Team Name: Per Origami Ad Astra

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1 Team Introduction

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Date: October 19th, 2020

2 Technical Section

Full title: Compliant Mechanisms in Microgravity: Modal and Fatigue Analysis for Improved Model Correlation
Short name: Compliant Mechanisms' Spatial Sustainability
Experiment Category: Sustainability

2.1 Abstract

Compliant mechanism technology will simplify manufacturing pipelines, reduce production costs, and save precious space in rocket payloads. For these reasons and more, it is expected that the use of these mechanisms will become more widespread on satellites and space stations as we push to make the human presence in space more sustainable. However, current modal and fatigue models for arrays constructed from these mechanisms have yet to be proved with a controlled, parallel experiment in space. Through the use of small-scale models deployed in space and on Earth, we aim to collect significantly more accurate data for the deployment and retraction of compliant mechanism systems that will help us compare across Earth-bound, simulated, and microgravity models, find weaknesses in the current methodology, and ultimately facilitate future use of compliant mechanisms in zero gravity.

2.2 Technical Merit

Transporting equipment to space is expensive, because rocket payload capacities are limited. If we can reduce the payload capacity required by our equipment, and simultaneously improve the durability and reliability of the equipment itself, our efficiency increases dramatically. Fortunately, a technology that would improve equipment–such as solar arrays–while being more compact, already exists. The technology is known as **compliant mechanisms**. Significant work has been done to explore the possibility of simulating the behavior and sustainability of compliant mechanisms in space; however, simulation accuracy has yet to be proved by running an actual experiment in space. We propose a controlled experiment that tests the movement of a compliant-mechanism-based array (a sub-scale model of a proposed solar array) in space, so that future development of cost-saving compliant mechanisms for space will be inexpensively testable on Earth.

2.2.1 Benefits of Compliant Mechanisms

Compliant mechanisms are devices which utilize the deflection of flexible members rather than movable joints to achieve mobility. This type of mechanism is already found in a variety of space applications, including optics and deployable booms (Pehrson, Ames, Smith, Magleby, & Arya, 2019). Researchers from JPL and Brigham Young University's Compliant Mechanisms Research (CMR) lab designed and built an origami-based solar panel array (see Figure 1), which NASA developed for use on a future satellite (Landau, 2015).

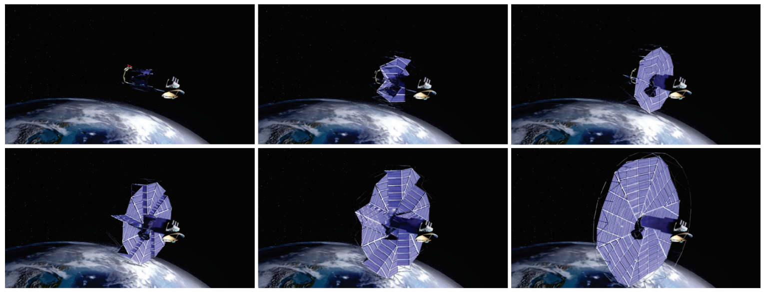

Figure 1: Digital model of the solar array as it might work on a spacecraft (Zirbel, 2014)

Compared to ordinary mechanisms, compliant mechanisms can be produced at lower cost and total part count while increasing performance, reliability, and wear resistance while decreasing weight and maintenance requirements (Howell, 2013). These aspects make compliant mechanisms essential for increasing sustainability of mechanical systems in space. Since significant cost and durability benefits are at stake, we expect that the use of deployable structures (a subset of compliant mechanisms) will become more widespread on satellites and space stations.

Dr. Nathan Pehrson's dissertation, entitled "Developing Origami-Based Approaches to Realize Novel Architectures and Behaviors for Deployable Space Arrays," discusses this topic. He introduces one of the most recent space-oriented designs that utilizes compliant mechanisms, which is termed the "self-deployable, self-stiffening and retractable" (SDSR) array.

Dr. Pehrson lists many of the benefits SDSR arrays have over the state-of-the-art space mechanisms. These benefits are, as quoted from his dissertation:

- SDSR arrays can reduce mass since deployment and stiffening systems (such as booms or trusses) can constitute a significant amount of the total mass of deployable space structures
- SDSR arrays can use the volume saved by not using other deployment and support mechanisms to increase the deployment area of the space structure
- SDSR arrays can handle large deployable structures using rigid panels for higher functional performance (i.e. high-efficiency solar cells with protective glass)
- SDSR arrays can repeatedly deploy and retract to alow for higher-intensity spacecraft maneuvering–a mission-enhancing technology for solar arrays
- SDSR arrays can retract to avoid collision with micrometeoroids
- SDSR arrays can tune its stiffness using retraction cables to attenuate vibrations
- SDSR arrays can self-deploy in cold-temperature environments by avoiding binding of joints with the utilization of strained compliant joints
- SDSR arrays can transmit electrical power and signals across compliant joints

He closes this list with this statement: "these benefits make the SDSR a viable and promising candidate as a new class of space deployable structures"(Pehrson, 2019).

