Testing and Development of NEA Scout Solar Sail Deployer Mechanism

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Abstract

The Near Earth Asteroid (NEA) [1] Scout is a deep space CubeSat designed to use an 86 m^2 solar sail to navigate to a near earth asteroid called VG 1991. The solar sail deployment mechanism aboard NEA Scout has gone through numerous design cycles and ground tests since its conception in 2014. An engineering development unit (EDU) was constructed in the spring of 2016 and since then, the NEA Scout team has completed numerous ground deployments aiming to mature the deployment system and the ground test methods used to validate that system. Testing a large, non-rigid gossamer system in 1G environments has presented its difficulties to numerous solar sailing programs before, but NEA Scout's size, sail configuration, and budget has led the team to develop new deployment techniques and uncover new practices while improving their test methods. The program has planned and completed 5 separate full scale sail deployments to date, with a flight sail deployment test scheduled for FY18. The paper entitled "Design and Development of NEA Scout Solar Sail Deployer Mechanism" [2] was presented at the 43rd Aerospace Mechanisms Symposia. Since then, the system has matured and completed ascent vent, random vibration, boom deployment and sail deployment tests. This paper will discuss the lessons learned and advancements made while working on solar sail deployment testing and mechanical redesign cycles.

Introduction

In May of 2016, the Near Earth Asteroid (NEA) Scout engineering development unit (EDU) solar sail was prepared for a suite of environmental tests culminating in a full scale deployment at NASA Marshall Space Flight Center's (MSFC) flat floor facility. The full scale deployment premiered a fully machined EDU, flight-like motors, and a developing control system. Numerous half scale deployments and mechanical development efforts were completed in preparation for the full-scale test.

The solar sail development team developed a test suite that would begin with an ascent vent test to simulate the rapid depressurization during ascent on NASA's Space Launch System (SLS). This test was performed to indicate the viability of the sail folding pattern and verify that the vent paths were performing nominally. The folding pattern and vent paths proved to be acceptable and no sail damage was noted due to trapped air. After ascent vent the team prepared for a random vibration test. This test was intended to vibrate the system in all 3 axes with intermittent, boom only deployment tests after each axis of vibration. The team encountered their first major lesson learned through an undersized stepper motor, which disabled the ability to perform intermittent tests. The team proceeded with the random vibration test with the undersized stepper motor. Post-test, an investigation into the undersized motor commenced. Causes identified included limited design space, improper scaling of half scale loads to full scale designs, and poor assumptions regarding the system's internal friction. The redesign effort required a major system reconfiguration.

After the redesign activities, boom-only deployments and retractions tests were completed. With the new configuration and properly sized stepper motor, the boom-only deployments demonstrated the capability and robustness of the system during nominal operations and risk mitigation activities, such as boom blooming characterization. The team learned several lessons learned that will be highlighted in the

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extended paper. For example, retraction rates to remove blooming, boom buckling recovery, and deployment shape dynamics.

Once the team was comfortable with the boom deployments, the EDU sails were deployed. Two sails were produced for EDU activities: a Mylar sail and a colorless polymer-1 (CP1) sail. Both sails were 86 m^2 in size, and the CP1 version was built as flight-like as possible. During the deployments, the team updated procedures with boom support information, electrical inputs, sail attachment methods and mechanical fixtures. These tests proved to be the most eye-opening test to date.

Stepper Motor Deployment Failure and Motor Sizing Lessons Learned

Prior to the solar sail deployer (SSD) random vibe test, the engineering team conducted a boom-only deployment and learned that the existing stepper motor was undersized. This became a 3 month setback land led to a drastic SSD mechanical redesign, lengthy coordination with the motor vendors, and a long list of failure causes.

Following the failure, it was clear that the undersized motor was performing properly with suitable electrical inputs, but it was unclear why the booms would not deploy. After investigating, the team determined that the torque requirement was vastly underestimated and a larger motor was needed. The design team then set about to redesign the deployer to house a larger stepper motor. Unfortunately, the SSD had no volume to spare. The motor volume was specifically tailored the previous motor with no margin. After weeks of redesigning 4 of the 5 primary structural components, the larger motor—just 4 mm taller than the undersized motor—was accommodated.

The rest of the team began a failure analysis in parallel with the redesign effort. After a month of discussion and investigation, a list of possible causes was created and the team commenced to find the root cause or causes. The team investigated the control board settings, the test setup and the deployer. Luckily, the SSD's redesign activities required complete deconstruction allowing the designer to inspect the assembly alignments and each part for wear, deformation, and/or any other visible damage. Wear and more severe damage was discovered and documented. Analysis comparing the CAD models, mechanical drawings, plastic prototype and as-built EDU uncovered 6 contributing errors. The causes are listed in the order they were discovered with the final cause, number six, identified as the root cause.

1. The motor was undersized and lacked volume margin to allow for a larger version.
2. The prototype control board was overpowering the motors, producing more torque than expected.
3. The system was unknowingly susceptible to mechanical interference and wear.
4. Internal friction was grossly underestimated.
5. The boom spooling operation was prone to large irregularities and damaged other components.
6. The team drew too many comparisons between the plastic prototype and EDU.

Each item will be discussed and present a lesson learned.

Undersized Motor Volume Allocation

The mechanical design team determined years before the EDU tests that stepper motors would power the SSD. There were few motors to choose from in a desirable form factor—about 15mm in diameter or less—and steppers would produce the most torque per unit volume. Significant prototype testing with 3D printed components, friction estimation and torque calculations were made to select the first motor: a Faulhaber AM1524 with a 91:1 planetary gearbox (Figure 1). After selecting the motor, the designer matured the SSD design without allocating any significant clearances between the motor and other structural components. The motor was boxed in.

