Inflatable Antenna for CubeSat: A New Spherical Design for Increased X-band Gain

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Abstract—**Interplanetary[1] CubeSats and small satellites have potential to provide means to explore space and to perform science in a more affordable way. As the goals for these spacecraft become more ambitious in space exploration, the communication systems currently implemented will need to be improved to support those missions. One of the bottlenecks is the antennas' size, due to the close relation between antenna gain and dimensions. Hence, a possible solution is to develop inflatable antennas which can be packaged efficiently, occupying a small amount of space, and they can provide, once deployed, large dish dimension and correspondent gain. A prototype of a 1 m inflatable antenna for X-Band has been developed in a joint effort between JPL and ASU. After initial photogrammetry tests and radiation tests, it was discovered that the design was not able to meet the required gain. As a result, a new design, based on a spherical inflatable membrane, is proposed. This new design will allow reaching a more stable inflatable surface, hence improving the electromagnetic performance. This paper will detail the principle challenges in developing this new antenna focusing on: design, EM analysis, fabrication and tests.**

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1. INTRODUCTION

Interplanetary Cubesats and small satellites are now becoming a new way to explore space. The term "Interplanetary CubeSats" indicates now a set of missions which aim to explore deep space using CubeSats or Small Satellites bodies. Example of these missions include: INSPIRE [1], MarCO [2], Lunar Flashlight [3], NEASCout [4], LunarIceCube [5], LunaH-Map [6], CusPP [7].

As CubeSats are becoming a way to explore deep space in a more affordable way than traditional spacecraft, new needs emerge. Specifically, interplanetary CubeSats need telecommunication systems that can sustain a severely increased path loss. In fact, one of the biggest issues in interplanetary exploration with CubeSats is that free space loss increases with the square of the distance. Different communication technologies are in development to approach this problem and to support interplanetary exploration with CubeSats and small satellites. Examples are: the IRIS radio [8], reflectarray antennas [9], deployable antennas [10] [11], CDMA techniques [12], optical communication [2], MSPA (Multiple Spacecraft Per Antenna) [13], and the inflatable antenna [14] [15] [16] [17] [18].

Among the previously mentioned technologies, the inflatable antenna is an innovative technology as it provides an extremely high stowing efficiency (20: 1), low mass (<0.5 Kg), scalability and inflation with sublimating powder. The first inflatable antenna for CubeSats was designed at the S-Band [14] [15]. Recently, an effort to design an X-Band prototype started at JPL [16] [17] [18] with the motivation of making this technology compatible with radio and DSN developments. As part of this current effort, a new prototype was designed, manufactured and tested. Initial tests revealed

[1] Part of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

however that a redesign of the structure and of the feed was needed to achieve high gain. This paper describes a new circular design for the inflatable antenna.

The paper is organized as follows: Section 2 describes the initial inflatable antenna design and presents the new spherical design; Section 3 presents the EM analysis used to determine the optimal reflector size as well as the feed displacement; Section 4 describes a possible design for the deployment system; Section 5 presents a rigidization experiments performed using UV curing on the entire surface of the antenna; Section 6 describes the dynamic test performed on the antenna; Section 7 provides a summary and future works.

2. SPHERICAL DESIGN

The original design for the inflatable antenna is described in [18]. It is designed as a parabolic dish reflector made of one side metalized Mylar, one side clear Mylar and a patch antenna as the feed. The original configuration had a supporting Mylar cone and a parabolic designed reflector. The fundamental inflation concept for this reflector was the idea of using the sublimating powder to inflate the reflector into a parabolic shape. However, many experiments with photogrammetry have shown [18] that every time the membrane is inflate, the final shapes tends to strongly deviate from a parabola. This is because the gas tends to inflate the structure into a sphere. As a result of these findings a new design was conceived.

In this new design the inflatable antenna is basically a sphere in which only a portion of it is reflective, while the rest is transparent. In this way, when inflated, the membrane will tend to naturally reach a spherical shape. Challenges of this new design are however mostly driven by three aspects:

1. Feed placement: the change of the design from a parabolic to a spherical shape implies also that in order to obtain the best illumination, the feed needs to be placed inside the reflector. As a result, an additional support is needed and it had to be designed inside the membrane. The support can be seen in Figure 1.