2.2.2 Benefits of Our Proposed Experiment

Dr. Pehrson also proves that the movement of much more complex SDSR arrays can be modelled to analyze stiffness, power generation, and mass performance metrics of a very simple SDSR array, known as a “z-fold origami pattern” (see figure 2). However, he remarks in another paper, “Self-Deployable, Self-Stiffening, and Retractable Origami-Based Arrays for Spacecraft,” that the mathematical and physical models are not particularly accurate, because of an inability to perform zero-gravity testing.

Figure 2: Extension Process for Z-fold Mechanism
(Pehrson, 2019)

Unfortunately, BYU’s CMR lab lacks access to a zero-gravity test system. While simple static or linear-motion offload systems could readily be constructed at BYU, a problem stems from the dynamics of the coupled array and offload system during deployment and/or vibrational testing. When the array moves, the gravity offload system (which has mass) moves with it, and therefore the system is coupled. Additionally, the motion may not be linear; it may include 3D motion for deployment, further complicating the offload system. Running experiments in a true microgravity environment provides the opportunity to isolate the dynamics of the array, thus improving model correlation.

Further empirical observations are therefore needed to increase the accuracy of mechanical and mathematical models to enhance future iterations of the solar panel design. Such observations include the operational mechanics of expansion and retraction of the foldable solar array in a microgravity environment–an environment that is impossible to replicate long-term on Earth. Thus, we will perform an experiment that tests the movement of a sub-scale modelled array of a proposed solar array design in order to support further compliant mechanism research and development and to further human expansion into the cosmos.

2.3 Our Experimental Strategy

By obtaining inertial measurements from an SDSR array in microgravity, we will be able to improve upon the current mechanical models for SDSR arrays in space. Our proposed experiment will further the research on how the deployment and retraction of complex arrays are affected by microgravity by comparing finite element analyses to inertial measurements and empirical fatigue measurements from a deploying and retracting z-fold array. This array makes use of Lamina Emergent Torsional (LET) joints (see Figure 2), which cut away sections of material and leave torsional bars between others in order to enhance the compliance of the array. Two analyses will be performed on the simplified array: a fatigue analysis of the LET joints, and a modal analysis of the entire array. Each approach will utilize both a computer-generated model and a physical model.

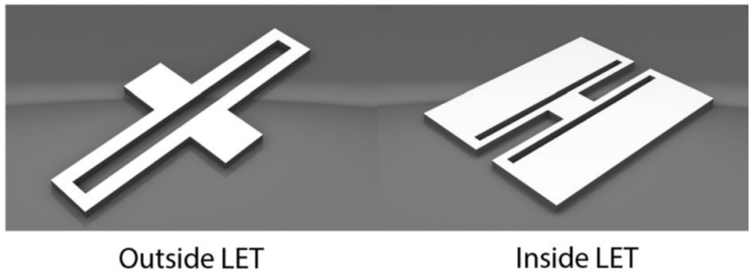

Figure 3: Two types of LET joints
(Nelson, Lang, Nathan, Magleby, & Howwell, 2016)

2.3.1 Fatigue & Modal Analysis

The fatigue analysis portion of the experiment will be performed in two different ways. First, we will perform a finite element analysis on a simulated model of our LET joints, to obtain theoretical values for stress, strain, and creep after a specified number of cycles. During the experimental phase, a camera module will be used to track the creep. Then, after the conclusion of the experiment, destructive fatigue analyses will be performed on both the Earth-bound model and our microgravity-bound model to determine the resulting stress and strain in the LET joints.

The second analysis gives insight into the array's modes during deployment and retraction. The simulated, theoretical values for our modal analysis will be obtained using a finite element analysis that will be performed on a model of the entire array. Following the simulated modal analysis, experimental data from the Earth and microgravity-bound models will be obtained by using strategically placed microelectromechanical (MEMS) inertial measurement units (IMU). Experimental modal techniques are then used to derive the modal response.

At BYU we have experts in MEMS, experimental modal analysis, and compliant mechanisms, further adding to the resources we can draw upon for this experiment's success. Thirty days aboard the International Space Station will provide invaluable data about the deployment of the desired array, namely, the z-fold origami pattern. This pattern, as we plan to manufacture it, exhibits all of the unique characteristics of a compliant mechanism.