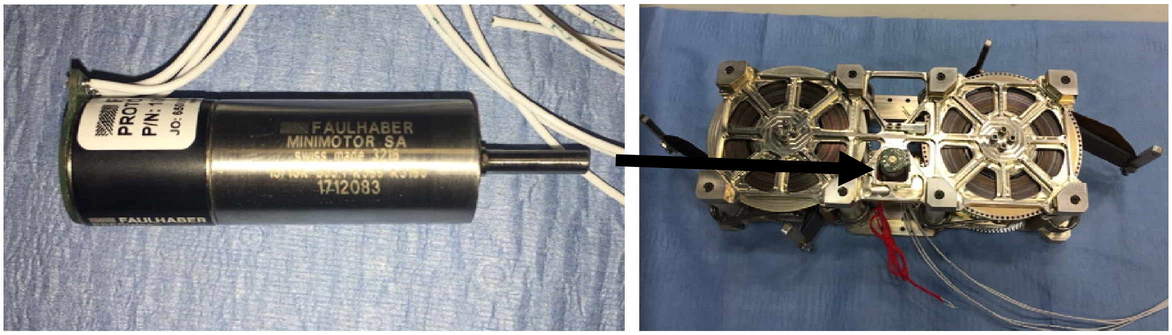

Figure 1. Faulhaber stepper motor and respective location on the NEA Scout SSD

Just as it is common practice to design mechanical interfaces with extra material in the event larger fasteners are needed, the design team learned that this cautious practice applies to motor volume allocation as well. A new motor just 4 mm taller than its predecessor required a 3 month redesign effort including major changes to 80% of the SSD structural components. All of the redesign efforts and cost could have been avoided if the motor volume allocation had just 10% of height margin.

Incorrect Electrical Inputs

During consultation with the motor vendor, the team learned that the SSD's electrical inputs needed improvement. The prototype control board had a single step input, commanding the running speed without ramping. This requires more current to instantaneously accelerate the motor to operational speeds. The overcurrent provided a "false positive": overpowering the motors produced more torque than the datasheets and designs allowed. The overcurrent lasted for the 15 minute deployment duration and showed no evidence of failure through about 50+ prototype tests. However, it did give a false sense of confidence that the smaller motors could produce the required torques due to the gross overcurrent. To correct the overcurrent input, the board designer reconfigured the algorithms to include a gradual ramp rate which reduced the heat output. It should be noted that this input change saved a potential failure at the next thermal vacuum test (This error nearly crippled the development of another NEA Scout subsystem, the Active Mass Translator and is discussed at length in "Testing and Maturing a Mass Translating Mechanism for a Deep Space CubeSat"). Had the board not been reprogrammed, the motor may have passed ground testing, hiding the issue until later in the program development.

Mechanical Interference and Wear

There were clear signs of interference and wear on most of the rotating components within the deployer. As the SSD was tediously deconstructed, each part was inspected and any wear and debris was photographed. It was clear that the as-designed air gaps had closed either during assembly or operation. Some of these air gaps were 0.25 mm or less and resided between stiff structural plates and thin, rotating flanges (Figure 2, 3). The flanges deformed during spooling and/or deployment and contacted their neighboring structural components. This produced gouges, aluminum dust and removed the chemical conversion coating from the contacting surfaces. Images of the damage are shown below (Figure 4, 5).

