Compliant Mechanism and Origami usage in Aerospace and Space Application

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Abstract. It is 2021 of the 21st century, the world is already shifting dramatically towards complex machinery and procedures. A Compliant mechanism can help to make things simpler and elegant by decreasing the member elements in the machinery. We use flexure joints and simple members to perform operations. We focused on the aerospace uses of compliant mechanisms likebistable monolithic devices, deployable arrays by figuring out the origami oblivion applications, temporary or permanent structures, and mainly focused on Aerospace Applications. Well, looking for a more sustainable approach to the current space applications and planetary technologies that can behold the promises of primary mission goals. We mostly rely on rigid mechanisms for performing motions and transmission, here we showcase the actual science behind the flexible deformations lead to easier, cheap, and less complexity to the mechanism. The global sustainability part is considered in this paper while designing and material the components. The thickness of the material brings the mathematical models into the picture by which the origami is structure is formed and graphs analysisshows the compliant motions of the structure.

Keywords: Compliant Mechanisms, Origami, solar arrays deployment, Aerospace and space applications,

1. Introduction

Compliant mechanics comes with problem-solving solutions with bargaining in several parts tally, lightweight, economical, easier for maintenance, shrunk complexity, wear and tear is almost negligible. A combination of flexure components can deliver a significant amount of force and motion transmission ranges from micro to macro usages. The material is generally stiff and elastomeric that helps in bending and allows excess stresses. The beauty of this mechanism is that it stores energy into it and dissipates when actuated and the same energy is used for elastic deformation. The linkages and flexural joints play an important role in this mechanism like the bistable linkage, Morphing of Wing, bending, and many more. The innovative mechanisms are developed in this while using origami and compliant mechanisms having DOF and sustainability of the component with least chances of failure and rupture. As sustainability is achieved by polymer material used as the single-molecule is repeated results in non-reactive, non-toxic, and as well as environmentfriendly.

2. Review of Literature

Hereby in the picture *(Fig. 1)* is the 3D printed titanium alloy made using Electron Beam Melting technology, achievea -90 to +90 degree of flexibility.While developing flexures the minimum thickness and material are Ti6Al4V ELI. Sustainability and environment-friendly factors arise when dealing with titanium, as it is quite complicated and difficult to mine and refining. Also, waste by-products are developed during the process from start to finish. It's not environment-friendly material. Whenvarious components and tools have been developedto achieve design supremacy and enhance the reliability of components. Millimeters accuracy is essential in functioning the mechanism and material with a high stiffness factor is used with durability constraints. [1]

Fig. 1: 3D printed titanium alloy made by using Electron Beam Melting technology, shows flexibility.

Variable Wing's Ailerons and Flaps using a compliant mechanism for high altitude and long airborne goals. Conventional flaps produce more drag and flow separation but this whole mechanism of variable flaps integrated inside the aerofoil as shown in the below picture*(Fig. 2)* cause an increase in L/D ratio by 50% and an increase in 25 % at an Angle of attack 6 degrees; Also it is capable of achieving +10 to -10 degree angle of attack (AOA). As mentioned earlier compliant mechanics simplified the mechanism and make it as compact as possible. Hereby is a picture of an aerofoil with an integrated flexible mechanism.Morphing aircraft structures and wing technology is developing with compliant mechanisms for shaping the future with more possibilities and satisfactory results. [2]

