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Highly Compressible Origami Bellows for Microgravity Drilling-Debris Containment

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The design and testing of an origami-based bellows for microgravity drilling is described. The potential benefits of an origami-based solution created an opportunity for application on NASA's Asteroid Redirect Mission (ARM) to protect sensitive parts from debris. Origami-based bellows were designed to fit spatial limitations and meet needed compression ratios. Designs have demonstrated high mass reductions, improved stroke length, greatly decreased stowed volume, improved flexibility, and reduced reaction forces in comparison with traditional metal bellows. A nylon-reinforced polyvinyl fluoride based bellows with an aramid fiber stitched seam is well suited for debris containment in space conditions. Various epoxies maintained an adequate bond with polyvinyl fluoride below expected environmental temperature for bellows mounting. Asymmetric compression of the bellows occurs at extreme low temperatures and is preventable by balancing stiffness within the structure.

Nomenclature

D = outer bellows diameter
d = inner bellows diameter
n = number of tessellated bellows sides
h = deployed height of single bellows story
H = deployed bellows height
s = number of stories in bellows
δ = deployment angle of single bellows story

I. Introduction

The objective of this work was to develop methods and an apparatus for containing drilling debris in microgravity, specifically for use in outer space and its associated harsh environment. This paper describes the results of designing and evaluating origami-based bellows as a solution for dust containment during microgravity drilling.

The harsh environments of outer space create difficulties when operating space-based mechanisms. Dust and debris,[1] outgassing of lubricants, high mass, large volume, manufacturing complexity, and joint binding

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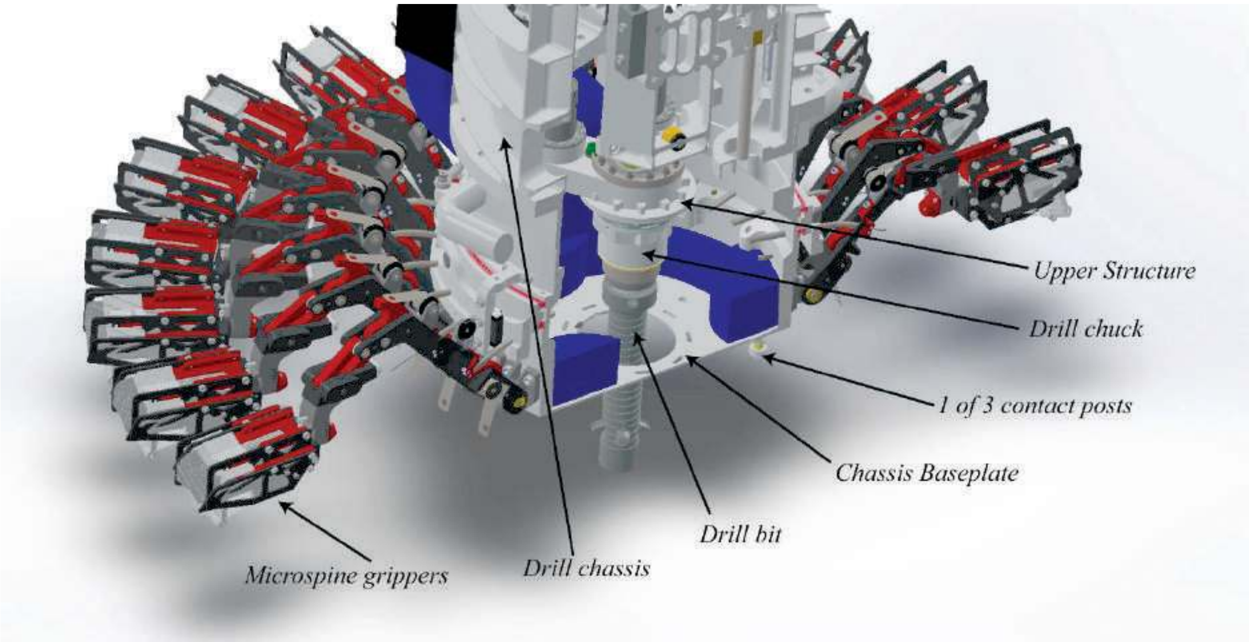


Figure 1. Microspine tool for the Asteroid Redirect Mission (ARM)

increase the risk of spacecraft failure.[2] Many of these challenges can be overcome by employing compliant mechanisms which gain their motion from elastic deformation rather than bearings or hinges. Utilizing compliance in mechanism design can both reduce cost and increase performance by reducing part-count, wear, mass, and maintenance while increasing precision and reliability.[3] Examples of compliance-based space design can be seen in retractable booms and masts,[4] solar cells,[5] and compliant sheet materials for deployable parabolic antennas.[6]

Origami-based mechanisms are an example of compliant mechanisms uniquely suited for space applications. While they maintain many of the benefits of compliant design, they are capable of large compression-to-deployment ratios. Origami-based mechanisms require no lubrication and can be designed using already tested and flight approved materials. Existing origami patterns can be adapted or modeled to design structures with improved packaging and deployment efficiency, thus reducing costs.[7] The benefits of origami-based space design have been demonstrated as viable and effective in NASA's star shade,[8] deployable solar panels,[9] parabolic antennas,[10] pneumatic solar tracking systems,[11] inflatable structures,[12, 13] the James Webb telescope, Lang's Eyeglass,[14] sunshields for space telescopes,[15] and highly compressible bellows.[16]

The benefits of origami created an opportunity for application on NASA's Asteroid Redirect Mission (ARM). The ARM would collect a multi-ton boulder and use the boulder to perform an Enhanced Gravity Tractor asteroid deflection demonstration. The boulder would then be transported to a stable orbit around the Moon where astronauts could investigate the boulder and return findings to Earth.[17]

During the surface phase of the ARM, NASA plans to land the spacecraft on the asteroid, straddling a 1 to 4 meter boulder. Two robotic arms with Microspine Tools (Figure 1) would then secure the boulder before extraction. This sequence begins by aligning a tool to the local boulder surface normal using three contact posts. The microspine gripper then stabilizes the arm and is used to react the forces and torques of drilling into the boulder.[18] Once a sufficient depth has been reached, an anchoring feature in the drill bit is deployed that cuts a groove in the bottom of the borehole. This provides a geometric anchor point with the boulder.[19] The drilling and anchoring operations will create significant debris that, if left unconfined, could drift in the microgravity environment and contaminate sensitive parts within the tool and degrade or potentially inhibit its function.