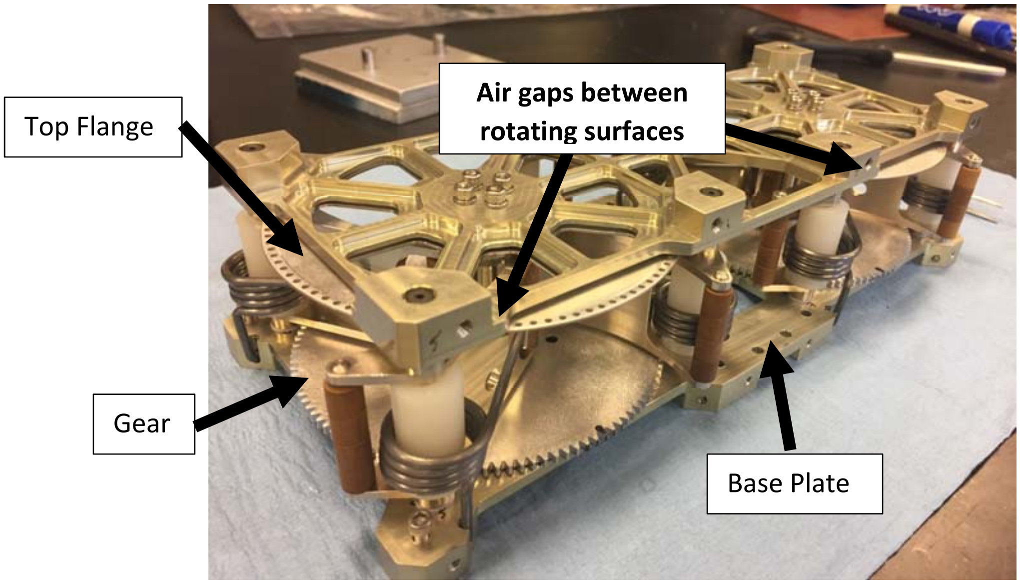

Figure 2. Boom-less assembly and as-expected airgaps

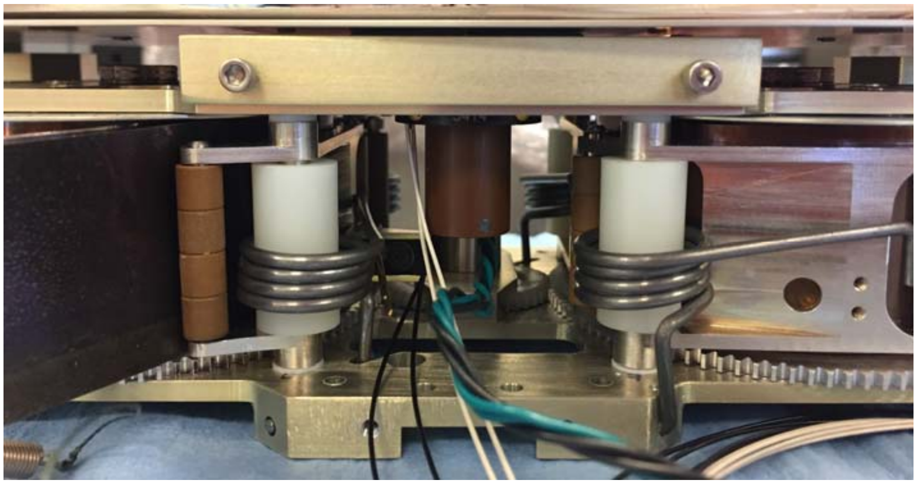

Figure 3. As-built air gaps. Note the near line-to-line contact between the gear and base plates

Figure 4. Visible wear on top flange caused by boom coil irregularities. Note that the gold conversion coat has been removed.

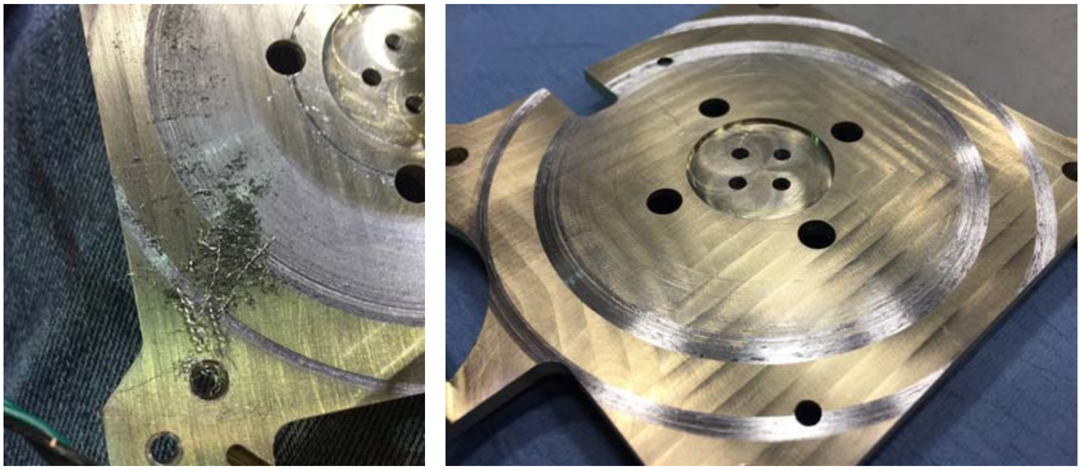

Figure 5. Gouging and wear on base plate caused by gear interference and coil irregularities

The interferences had three main causes. First, CAD models were made to the desired values and the associated clearances respected a “perfect” construction. Areas showing reasonable clearances in the models did not respect potential over or undersized components. Had the models been sized to their least desirable extremes, the areas susceptible to interference would have been more obvious. Furthermore, the tolerance analysis did not include a minimum clearance requirement on the rotating features, so even if the parts were made to specification, any deformation would have caused damage. Sadly, there was also no quality inspection on the EDU components so we are not sure that the EDU components even met the drawing requirements.

Second, the rotating flanges were too thin to resist loads from the improperly boom coils and deformed. We did not understand the spring energy in the booms and that the thin flanges would be in the spring energy’s load path. The flanges and gears were not stiff enough to resist and deflected through the as-designed air gaps into the structural components.

The final contributor was a poor material selection. All wearing surfaces were aluminum to aluminum, producing a high friction coefficient (approximately 1.0) and covered surface areas around 50 cm^2. The flanges were not structural and could have easily been changed to plastic or a polytetrafluoroethylene (PTFE) embedded material, reducing friction by a factor of 2 at least. Though the interference was an off-nominal case, lower friction materials would have reduced the torque requirement in the event of physical contact between these components.

The interferences were removed by making larder air gaps between the rotating components. The flange damage was repaired and the base plate was redesigned to accommodate for the new motor design. The gears’ height was reduced by about 0.2 mm and 0.2 mm shims were added between the top flange and top plate. These changes nearly tripled the air gap widths, allowing for spooling irregularities and reduced the wear observed at the next deployment tests.

Much of the mechanical interference and wear investigation uncovered other problems that were addressed in the SSD’s redesign and test development. These causes were related to the internal friction assumptions, boom spooling irregularities and 3D prototype comparisons.

Poor Understanding of Friction

The SSD is designed to slowly release the spring energies of four tightly wound 7.2 meter stainless steel booms. The spring forces naturally produce friction during boom deployment and retraction. The booms are rolling over numerous thermoplastic bushings, sliding along 2 thin aluminum surfaces and rubbing between their concentric coils as they “bloom” [2]. These loads are relatively straightforward to calculate individually, but as a system, there was no accurate way to represent behavior other than with prototype testing. The half scale plastic model provided some torque estimations and allowed the team to optimize contact surface designs, but the measured torques were not properly scaled to represent a full scale system. This will be expounded upon in the "Inaccurate Correlation" section.