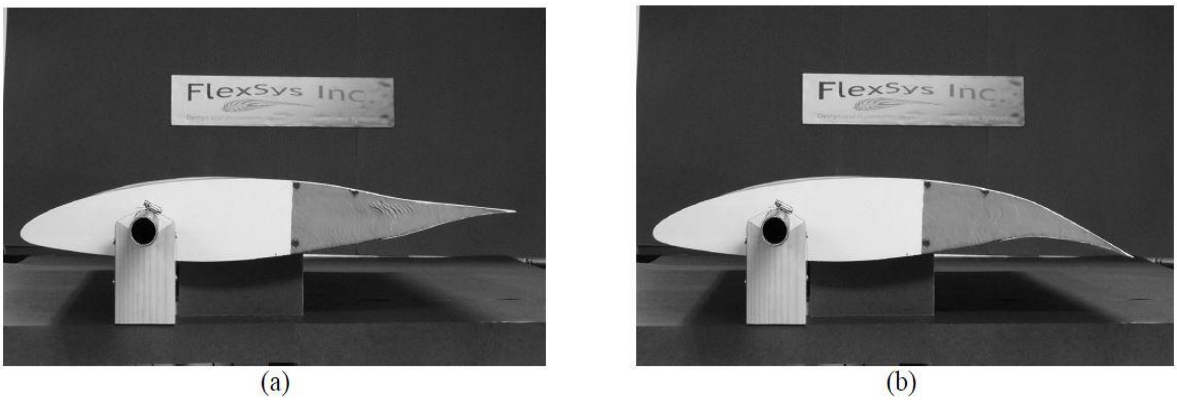
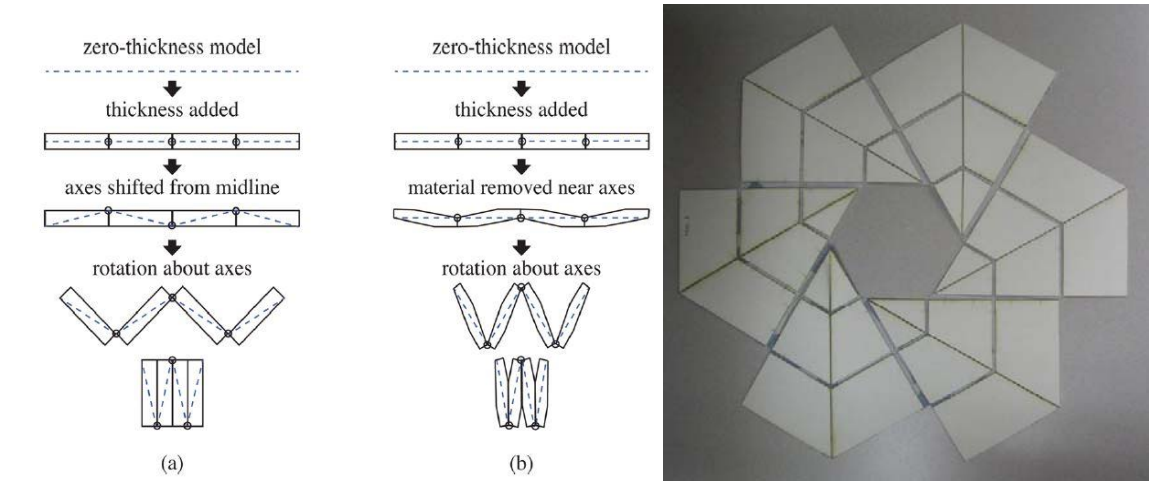


Fig. 2:(a&b) Morphing wing with integrated Mechanisms for variable AOA

Origami is a folding technique that has an origin in Japan since; it has very distinctive applications in aerospace like deployable array solar panels for satellites or spacecraft. Numerous mathematical models and theories are available it considers the null thickness of paper but in real practice, it has a thickness. Hereby is the picture *(Fig. no 3)* depicting the Origami. The most elegant part of deployment with Origami and Compliant mechanics is several unknown failure conditions are eliminated and avoided; For Example, Outgassing, Cold welding, periodically solar winds, Unfavorable temperature fluctuations, etc.



(C)

Fig. 3*: a) shows zero thickness material and (B) shows added thickness material after folding (C) shows the thickness of material resulting in creases with gaps before assembly.*

Deployment of solar panels is always being challenging in space history as the cold welding and improper fittings caused the failure of the missions. This specifically fails missions and causes a huge expense to look after. Compactness is attained over and done with origami and bends should be replaced with a compliant mechanism that could solve the existing complications. [3] Hereby is the picture *(Fig. 4)*is the deployment of the panel made with an intricate design of origami and consisted of 3-4 layers of different materials. As NASA technology is developing under the material identification that should be flexible and durable to withstand extreme conditions and proves compact while in the payload that can be deployed in space as much as wider as possible with integrity. Types of Linkages are found promising like rigid linkage with thin membranes as weight and design optimization.also inspecting the standard graphs and patterns to identify the motions that result in transformations of forces as the system is interrelated and coupled. [4]