While our experiment represents only a scaled fraction of the intended system, we will compensate for the inherent stiffness of smaller panels by scaling the thickness of the materials to maintain a relationship between our experimental array and any scaled version. The data procured from these tests will be applicable to many related SDSR designs that are destined for use in space. In particular, the z-fold design that we have chosen has immediate applicability for use in small satellites such as CubeSats, and future potential implementation in solar sails, space-deployed coronagraphs, and antenna arrays. By understanding more fully how this SDSR design operates in space, engineers will be more capable of integrating such hardware into their systems without the need for extensive and costly experimentation in orbit.

2.3.2 Evaluation

After the conclusion of the experimental data collection, we will compile the data and compare the simulated model data, Earth-bound model data, and microgravity-bound model data. The three-way comparison of data shows us whether or not the simulated data or Earth-bound experimental data aligns well enough with the microgravity-bound data to justify orbital deployment of SDSR arrays that are tested on Earth or in a purely simulated environment.

To determine if the resulting data aligns well, we will conduct an analysis of variance (ANOVA) test between the simulated, Earth-bound, and microgravity-bound data. If the differences are statistically significant, we will use a posthoc statistical analysis to determine which groups are misaligned, and investigate the existence of a transfer function or constant that will allow for Earth-tested or purely simulated models to be used for accurate representations of SDSR arrays in microgravity. If it is not possible to find an applicable transfer function or value, we will conclude that orbital testing is essential to understanding SDSR behavior in microgravity. However, if there are no statistically significant differences, we will conclude that in terms of statistical hypothesis testing, there is evidence to support the accuracy of Earth-bound or simulated testing.

2.4 Experimental Design

2.4.1 Data

Measurements will be obtained from multiple stages of the experiment. Data collection falls into 3 categories:

1. Active Spatial Collection - Measurements are recorded aboard in the International Space Station and sent to the ground team. Recorded measurements include:
   (a) State of material through on-board camera
   (b) Movement of material (i.e. acceleration and displacement) through IMUs attached to the side of each panel's midpoint on the z-fold array
   (c) Uplink rate: 50 bytes per second
   (d) Downlink rate: 3 Megabits per second
2. Active Terrestrial Collection - Measurements are recorded from identical experiments conducted on Earth and are retrieved by the ground team. Recorded measurements include:
   (a) State of material through on-board camera
   (b) Movement of material (i.e. acceleration and displacement) through IMUs attached to the side of each panel's midpoint on the z-fold array
3. Post Cyclic Collection - Additional observations are made on the terrestrial experiment and the spatial experiment (after its return to BYU), and then recorded. Recorded data will include:
   (a) Final fatigue/state of LET joints of material

Environmental Constraints: None

2.4.2 Experiment Limitations

As with all experiments, limitations in our design exist and are here acknowledged. Due to the environment to which the experiment is subject, data regarding the impact of temperature and vacuum cannot be accounted for. However, material properties are affected either not at all or predictably by temperature–Young's Modulus, which will be the most relevant material property in our experiment, is constant for Al 6061-T6 (the material we will likely use in our experiment) across all temperatures (Summers et al., 2015).

2.4.3 Procedures

Upon arrival to the ISS, connect experiment to 5v 2A power source (manual)

Connect data cable to Windows XP (manual)

While the experiment is on the ISS (all processes automated)

1. Sends data packet informing team of successful start up and
2. Deploy Origami Array
   (a) Strain energy will deploy the array (No mechanism for deployment is needed. Rather, deployment utilizes the material's properties.)
3. Measurement during deployment phase
   (a) Daily picture is taken, continuous video saved to storage device
   (b) Data from this phase is stored
4. Retract origami array
   (a) Stepper motor retracts array
5. Measurement during retracting phase
   (a) Daily picture is taken, continuous video saved to storage device
   (b) Data from this phase is stored
6. Data packet is sent to ground team by means of email through the nanoracks system
7. Repeat processes (2) - (6) for the remaining allotted time

Return experiment to Earth and to Brigham Young University (manual)

2.4.4 Experiment Timeline

See Appendix A - Figure 5a 5b for Project schedule (Gantt chart format).

2.5 Experiment Build

2.5.1 Materials

The z-fold mechanism will be constructed of materials that would be used in a common space-based application: either aluminum (Al 6061-T6) or stainless steel (UNS S32100). Other materials necessary for our experiment include those used in instrumentation, such as accelerometers and cameras.

2.5.2 Manufacturing and Fabrication

The z-fold mechanism will be laser cut, which will be outsourced to a company specializing in laser cutting. The rest of the test bed will be assembled in the CMR Lab. This lab also contains various instruments to perform preliminary testing on the test beds.

2.5.3 Electrical

Testbed electrical components include:

1. Raspberry Pi Zero W
2. Raspberry Pi Camera Module V2 8 Megapixel
3. Memory Storage Devices
4. Stepper Motor
5. MEMS IMU
6. White LED
7. Fan

2.5.4 Estimated mass of experiment

We estimate the total mass of the experiment to be 0.5kg.