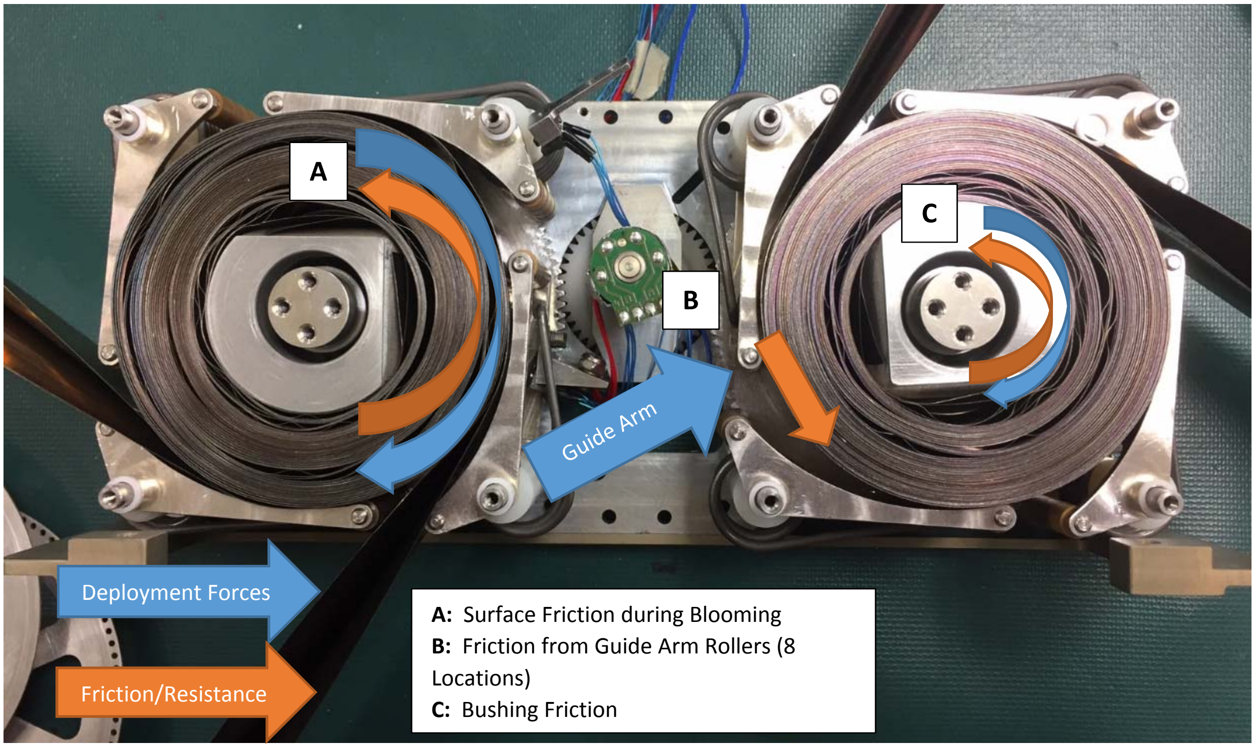

Figure 6. Three sources of friction in the deployer system

The three friction sources noted above—rolling, sliding, and blooming—are great contributors to the torque load, but there were many more that had to be considered during the redesign (Figure 6). First was the motor transmission inefficiencies. The vendor datasheets noted that the 91:1 motor operated at about 70% efficient, meaning only about 70% of the motor shaft output was transmitted to the gearbox shaft [3]. This means the speed was knocked down by a factor of 91, but the torque only increased by a factor of 63. This was a small oversight on a datasheet with huge ramifications. Furthermore, friction in the rulon bushings and between gear teeth was ignored, and given that there was no quality inspection on the individual parts, these could have been either non contributors or primary causes of our system failure. The designers should have taken the time to create either a complete system dynamics analysis or a few simple subcomponent models to determine more realistic friction estimates.

Lastly, there was significant external friction that had yet to be considered. As the booms deploy, small sliding feet were attached every couple of meters to prevent contact with the floor and boom flanges. These friction forces react back into the deployer and act as resistance loads against the motor torque. We had never considered this and even if the motor could have initiated deployment, there was a good chance that the ground testing would fail due to the test-induced loads as the booms deployed across a surface. The slider and test design impacts will be covered in the "Sail Deployment Development and Testing" section.

Boom Spooling Irregularities

One of the primary focuses during the de-integration activities were the spooled boom configurations and their impacts on surrounding components. The coiled booms were expected to be 35 mm tall, but as they were deployed and retracted over time, small irregularities produced an inconsistent spool height. Within the concentric coils, the spool height may rise or fall by 0.3 mm. This inconsistency pressed against the spool flanges and gears, causing the deformation and wear shown in figures 4, 5, and 7. The lack of alignment features for the boom spooling operation damaged surrounding components on retraction and deployment.