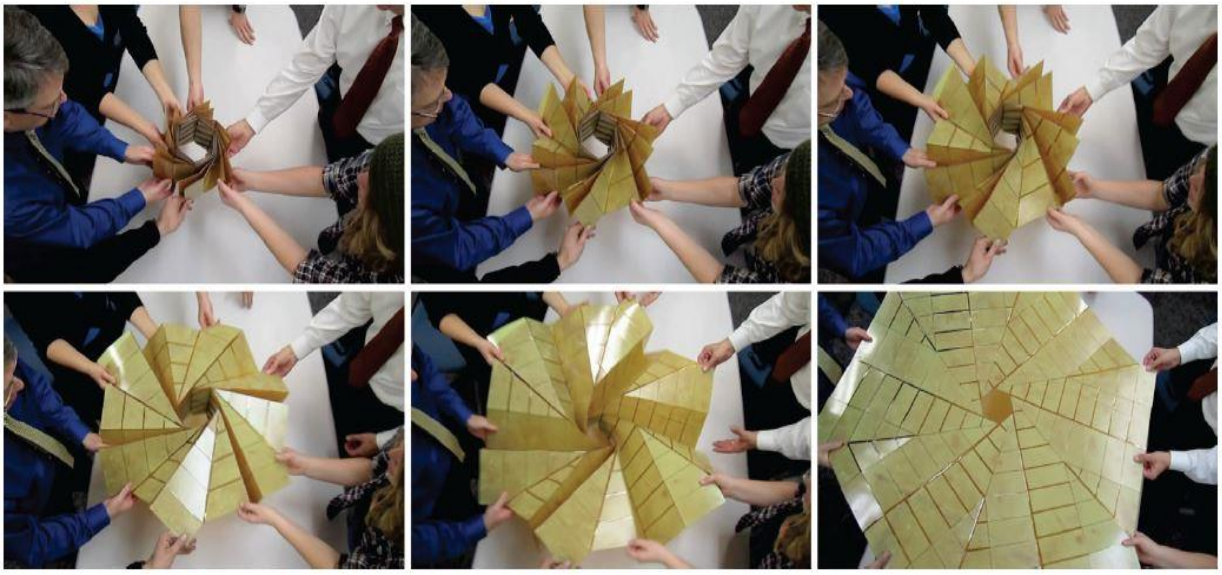


Fig. 4: shows the expansion of the origami solar array prototype with preceding levels.

There are several mechanisms available these days to fulfill the need for modern technology, The Compliant mechanism is one of them to transfer the motions, forces, and transmission of energy. The compliant mechanism is used in various industries and different fields to get desired motions and smooth outputs by using elastic

deformations under conditions. In below Fig. 5 number of day-to-day products that we all use to get things done; are displayed with the implementation of the Compliant mechanism. It has been used in Aerospace applications since the 1950s or maybe before that too! Such a remarkable technology would bring probably big inventions in the coming future. Optimization of design in compliant mechanisms plays a key role as a lot of efforts are required to reshape the actual device or tool. [5]

Figure 1. Compliant tweezers.

Figure 2. Displacement inverter mechanism.

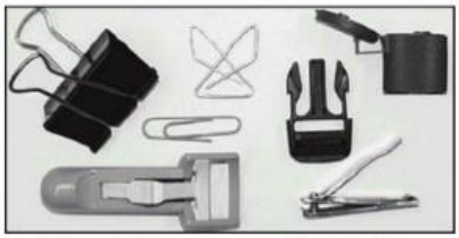


Figure 3. Common compliant devices.

Fig. 5: Shows the daily life equipment and tools made from compliant mechanics and origami.

Space application of compliant mechanisms and origami proves successful at every step of the mission and in problem-solving. Sometimes, mission objectives are compromised due to uncertain failures like friction, joint failures, lubrication leakage, and outreach to the limits of a factor of safety. To be specific all this is a result of the harsh environment of space and catastrophic failure of components. The space mechanism types are listed in *Fig. Number. 6.* The flexural joints can be designed in different applications like revolute, planar, torsional, and many others. The efforts have been made to improve the mechanical performance as well as the optimizing the design perspective to achieve a greater extent of quality performance. Mostly compliant mechanics is used in vibration damping in solar arrays also propellant tank tab flexures, compliant universal linkages, and joints. There are types of space mechanism such as restraint and release, vibration damping, separation, shape control, drive, landing, suspension, pointing, deployable and docking.[6]

In the evolution of technology, the successful merger of compliant in space applications shows pretty good outcomes and shows the potential to the extent of the limits. For example, NASA developed a SoftRide vibration isolation mechanism. Designed and tested successfully for damping the vibration generated in the process. The design parameters are to replace the existing mechanism with a new compliant one; the joints can withstand high-temperature gradients, statically balance joints, high tolerance of deflection of joints (+90 to -90 degrees) as shown in Fig. 6 below [6].

