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LOW-COST SCIENCE LABORATORY IN MICROGRAVITY USING A CUBESAT CENTRIFUGE FRAMEWORK

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Gravity is known to play a critical part in many physical, biological and technological processes that we take for granted on Earth. Long duration human spaceflight has shown the critical importance and dangers to human life, particularly with the irreversible loss of bone calcium and the challenges with growing food and plant-life in microgravity. Long duration human spaceflight can be made feasible by introducing artificial gravity. However previous concepts contained a spinning spacecraft 'attached' to a stationary one such as the ISS which imparts high complexity and cost. The focus of this paper is a scalable, 6U, CubeSat with the ability to deploy and extends its pair of experiment chambers a distance of up to 2.5 meter using, spinning at up to19 rev/min to generate one g. Our current work focuses on investigating the concept feasibility, system design, deployment mechanism and power.

I. INTRODUCTION

Human exploration and permanent habitation of space, nearby planets and the Moon will require overcoming the limits of microgravity and low-gravity. Metallurgy, manufacturing, and various fundamental chemical and biological processes to support life all rely on gravity. Adapting these processes to microgravity or low-gravity is a daunting challenge.

Crew health and food production is most critical for any long-term habitation and travel in these environments. Studies have shown mixed results with certain plants and animals able to survive under microgravity, while others die off [1-3]. Long duration human spaceflight experiments have shown irreversible losses in bone calcium that mimics accelerated aging [4-5]. Under microgravity, certain diseases increase in virulence [6]. This coupled with weakening of the human immune system [7] will pose significant hurdles in missions with large number of crew. Another challenge is the severe discomfort, particularly space - sickness faced by astronauts during the first few days transitioning from earth gravity to microgravity. Micro-gravity also weakens muscles and this requires extensive exercise, thus reducing overall time available to perform productive tasks. With all these challenges, a better solution is required.

One promising solution is to develop a centrifuge in space that produces artificial gravity. Conventional centrifuge concepts have relied on a spinning system attached to a stationary spacecraft. This poses significant technical challenges particularly isolating the spinning section from the stationary spacecraft in addition to correcting for perturbations induced by the spinning centrifuge. In this paper, we propose a simplified, low-cost, 10 kg, 6U (60 cm x 10 cm x 10 cm) CubeSat centrifuge laboratory, where the entire spacecraft spins making the approach simple. The centrifuge would operate up to 1 g. The satellite would be composed of Commercial off the Shelf (COTS) components except for the custom-designed deployment mechanism and flywheel. The laboratory will be deployed in space, extending in length to 5 m using one of three proposed mechanisms described in Section III.

A central chamber would house the main spacecraft computer, communications antenna and attitude system. The two side chambers would contain 3,000 cm^3 of payload volume for experiments. In the following sections, we present background on centrifuges (Section II), description of the spacecraft design (Section III), design and analysis of critical mechanisms, followed by conclusions and future work (Section VI).

II. BACKGROUND

Space centrifuges are not new. Centrifuge concepts from 1950s and 1960s had influenced many in proposing spinning space colonies (Figure 1). More practical attempts at developing centrifuges include the Centrifuge Accommodation Module (CAM) [8].

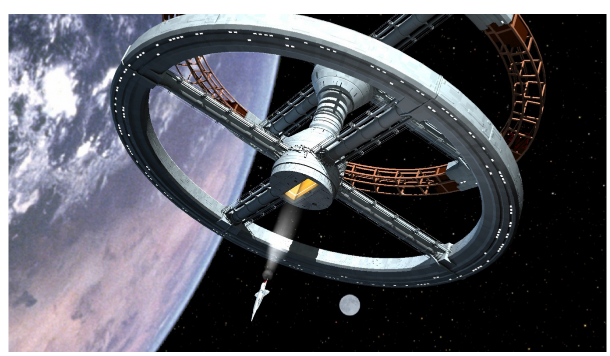

Figure 1: Artist Concept of a Spinning Space Colony (courtesy of Mark Tims).