2.5.5 Block Diagram

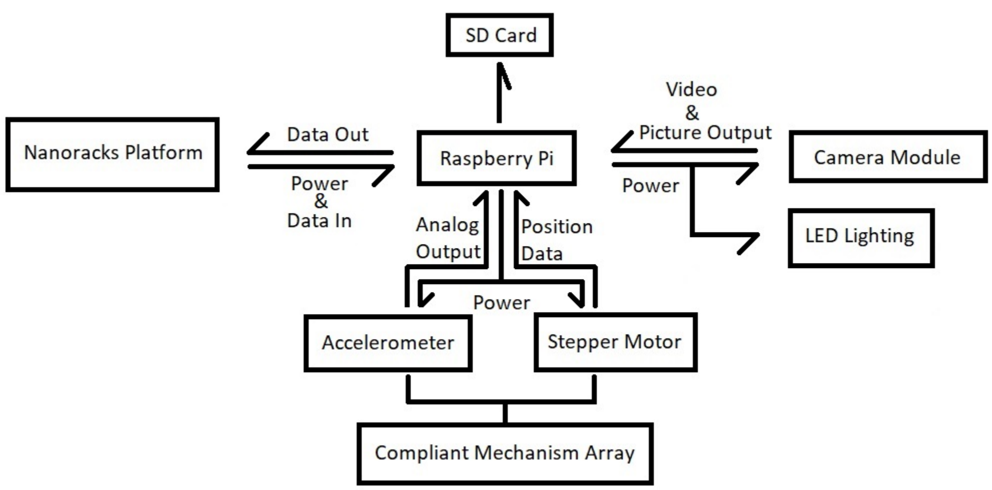

Figure 4: Experiment block diagram

2.6 Safety Concerns

Concern	**Yes/No**	**Explanation**
i. Liquids, gases, or other hazardous materials (How do you plan to contain it?)	No	No liquids, gasses, or other hazardous materials ar e required.
ii. Wireless devices	No	All devices (linear actuator, sensors, camera) will be wired directly to a microprocessor, which will utilize a Nanoracks usb connection terminal for data transfer. No wireless or infrared devices are required.
iii. High voltages (indicate voltage, its use and any expected protection devices; any step up from the provided 5V USB power should note both voltage and amperage)	No	We anticipate being able to constrain all powered hardware to the 5V 2.1A power supplied by the Nanoracks usb terminals.
iv. Electric or magnetic fields that can cause disruptions	Yes	According to the Nanoracks specification sheet, any use of a motor requires direct contact with Nanoracks to ensure the compatibility of the motor with their product. As our design will use a stepper motor, we will contact Nanoracks to confirm compatibility of our experiment's motor before the manufacturing of the experiment.
v. Lasers (which class? is the path securely contained?)	No	We do not currently intend to use lasers in our experiment.
vi. Moving parts (do they cause noise, vibrations or shaking?)	Yes	We will perform ground tests of the system to optimize the frequency of our retraction and expansion for minimal noise, vibrations, and shaking.
vii. Flammable, explosive, radioactive, corrosive, magnetic or organic products	No	No, except for magnetic components (see part iv).
vii. Flammable, explosive, radioactive, corrosive, magnetic or organic products	No	No, except for magnetic components (see part iv).
viii. Hot (above 50C) parts—include electronics that may heat up	Yes	We will minimize heat by optimizing power draw, and adding a motor heatsink, and/or low-power fan to keep stepper motor heat below 50 degrees C.

2.7 Other Concerns

Concern	**Yes/No**	**Explanation**
i. Sensitive to light	No	No sensitivity to light
ii. Sensitive to vibrations	Yes	Our experiment is liable to be sensitive to large vibrations. However, a very large sample size of contractions/expansions will make individual readings affected by external vibrations statistically insignificant and won't adversely affect our data.
iii. Sensitive to temperature	No	Only extreme temperature changes which could affect the physical properties of materials used in our array.
iv. Pressurized (what pressure level?)	No	No necessary pressure levels
v. Any other potential safety concerns not previously addressed	No	No other concerns

3 The Case For Compliant Mechanisms

Compliant mechanisms have been repeatedly proven to improve sustainability of equipment used on Earth such as bulletproof barriers, novel medical devices (including laparoscopes), and micro-electromechanical systems (MEMS). It is only a matter of time before we see these benefits in space. This small proposed experiment will enable us to more accurately forecast the behavior of this improved technology. While this experiment is fairly simple in nature, the value it provides will be increasingly obvious as deployable compliant mechanisms continue to make their way to space.

References

Howell, L. L. (2013). Compliant mechanisms. In J. M. McCarthy (Ed.), *21st century kinematics* (pp. 189–216). London: Springer London.