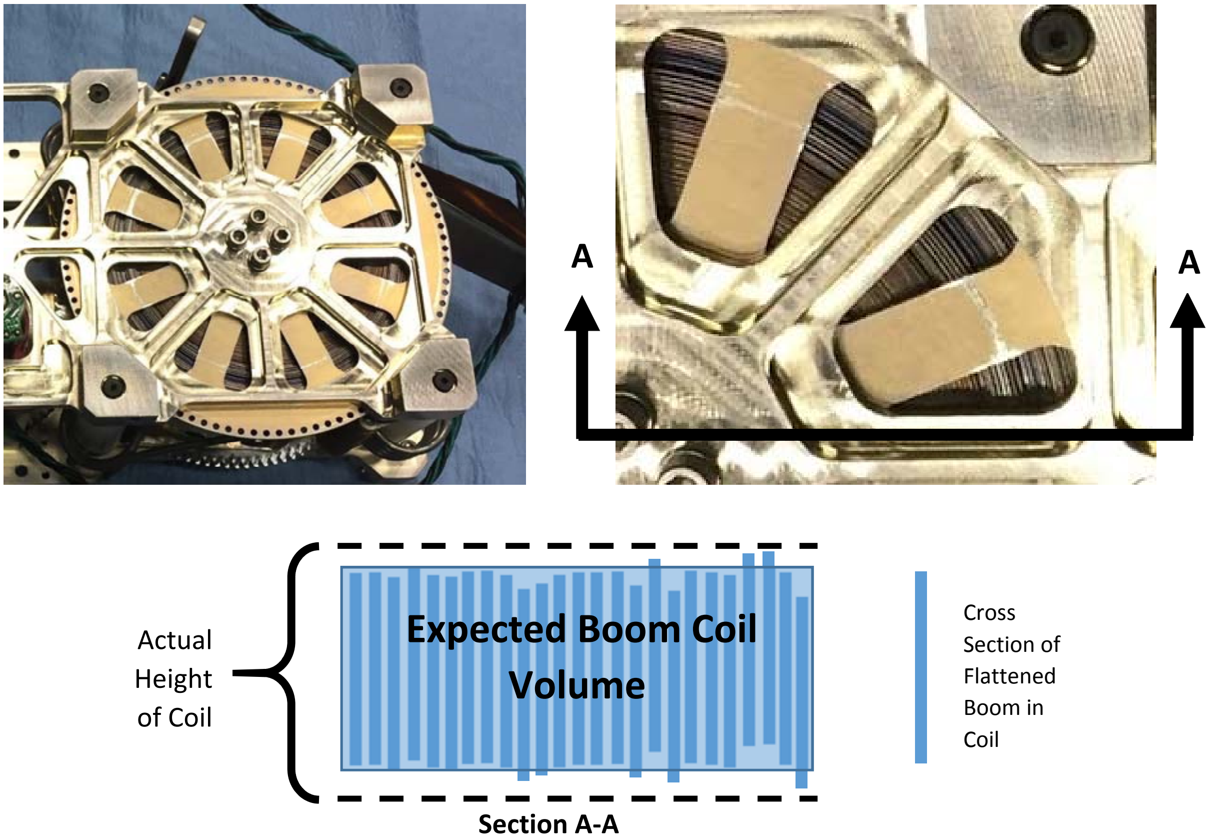

Figure 7. Visible Wear after a few boom-only deployments due to boom irregularities and depiction of spool cross section

This design flaw was remedied during spooling operations. The retraction speed was reduced to about half the deployment speed and required two people to closely monitor the booms' entrance angles and clearances between the upper flanges and lower gears. There was not enough structure or volume to include passive alignment features, and the hands-on solution proved to be acceptible. After properly spooling the booms, flange and gear damage was greatly reduced and deployment torque requirements were noticably different.

Inaccurate Correlation between Prototype and EDU

The team's false confidence supplied by a full scale 3D printed prototype is determined to be the failure's root cause. The prototype testing was critical to the development pace for the SSD, but where it did provide wonderful design inputs, it also gave a deceiving since of familiarity to a vastly different EDU system. The ½ scale prototype was made of 3D printed ABS. Though the plastic parts may have resembled the aluminum parts on the EDU, the mechanical properties were incomparable. The similarities can be observed in Figure 8. Furthermore, the booms' lengths on the prototype were 4 meters as compared to the 7.2 meters on the EDU.

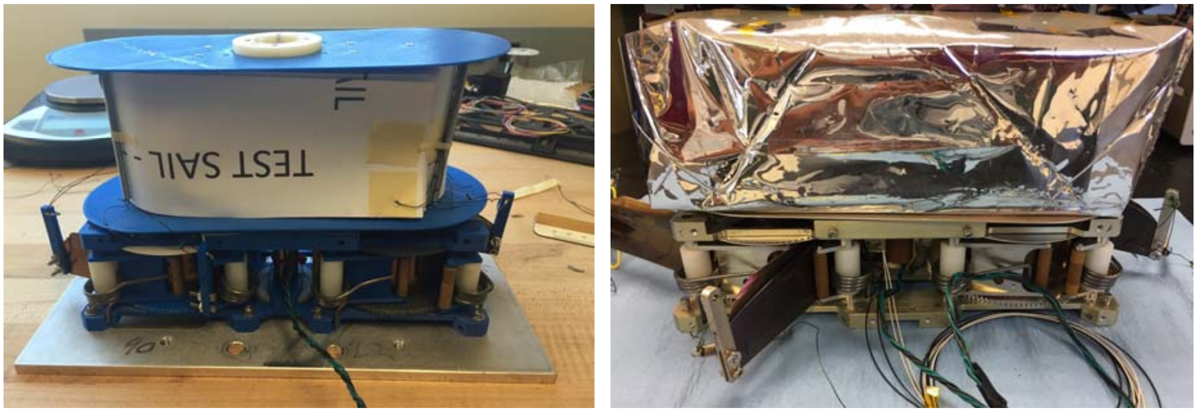

Figure 8. Prototype and EDU SSD

The boom lengths were used as improper metrics when relating the prototype and EDU. If the booms are examined as a spring, the deployed lengths relate to the square of the stored energy in the spool. Therefore, the coiled EDU booms, being about 1.8 times longer than the prototype booms contained about 3 times more energy. The plastic-to-plastic friction was an estimated 2x less than the EDU's aluminum-to-aluminum friction forces. To exacerbate this condition, the plastic would also deform more easily than the aluminum EDU. Therefore, the differing friction and stiffness properties discredited any linear correlation between the prototype and EDU based upon boom lengths. This correlation error played a significant role in leading to the 5 causes described above.

When the motor was sized, the designer assumed a linear relationship between the prototype and the EDU torque requirements. The controller board for the prototype was also used to baseline the EDU controller board, hiding some of the control input errors. The plastic material would also hide mechanical interference as it deformed in the presence of significant load. In continuance, the friction between plastic parts was more advantageous than aluminum. Lastly, the boom spool irregularities were hidden because the booms were shorter and less likely to spool improperly. All in all, the design team was inexperience with prototyping mechanical systems with plastics and allowed a prototype to hinder a much-needed critique.