2. Reflector size: given that the membrane is 1 m in diameter and the reflector side is only a subset of the circular shape, the size of the reflector is reduced from the original 1 m (as in [18]). The next section describes an analysis that was performed to look at two possible values of the reflector size which ended up being 71.3 cm in diameter. It is worth noticing that despite the smaller size, the projected peak gain of the antenna is still very high (more than 32 dBi) due to the location of the feed.

3. Manufacturing: this antenna design is definitely more challenging for what concerns the manufacturing with respect to the previous design. The circular shape will need to be cut out of different portions of Mylar and the support for the patch antenna will also need to be accommodated. More pieces of Mylar bring inevitably more seams which can cause more losses. A new photogrammetry test will be needed to assess the quality of the surface

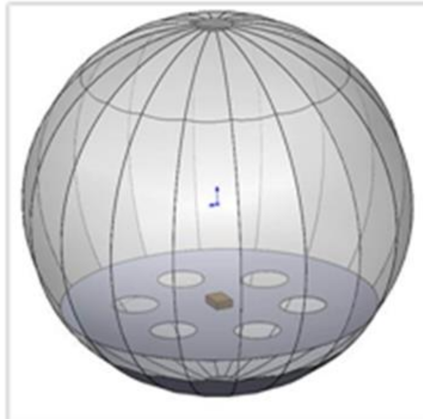

Figure 1: New circular concept design for the inflatable antenna. The CubeSat structure is mounted on the opposite side of the reflector which is on the bottom of the sphere.

The next section discusses the results of the EM analysis for the feed design and placement.

3. FEED REDESIGN AND ANALYSIS

A single patch was selected as the feed for the inflatable reflector antenna. A patch array was considered to correct for the reflector's non-parabolic shape, however the tolerance on the membrane's radius is a significant portion of a wavelength making it impossible to design an array. The selected patch is a single RHCP antenna with a peak gain of 7.16 dBi.

Two reflector-feed configurations were considered and evaluated with TICRA GRASP. The first design prioritized gain maximization. Figure 2 below demonstrates how gain changes when the reflector diameter is held constant and the feed placement is varied. Gain is a function of both feed placement and reflector diameter and is maximum when reflector diameter is 71.3 cm and feed placement is 22 cm from the reflector.

The second design constrained the feed placement so that the seam of the feed support structure was co-located with the reflector seam. This design would have been easier to manufacture. The seam constraint caused feed placement to be a function of reflector diameter. Therefore, gain was only a function of reflector diameter and was maximum with a reflector of 81.9 cm. Figure 3 below compares the radiation patterns of the two reflector-feed configurations. The first design with a reflector diameter of 71.3 cm was selected because it yields a higher gain with lower sidelobes and the increased manufacturing complexity is non-consequential. The antenna is currently being manufactured and tests will be performed by the end of this calendar year.

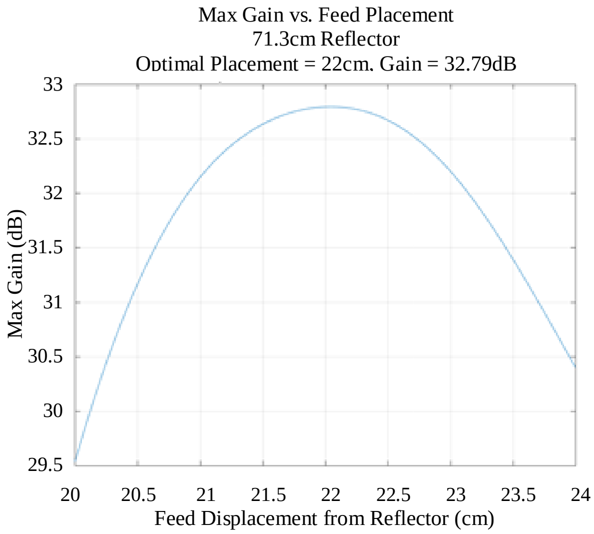

Figure 2: Gain vs. feed displacement for a 71.3 cm reflector.