Landau, E. (2015, Jul). *Solar power, origami-style.* NASA. Retrieved from `https://www.nasa.gov/jpl/news/origami-style-solar-power-20140814`

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Summers, P. T., Chen, Y., Rippe, C. M., Allen, B., Mouritz, A. P., Case, S. W., & Lattimer, B. Y. (2015). Overview of aluminum alloy mechanical properties during and after fires. *Fire Science Reviews*, *4*(1), 3.

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4 Citizen Science and Outreach Section

4.1 Citizen Science Plan

The citizen science goal for this experiment will involve data collection and processing from several control experiments by local high school and middle school students, and options for creative activities for elementary school students. We established a firm collaboration with Quest Academy Charter School in West Haven, Utah through contact with Mrs. Jen Jones, the Space Foundations Teacher Liason. A member of our group attended a local high school in Provo and has connections to collaborate with students from the Utah County Academy of Sciences, Timpview High School, and Provo High School, all in Provo, Utah.

4.1.1 High school student involvement

In coordination with the outreach goal, the selected high school students will take charge of the data collection and processing of the control experiments hosted by their schools. Prior to setting up and beginning the control experiments, the selected high school students will receive training on how to use Microsoft Excel for data collection from the control experiment. The students will then receive additional instruction on how to process and consolidate the data in a usable manner. This will instruct the students on performing the following data analysis steps:

1. Watch a presentation where we give a big picture vision of the experiment and analysis
2. Download the ground experiment at the school (data collection from all experiments will be hosted on our central servers). Schools will be given an API key linked to their instance of the experiment. The data will be retrieved as a CSV file that can be imported into Microsoft Excel.
3. Inspect the data and record their observations in response to questions that we provide.
4. Calculate a projection of ¡HELP? some kind of data? what kind of data are we collecting anyway? like what does 1 instance of data look like?¿ and interpret them in their own words. Teachers can provide an example interpretation if student find this question difficult.
5. Download the ISS experiment data using a separate API key that we provide
6. Retrieve a ”time slice” of the ground and ISS data, and conduct a statistical comparison (we may provide software packages to conduct this comparison if it is significantly involved)
7. Interpret the results of the comparison and decide for themselves whether the estimates look accurate for their time slice
8. If possible, teachers will upload student results and combine analyses across all time slices to gain a ”holistic picture”
9. Students and teachers will discuss what they learned, what they enjoyed, what they felt was confusing, and whether they're confident in the integrity of their hosted ground experiment.

Our hope is that these steps will give students a hands-on experience in data analysis and interpretation. We will structure this to ensure students of many levels of expertise can participate, and that all students will at least be able to grasp the big picture and become excited about the future findings of our experiment.

4.1.2 Middle and elementary school involvement

¡TODO¿ DANIEL

4.2 Outreach Plan

4.2.1 Outreach to local schools

Our team will present the big picture view of our experiment at the local high schools and elementary schools that will be hosting the control experiments. High school presentations will be targeted towards students in the junior and senior grades to encourage future participation in STEM careers. Elementary schools focus on simple, memorable explanations, demos, and hands-on origami activities to captivate their interest. Overall, the presentations will include an overview of the experiment, the purpose and importance of the control experiments, as well as an overview of the importance and opportunities available through the STEM fields. Later, a similar presentation will be available to a larger body of students through a booth at BYU's yearly EngTech Expo, and the Provo recreation center's yearly "Kid's science palooza."

In addition to our presentations, we will create several control experiments to be placed in glass cases at local high schools. Because of the public nature of our control experiments, students at the host high schools will be able to observe the exact experiment taking place on the ISS. We hope that this will inspire and motivate interested students in the Utah Valley area to pursue education and future careers in STEM fields.

The schools that we intend to work with include: LIST OF SCHOOLS TODO. Altogether, we will be giving N presentations, and hosting M experiments.

4.2.2 Global outreach

We plan to create a presence on social media to generate interest in our experiment, by maintaining an Instagram page and website. We have already prototyped the website (IF NEED MORE DETAIL: written in React/Gatsby Javascript, HTML, and Tailwind CSS, hosted with Netlify, scaling serverless backend with Google Firebase), with which we plan to feature our ongoing progress, allow people across the world to ask questions (we will post responses to the most common questions), and show our experiment results. With the proper permission, we may consider releasing a small set of "demo" data that can be presented in an interactive online sandbox.

To boost our social media presence, we plan to leverage our contacts with several influencers, including Mark Rober, a BYU and NASA alumnus. We hope that he will feature us in a video of our project and experiment, and explore applications of origami in space. His videos are STEM-education focused and will help us reach a wider audience than just the Utah Valley area.