The overarching lesson from the SSD motor-related failures is this: do not base any dynamic or loads-related mechanical requirements on a printed prototype. Volumetric data, part fit up, and interface development can and should benefit from a 3D printed model, but scope should not increase without significant factual support.

Sail Deployment Development and Testing

As a risk mitigation strategy, the team planned several deployment tests during the project's design and development phases. The goal of ground deployment tests were to demonstrate the functionality of the deployment system. The ground tests did have two inherent flaws that were difficult to overcome – gravity and friction. Demonstrating the SSD's functionality in a 1G environment was taken into consideration while developing the test plan. The team started with half-scale, 3D prototype units and transitioned to a flight-like unit for full scale testing. The team planned to perform two full-scale engineering development unit tests and two flight scale tests. By the conclusion of the engineering development unit test phase, the team had completed five full scale development tests. The development tests did not focus on simulating the space environment conditions during deployment and all deployment tests were conducted in an ambient environment. The team communicated to the project management the potential for false positives and negatives produced during the test due to the 1G environment.

The first set of deployment tests were completed with the half-scale prototype using 4 meter booms and a 40 m^2 Mylar sail. The smaller sail took less time to refold and spool, allowing for quicker turnaround between tests and kept the focus on troubleshooting the deployer system. The deployment tests were conducted in the Flight Robotics Laboratory at Marshall Space Flight Center. The test location was a major factor in the success of demonstrating the systems capabilities. Due to resource constraints, the team was unable to design and build a support structure to offset the effects of gravity. Therefore, the approach to the deployment test was simple – deploy the system on a large, flat, clean, and low friction surface with minimal human intervention and ground support equipment.

The facility, also known as the “Flat Floor”, allowed air bearings to float across the surface of the epoxy floor with negligible friction. Without friction loads, the air bearings were intended to simulate two lateral degrees of freedom in the floor’s plane and a rotational degree of freedom normal to the floor. The team attached the deployer body and each boom tip to an air bearing and a compressed air supply (Figure 9). The “frictionless system” was supposed to help study the SSD’s natural deployment motion, angular rates and angular accelerations. This information would have been beneficial for the guidance and control team’s deployment modes and models, but the forces created by the air supply hoses dominated deployment dynamics and produced inconclusive results. The air bearings were never used again on account of their high inertias and hose-induced loads.

Figure 9. First sail deployment test: half scale 3D-printed prototype.

After abandoning the air bearing system, the half scale sails were deployed using low friction furniture sliders as boom supports. Though this method was cruder in nature, the results were more symmetric and predictable, helping baseline progress during the prototype phases. Despite the less flight-like test system, the prototype deployer helped determine intermittent sail shapes, reflective areas, and deployment failure modes. After about 10 boom only and 3 half scale sail deployments, the prototype was set aside as the team began focusing on SSD testing.

After the SSD redesign work, the NEA Scout team re-entered test activities and completed its final EDU deployment test in the fall of 2017. Full scale SSD testing was a logistical and technical challenge for the team. The deployed sail is 9.3 x 9.2 m, 2.5 microns thick and incredibly fragile (Figure10). The sheer size and sensitivity of the material limited the team to available facilities for large scale testing. Even after looking to other NASA centers for possible deployment tests, the team determined the Flat Floor to be the most suitable facility.

Throughout the full scale deployment test suite, the team studied and applied lessons learned from more than a dozen off-nominal deployment cases, characterized the booms and sail in a 1G environment and produced a detailed deployment procedure. Sliding friction forces were reduced by 50%, a simple and effective method to gravity offload the boom tips developed. Furthermore, the team characterized boom and sail-related failure modes and operational methods to avoid them. These careful experiments developed a new test scheme that would remove some of the complicating factors present in deploying flexible gossamer structures in 1G and allowed the booms and sail to behave in manners more similar to the 0G flight environments.

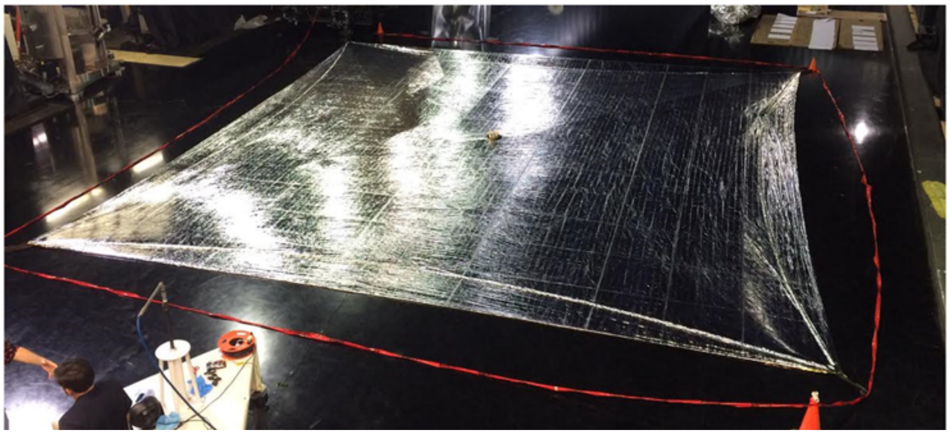

Figure 10. Full scale EDU deployment

Sail Development Test Lessons Learned

The first lesson learned relates to the air bearings. The air bearings were a large mass at the end of each boom (Figure 9). Even after allowing 3 degrees of freedom, the bearing masses dominated the boom tips' natural paths. The air hoses connected to each air bearing also introduced significant friction forces into the system. Though the air bearings were frictionless, their air supply hoses had to drag along the floor and the hoses bending resistance completely overwhelmed the booms' restoring forces. This problem only worsened as the booms increased in length until the booms eventually buckled. For large sail systems, large masses at the boom tips will dominate deployment dynamics and lessen the booms' abilities to self-correct. Avoid large masses and force inputs near boom tips during deployment testing.