It was developed by JAXA but was to be operated by NASA. The CAM would be used to conduct various biological and life-science experiments, provide between 0.01g to 2 g. Importantly, the chamber could operate at two different artificial g. A more ambitious centrifuge concept was proposed from NASA JSC in 2011 [9]. It would consist of an inflatable centrifuge attached to the ISS. The attached centrifuge would be the sleeping module for the ISS crew. The centrifuge was intended to be a low-cost demonstration for a multi-mission manned space exploration vehicle, NAUTILUS-X that would be placed at L1 as staging ground/living quarters for journey to Mars and beyond. Other implementations include a small table-top centrifuge for microbiology experiments, with a flight scheduled to the ISS in 2014-2015 timeframe [10].

Our work starts with the Asteroid Origins Satellite (AOSAT) [11-12] a low-speed centrifuge system designed for use on orbit and intended to simulate asteroid few hundred meters in diameter. The design consists of a 3U CubeSat, 30 cm x 10 cm x 10 cm structure composed of two 1000 cm^3 chambers on each end containing crushed meteorite (Figure 2). As the spacecraft spins at rates of 1 rev/min it produces a centripetal force, resulting in the formation of a simulated asteroid surface with a 0.01g. The advantage with this approach is its simplicity. The entire spacecrafts spins and there is no need to keep any component within the spacecraft stationary. The spacecraft will make use of a motor to spin on one of its axis while magneto-torquers will be used to stabilize the spacecraft in the other two axes.

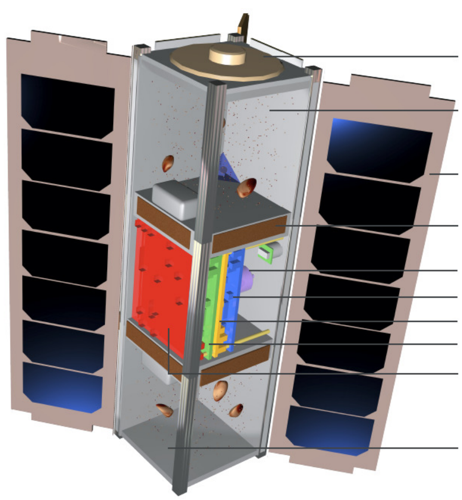

Figure 2: Asteroid Origins Satellite (AOSAT).

The spacecraft doesn't require high pointing accuracy and hence this avoids the need for 3-axis reaction wheels. However, there are some important limitations. Because the centrifuge radius is 15 cm, a significant difference in simulated gravity will be experienced throughout the science chambers. However because the experiments will be conducted at 0.01g this will have limited effect. The proposed approach is insufficient for experiments that need to be conducted at 0.5 to 1 g. For us to overcome this challenge requires extending the end chambers so as to minimize variance in simulated gravity within the chambers.

This brings us to the proposed 6U CubeSat concept. A 6U configuration has enough volume to stow a deployment mechanism to extend 2.5 meters on each side, together with tripling the volume available for science and technology experiments compared to AOSAT. The principle challenge lies in the development of an extension mechanism.

Space missions due to their restrictive mass and volume constraints have long benefitted from various deployment mechanisms. These include the use of collapsible helical structures, inflatables, booms and truss structures. These have been used for a variety of purposes including deploying communication antennas, instruments and solar arrays. One approach that requires minimal stowed volume is using inflatables. Inflatables have been suggested and demonstrated for parabolic communication antennas [13-15]. They are being considered for use as space structures [16]. Methods such as origami folding techniques [17] open new possibilities for inflatables particularly for small space missions [18]. Other uses being proposed are sun shields for telescopes [19] or for solar sails [20] on the proposed Sunjammer spacecraft.

Another approach is to use helical structures. Helical structures are typically used to deploy instrument booms [21]. They store strain energy that is released into the designed helical shape. Scissor mechanisms are another option [22]. Cylindrical scissor mechanisms are of particular interest because they can be compacted and bring excellent rigidity.

Another viable option is the STEM or carpenter tape reinforced (CTR) boom. These devices use a roll of support material that is extended flat and curls to form a cylindrical shape from the tip to the base, much like a tape measure [23] Such techniques make them ideal for CubeSat applications. STEM has been used both on the Hubble Telescope and Mars Pathfinder mission but have yet to be applied on CubeSats. These three options show some promising pathways for the development of a general purpose centrifuge laboratory.

