SIX DEGREES OF FREEDOM EXPERIMENTAL PLATFORM FOR TESTING AUTONOMOUS SATELLITES OPERATIONS

D. Gallardo, R. Bevilacqua
Rensselaer Polytechnic Institute, Troy, NY, USA
gallad3@rpi.edu, bevilr@rpi.edu

ABSTRACT

This paper presents recent developments in designing and operating 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 3 sets of air bearings: planar motion of the platform over an epoxy floor will be achieved by using a system of linear air bearings; a mass balancing system, based on air bearing pulleys, will guarantee the gravity-free vertical motion, while a spherical air bearing will provide the additional 3 rotational DOF. The testbed directly addresses the challenges of near gravity-free vertical translation in a 1g field using a unique counterbalancing system.

1. INTRODUCTION

Air-bearing based spacecraft simulators are used to experimentally test guidance navigation and control (GNC) algorithms 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 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];

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 (the system that is presented in this paper), “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. 1shows the three rotational systems configurations.

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] is a dumbbell rotational system. This system provides full freedom for yaw and roll and ± 45° in pitch;

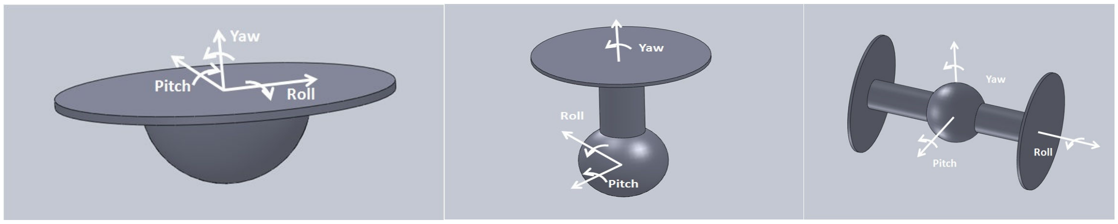

Fig. 1 *a) Tabletop System, b) Umbrella System, c) Dumbbell System*

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]. An interesting example of 6 DOF testbed is the MIT "SPHERES" project [19]. 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 unique design of the 6 DOF test bed under development at the Advanced Autonomous Multiple Spacecraft (ADAMUS) laboratory. The test bed differs from the existing 6 DOF systems because it will guarantee 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]. In the ADAMUS testbed the attitude stage will be connected to the spherical air bearing using a set of linear actuators which will allow precise 3D translations of the entire attitude stage. A very fine calibration will be performed before beginning the experiments, in order to align the center of mass and the center of rotation. This design choice will potentially allow for different spacecraft 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.

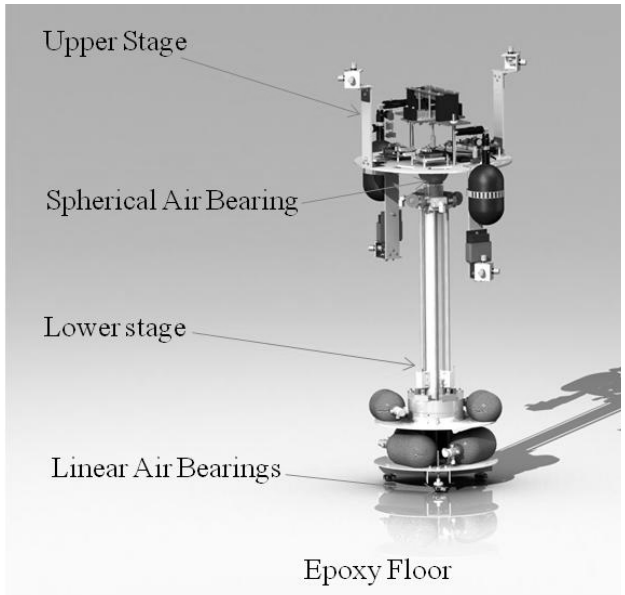

Fig. 2 *Interchangeable Attitude Stage connected to the Translational Stage through a spherical air bearing*

Most importantly, the ADAMUS testbed directly 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 will be 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. The air will be stored in two identical tanks that will deplete at the same rate, mounted on the lower arms so that their center of mass will coincide with the center of rotation of the attitude stage.
The overall system represented in Fig. 2 is intended to be operated on a flat epoxy surface. The position and attitude of the robotic simulator is provided in real time by the PhaseSpace Impulse System®, which streams tracking data to the platform's onboard computer.
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.