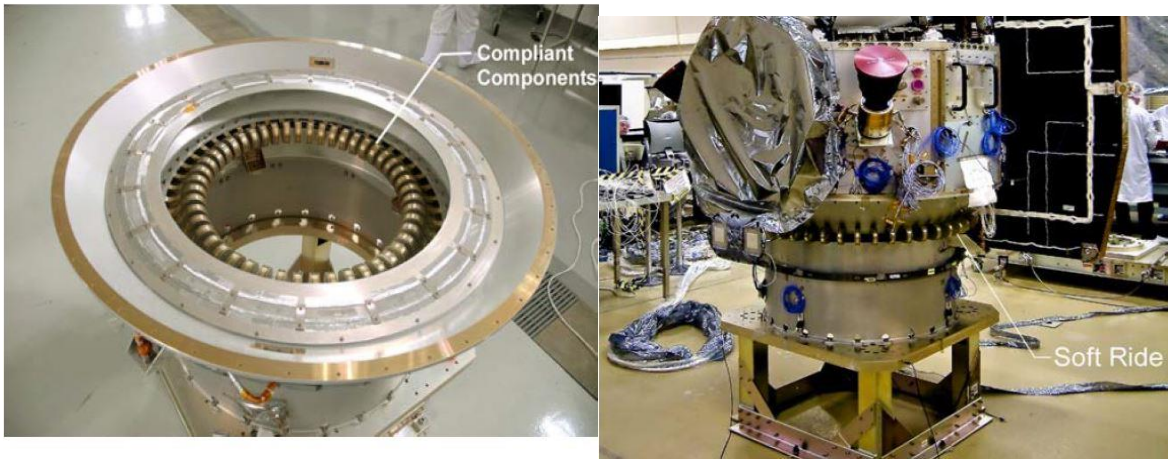
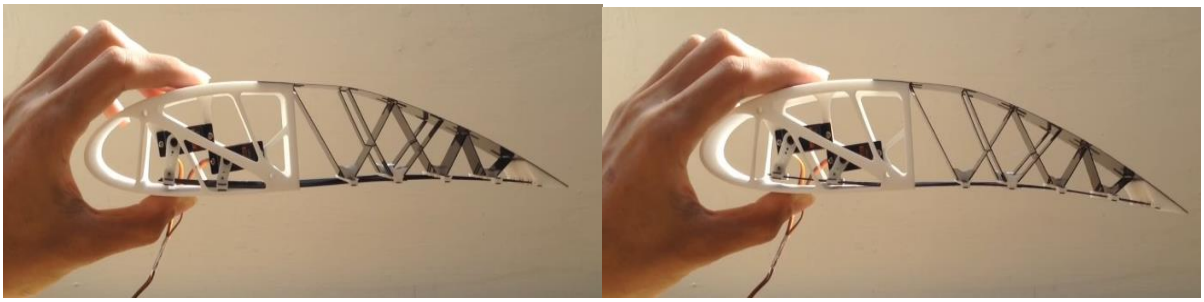


Fig. 6*:SoftRide (Name) Vibration isolation mechanism. Compliant segments are labeled.Courtesy of U.C. Berkeley.*

Advantages of using and researching complaint mechanism in space applications to enhance the accuracy, endurance of the particular space mechanism. A compliant mechanism can be used to replace the hinges, joints

dependent parts with a simple monolithic compliant mechanism. The Flexural joints can sustain in harsh vacuum conditions. In most cases, Solar wind is the main cause of failure of mission as the satellite is unable to maintain its course. The mechanism must be developed in such a way that no off-axis movement and motion can happen and no other factor harm or mal-functionalize the part. [6]

Morphing wings with the use of a compliant mechanism by using a unit cell truss *(clamped)*to build a complete structure of the wing and converting the wing of NACA 23015 to FX60-126. Also, the Morphing wing can withstand altered weather conditions and is found promising with effective results. As it includes changing the whole structure, the unit cell truss are joined together in such a formation that when the couple forces act upon the wing it changes its shape. To be specific they are clamped at multiple positions as shown in *Fig. 7.*



(A) (B)

Fig. 7: (A) shows the linkages made for the morhphing wing while (B) shows the stretched membrane resulting in variable wing shape

The Morphing Wing design developed by the author and tested under circumstances the initial topology can be seen in Fig. 8 [7] as discussed earlier the wing can make the suitable difference when comes to the conventional design of a wing.