5 Administrative Section

5.1 Funding and Budget Statement

Material	Count	Price per Unit	Cost
Array Materials	3	$500.00	$1,500.00
Actuators	3	$25.00	$75.00
Raspberry Pi Zero W	3	$10.00	$30.00
Raspberry Pi Camera Module V2	3	$30.00	$90.00
Raspberry Pi Zero W Case	2	$10.00	$20.00
Other Raspberry Pi Zero Accessories	3	$20.00	$60.00
Range Finder (TBD)	3	$20.00	$60.00
Counter Display	2	$5.00	$10.00
LIPO Battery	3	$25.00	$75.00
Acrylic Display Case	2	$60.00	$120.00
			$2,040.00
Manufacturing	Count	Price per Unit	Cost
Array Material	3	$200.00	$600.00
			$600.00
Community Outreach	Count	Price per Unit	Cost
Origami Paper	1	$50.00	$50.00
NASA Stickers	300	$0.50	$150.00
Large Event	1	$1,000.00	$1,000.00
			$1,200.00
K-12 Citizen Science	Count	Price per Unit	Cost
Large Event	1	$500.00	$500.00
			$500.00
Labor Hours	Hours	Hourly Wage	Cost
Undergraduate Students	800	$11.00	$8,800.00
Advisor	20	$70.00	$1,400.00
			$10,200.00
Total Cost			$14,540.00

5.2 Letters of Endorsement

DEPARTMENT OF
MECHANICAL ENGINEERING

COLLEGE OF ENGINEERING

Re: Student Payload Opportunity with Citizen Science (SPOCS) Sept. 24, 2020

Dear SPOCS Committee,

As Chair of the Department of Mechanical Engineering at Brigham Young University, I am writing to provide my enthusiastic support for the BYU Commercial Space Club's application to receive funding to build an experiment to be performed on the international space station. They are excited to look into the fatigue of compliant materials in space. We have a strong research group in the area of compliant mechanisms that has already completed designs for satellites. The department is committed to provide them with the space, computers, and other facilities needed to carry out this project. BYU currently has nine student project teams and it is a normal part of our operating procedures to support student project groups. This team has identified a faculty advisor and has developed concepts for their experiment.

I hope they will receive your highest considerations.

Thank you,

Sincerely,

Dale R. Tree

Dale R. Tree
Professor and Chair, Brigham Young University
Department of Mechanical Engineering

BRIGHAM YOUNG UNIVERSITY, 435 CRABTREE BUILDING, PROVO, UTAH 84602
(801) 422-2625 / FAX: (801) 422-0516

MECHANICAL ENGINEERING

2 October 2020

Re: Advisor Statement for Student Payload Opportunity with Citizen Science Application

SPOCS Committee:

I am the advisor of a student team that is focused on exploring technology for space travel and am also the head of the BYU Mechanical Design Collective that conducts research relevant to the topic that the team is proposing. Relative to this proposal the Collective has a long and successful history of developing and testing innovative compliant mechanisms including many for NASA, JPL and the Air Force. See https://www.compliantmechanisms.byu.edu/ for additional background.

I am pleased to support the submission of an experiment entitled "Compliant Mechanisms in Microgravity - Modal and Fatigue Analysis for Improved Model Correlation" proposed by a team of students from Brigham Young University, I concur with the concepts and methods by which this project will be conducted. I will ensure that all reports and deadlines are completed by the student team members in a timely manner. I understand this project will continue through expected flights in 2021.

In our lab and in the department the student team will have access to all necessary expertise, computing, fabrication means and testing facilities for the proposed project.

Please contact me with any questions,

Spencer P. Magleby, PhD
Professor of Mechanical Engineering
Associate Dean, Undergraduate Education
Director, University Honors Program