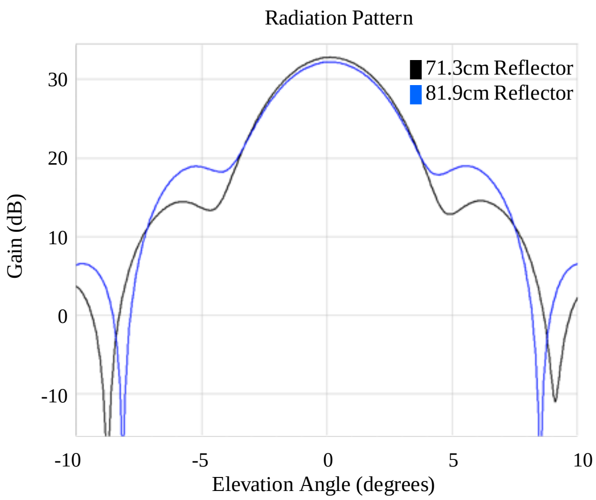

Figure 3: Radiation pattern of the inflatable antenna for two different values of the reflector size (71.3 cm is blue, 81.9 cm is black)

4. DEPLOYMENT SYSTEM

A deployment mechanism (see Figure 4) was designed to allow the inflatable membrane and the patch antenna to be safely stored and deployed in orbit. The deployment system is composed by a canister which hosts the electrical connections and a sublimate tank. The sublimate tank is designed to improve the safety of the inflation process by containing the sublimating powder into a confined space where the powder cannot sublimate. Upon triggering of the inflation, process the powder will be released into the antenna for the inflation process to start. The yellow structure is the membrane interface part which connects the membrane with the rest of the structures to ensure adequate support during the deployment and inflation. Springs are used on the bottom to initially contain the membrane and then to push it out of the CubeSat once the canister is opened. The door of the canister is not shown in Figure 4, but it is assumed that it will be hold in its initial position and later deployed using a burn wire.

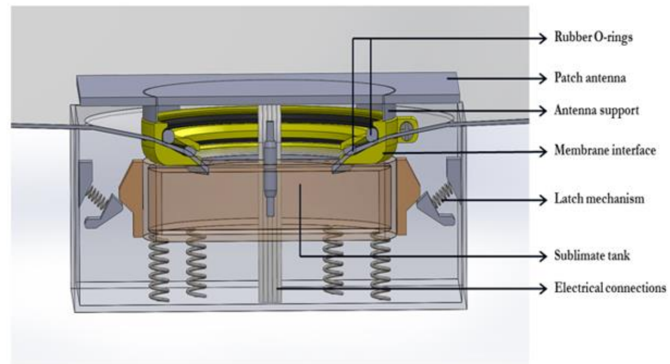

Figure 4: Design for deployment of the inflatable antenna.

The deployment mechanism described is still in its design phases. Much improvement is needed, especially now that the new antenna design will contain the patch inside and not outside of the inflatable structure. Future work in this area will focus on design refinement, prototyping and testing in the vacuum chamber.

5. RIGIDIZATION

One of the critical aspects of the inflatable antenna design is its resistance to environmental phenomena. Once the antenna is deployed in space, micrometeoroids can impact the antenna puncturing holes and causing the sublimating powder reaction to start once again. Although the design includes a certain amount of "extra" powder to compensate for such events, this could eventually lead to a very strong reduction of the antenna lifetime if not counteracted. Rigidization would allow the antenna to still maintain its shape even in case of puncturing and loss of pressure in the membrane. In addition to the issue of the micrometeoroids, thermal control of the antenna is a challenge. As shown in previous papers [18], the antenna is very sensitive to temperature fluctuations which can cause the shape to vary significantly. As a result, it would be definitely better to rigidize the antenna structure right after deployment to avoid these temperature-driven shape fluctuations.