III. SPACECRAFT DESIGN

The proposed 6U CubeSat will be designed for operation in Low Earth Orbit (LEO) or a Sun Synchronous Orbit. As described earlier, the spacecraft will be 60 cm long in its stowed configuration and extends to 5 m once deployed (Figure 3, Table 1). The spacecraft in effect consists of 3 compartments with each compartment connected by a 2.5 m extension.
This design was selected to reduce complexity of the deployment mechanism. Use of long wire to transmit power and communicate between the central and end-chambers, while simplifying the power system could cause tangling of the deployment mechanism.

System Specifications	
System:	6U CubeSat Centrifuge spinning up to 19 rev/min
Simulates:	10^{-3} to 1 g
Instruments:	Force-Moment Sensor, IMU, Stereo Cameras, User customized instruments
Mass (Total):	10.2 kg
Payload Mass:	2.5 kg
Volume:	6,000 cm^3
Payload Volume:	3,000 cm^3
Payload Chambers:	2
Payload Power:	40 W (peak), 6 W (avg.)
Payload Battery:	30 Whr (per chamber)
Main Chamber Power:	20 W (Peak), 6 W (avg.)
Communications:	S-band (2 Mbps), UHF (256 Kbps)
Life:	1-4 years
	LEO or Sun Synchronous

Table 1: CubeSat Centrifuge Laboratory Specifications.

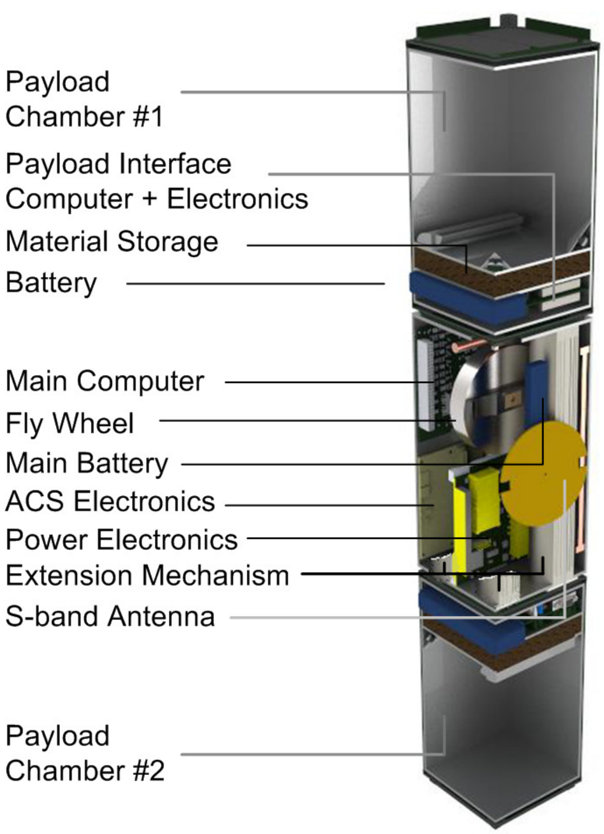

Figure 3: CubeSat Centrifuge Laboratory Concept.

The spacecraft mass budget is shown Table 2. The central chamber contains the main computer (Tyvak Intrepid, ARM-9 system) that includes watchdog circuitry and power control, a Tyvak UHF communications daughterboard, attitude control and an S-band communications system (Figure 3). In addition, the central chamber contains a motor-flywheel assembly for spinning the spacecraft. Power for the central chamber will be supplied by the body mounted photovoltaics that will charge a 40 Whr lithium ion battery.

Subsystem	Mass (kg)
Structures	0.78
Computer	0.24
Electronics	0.16
Power	1.15
Deployment	2.66
ACDS	0.76
Misc.	0.28
Payload × 2	2.50
Total	8.5
Total + Margin (20 %)	10.2

Table 2: System Mass Budget.

With this distributed design, the end chambers contain their own computers consisting of the Tyvak Intrepid board that includes power control circuitry and a separate short range WiFi communication system. The end chambers would be customized to handle custom payloads that are controlled using the Tyvak Intrepid computer system. The end chambers much like the central chamber will produce their own power using body mounted PV that will charge 30 Whr lithium ion batteries. Our design envisions data acquisition using one or more cameras and other sensors relevant for a range of experiments. These instruments can communicate with the computer using SPI, I2C, USB and through a serial connection. The spacecraft will use s-band for primary communications and will have a maximum data throughput of 2 MBps.