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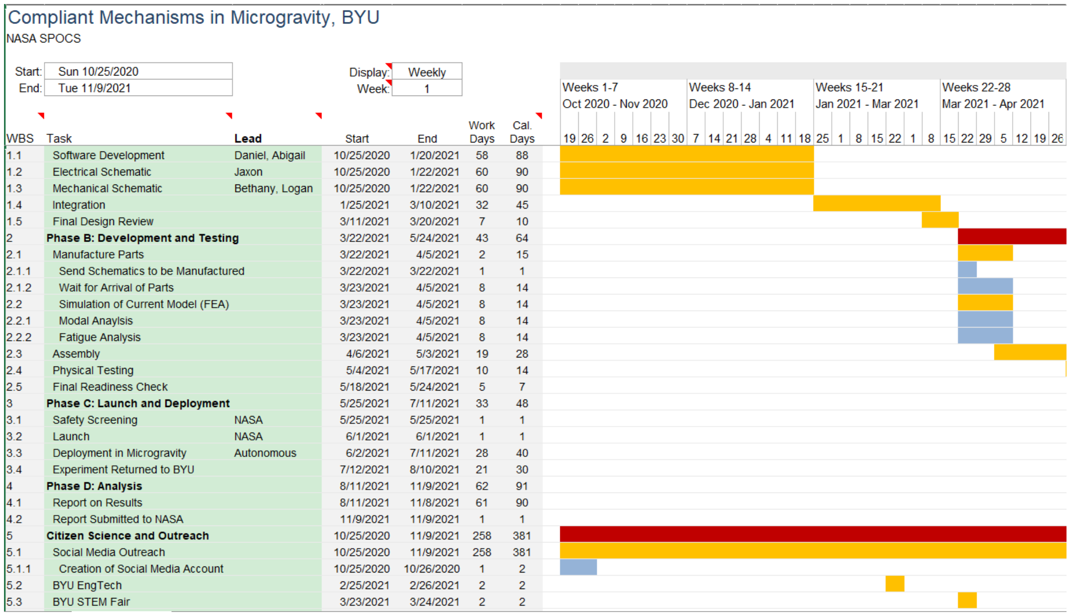
6 Appendix



Compliant Mechanisms in Microgravity, BYU
NASA SPOCS

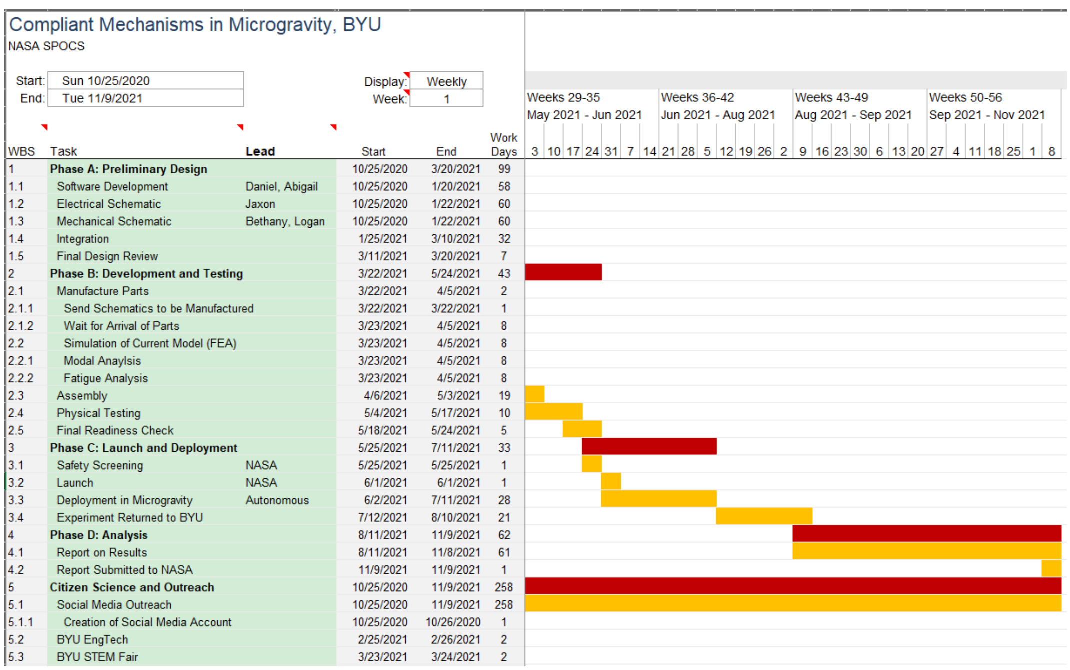
Start: Sun 10/25/2020
End: Tue 11/9/2021
Display: Weekly
Week: 1

Weeks 1-7 Oct 2020 - Nov 2020 | Weeks 8-14 Dec 2020 - Jan 2021 | Weeks 15-21 Jan 2021 - Mar 2021 | Weeks 22-28 Mar 2021 - Apr 2021