2. SYSTEM CONFIGURATION

A. GENERAL OVERVIEW

The simulator, or moving platform (MP) shown in Fig. 2, will be composed by a Translational Stage (TS) (Fig. 3) built by Guidance Dynamics Corporation® (GDC) and by an Attitude Stage (AS) (*Fig. 4*) designed and built by the ADAMUS lab. team. 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 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-bearing 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 according to the navigation information streamed by PhaseSpace Impulse System. The PhaseSpace Impulse System® will track the position and the attitude of the AS using a set of LEDs properly distributed on the AS 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 mass balancing platform will guarantee alignment between the center of mass and the center of rotation. The platform will be composed by two non-captive motors that will move the center of mass on the plane. The platform itself will be moved vertically by a third captive motor that will move the center of mass along the vertical axis. Table 1 lists the main components of the testbed, and the companies they have been purchased from. See also *Fig. 4*.

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
		Motor Controller Card	DCM-2133	Galil Motion Control
		Motor Drives	SDM-20242	Galil Motion Control
		Non-Captive Motor, 2x	35F4N-2.33-024	Haydon Kerk
		Captive Motor	35H4N-2.33-049	Haydon Kerk
		Onboard Computer	ADLS15PC	Advanced Digital Logic
Epoxy Floor	-	-	-	Precision Epoxy Products
Tracking Apparatus	-	Camera, Server, Wireless devices	PhaseSpace Impulse System	PhseSpace Inc.

B. TRANSLATIONAL STAGE

The TS is being custom built by Guidance Dynamics Corporation®, according to the ADAMUS laboratory team's specifications. Fig. 3 shows the TS:

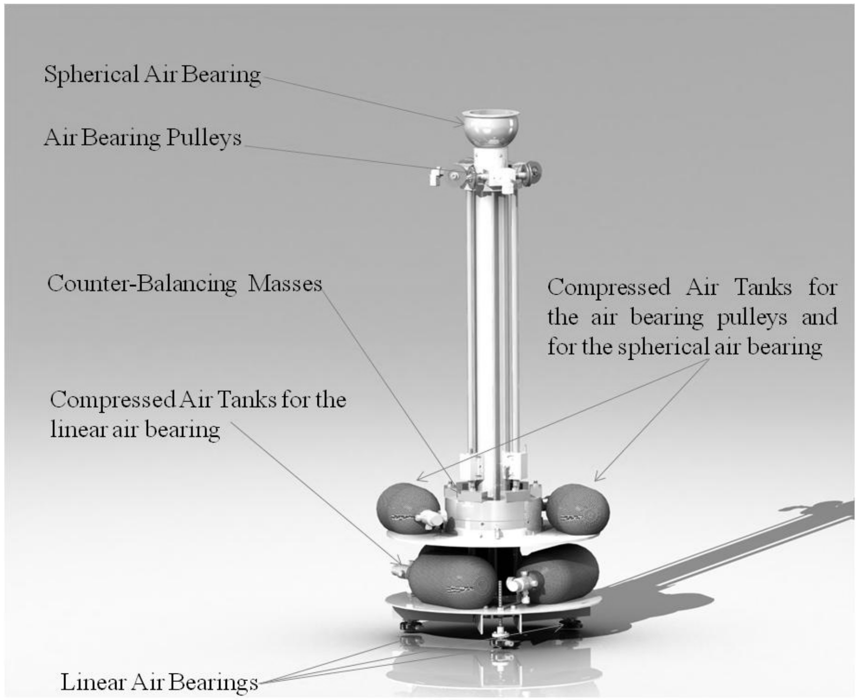

Fig. 3: *Translational Stage*

The TS contains the linear air bearings necessary to create the air cushion that separates the structure from the floor and a mass counterbalancing system, based on air pulleys, necessary for near gravity-free vertical motion of the AS. The TS will terminate 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 the air bearings.

