management Subsystems

All the subsystems rely on 2 Lithium-Ions batteries. These batteries are connected to a Power Management System from Ocean Server Technology (IBPS: Intelligent Battery and Power System). This system is extremely versatile and is able to 1) recharge the batteries thanks to a safety charging circuit, when connected to the 110V grid, and 2) provide the required power at several voltages. More specifically, the power management itself provides 5V power to the onboard computer (Advanced Digital Logic ADLS15PC Rev. 1.3) and 12V power to a secondary DC-DC booster converter, which brings the voltage to 24V. Also, the IBPS is connected to the motor drives and to the motors controller card. The 12V to 24V DC-DC is connected to a relays module to which all the thrusters are attached. The output ports of the onboard computer are connected to the same module. The relays are activated by computer signals and open or close the electrical connections of the thrusters electro-valves, activating the solenoids and switching between the on and off states.

The computer gives the signals to the relays according to a Guidance Navigation and Control (GNC) set of algorithms stored in its memory, and according to the tracking information streamed by the PhaseSpace Impulse System®. The onboard computer is also connected to the motor controller card, in order to precisely control the position of the motor on the BP. This operation of calibration is mainly done in a setup phase, before the GNC experiment, so that the initial condition will be a completely balanced platform. The laboratory is also developing algorithms that will allow continuous balancing of the platform during the experimental phase (during the testing of GNC) since there are minimum variation of the position of the center of mass that could provoke undesired gravity torques, compromising the optimal control of the satellite and the simulated 0g conditions. Fig. 8 represents a scheme of the electrical connections and of the signals in the system.