The authors have been considering rigidization for over 2 years now. An initial survey of rigidization methods was performed and an initial experiment using a small piece of Mylar was described in [18]. During this past year, the first attempt to rigidize the entire antenna shape was carried on and tested at Arizona State University. Specifically, the antenna was partially covered with UV curing paste as shown in Figure 5.

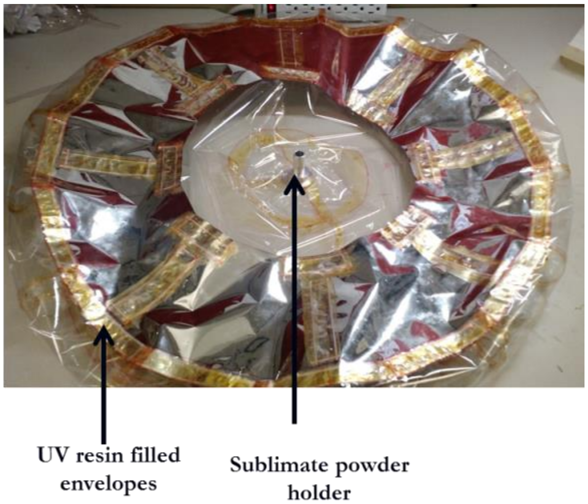

Figure 5: Attempt to rigidize the membrane using UV curing. The yellow sectors show where the resin is injected.

UV resin filled envelopes were used to provide the amount of UV paste needed for the rigidization while minimizing the risk for outgassing in the vacuum chamber. The vacuum chamber is the same used for the experiments described in [18], and it allows to reach the desired pressure to trigger the sublimating powder reaction. However, before lowering the pressure the antenna is vacuumed as shown in Figure 6.

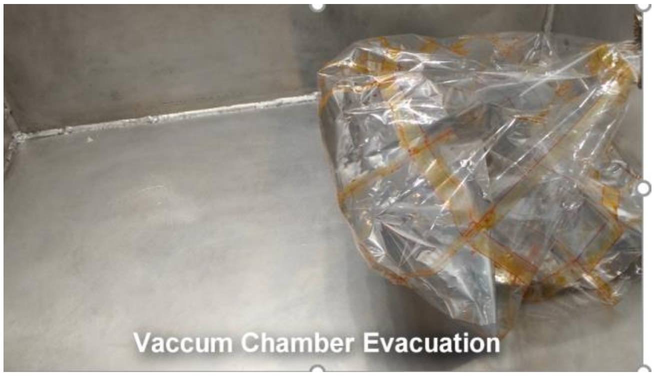

Figure 6: Phase A of the rigidization experiment. The inflatable membrane, treated with the UV resin, is inserted in the chamber and vacuumed.

Right after the antenna is vacuumed, the pressure is slowly reduced up to the point when it triggers the inflation with the sublimating powder which is shown in Figure 7. The time required for the chamber to start the inflation process is approximately 15 minutes and once the reaction is triggered, the inflation proceeds very fast in a matter of a couple of minutes.

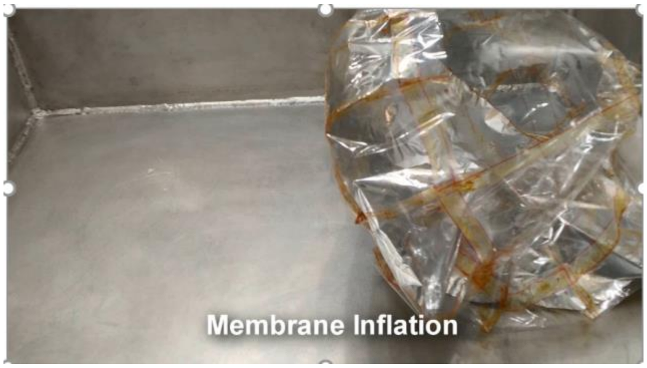

Figure 7: Phase B of the rigidization experiment. The pressure is lowered enough to trigger the inflation with sublimating powder.