Shown in Figure 2(a) are axially-compressing metal bellows commonly used to protect sensitive parts of machinery. Spacecraft have traditionally relied upon metal bellows for protection. Bellows are found in a diverse range of terrestrial applications, including machine way covers, cameras, Jetways™, and automobile

(a) Traditional metal bellows.

(b) The bellows will encase the drill bit within the chassis.

Figure 2. Traditional metal bellows and the need to protect the inner ARM drill mechanisms from debris.

seats. In space, bellows are frequently used to protect sensitive instruments and moving parts from dust and debris. Use of a bellows-like device is needed within the drill chassis to protect gears, bearings, and other moving parts as shown in Figure 2(b). During operation, the drill bit emerges from a hole in the chassis baseplate of the tool as shown in Figure 1. Origami-based bellows offer opportunities to reduce mass, improve compression to extension ratios, and lower reaction forces during compression. They also have the flexibility to rotate or bend to accommodate system motion. The manufacture of origami-based bellows is likely to be less expensive than metal bellows.

The improved performance of the mechanism due to increased compressibility of the bellows is shown in Figure 3. An origami-based bellows enables the entire mechanism to be smaller because of its improved compressibility. A bellows with higher compressibility will allow for deeper drill penetration and increase the likelihood of mission success. Previous compliant mechanism research has demonstrated origami-based bellows capable of compression ratios exceeding 1:30, compared to 1:8 for metal bellows, making them a strong candidate in bellows design for space mechanisms.[16] Use of an origami-based bellows would achieve the desired compressibility while significantly reducing mass (Figure 4) and the parasitic reaction forces in the bellows.

II. Background

Mass reduction for space mechanisms continues to be an area of interest within the space community. While optimization techniques can be used to best utilize available mass using traditional design methods, improving packaging volume and geometric form of folded structures shows great potential to reduce mass and improve performance in space mechanisms.[20]

Recent research has shown possibilities for origami-based bellows design, including various origami patterns that can be modified to give predicted results.[15,16,21,22] Figure 5 shows an origami pattern adaptable to various design constraints. This triangulated cylinder, introduced by Guest,[23–25] folds into a cylindrical shape much like a bellows. It provides relatively high compressibility compared with other patterns but requires far fewer folds, allowing for faster fabrication by removing the number of creases required to create the cylinder.

A. Modeling of Origami Bellows

The triangulated cylinder origami-based bellows is designed using mathematical models defined by input parameters for the desired inner and outer diameters, stroke length, and number of sides of the bellows, resulting in output dimensions that will create a physical pattern used to fabricate a bellows. The inputs are dependent upon the spatial limitations for a specific application. Figure 6 demonstrates how the bellows is generally constrained by an annulus defined by an inner and outer diameter. The values selected for the

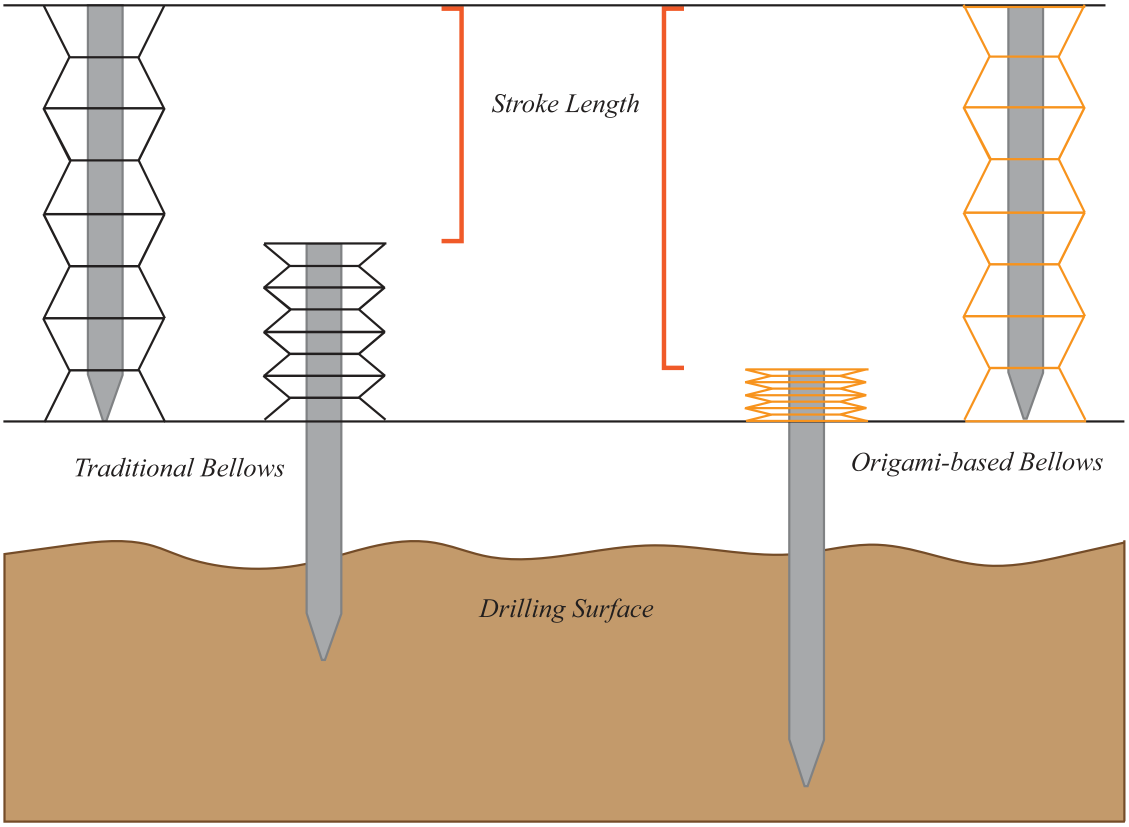


Figure 3. Increased compressibility enables increased stroke length and deeper drill depth into the drilling surface.