IV. DEPLOYMENT SUBSYTEM

A critical component in the design of the centrifuge laboratory is the deployment mechanism. The deployment mechanism will be used to increase the effective length of spacecraft to minimize angular velocity required to achieve 1 g at the end chambers. Too high an angular (spin) velocity can cause perturbation that result in the spacecraft tumbling out of control, loss of communication and even structural damage to components. Our studies show that the best deployment mechanisms are limited to extension of 13 times their stowed length. This gives us maximum radial length of 2.5 m. Based on these results, we compared the required angular velocity (Figure 4) to achieve 1g. The results suggest operating at 19 RPM for radial length of 2.5 m (Figure 5).

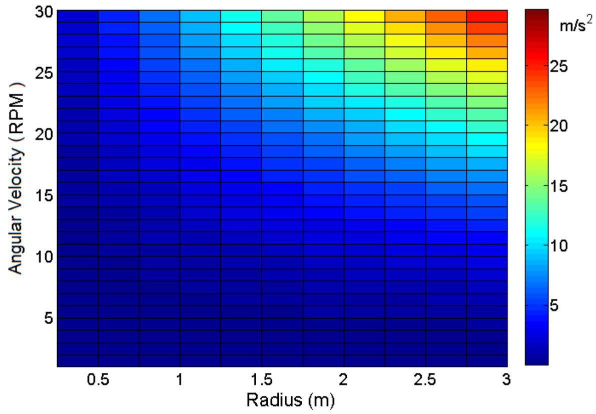

Figure 4: Effect of Centrifuge Radius and Angular Velocity on Centripetal Acceleration.

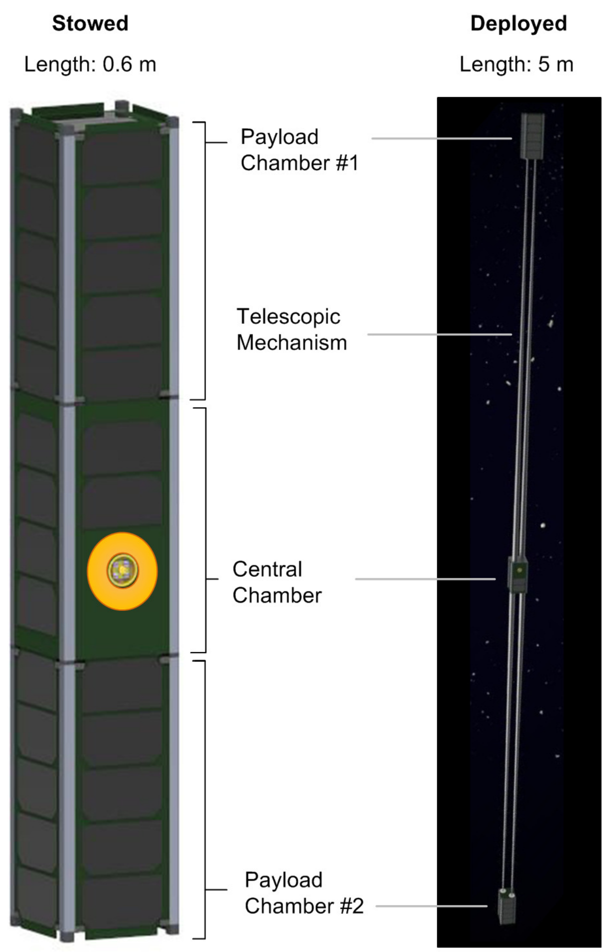

Figure 5: CubeSat Centrifuge Laboratory in its Stowed and Deployed Configuration.

We consider three different deployment mechanisms that would extend the end chambers up to 2.5 m length (see Table 3, Figure 6). One is a scissor mechanism that would be actuated by a spring or linear actuator. One of the main challenges is to make the scissor mechanism reliable. Such mechanisms have never been used on small spacecrafts. One of the problems with mechanical mechanisms is cold-welding, that is where metals surfaces bond together due to the combination of vacuum and cold temperatures for extended time. However, in our design, the spacecraft will be quickly deployed after launch. In addition, with an appropriate surface coating, this risk will be mitigated [24]. The primary concern with the scissor mechanism is that if the spring used to power the expansion fails then there is nothing else available except adding a second spring or powered actuator which adds mass and complexity.