Once the membrane is inflated, a UV light source is turned on in the chamber to allow for the UV resin to perform its function, as shown in Figure 8.

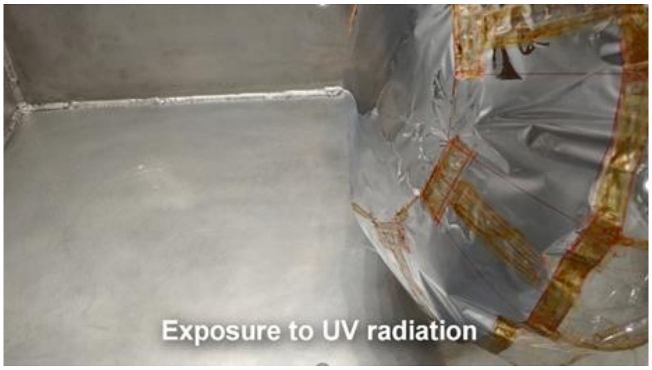

Figure 8: Phase C of the rigidization experiment. A UV source lamp is activated.

During the rigidization phase, the membrane is treated for approximately 2 hours which are sufficient to allow for a rigidization of the structure.

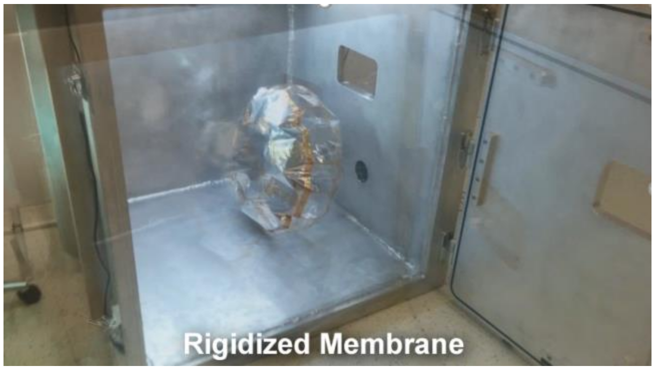

Figure 9: Rigidized membrane can be seen at the end of this experiment when ambient pressure is restored.

At the end of the experiment, the pressure is slowly raised back to ambient so as to allow the opening of the vacuum chamber to verify the status of the membrane. As observed in Figure 9, the UV curing process allows the antenna to partially maintain the inflated shape: if the antenna would have not been treated with UV paste, it would have all been deflated as the sublimating powder goes back to powder state when pressure is raised. It is possible to notice however, that the obtained shape is far from perfect. This is due to the fact that the UV curing is not applied uniformly on all the reflector surface due to the inevitable increase in mass and power that would make the antenna not be able to fit in the 0.5 U. The current research is now focused on improving the rigidization procedures by identifying the most appropriate distribution of the UV curing lines so as to improve surface accuracy. This approach seems to be very promising and key in increasing the life of the inflatable antenna in space.

6. DYNAMIC TESTS

The integration of the presented inflatable antenna in a CubeSat mission poses several challenges from the spacecraft dynamics point of view. The antenna dimensions, coupled with the partial flexibility of its material and with the presence of the sublimating powder in its internal volume add further complexity to the design of a reliable attitude control system. In order to provide meaningful information to the subsystem designers, a test campaign has been carried out in the Small Satellite Dynamic Testbed facility at JPL.

The purpose of the test campaign realized was to characterize the dynamical behavior of the inflated antenna, and in particular its response to rotation commands along a direction perpendicular to the boresight. To perform this, the antenna was placed on a 3 Degree of Freedom (DOF) spherical air bearing system. In order to obtain data, two options were considered: Vicon Motion Capture system and high-speed video acquisition. A tradeoff to select the appropriate technology was performed (Table 1).

Table 1: Tradeoff on data acquisition technology

	Vicon Motion Capture	High-speed Video Camera
Technology	Infrared (IR)	Visible
Setup complexity	High	Low
Post-processing complexity	Low	High
Data quality	High	Medium

Vicon Motion Capture was selected as the main measurement system, as the setup complexity was preferred over the post-processing complexity. It also provided more precise information. As a redundancy, a set of coded targets was placed on the antenna to provide a second data source for additional post processing. The capturing of these secondary coded targets was performed by using traditional cameras working at 30 frames per second.