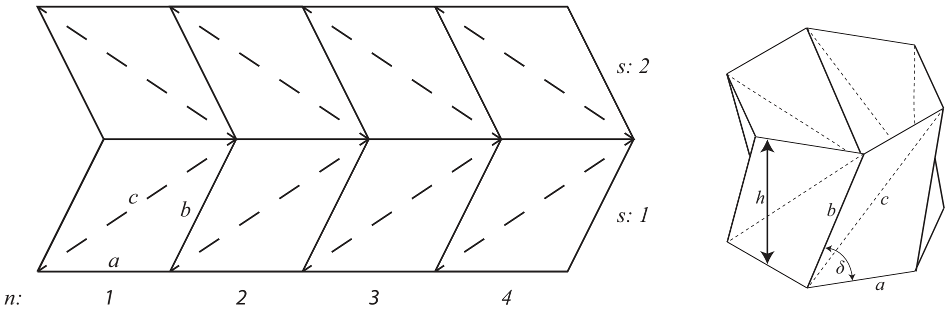
(a) Traditional metal bellows.

(b) Origami-based bellows.

Figure 4. Mass comparison of traditional metal bellows and comparable origami-based bellows.

input parameters will dictate the amount of available rotation and the compressibility of the bellows.

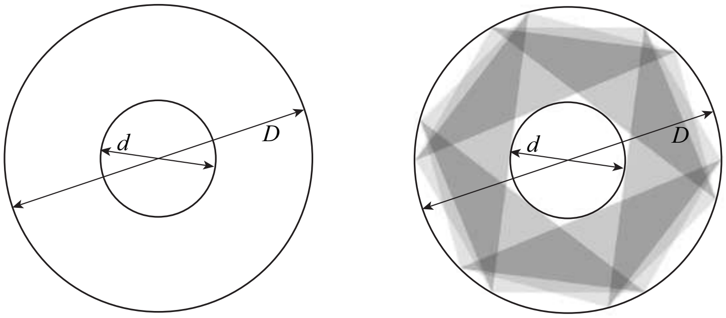
Functions are used to model a triangulated cylinder origami-based bellows using the specified design variables of D (outer diameter), d (inner diameter), and n (number of sides). Figure 5(a) shows the resulting dimensions for each individual tessellated unit within the bellows pattern. The functions to model one of the



(a) 4-sided 2-story triangulated cylinder pattern with defining parameters.

(b) 6-sided triangulated cylinder pattern folded into a single story.

Figure 5. Triangulated cylinder origami pattern.



(a) Annulus defined by inner and outer diameter.

(b) Origami-based bellows fit within a specified annulus.

Figure 6. Annulus constraint for bellows.

tessellation units shown in Figure 5(a) are:

$$a = D \sin\left(\frac{\pi}{n}\right) \tag{1}$$

$$b = D \sin\left(\arccos\left(\frac{d}{D}\right) - \frac{\pi}{n}\right) \tag{2}$$

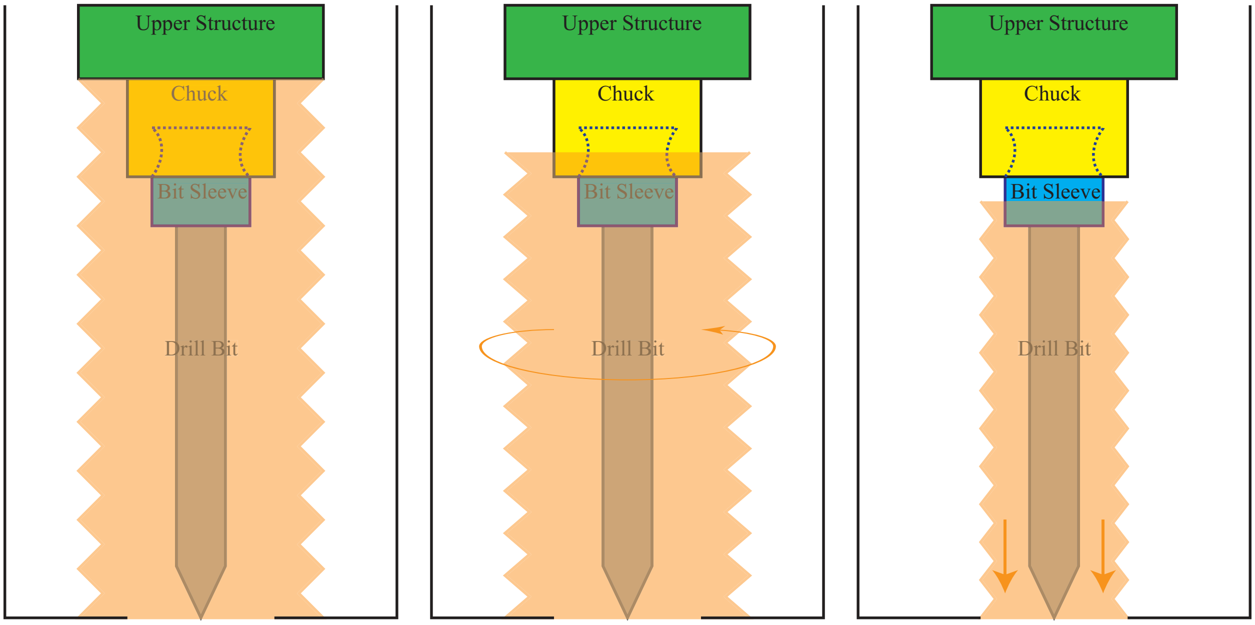
$$c = D \sin\left(\arcsin\left(\frac{b}{D}\right) + \frac{\pi}{n}\right) \tag{3}$$

where a, b, and c are shown in Figure 5. Using the results of these equations, a tessellation unit can be modeled, propagated to create a full pattern, and finally applied to fabricate the bellows.