	Inflatable	Telescopic Mechanism	Scissor Mechanism
Mass	0.3 kg	2.7 kg	0.3 kg
Stowage Volume	0.3 L	0.6 L	0.2 L
Energy (Electricity)	0.1 Whr	NA	NA
Power Source	Chemical – NaN_3	Spring, Spacecraft spin	Spring, linear actuator
Deployment Time	2-6 hrs (rigid)	0.5 hrs	0.15 hrs
Max Length (Possible)	1 m	2.5 m	2.3 m
Failure Mode	Puncture, Brittle	Jamming	Jamming

Table 3: Comparison of CubeSat Centrifuge Deployment Mechanisms.

A second option is the use of a telescopic structure, with helical springs. Each end chambers would be attached to two of these telescopic structures to provide enough rigidity and for redundancy. The telescopic structure would be composed of hollow, Al-7075 T651 cylinders and be 1 mm thick. Each telescope segment would be 0.25 m. The structure would be deployed using helical springs that would be unlatched. During deployment, the spacecraft will also be spinning in effect dampening out the oscillations from the spring deployment. In addition the spacecraft could be spun up to produce enough centripetal force to expand the mechanism in case the helical springs are jammed.

A third option is using inflatables. The system would deployed, beginning with a chemical reaction that would heat a solid powder, Sodium Azide (NaN_3) and produce Nitrogen (N_2) gas. The bladder would be packaged into bellows with equal height and width. Once inflated, the bladder would form a cylinder (Figure 6, top). The cylinder radius would be 1/3 of the bellow width. After the bladder has fully inflated, it would undergo a UV/heat curing process that requires exposure to the sun. At the end of the curing, the inflatable would turn into a glass like structure. Thin glass structures are typically brittle and under small deflection loads can experience failure. Another concern is the problem of micrometeorites or debris puncturing the glass structure.

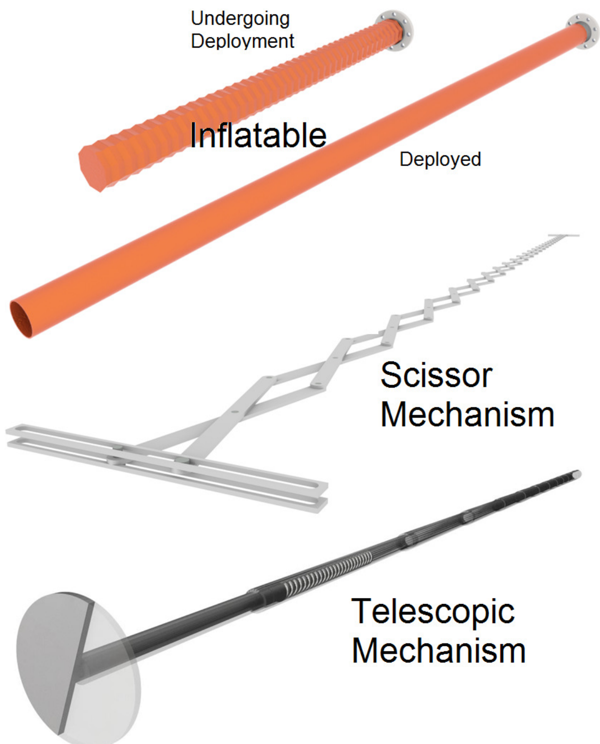

Figure 6: Deployment Mechanisms Considered for CubeSat Centrifuge.

Out of these options, our preference is for the telescopic structure, because it offers excellent stowage density and is intrinsically robust, using a compressed helical spring. In case of mechanism jamming, it can rely on the centripetal force caused by the spacecraft spin for deployment. Considering the mechanism will be actuated right after launch, this will minimize concerns of cold-welding between metal surfaces.

We performed structural analysis of our telescopic mechanism. In our analysis, we assumed the telescopic structure was a tapered design. The telescopic boom because of its hollow cylindrical shape is expected to have enough strength to withstand a maximum tensile load of 5 kg $\times$ 9.8 m/s^2 = 49 N. However the concern is from a lateral load that imposes deflection on the structure (Table 4).