The device was equipped with the XACT suite, from Blue Canyon Technologies. The suite includes, among other components, a set of reaction wheels and gyroscopes, controlled wirelessly from a console. A Matlab/Simulink® controller was used to feed the actuators with real-time commands and to handle the sensors readings. The inflated antenna was mounted with the boresight direction parallel to the gravity vector, with the reflector on top and the base connected to an adapter (Figure 10). The adapter, 3D printed, was included to offset the antenna from the others components, to allow for unobstructed oscillations.

Figure 10: Test setup.

One of the issues encountered was that the Vicon system relies on IR emissions and sensors to locate the markers on the body. This particular type of emissions is reflected by the antenna material, in particular by the reflector that is composed of aluminum-metalized mylar. To avoid these reflections and to block them, coded targets alternated with paper were used. The mass increase was quantified in 13 grams, compatible with the mass increase due to the presence of UV curing material that will be applied during the manufacturing of the final model. The five markers (Figure 11) were positioned in asymmetrical points on the upper part of the antenna, and the five Vicon cameras were placed on the ground in five locations around the air bearing stand.

Figure 11: Vicon markers

The test itself consisted in observing the behavior of the system when a step command is applied to the frictionless plate. Reaction wheel controller was programmed to stabilize the system, and was functioning for an average of 40 seconds. Tests were stopped either because of wheel saturation or because the system diverged (Figure 12 and Figure 13). The reason for this behavior was identified in the gravity torque, that was characterizing the system as an inverted pendulum.

In addition, during the test, several contributions to the dynamics were different to the conditions found in orbit:

- Gravity torque

- Air in the environment, as opposed to vacuum
- Air in the antenna, as opposed to benzoic acid sublimating powder
- Antenna position on the plate, not centered
- Inertia of the additional equipment and components

Nonetheless, test results showed that the inflated antenna is controllable with state of the art reaction wheel systems for CubeSats. The disturbances induced on the system by the oscillations of the antenna coupled with a flexible material were found to be negligible, and therefore compatible with foreseen mission profiles and selected hardware configurations.