These equations describe the bellows in a compressed state and are used to create discrete stories, s, in the bellows. While the inner diameter will increase as the bellows is extended, the outer diameter remains constant, thus ensuring the bellows never extends outside of the allotted annulus.

B. Prevention of Crease Inversion

A challenge to origami-based bellows modeling arises when the bellows is deployed far enough to cause buckling in the creases. If the bellows is extended too far, creases can invert, either temporarily or permanently,



(a) Compressing Bellows (b) Rotating Bellows (c) Disposable Bellows

Figure 7. Final design concepts for origami-based bellows.

and cause the bellows to fail prematurely. If the over-extension is only slight, the crease inversion will cycle between the normal and inverted state, greatly reducing the fatigue life of the bellows. If the over-extension is significant, the crease may become permanently inverted and cause asymmetric compression. This catastrophic failure prevents the bellows from providing its intended function and most often deforms the bellows outside of the allotted annulus.

Prevention of crease inversion is done by ensuring each individual story does not deploy past a specified value. Figure 5(b) presents the deployment angle δ, which is evaluated experimentally for given bellows parameters and materials to ensure δ remains below a specified δ_{max} to prevent crease inversion. The full extended length is then achieved by taking the deployed height of a single story, $h_{deployed}$, and observing

$$h_{deployed} = b \sin \delta_{max} \tag{4}$$

It then follows that the full extended bellows height is

$$H = s h_{deployed} \tag{5}$$

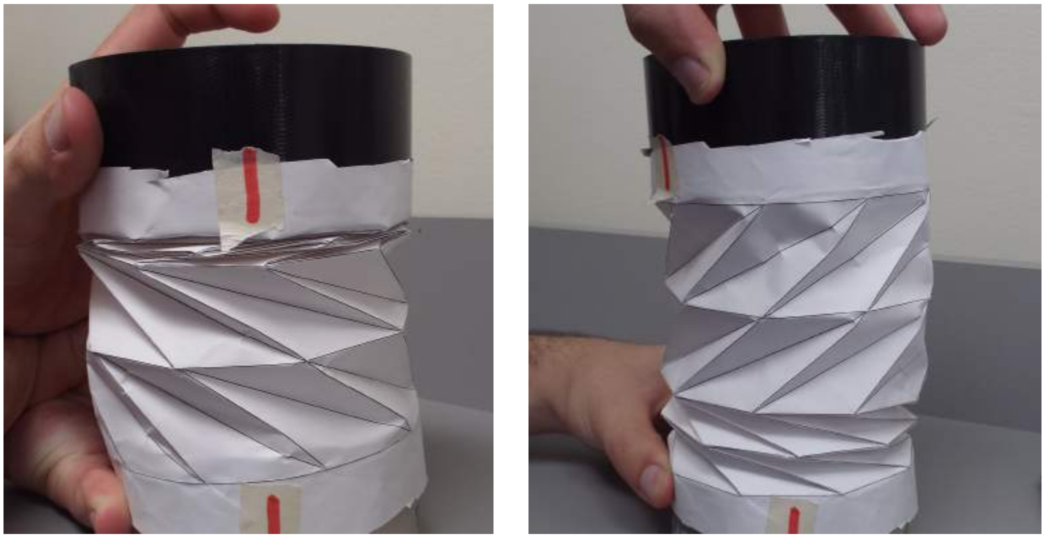
III. Bellows Design

A. Origami Designs

The ARM utilizes a removable drill bit for drilling in the event a bit fails before successful anchoring is achieved. This requires a chuck that will rotate 30° to release a failed bit, receive a new bit, and rotate again to restrain the new bit. The bellows cannot interfere with this rotation and must either avoid or comply with this motion.

The rotating drill chuck is at risk for malfunction due to debris exposure. Debris may accumulate between the rotating parts of the chuck and prevent it from fully rotating. A removed drill bit could also expose the inside of the drill chuck to floating debris and potentially prevent a new bit from successful insertion and retention. The bellows must also remain a safe distance from the spinning drill bit.

Several designs were considered in light of these requirements and are summarized in Table 1.



(a) (b)

Figure 8. Rotation of bellows prototype using origami-based design.

1. Compressing Bellows

The most straightforward design is a bellows that attaches to the structure located directly above the drill chuck. This allows for the largest possible annulus for the bellows to occupy, permitting greater deployment for each story and reducing the risk of crease inversion during deployment. This design maintains the greatest distance from the rotating drill and simplifies mounting and bellows design. Conversely, it exposes the chuck to drilling debris during rotation and bit removal.

2. Rotating Bellows

Traditional metal bellows cannot easily be designed to allow rotation about the axis of compression. The triangulated cylinder pattern is able to compress and expand through collapsing and expanding single-story origami structures. Since each of these collapsing structures rotates during motion, the entire mechanism can be designed for desired rotations at its boundaries when held at mid-stroke length. The compliant nature of the triangulated cylinder pattern could be utilized by attaching a bellows directly to the base of the chassis and to the drill chuck, allowing for rotation of the chuck while protecting its rotating parts in addition to the other sensitive parts surrounding the drill. This would reduce part count and prevent the use of a bearing or bushing to accommodate this rotation.