The second deployment test was conducted on a basketball court. The team explored using the basketball court out of necessity of needing available floor space. The air bearings could not be used on the hardwood surface, requiring the team to get creative in the test approach. The wax finish on the floor coupled with the introduction of felt sliders proved to be a successful combination. The team introduced a felt slider design that would support the booms at multiple locations only grams of extra mass added to each boom. This removed the concern of ground support equipment mass overwhelming the dynamics of the test.

The next lesson learned came during the first successful SSD prototype deployment on a basketball court. This test showed a sail and boom shape progression that seemed more indicative of a flight deployment. Initially, team assumed the sail would deploy in a uniform, rectangular manner. However, test showed that the sail would form in a “bow-tie” shape during deployment (Figure 11 A-B). At half-scale, the booms were able to compensate and correct at the end of deployment (Figure 11 C-E).

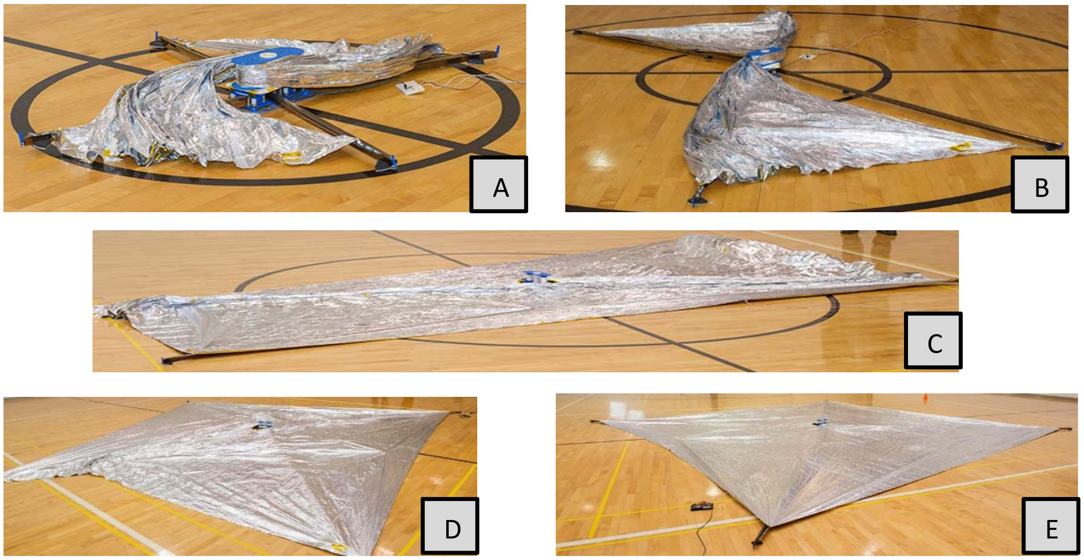

Figure 11. Sail shapes during nominal deployment.

With the success of the half-scale deployment tests, the full scale tests followed the same procedure of integrating felt sliders on the booms at predetermined points. Originally the team thought the only human intervention needed was to monitor when to initiate and conclude the test. Additionally, the team was confident the boom's self-correcting behavior observed in the half-scale test would repeat in the full scale test.

The third lesson learned through the deployment tests was boom buckling. During half-scale tests, when the sail was fully removed from the central spool, the tension along the perimeter of the sail assisted the booms in assuming the final shape at the end of the deployment (Figure 11 C-E). The team noted that increasing the boom length from 4 to 7.2 meters for the full scale test uncovered potential issues with boom buckling due to the shape dynamics during deployment.

The first area of focus while investigating boom buckling was the friction between the felt sliders and the test surface. The full scale tests were conducted at the flat floor facility. The felt sliders were placed along the length of the boom at predetermined locations, shown in Figure 12. The sliders were assumed to put a negligible force back into the system, which the booms could overcome. This was found to be untrue. Even the small applied force of the sliders on the epoxy floor restricted the booms to follow their natural path out of the deployer. The epoxy flat floor has a higher coefficient of friction than the waxed hardwood floor. These forces had larger effects on the SSD and the boom root as the boom lengthened. The longer booms had significantly more lateral loads to correct as the booms lengthened and the sail area increased (Figure 13).

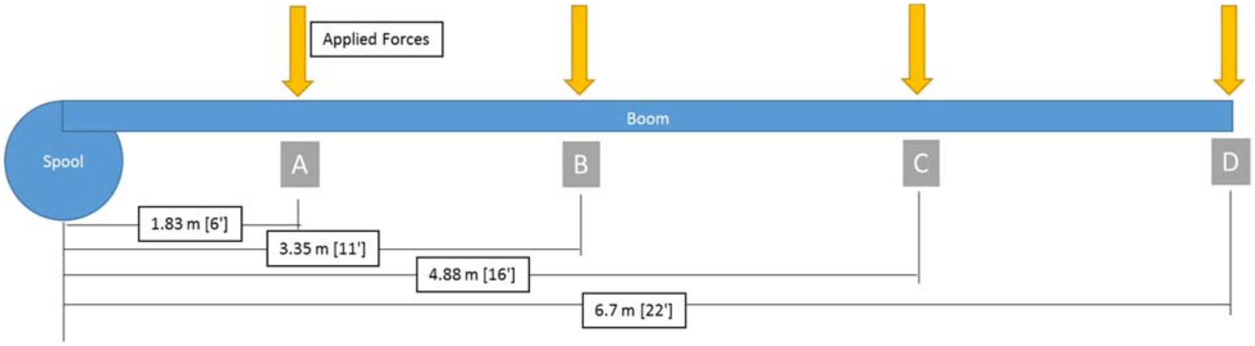

Figure 12. Boom slider locations for ground testing.