Analysis	Axial (49 N)	Lateral Load (5 N)
Max Stress		
FEM	0.31 MPa	8 MPa
Analytical	0.31 MPa	14 MPa
Max Displacement		
FEM	< 0.001 m	0.02 m
Analytical	< 0.001 m	0.04 m

Table 4: Structural Analysis of the Telescopic Mechanism

A 5 N lateral load approximates the lateral load experienced when spinning up a spacecraft to 19 RPM over 1 minute and then maintaining a constant angular velocity. The results suggest that we have a factor of safety in excess of 10 with respect to the relevant yield strength parameters for Al-7075 T651. These results suggest the proposed design can comfortably handle the expected loads.

V. ATTITUDE CONTROL

Apart from the deployment mechanism, the proposed spacecraft needs to spin at a constant angular velocity of up to 19 RPM. Three options were considered (see Table 5). This includes a flywheel (Figure 7), cold-gas thrusters and chemical propulsion. Out of these three options, flywheels are the most mature and reliable technologies for inducing spin in satellites. Cold-gas and chemical propulsion can provide higher angular acceleration for lower mass, but they need to be located at the end chambers. This reduces the available volume for the payload.

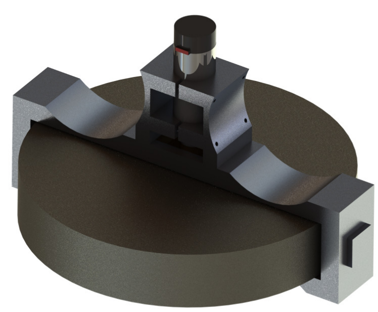

Figure 7: Proposed Flywheel Assembly Design

A second major challenge with cold gas and chemical propulsion is the finite volume of propellant available. A propellant based system may be sufficient for a 3-6 month mission where there are periodic start-stop cycles. However, it will not be sufficient for longer missions particularly in a sun synchronous orbit. An additional challenge with the cold gas and chemical propulsion is the risk of uncontrolled tumbling in the event of propellant leakage. Combustive propulsion also poses additional challenges, particularly with the limited launch opportunities available.

	Motor-Flywheel	Cold Gas	Chemical Propulsion
Mass	High	Medium	Low
Volume	Medium	High	Low
Location	Centre	Outer Edges	Outer Edges
Failure Scenario	Vibration at high ω	Tanks depleted	Tanks Depleted
Disadvantage	Periodic Momentum Dumping	Limited Life	Limited Life, Combustive
Advantage	Mature Technology	Quick Start-up	Very Quick Start-up

Table 5: Comparison of Centrifuge Attitude Control Options

Using a motor-flywheel solution, our studies show the spacecraft will require 0.3 Whr to attain the maximum angular velocity (estimated power losses totalling 50 %). Magne-torquers embedded in to the PV panels and in the main body will be used to stabilize the spacecraft in the other axes. Magneto-torquers will also be used for periodic momentum dumping from the flywheel. The motor selected is a Maxxon EC 10, 8 Watt, 10 mm brushless motor. Our studies show that feasible cost-effective solutions are possible for this proposed general purpose CubeSat Centrifuge laboratory.

VI. CONCLUSIONS AND FUTURE WORK

This paper presents a general purpose, low-cost CubeSat Centrifuge laboratory concept that can achieve 1 g. Our studies show that the spacecraft can be constructed entirely of Commercial off the Shelf (COTS) components except for the deployment mechanism and flywheel. We analysed various options for a deployment mechanism and find a spring-loaded telescopic structure to be the most viable solution for the given mass and volume constraints. Using this mechanism, the spacecraft will extend to 5 m in length and spin at 19 RPM to achieve the desired 1 g. Structural analysis of the proposed mechanism under expected loads suggest excellent margins of safety. Further work is required in analysing the reliability of the deployment mechanism. This will proceed with construction of a proof-of-concept system that will be tested in the laboratory.