This rotation is dependent upon the annulus area permitted by the rest of the structure. As the annulus is increased and inner diameter reduced, the amount of rotation in each story of the bellows will increase. If given insufficient space, the rotation of the bellows will be only slight and insufficient to provide the needed rotation to remove the drill bit.

3. Disposable Bellows

Another option includes having multiple bellows, each one living with an associated drill bit. If a bit fails, the bit and bellows would be removed from the chassis and replaced with a new set of bit and bellows. This would allow debris that has collected inside the bellows to be discarded when a failed bit is removed.

While removing current debris is highly desirable, doing so will temporarily expose highly sensitive parts within the ARM to other drifting debris. There are other additional complications, including higher part count and the need for reliable disengagement and attachment of a new bellows.

B. Materials

Research continues to expand our capacity to efficiently protect external spacecraft parts from high-velocity debris impacts.[26] Immobile external spacecraft parts can be adequately protected from expected debris impacts with proper material selection and integration. Likewise, proper material selection for origami-based bellows design can allow for more function while adequately containing debris.

Consideration must be taken for uncertainties in drilling environments to reduce risk of mission failure.[27] Since the drilling surface may contain jagged conglomerate which could impact bellows at relatively high velocities, proper material selection mitigates the risk of failure in the bellows.

Various materials were investigated for use in the ARM bellows, most of which were selected from a range of materials already flight-approved for NASA missions. Their known properties are not discussed here, but much can still be learned about their behaviors related to origami-based design and application in harsh environments.

1. *Kapton®*

A common space material, polyimide (Kapton®) is easily creased and maintains crease memory well. Its resistance to radiation makes it useful for long-term application where exposure to radiation may be an issue. Kapton® has a relatively high tensile strength, but if cut or torn, the cut will easily propagate.

2. *Ultra-High Molecular-Weight Polyethylene*

Ultra-High Molecular-Weight Polyethylene (UHMWPE) is resistant to ablation, tearing, and other abuse. It maintains crease memory and is easily worked. Once torn or cut, UHMWPE is resistant to cut propagation. The material requires a large amount of yield before separation occurs. UHMWPE has a relatively low melting temperature. It is also not a commonly used material on NASA missions.

3. *Tedlar®*

Double-laminate fiber-reinforced polyvinyl fluoride (Tedlar®) is easily creased, does not propagate cuts, and maintains crease memory well. Though it is not as robust as UHMWPE, it has been used in many flights. It provides low reaction forces when compressed or extended. It is less stiff than the other materials considered, making the panels created in origami folding more prone to flexure and bending. This will reduce the axial stiffness, making actuation of the bellows easier, but also reduces the lateral stiffness, making the bellows more prone to buckling.

4. *Vectran®*

Vectran® is a woven fiber from a liquid crystal polymer. It will hold a crease well when heat treated and does not have its properties altered by the heating process. Vectran® has low resistance to UV exposure. It is strong and does not propagate cuts. Its stiffness is low, making creases relatively easy to invert.

Table 1. Summary of key design parameters for origami-based bellows.

	Risk of Inner Chassis Contamination	Risk of Inner Chuck Contamination	Risk of Chuck Rotation Contamination	Complexity and Part Count
Compressing Bellows	Low	Mid	Mid	Low
Rotating Bellows	Low	Mid	Low	Low
Disposable Bellows	High	Low	Low	High

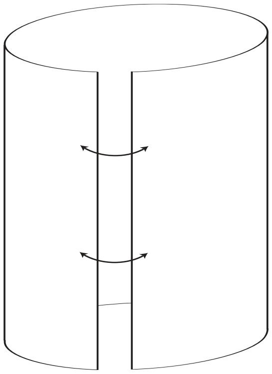
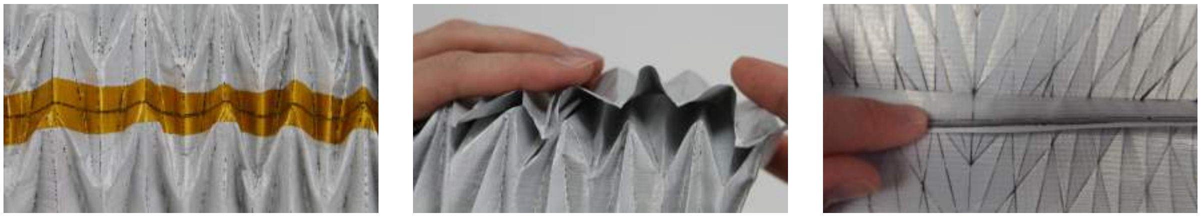


Figure 9. Creating and maintaining an adequate seal is a challenge for origami-based bellows design.



(a) Seam edges placed adjacently and taped.

(b) Seam edges overlapped then sealed.

(c) Seam edges overlapped and flanged outward.

Figure 10. Various configurations for possible seam closure.

5. *Beta Cloth*

A silica fiber cloth, Beta cloth is commonly used in the outer layers of space suits. Though robust, Beta cloth is difficult to crease and has poor crease memory.

C. Seam Closure

Perhaps the greatest challenge to origami-based bellows design is illustrated in Figure 9. When fabricated from a single sheet, the material is curved to a cylinder and sealed at the seam to create the bellows. This requires the seam to both maintain integrity through its expected actuation life as well as perform well under expected environmental conditions.

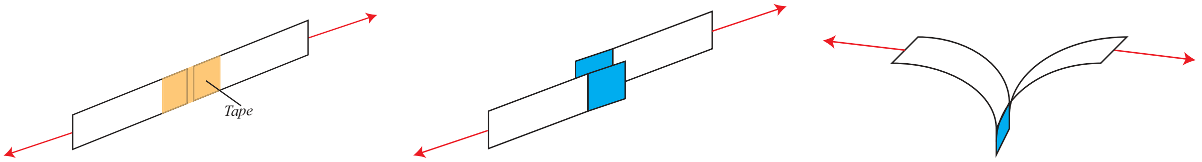
While other methods for fabricating a bellows without the need of a seam are currently under development, this work requires seam closure from single-sheet fabrication. Several options were considered and are presented below.