Another contributor to the boom buckling was the location of the sail material at initial deployment. The 1G environment pushes the sail material towards the floor, and as the sail deployed, friction and static electricity pulled the boom tips towards the centers of the sail areas. If the material was on the wrong side of the boom, the material would pull the boom in the wrong direction, thus starting a buckle like in Figure 13. In the 0G environment, this behavior would not be observed. To mitigate this during test, the team decided that human intervention would be necessary if the sail material dragged over the booms and would be placed in the proper quadrant before resuming testing.

Figure 13. Boom buckling in full scale deployment test

The final contributor to boom buckling is the boom mass. On orbit, the booms would not need to compete with gravity to support their own weight or deployment friction forces created by boom supports, sail friction or static electricity. As friction and electro-static forces move further from the boom root, the boom root's restoring moment and stiffness loses any ability to correct. Figure 14 shows that the friction forces furthest from the boom roots dominate boom deployment dynamics.

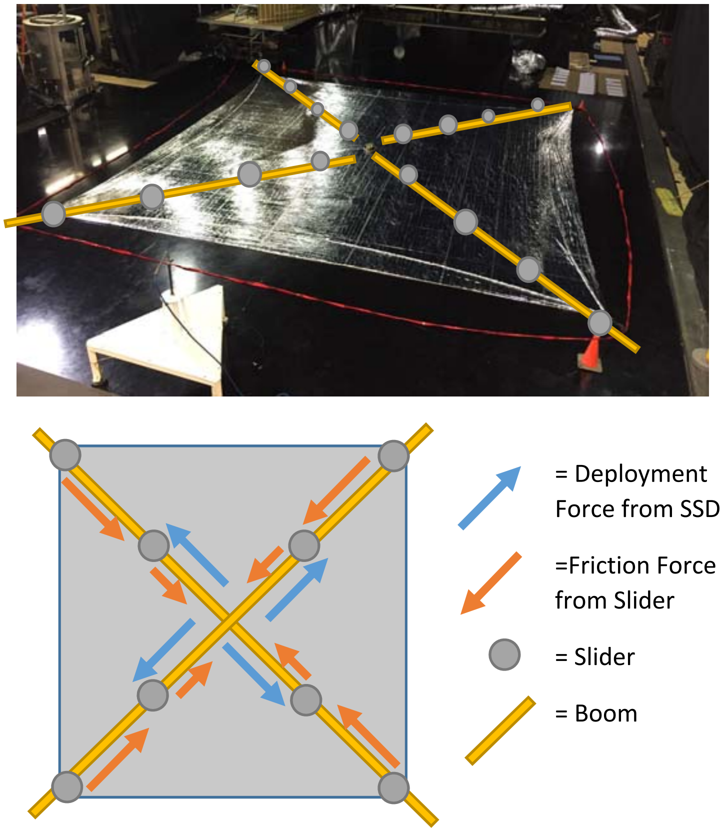

Figure 14. Deployed sail and deployment force diagram.

After observing this characteristic in many boom-only deployments, the team determined that any effort to gravity offload the boom tips would remove 1G deployment characteristics and produce a more flight-like test. Many offload options were traded, but tying balloons to the boom tips proved to be the simplest solution (Figure 15). By removing some weight and friction forces from the regions furthest from the boom root, the booms followed a more flight-like deployment path (similar to what was observed at the half scale tests). Furthermore, boom tips were more realistically affected by the sail edge tensioning created at the final stages of deployment (Figure 11 D-E). The gravity offload and friction reduction methods gave the team far more insight in the boom behavior on orbit.

Figure 15. Boom tip gravity offloading.

During the ground tests, when buckling was initially observed, the team manually removed the buckling from the system. As a risk mitigation activity, the team investigated whether or not the system could remove a boom buckle autonomously. The new SSD motors could produce enough torque to retract the booms on ground and on orbit. Knowing this, the team tested to see if strategic retraction operations during deployment could remove buckles formed during off-nominal cases. The team learned that retraction steps near the 75% and 95% deployment stages would remove buckles while also reducing blooming in the boom spools. Though this was a convenient operational change, the SSD has no method to determine the presence of a buckle, nor that the buckles, if present, are removed.

Conclusion

Future solar sailing missions are already calling for sails 3-15x larger than the NEA Scout SSD. As solar sails continue to increase in area, projects need to designate a considerable amount of effort into developing a scaled test plan that can feasibly verify system level requirements on the ground. The effects of gravity and friction in the test set up can greatly influence the success of the deployment tests. Large, thin film membrane structures are more susceptible to the effects of gravity and do not behave in a manner than is easy to predict in flight.

Scaled testing in this project proved to be valuable and educational path for this system design. For future cubesat missions with large deployable, thin-film structures, the project recommends allowing schedule and resources for scaled testing. Facilities to test sails greater than 100 m^2 will be difficult to find. Future projects should reserve time to consider the efficacy of performing full-scale tests and determining the risk posture of accepted scaled tests. Scaled testing with 3D prototype materials, motor sizing calculations, and sail dynamics during testing were the main areas of lessons learned for the solar sail subsystem.

In summary, the mechanism encountered design challenges that stretched the team's knowledge and limited resources. The resiliency of the team and novel approaches kept the project aligned with the class-D mission classification while keeping the overall success of the project in mind. The team hopes this paper will provide valuable information for future solar sail mechanism designers.

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