C. ATTITUDE STAGE

The attitude stage (AS) will be composed of a disc connected to four arms. Two arms will extend upwards while the other two arms will extend downwards. The arms will be attached symmetrically to the disc, in order to ensure mass balancing and proper propulsion when the thrusters are activated. There will be three thrusters per arm mounted along its edge. Using the proper combination of active thrusters it will be possible to obtain translational or rotational yaw, pitch or roll motions. The AS will provide full 360 degrees of yaw freedom and ± 45° about the pitch and roll axes. The thrusters will be fed with compressed air, which will be 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 will be placed having their combined center of mass coincident with the center of rotation. The flat disk of the AS will also support 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 will be positioned on the edges of the arms and on the middle of the upper platform. The batteries needed to power the system will be located on the lower arms in order to lower the center of mass position. The AS will also support the motors controller card and the motors drives, needed to control the motors of the mass balancing platform. Fig. 4 shows the AS connected to the air bearing but detached from the translational stage. Wiring is not shown in the drawing for clarity reasons.

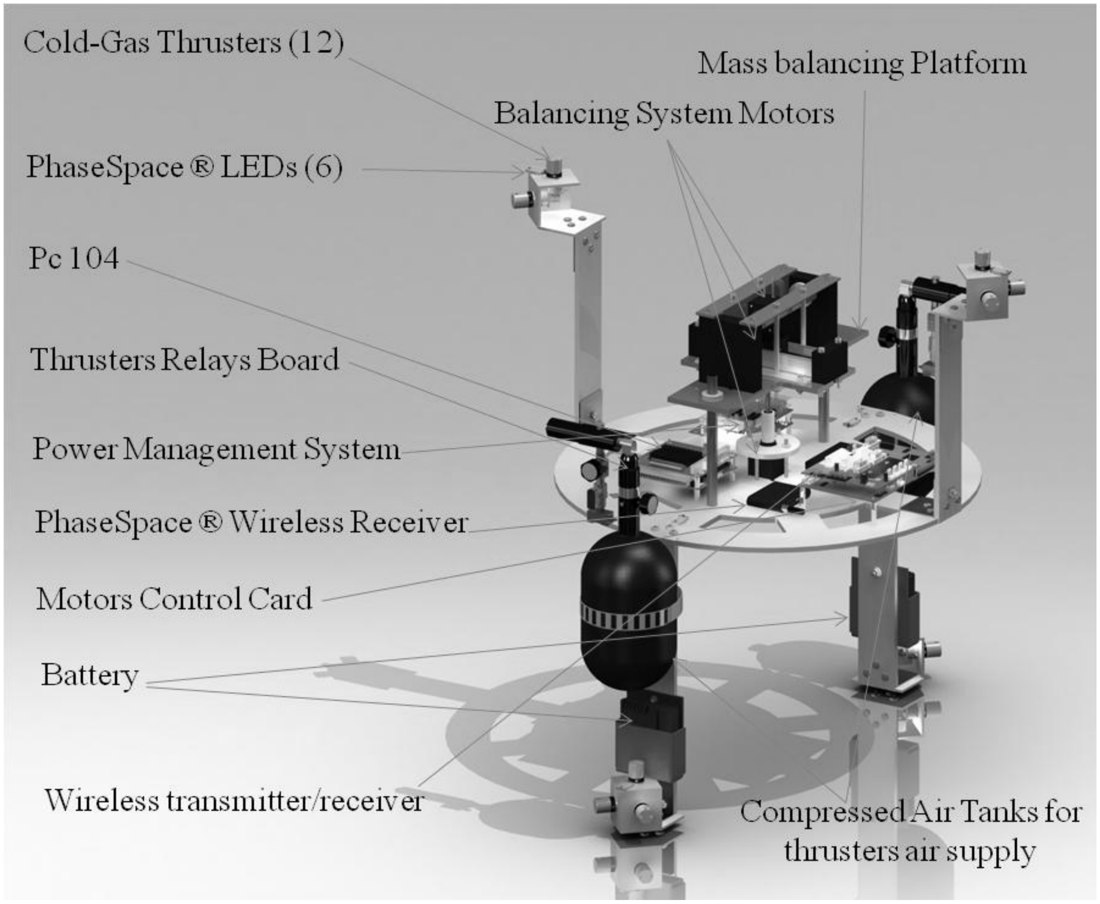

Fig. 4: *Attitude Stage*

D. POWER AND DATA MANAGEMENT SUBSYSTEMS

All the subsystems will rely on 2 Lithium-Ions batteries. These batteries will be connected to a Power Management System from Ocean Server Technology (IBPS: Intelligent Battery and Power System). This system is extremely versatile and will be 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 will provide 5V power to the onboard computer (Advanced Digital Logic ADLS15PC Rev. 1.3) and 12V power to a secondary DC-DC booster converter, which will bring the voltage to 24V. The DC-DC will be connected to a relays module to which all the thrusters will be attached. The output ports of the onboard computer will be connected to the same module. The relays will be activated by the computer signals and will open or close the electrical connections of the thrusters electro-valves, activating the solenoids and switching between the on and off states.

The computer will give 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®. *Fig. 5* represents a scheme of the electrical connections and of the signals in the system.