1. *Tapes and Adhesives*

Adhesives prove to be the simplest option for seam closure. Under standard conditions, many adhesives are flexible, bond well, are easily applied, and have good fatigue life. Difficulties arise when environmental conditions become extreme since not all adhesives are meant for high strain. Poor performance is exacerbated most notably when temperatures drop below the rated temperature of the adhesive.

Several adhesives were considered for application. Figure 10(a) demonstrates how use of a tape allows for seam closure without the need to overlap any layers of material. Kapton® tape with a silicon adhesive backing bonds well at a large range of temperatures and with a variety of materials, including Tedlar®. It has demonstrated performance in field applications ranging from -269° C and as high as 260° C.

Other adhesives considered were 3M's Y966™ and VHB™ adhesives. These adhesives will require an overlap at the bellows seam as demonstrated in Figures 10(b) and 10(c).



(a) Adjacent strips bonded with tape under tensile seam separation.

(b) Overlapping seam under tensile seam separation.

(c) Overlapping seam under peeling seam separation.

Figure 11. Different testing configurations for seam closure design. Shaded regions represent bonded areas.

2. Stitching

Another method to close the bellows seam is to stitch the edge using a high-strength thread. Stitching would remove the ambiguity surrounding adhesive bonding in any temperature and ensure the bellows is always held together properly.

Drawbacks include perforating the material and causing the bellows to be asymmetric. Stitching the seam creates small perforations that could potentially allow small debris to pass through and collect on sensitive parts within the ARM. Asymmetry will also cause one side of the bellows to be stiffer than any other side. This could effect compression and behavior.

Depending on the required life of the parts being protected, stitching may be an acceptable option even considering the perforations allowing debris to pass through the bellows. If the life of the mechanism is low, such as for the ARM drill, allowing small debris to pass through the holes created by stitching will have little impact on the performance of the mechanism. The bellows can also be designed to have multiple stitches to help balance the stiffness to more accurately predict the bellows behavior.

IV. Design Selection

A. Origami Design Selection

Table 1 summarizes key design parameters for each bellows option. While the disposable bellows is beneficial for minimizing contaminants in and around the chuck, the potential risk of debris drifting within the chassis is too great for further investigation. Its features would be more appropriate for applications involving lower risk of inner contamination or where gravity could be a greater influence in controlling drifting debris.

The rotating bellows demonstrates great promise for use and prototypes performed well. However, the annulus limitations within the ARM restrict the bellows from achieving sufficient rotation (30°) for bit removal. Due to these limitations, a traditional compressing bellows was selected for use within the chassis of the ARM. It provides permanent protection of sensitive parts from debris while maintaining simple and permanent mounting to the chassis. The chuck is designed to meet its requirements in the presence of the small amount of debris that may contaminate the surfaces after an aborted drill bit is released.

B. Material Selection

Tedlar® was selected for use in the ARM bellows. Though it does not have high resistance to radiation, it will be housed withing a metal chassis that will shield it from the most damaging radiation. The bellows may be exposed to high-velocity debris, thus leading to Kapton® being rejected because of its tendency to propagate cuts. UHMWPE is not currently approved for flight on NASA missions and has a high outgassing rate. Tedlar's® low axial stiffness make it an ideal candidate for use. The lateral stiffness can be accommodated by providing the origami bellows design with sufficient stories, s, to prevent excessive extension of any singular story.

C. Seam Testing and Selection

Tapes and adhesives were tested for their efficacy by bonding two sample coupons of material and putting them in different testing configurations to test their bond at low temperatures. Expected temperatures for the ARM are above −150° C. These samples were placed in liquid nitrogen (−196° C), allowed to reach

(a) A full sized bellows epoxied within aluminum mounting plates.

(b) A Kevlar® stitch along the seam of the bellows provides sufficient seam closure for expected temperatures.

Figure 12. Final bellows for ARM application.

equilibrium, removed, and then immediately placed under a tensile load. Tests were done using Tedlar® as the coupon material and the selected adhesives and tapes to bond the samples.

All tapes and adhesives were effective in seam closure at room temperature but were unable to maintain a bond with Tedlar® at liquid nitrogen temperature (−196° C). Ten samples of each adhesive were tested. All samples failed to reach a 5 N load before failure.

Coupon testing for a stitched design was performed using the configurations demonstrated in Figures 11(b) and 11(c). Testing showed no significant difference between performance at room temperature and at liquid nitrogen temperature. Due to its permanence regardless of temperature, the ARM bellows was stitched using a Kevlar® thread. The stitch length was maximized to reduce the number of perforations created in the Tedlar®.