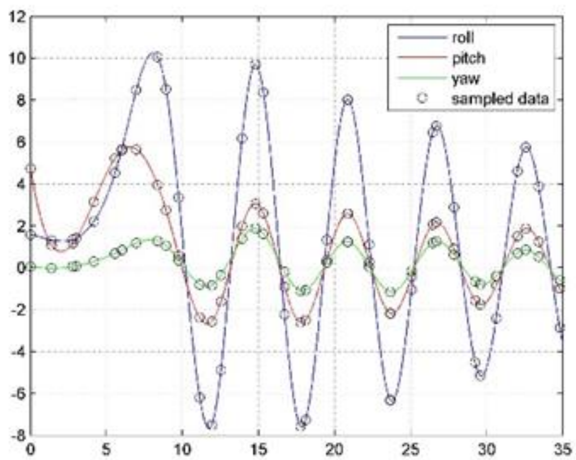

Figure 12: Stabilized behavior

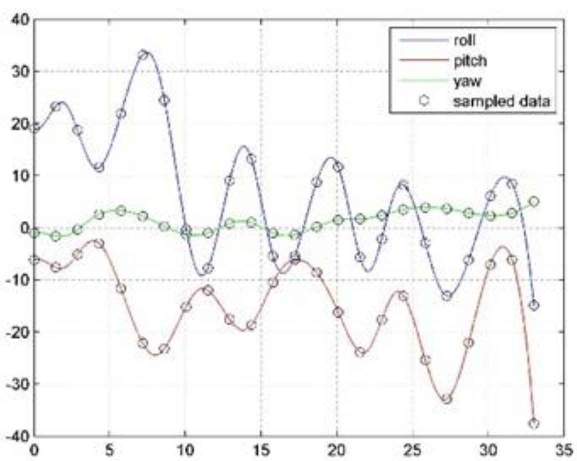

Figure 13: Unstable behavior

7. SUMMARY

This paper describes the latest developments in the inflatable antenna for CubeSat project. A new design, based on a circular reflector is presented, together with a newly designed patch antenna. Simulation shows that the shape of the reflector and the optimal placement for the patch antenna will allow to obtain a gain of approximately 32 dBi. In addition, a concept for the deployment system is presented which would allow to contain the membrane in 0.5U CubeSat and later deploy and inflate the antenna in space. Progresses have also been made in the process of rigidizing the antenna to increase its lifetime. A full scale rigidization experiment was carried on at Arizona State University. Finally, an effort to investigate dynamic effects was carried on through tests at the JPL small satellite dynamic testbed. Future work include test the new design in the anchechoic chamber and characterize the gain of the antenna.

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Jonathan Sauder *is a mechatronics engineer at Jet Propulsion Laboratory, in the Technology Infusion Group, which seeks to bridge the TRL "Valley of Death" for innovative, promising technology concepts. Dr. Sauder focuses on developing unique and innovative solutions for deployable antennas, sunshades and other precision structures, taking concepts from ideation to verification by environmental and deployment testing. He completed a Ph.D. in Mechanical Engineering in 2013 from the University of Southern California focusing on how collaboration aids engineers in creating innovative designs, and also holds a M.S. in Product Development Engineering and a B.S. Mechanical Engineering. Prior to receiving his Ph.D., he had worked in a number of R&D roles for companies like Mattel, Microsoft, and tech startups.*

Aman Chandra *received a B.E in Chemical Engineering from M.S Ramiah Institute of Technology, Bangalore, India in 2012 and is currently a final year gradute student in Aerospace Engineering at Arizona State University. His master's thesis dissertation is on the design and optimization of inflatable space structures for small satellite communication. His research interests include space systems engineering, computational solid mechanics, multi-parameter robust optimization and statistical risk assessment.*

Jekan Thangavelautham *has a background in aerospace engineering from the University of Toronto. He worked on Canadarm, Canadarm 2 and the DARPA Orbital Express missions at MDA Space Missions. Jekan obtained his Ph.D. in space robotics at the University of Toronto Institute for Aerospace Studies (UTIAS) and did his postdoctoral training at MIT's Field and Space Robotics Laboratory (FSRL). Jekan Thanga is an assistant professor and heads the Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory at Arizona State University. Jekan is broadly interested in the exploration of space and extreme environments, using networks of robots, interplanetary CubeSats and smart sensors. His research focuses on developing enabling technologies that spans system design, propulsion, networking and power to permit smart, fully autonomous operation for long durations. He is the Engineering Principal Investigator on the AOSAT I CubeSat Centrifuge mission and is a Co-Investigator and Chief Engineer on LunaH-Map, a CubeSat mission to the Moon.*

Lorenzo Feruglio *is a Lorenzo Feruglio is a Ph.D. student at Politecnico di Torino. His research activities include small satellite mission autonomy, artificial intelligence, system engineering methodologies. He has been working with ASSET and CubeSat Team of the Mechanical and Aerospace Department of Politecnico di Torino since 2009, working on small satellite projects. He had been involved in the design, verification and launch campaign of e-st@r-II CubesSat. Lorenzo Feruglio is author of papers published in conference proceedings, and he is currently involved as teaching assistant for the course "Space missions and systems design" of the Aerospace Engineering master course.*

Nicole Bienert *is an undergraduate honors scholar at The Pennsylvania State University. In 2018 she will graduate with a B.S. in Electrical Engineering. Since 2015 she has been engaged in research of EMI and antenna design. Nicole is currently working on her undergraduate honors thesis which will aid probe selection for near field antenna measurements. Nicole is also working on a CubeSat communication system for the Student Space Programs Laboratory. Every day Nicole looks forward to learning something new and taking on the intellectual challenges that the world has to offer.*