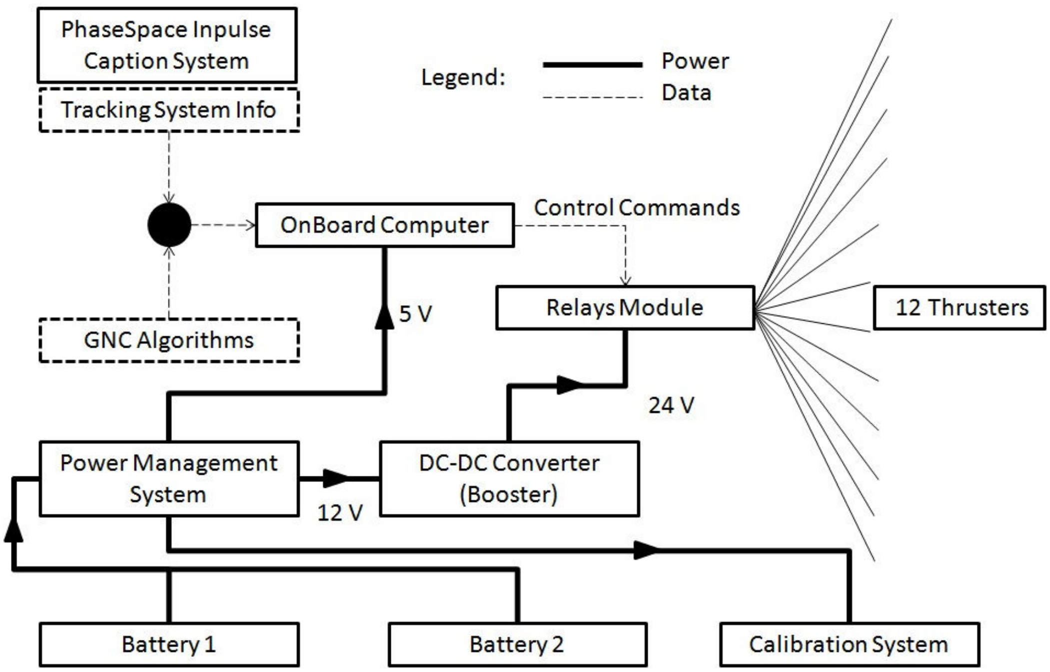

Fig. 5: *Electrical Connections and Signals*

E. PHASESPACE IMPULSE SYSTEM, SOFTWARE AND DATA FLOW

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

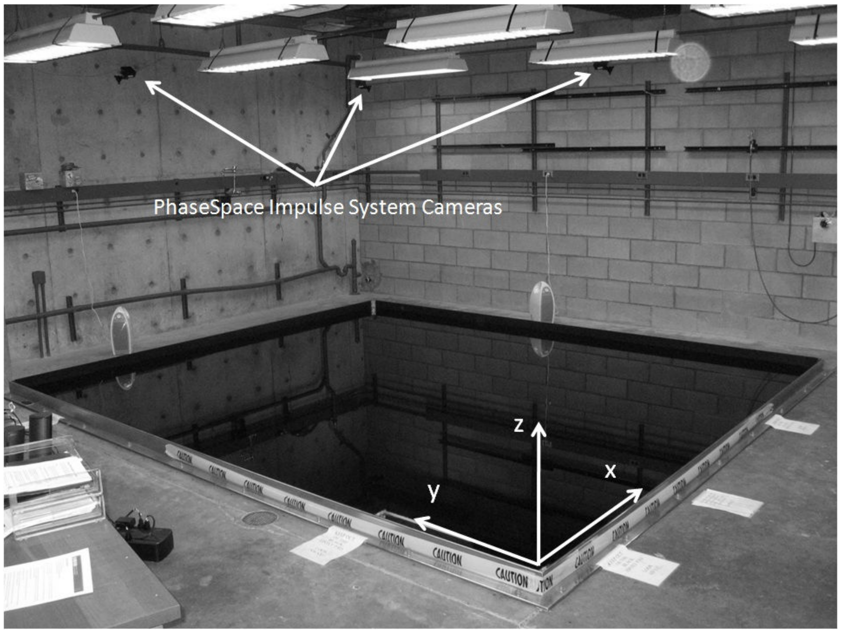

Fig. 6: *ADAMUS Laboratory experimental space*

3. ENVISIONED EXPERIMENTS

The following tests are planned:

1) Calibration system verification, in order to determine the effectiveness and precision of the positioning table for the alignment of center of mass and center of rotation.

2) Mass balancing system calibration, in order to compensate the center of mass movement provoked by the compressed air consumption. The air mass inside each tank will be measured in order to ensure that an identical quantity of air is consumed. The balancing system will be tested to determine the time response and the positioning accuracy.

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.

4. 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 6th DOF being kinetic only.

A calibrating system will allow 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 will constitute an experimental test bed for testing guidance and navigation control algorithms, in order to reduce costs and time-to-launch of autonomous satellite systems. A natural development of this work will be building another platform and test algorithms for formation flight, rendezvous, and docking. Also, attitude stages could be modified in order to have additional operating arms to perform collaborative repairing, refueling, and construction operations. Fig. 7 **represents the current state of the assembly**:

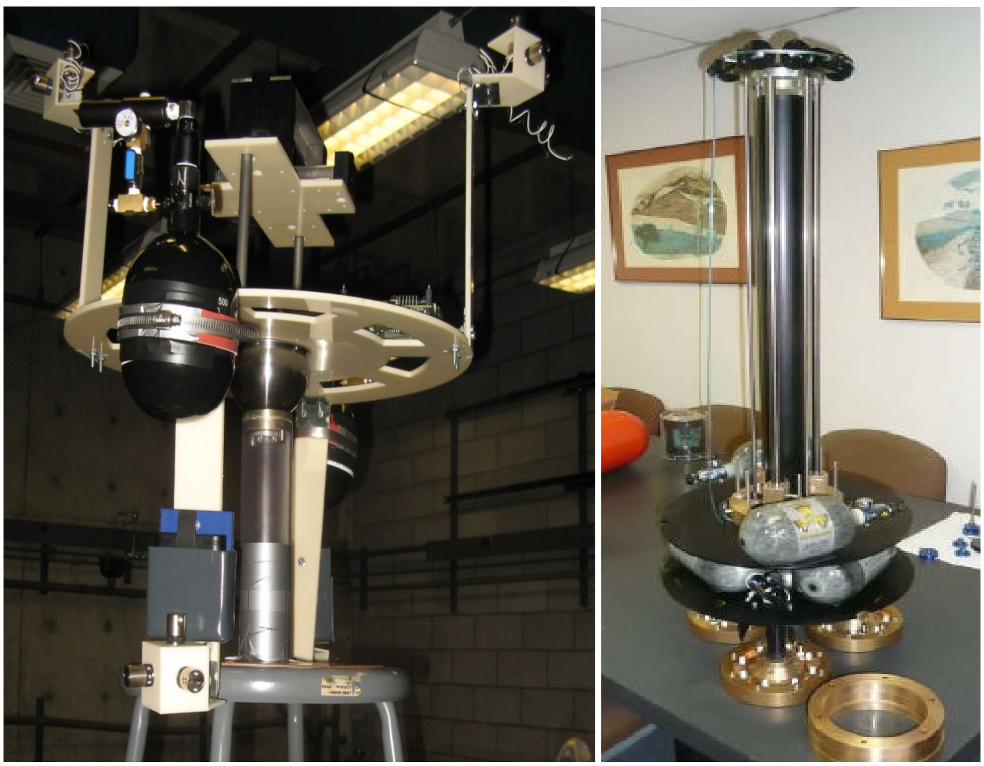

Fig. *7: a) Assembled Attitude Stage b) Partially Assembled Translational Stage*

5. REFERENCES

[1] Schwartz, J.L., Peck, M. P., Hall, C. D., "Historical Review of Spacecraft Simulators", *Journal of Guidance, Control and Dynamics,* Vol. 26, No. 4, July-August 2003

[2] Boning, P., and Dubowsky, S. "An Experimental Study of The Control of Space Robot Teams Assembling Large Flexible Space Structures," *Proceedings of 9th International Symposium on Artificial Intelligence and Robotics in Space (ISAIRS 2008)*, Feb 26-29, 2008, Pasadena, CA.

[3] Romano, M., Friedman, D.A., Shay, T.J., "Laboratory Experimentation of Autonomous Spacecraft Approach and Docking to a Collaborative Target" *Journal of Spacecraft and Rockets*, Vol. 44, No. 1, January–February 2007, doi 10.2514/1.22092

[4] Pond, B., and Sharf, I., "Experimental Demonstration of Flexible Manipulator Trajectory Optimization," *Proceedings of the AIAA Guidance, Navigation, and Control Conference and Exhibit*, no. 99-4302, (Portland, Oregon), pp. 1869-1876, August 9-11-1999.

[5] Meyer, J.L., Harrington, W.B., Agrawal, B.N., and Song, G., "Application of piezoceramics to vibration suppression of a spacecraft exible appendage," in *Proceedings of the AIAA Guidance, Navigation and Control Conference*, no. 96-3761, (San Diego, California), July 29-31-1996.

[6] Choset, H., and Kortenkamp, D., "Path Planning and Control for Free-Flying Inspection Robot in Space," *Journal of Aerospace Engineering*, vol. 12, pp. 74-81, April 1999