D. Selected Design

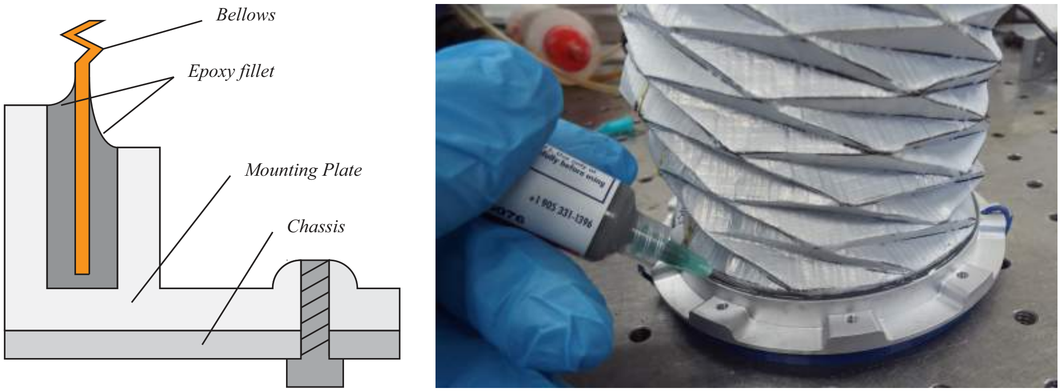
Figure 12(a) shows the selected design for the origami-based bellows. It is secured within two aluminum mounting plates for attachment to the ARM microspine tool. The pattern is designed to fill the maximum annulus available within the drill chassis to reduce the number of stories necessary to reach full stroke length. Additionally, the number of sides on the bellows is $n = 9$ based on recommendations in previous work.[21]

The stitch used to close the seam of the bellows is shown in Figure 12(b). The stitch uses a Kevlar® thread and has maximized the distance between perforations to reduce the chance of debris accessing the inner chassis. Increased perforations also result in lower tensile loads before failure.

V. Fabrication of Origami Bellows

A. Creasing

Origami-based bellows were manufactured by printing a fold pattern onto a sheet of fabrication material. The fold pattern is hand-creased to create the desired bellows shape. Challenges with creasing the bellows using other methods arise when using a single planar sheet to create a cylindrical object that requires a seam for closure. Recent research has shown promise in creasing and fabrication methods of origami, including vacuum forming the pattern into a mold or using a device able to crease both mountain and valley folds



(a) Bellows epoxied within a slot. An epoxy fillet reduces stress concentrations.

(b) Epoxy being applied to bellows and mount.

Figure 13. Bellows mounted within aluminum slotted plate.

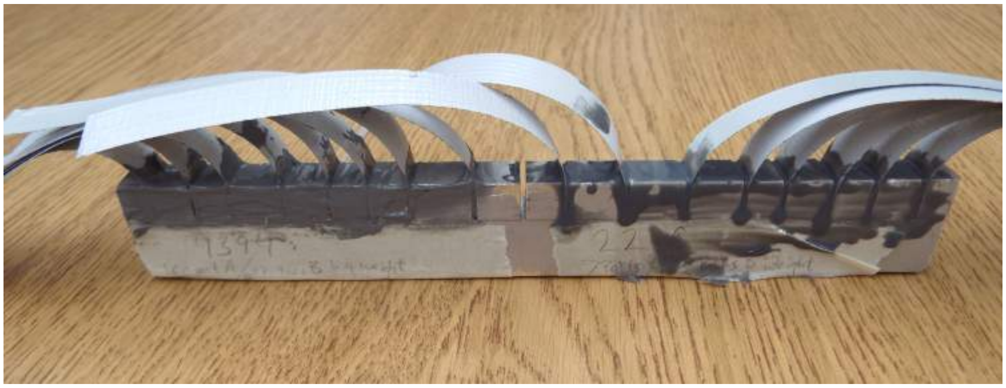


Figure 14. Tedlar® samples bonded to aluminum using various epoxies.

into a single sheet.[28,29] Increased precision in the fold pattern would increase the life of the bellows, prevent unwanted crease buckling, and enable the bellows behavior to more closely match that predicted by the model.

B. Epoxy Testing and Selection for Mounting

Figure 13 shows how the bellows is mounted to the drill chassis. A short tab is left at the ends of the bellows and inserted into a circular slotted plate. Epoxy is used to hold the bellows in the slot and seal gaps. The plate is then bolted to the drill chassis.

It was unclear if the epoxy would be able to hold under expected environmental conditions. Tedlar® samples were bonded to aluminum using both 3M Scotch-Weld 2216™ and Loctite® EA 9394 (Figure 14) and allowed to cure before temperature testing.

During testing, the samples were allowed to reach equilibrium in liquid nitrogen then immediately placed under a tensile load. Results are shown in Figure 15. It is shown that the mean difference in tensile strength using both epoxies was not statistically significant. Failure never occurred at the bond. Rather, all failures occurred in the test coupon, allowing the use of either epoxy for mounting.

The test samples failed first at the edge of the test coupon, shown in Figure 16. Stress concentrations likely led to the failure location. It can be concluded that failure is most likely to occur in the material before failure occurs in the epoxy. While both epoxies performed well, 3M Scotch-Weld 2216™ was selected for its low viscosity, making it able to more easily fill the small gap created by the mounting plate. Additionally,

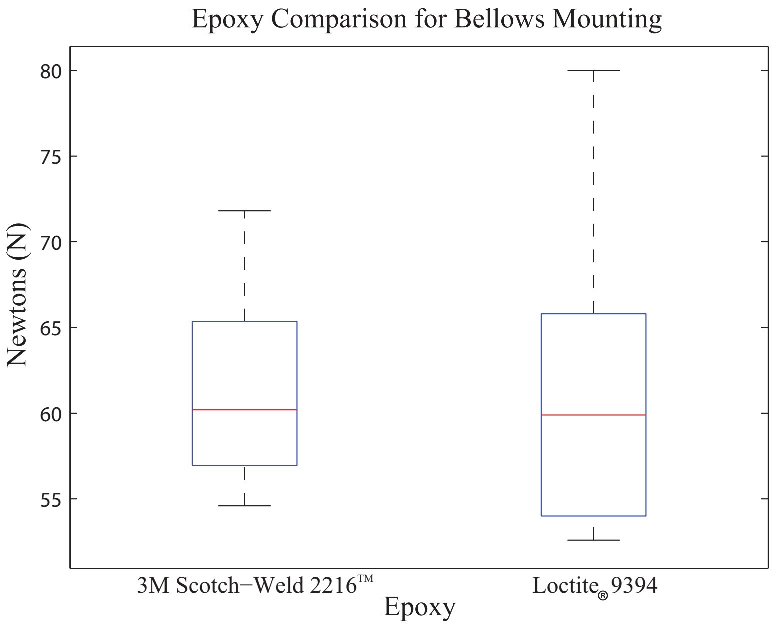


Figure 15. Load at failure between Tedlar® and aluminum. Samples were tested at $-196°$ C.