VII. ACKNOWLEDGMENTS

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VIII. REFERENCES

1. G. Perbal, "Plant Development in Space or in Simulated Microgravity," *Plant Biotech. 2002 & Beyond 2003*, pp 351-357
2. S. A. Wolff et al., “Effects of the Extra-terrestrial Environment on Plants”, *Life 2014*, 4(2), pp. 189-204
3. S. Wakayama et al., "Detrimental Effects of Microgravity on Mouse Pre-implantation Development In Vitro," *PLoS ONE* 4(8): e6753.
4. P. Piscitelli et al., "Microgravity-induced osteoporosis: a challenge for the future of space programs," *Bone Abstracts* (2013).
5. M. F. Holick, "Microgravity-induced bone lose will it limit human space exploration?," *The Lancet*, 355(9215), 2000, pp. 1569 – 1570.
6. C. Nickerson et al., “Microgravity as a Novel Environmental Signal Affecting Salmonella enterica Serovar Typhimurium Virulence,“ *Infection and Immunity*, 68(6), 2000, pp. 3147-3152.
7. G. Sonnenfeld, "Space flight, microgravity, stress, and immune responses," *Adv. Space Res.* 23(12), 199, pp. 1945-53.
8. C. Tsai et al., “Centrifuge Accommodation Module Cabin Air Temperature and Humidity Control Analysis,” *Proc. Int. Conf. on Env. Sys*, 2005.
9. M. Holderman and E. Henderson, "Nautilus-X Multi-Mission Space Exploration Vehicle," NASA Johnson Space Centre, Concept Presentation, pp. 1-28, 2011.
10. Astrium-Nanoracks, “Astrium to provide centrifuge for gravitational research in space through NanoRacks, LLC for NASA's U.S. National Laboratory on the ISS,” 2011.
11. E. Asphaug and J. Thangavelautham, “Asteroid Regolith Mechanics and Primary Accretion Experiments in a CubeSat,” *Proc. of Lunar and Planetary Science Conference*, 2013.

12. V. Perera, N. Movshovitz,E. Asphaug, J. Thangavelautham, “Material Studies of Asteroid Regolith and Accretion Using a Low-Cost CubeSat Laboratory,” Proc. of 65th *International Astronautical Congress*, pp. 1-6, 2014
13. P. Cadogan, S. Scarborough. "Rigidizable materials for use in gossamer space inflatable structures." *AIAA paper* 1417, 2001.
14. R.E. Freeland, et al. "Large inflatable deployable antenna flight experiment results." *Acta Astronautica* 41(4), 1997, pp. 267-277.
15. A. Babuscia, et al. "Inflatable antenna for cubesats: Motivation for development and antenna design." *Acta Astronautica* 91, 2013, pp. 322-332.
16. M. Schenk, S.G. Kerr, A. Smyth, S.D. Guest, "Inflatable Cylinders for Deployable Space Structures," Proc. of Transformables, pp. 1-6, 2013.
17. S. Zirbel, et al. "Accommodating thickness in origami-based deployable arrays." *Journal of Mechanical Design* 135(11), 2013, pp. 1110051-11.
18. M. Ravichandran, J. Thangavelautham, "CubeSat Based Inflatable Antennas and Structures for Interplanetary Comms. and Tracking," *Proc. of the Interplanetary Small Sat. Conf*., pp. 1-8 2014.
19. W. Lee, S. Pellegrino, and R. Danner. "Origami Sunshield Concepts for Space Telescopes." *54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, AIAA, 2013.
20. J. Heiligers, et al. "Sunjammer: Preliminary End-to-End Mission Design." *AIAA/AAS Astrodynamics Specialist Conference*, pp.1-8, August 2014.
21. S. Yuki, et al. "Extensible Flexible Optical System for Nano-scale Remote Sensing Satellite “PRISM”." *Tranaction. of Japan Soc. for Aero. and Space Sciences, Space Tech.* Japan, 2009, pp.13-18.
22. M. Feray, K. Korkmaz, and Y. Akgün. "A review of planar scissor structural mechanisms: geometric principles and design methods." *Architectural Science Review* 54(3), 2011, pp. 246-257.
23. D. Bruce, et al. "Big Deployables in Small Satellites," *Proc. of 28th AIAA/USU Small Sat. Conference*, pp. 1-8, 2014.
24. A. Merstallinger et al., "Assessment of Cold Welding Between Separable Contact Surfaces Due to Impact and Fretting Under Vacuum," *ESTEC Technical Report*, ESA, pp. 1-57, 2009.