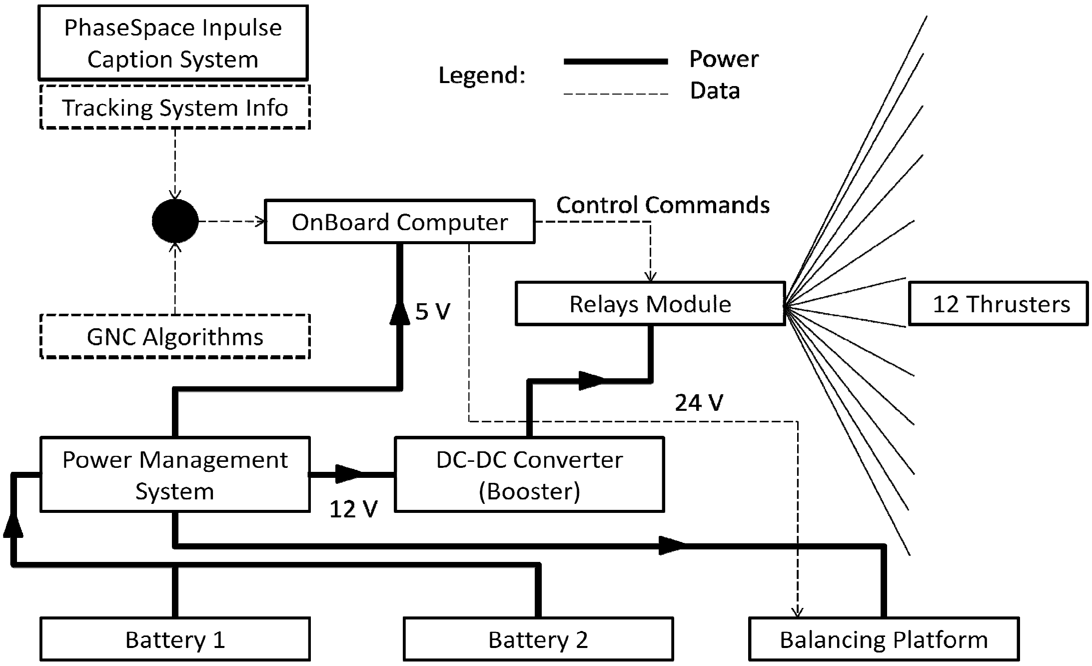

Fig. 8 Electrical Connections and Signals

E. PhaseSpace Impulse System, Software and Data Flow

The test bed utilizes the PhaseSpace Impulse System® technology to track the platform position and attitude. This technology is an optical motion tracker. The AS is covered with a net of 6 LEDs, positioned in key locations for determining attitude and position of the system. The LEDs are connected in series using a single cable and the cable is connected to a device called the "Puck". This device is wirelessly connected to a server to which are also connected to all the eight cameras that surround the experimental perimeter. Every LED is connected to its own electronic circuit, which establishes the identity of the LED. Once the series of LEDs is connected to the puck, it gives them a different flashing frequency (according to their identity provided by the electronic circuit). The flashing LEDs' images are captured by the cameras and the central server determines the position of each LED according to its flashing frequency, which is specific to each LED. The program that provides the values of position and the quaternions from the camera signals is proprietary software included in the PhaseSpace system. This data is streamed using a wireless router and is detected by the onboard computer thanks to a wireless receiving device. The computer works in a Linux environment. The GNC is programmed in Simulink and then compiled into a real time executable for RTAI Linux ([10]). The Simulink model, given attitude and position information, elaborates proper commands to the relays connected to the thrusters in order to achieve the GNC goals. Following, Fig. 9 shows the

PhaseSpace Impulse System® cameras grid, together with an indication of the axis on the experimental space (more cameras exist surrounding the space, which cannot be seen in this photograph):

Fig. 9 ADAMUS Laboratory experimental floor

III. Envisioned Experiments

The following tests are planned:

1) Calibration system verification, in order to determine the effectiveness and precision of the BP for the alignment of center of mass and center of rotation.
2) Air tank balancing test. Several experiments will be carried out to determine if the used quantity of air is the same for both the tanks. Also, several tests will be performed to determine the amount of air consumed by the thrusters given a set of operating times.
3) Epoxy floor characterization in order to determine the level of flatness and, in case of not perfect flatness, the fraction of gravity force that the system will be subject to.
4) Experimental verification, for the first time in 6DOF, of the Lyapunov approach of [24], specifically designed for spacecraft equipped with on/off thrusters only.

IV. Advances, Conclusions and Future Work

The ADAMUS spacecraft simulator is a unique example of completely dynamic 6 DOF simulator. The existing simulators are either of 5 DOF or 6 DOF, with the 6^{th} DOF being kinematic only.

The novel calibrating system allows precise alignment of the center of mass of the attitude stage with the center of rotation of the spherical bearing, canceling out the gravity torques.

The simulator constitutes an experimental test bed for testing several guidance, navigation, and control algorithms, in order to optimize the autonomous satellites operations.

Several changes have been made from the version of the testbed discussed in [25]. The original arms on the AS showed significant vibration problems. In order to augment the stiffness of the structure, the arms geometry and material have been changed. In the old version of the testbed they were made of ABS and they had a rectangular cross section. In the new version the arms are made out of a PVC pipe, which, other than increasing the stiffness, has proven to be much lighter than the previous version in ABS.

Another significant change is the material of the disc constituting the main structural part of the AS. The ABS disc has proven to be too flexible, adding to the control algorithms hardly predictable vibrations. For this reason, the material has been changed to fiber glass whose texture has been specifically designed to resist to flexural elastic deformations (the main source of vibrations in the previous version).

A significant additional change regards the position of the center of mass of the attitude stage. In the previous version of the testbed, the center of mass was almost coincident with the center of rotation. In the new version the initial location of the center of mass is coincident with the center of rotation along x and y axis but it is located below the center of rotation along the vertical axis. This design choice has been made because there will always be small uncertainties regarding the actual position of the center of mass. If the starting position is above the center of rotation, the BP won't be able to compensate it (due to its structure). Instead, if the center of mass is below the center of rotation, the BP will be able to align it with traditional control algorithms. The center of mass has been moved below the center of rotation moving batteries and battery holders at the bottom of the lower arms and changing the orientation of the air tanks so that the heavier part for the pressure regulation are now below the center of rotation (while keeping the center of mass of the tanks aligned with the center of rotation).

For future experiments, a natural development of this work will be building another platform and test algorithms for formation flight. Also, attitude stages could be modified in order to have additional operating arms for performing collaborative repairing, refueling, and construction operations.

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