[7] Toda, Y., Iwata, T., Machida, K., Otuka, A., Toriu, H., Shinomiya, Y., Fukuda, Y., Asakura, M., and Matuhira, N., "Development of Free-Flying Space Telerobot, Ground Experiments on Two-Dimensional Flat Test Bed," in *Proceedings of the AIAA Guidance, Navigation and Control Conference*, no. 92-4308, (Hilton Head Island, South Carolina), pp. 33-39, August 10-12-1992.

[8] Corazzini, T., Robertson, A., Adams, J.C., Hassibi, A., and How, J.P., "Experimental Demonstration of GPS as a Relative Sensor for Formation Flying Spacecraft", *Navigation: Journal of the Institute of Navigation*, vol. 45, no. 3, pp.195-207, 1996

[9] Hilstad, M.O., "*A Multi-Vehicle Testbed and Interface Framework for the Development and Verication of Separated Spacecraft Control Algorithms*", Master of Science, Massachusetts Institute of Technology, Cambridge, MA, June 2002.

[10] Bevilacqua, R., Hall, J.S., Horning, J., Romano, M., "Ad HocWireless Networking and Shared Computation for Autonomous Multirobot Systems" *Journal of Aerospace Computing, Information, and Communication*, vol. 6, May 2009, doi 10.2514/1.40734

[11] Agrawal, B. and Rasmussen, R. E., "Air Bearing Based Satellite Attitude Dynamics Simulator for Control Software Research and Development", in *Proceedings of the SPIE Conference on Technologies for Synthetic Environments: Hardware-in-the-Loop Testing VI*, (Orlando, Florida), pp. 204-214, April 16-18- 2001.