19 26 2 9 16 23 30 7 14 21 28 4 11 18 25 1 8 15 22 1 8 15 22 29 5 12 19 26

WBS	Task	Lead	Start	End	Work Days	Cal. Days
1.1	Software Development	Daniel, Abigail	10/25/2020	1/20/2021	58	88
1.2	Electrical Schematic	Jaxon	10/25/2020	1/22/2021	60	90
1.3	Mechanical Schematic	Bethany, Logan	10/25/2020	1/22/2021	60	90
1.4	Integration		1/25/2021	3/10/2021	32	45
1.5	Final Design Review		3/11/2021	3/20/2021	7	10
2	**Phase B: Development and Testing**		3/22/2021	5/24/2021	43	64
2.1	Manufacture Parts		3/22/2021	4/5/2021	2	15
2.1.1	Send Schematics to be Manufactured		3/22/2021	3/22/2021	1	1
2.1.2	Wait for Arrival of Parts		3/23/2021	4/5/2021	8	14
2.2	Simulation of Current Model (FEA)		3/23/2021	4/5/2021	8	14
2.2.1	Modal Anayisis		3/23/2021	4/5/2021	8	14
2.2.2	Fatigue Analysis		3/23/2021	4/5/2021	8	14
2.3	Assembly		4/6/2021	5/3/2021	19	28
2.4	Physical Testing		5/4/2021	5/17/2021	10	14
2.5	Final Readiness Check		5/18/2021	5/24/2021	5	7
3	**Phase C: Launch and Deployment**		5/25/2021	7/11/2021	33	48
3.1	Safety Screening	NASA	5/25/2021	5/25/2021	1	1
3.2	Launch	NASA	6/1/2021	6/1/2021	1	1
3.3	Deployment in Microgravity	Autonomous	6/2/2021	7/11/2021	28	40
3.4	Experiment Returned to BYU		7/12/2021	8/10/2021	21	30
4	**Phase D: Analysis**		8/11/2021	11/9/2021	62	91
4.1	Report on Results		8/11/2021	11/8/2021	61	90
4.2	Report Submitted to NASA		11/9/2021	11/9/2021	1	1
5	**Citizen Science and Outreach**		10/25/2020	11/9/2021	258	381
5.1	Social Media Outreach		10/25/2020	11/9/2021	258	381
5.1.1	Creation of Social Media Account		10/25/2020	10/26/2020	1	2
5.2	BYU EngTech		2/25/2021	2/26/2021	2	2
5.3	BYU STEM Fair		3/23/2021	3/24/2021	2	2

Figure 5a: Schedule in Gantt Chart Form (Weeks 1 - 28)



Compliant Mechanisms in Microgravity, BYU
NASA SPOCS

Start: Sun 10/25/2020
End: Tue 11/9/2021
Display: Weekly
Week: 1

Weeks 29-35 May 2021 - Jun 2021 | Weeks 36-42 Jun 2021 - Aug 2021 | Weeks 43-49 Aug 2021 - Sep 2021 | Weeks 50-56 Sep 2021 - Nov 2021

3 10 17 24 31 7 14 21 28 5 12 19 26 2 9 16 23 30 6 13 20 27 4 11 18 25 1 8

WBS	Task	Lead	Start	End	Work Days
1	**Phase A: Preliminary Design**		10/25/2020	3/20/2021	99
1.1	Software Development	Daniel, Abigail	10/25/2020	1/20/2021	58
1.2	Electrical Schematic	Jaxon	10/25/2020	1/22/2021	60
1.3	Mechanical Schematic	Bethany, Logan	10/25/2020	1/22/2021	60
1.4	Integration		1/25/2021	3/10/2021	32
1.5	Final Design Review		3/11/2021	3/20/2021	7
2	**Phase B: Development and Testing**		3/22/2021	5/24/2021	43
2.1	Manufacture Parts		3/22/2021	4/5/2021	2
2.1.1	Send Schematics to be Manufactured		3/22/2021	3/22/2021	1
2.1.2	Wait for Arrival of Parts		3/23/2021	4/5/2021	8
2.2	Simulation of Current Model (FEA)		3/23/2021	4/5/2021	8
2.2.1	Modal Anaylsis		3/23/2021	4/5/2021	8
2.2.2	Fatigue Analysis		3/23/2021	4/5/2021	8
2.3	Assembly		4/6/2021	5/3/2021	19
2.4	Physical Testing		5/4/2021	5/17/2021	10
2.5	Final Readiness Check		5/18/2021	5/24/2021	5
3	**Phase C: Launch and Deployment**		5/25/2021	7/11/2021	33
3.1	Safety Screening	NASA	5/25/2021	5/25/2021	1
3.2	Launch	NASA	6/1/2021	6/1/2021	1
3.3	Deployment in Microgravity	Autonomous	6/2/2021	7/11/2021	28
3.4	Experiment Returned to BYU		7/12/2021	8/10/2021	21
4	**Phase D: Analysis**		8/11/2021	11/9/2021	62
4.1	Report on Results		8/11/2021	11/8/2021	61
4.2	Report Submitted to NASA		11/9/2021	11/9/2021	1
5	**Citizen Science and Outreach**		10/25/2020	11/9/2021	258
5.1	Social Media Outreach		10/25/2020	11/9/2021	258
5.1.1	Creation of Social Media Account		10/25/2020	10/26/2020	1
5.2	BYU EngTech		2/25/2021	2/26/2021	2
5.3	BYU STEM Fair		3/23/2021	3/24/2021	2

Figure 5b: Schedule in Gantt Chart Form (Weeks 29 - 56)