Figure 16. Tedlar® samples failed at corners where stress concentrations were greatest.

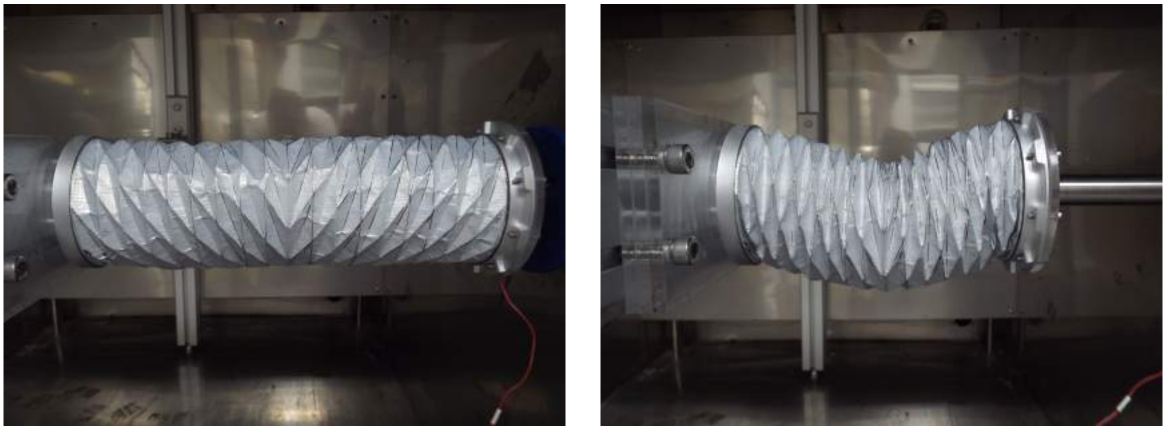
these results led to creating the fillets in the epoxy shown in Figure 13(a) during the bonding fabrication for mounting.

It should be noted that the design of the bellows creates an n-sided polygon per story. The mounting plate for the bellows has a slot for bellows insertion in a circle of constant radius. While the bellows will be slightly deformed when placing the polygon shape into the slots, the deformation is negligible since n is relatively large. For smaller n values, the mounting plate should be modified to reduce deformation.

VI. Environmental Testing

A. Temperature

Figure 17 demonstrates initial bellows performance testing for expected environmental temperatures. The full-length bellows was placed in a cold chamber and driven over its full stroke length using a linear actuator. The testing temperature was initially placed at $-50°$ C and the bellows was compressed and expanded 50



(a) (b)

Figure 17. Asymmetric compression after repeated cycling at $-80° \, C$.

times, whereupon the bellows was inspected for failure. The temperature was then lowered to −80° C and again cycled 50 times before secondary inspection.

The bellows performed as expected during initial cycling. Figure 17(b) shows the results of testing at −80° C. At this temperature, the bellows began to buckle under a compressive load. The side of the bellows that buckled inwards was directly opposite the stitched seam. The most likely cause of this behavior would derive from asymmetric compression. The stiffness within the bellows is slightly greater along the seam. While this stiffness difference is low at room temperature, the material response to changing temperatures augments the difference in stiffness, eventually causing the bellows to buckle during compression.

Tests were repeated with a second bellows. In these tests, the outer seam was trimmed to be much tighter to the outer annulus. The stroke length was shortened by several *mm* to reduce the risk of crease inversion. Tests were run similarly to the first trials but with no observed deformation.

B. Drilling

Figure 18 shows the prototype bellows mounted to the Microspine Tool for full-model drill testing at room temperature. After several months of drill testing, no observable failure has been identified. The bellows has demonstrated no signs of fatigue failure and remains fully intact around the epoxy. The stitched-seam has showed no signs of failure or propagation of perforations. Additionally, debris has been adequately contained as predicted.

VII. Conclusion

Highly compressible origami-based bellows have demonstrated advantages for use in NASA's Asteroid Redirect Mission, as summarized in Table 2. A Tedlar® based bellows with a Kevlar® stitched seam is well suited for debris containment in space conditions. Tedlar® was selected for its crease memory, resilience, and demonstrated use in past flights. 3M Scotch-Weld 2216™ epoxy maintained an adequate bond with Tedlar® below expected environmental temperature. A permanent origami-based bellows provides the needed compressibility while meeting spatial restrictions of the ARM drill.

The current design consisting of a single stitch for seam closure can be improved for high-cycle applications. Possible solutions would include using a pseudostitch along the edge of the bellows opposite the seam to increase stiffness and symmetry during compression. Other solutions will come through future development to remove the need for a seam.

The triangulated cylinder pattern is adaptable to many different design requirements. Origami enables a much greater compression ratio for origami-based bellows in comparison to a comparable metal bellows. The use of an origami-based bellows provides major benefits over metal bellows in compression and possible motion.

Figure 18. Prototype origami-based bellows mounted within Microspine tool.

The Asteroid Redirect Mission drill is only one example of origami-based bellows space applications. Origami-based bellows can be adapted through material selection and crease design to suit a variety of design needs. Origami bellows show great promise in space applications such as shaft protection, deployment mechanisms, supports, or protective barriers.

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Table 2. Summary of traditional and origami-based bellows features.

	Compression Ratio (best)	Mass	Compression Force	Performance in Harsh Conditions
Traditional Metal Bellows	1:8			Satisfactory
Origami-based Bellows	1:30	Reduced	Reduced	Satisfactory

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