[12] Kim, B., Velenis, E., Kriengsiri, P., and Tsiotras, P., "A Spacecraft Simulator for Research and Education," in *Proceedings of the AIAA-AAS Guidance, Dynamics and Control Conference*, no. 01-367, pp. 897-914, 2001.

[13] Cho, S., Shen, J., McClamroch, N.H., and Bernstein, D.S., "Mathematical Models for the Triaxial Attitude Control Testbed", in *Mathematical and Computer Modelling of Dynamical Systems*, Vol. 9, Issue 2, pages 165 – 192, June 2003, doi 10.1076/mcmd.9.2.165.16520

[14] Cho, S., and McClamroch, N.H., "Feedback Control of Triaxial Attitude Control Testbed Actuated by Two Proof Mass Devices," in *Proceedings of the 41st IEEE Conference on Decision and Control*, (Las Vegas, Nevada), pp. 498-503, December 2002

[15] Roe, F.D., Mitchell, D.W., Linner, B.M., and Kelley, D.L., "Simulation Techniques for Avionics Systems-An Introduction to a World Class Facility", in *Proceedings of the AIAA Flight Simulation Technologies Conference*, no. 96-3535, (San Diego, California), pp. 535-543, July 29-31, 1996.

[16] Cho, D., Jung, D. and Tsiotras, P., "A 5-dof Experimental Platform for Spacecraft Rendezvous and Docking," *Infotech at Aerospace Conference*, Seattle, WA, April 6–9, 2009, AIAA Paper 2009-1869

[17] Jian, X., Gang, B., QinJun, Y., Jun, L., "Design and Development of a 5-DOF Air-Bearing Spacecraft Simulator", *in Proceedings of the International Asia Conference on Informatics and Control, Automation and Robotics*, pp. 126-130, 2009

[18] Ledebuhr, A., Ng, L., Jones, M., Wilson, B., Gaughan, R., Breitfeller, E., Taylor, W., Robinson, J., Antelman, D.R., and Neilsen D., "Micro-Satellite Ground Test Vehicle for Proximity and Docking Operations Development," *in Proceedings of the IEEE Aerospace Conference*, (Big Sky, Montana), pp. 2493-2504, March 10-17, 2001.

[19] Nolet, S., Kong, E., Miller, D.W., "Ground and Flight Testing of Multiple Spacecraft Control on SPHERES During Close Proximity Operations*" in Journal of Spacecraft and Rockets*, Vol. 46, No. 6, November - December. 2009

[20] Kong, M.C., et al., "SPHERES as a Formation Flight Algorithm Development and Validation Testbed: Current Progress and Beyond" *in 2nd International Symposium on Formation Flying Missions and Technologies*, Washington, DC., September 14-16, 2004

[21] Regehr, M.W., Acikmese, A.B., Ahmed, A., Aung, M., Clark, K.C., MacNeal, P., Shields, J., Singh, G., Bailey, R.; Bushnell, C., Hicke, A., Lytle, B., Rasmussen, R.E., "*The formation Control Testbed*", in *IEEE Proceedings of Aerospace Conference*, March 6-13 2004.

[22] Kim, J.J., Agrawal, B.N., "System Identification and Automatic Mass Balancing of Ground-Based Three-Axis Spacecraft Simulator", *in AIAA Guidance, Navigation, and Control Conference and Exhibit,* 21-24 August 2006, Keystone, Colorado

[23] Kim, J.J., Agrawal, B.N., "Automatic Mass Balancing of Air-Bearing-Based Three-Axis Rotational Spacecraft Simulator", *in Journal of Guidance Control and Dynamic,* Vol. 32, No. 3, May–June 2009

[24] Curti, F., Romano, M., Bevilacqua R., "Lyapunov-Based Thrusters's Selection for Spacecraft Control: Analysis and Experimentation", in *Journal of Guidance Control and Dynamics*, Vol 33, NO. 4, July-August 2010, pp 1143-1160, doi 10.1016/j.actaastro.2010.08.012