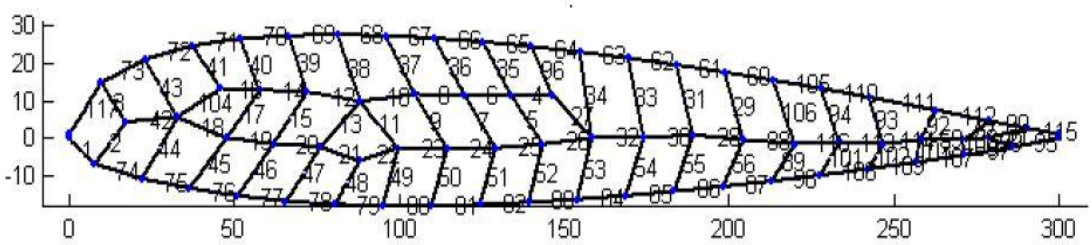


Fig. 8: A topology made for morhphning wing linkages determination and load test.

Tape Spring is used to demonstrate the model of bending with the goodness of non-linear mechanical behavior, the ends of the tape springs are generally clamped to get them as much as possible simpler and less complex structure. The bending mechanism can be made as unidirectional and bidirectional depends upon the need like a didymous. In*Fig. 9* the elastic deformation of this results in regaining the original shape but adding extra load leads to reach Maximum angle of fold in tape spring. However, disperse the stresses with unloaded and thereby reduces the extra parts in the conventional designs.The joints and linkages are subjected to equal deformations or an equal sense of bending. During unloading the original shape regains with a small angle which is quite negligible. [8]

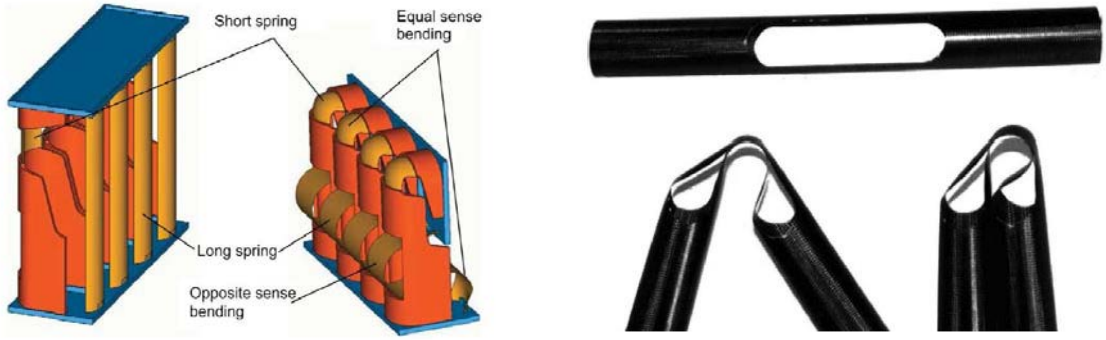
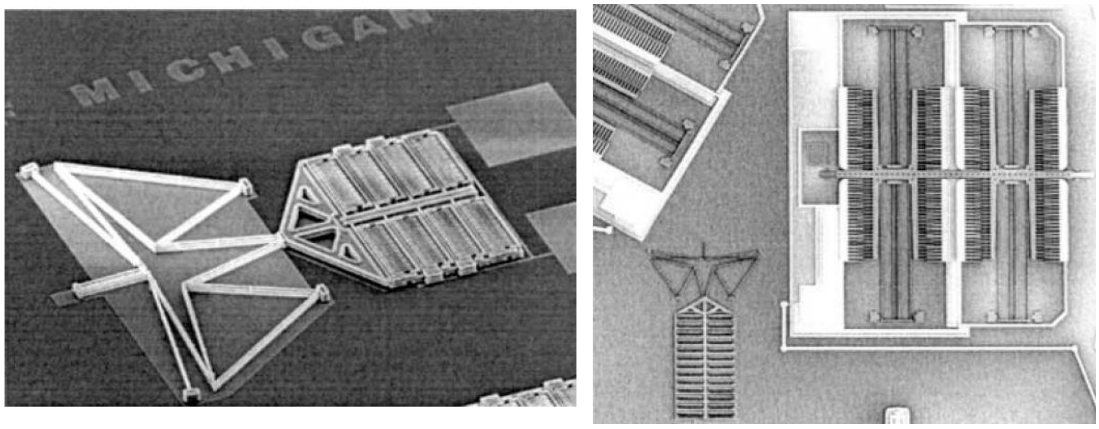


Fig. 9: Linkages when bent and deformed as requirement and when load release coming back to original shape and with maximum efficiency

The MEMS acronym is 'Micro-Electro-Mechanical Systems' is a method used by the industries from last few decades to increase area and workefficiency, The stiffness of the material is increased to achieve more structural integrity, as well as the capacity of the permissible load as well as stress is increased. Moreover, it is a micro-scale fabrication that is achieved by computers and all possible factors of safety and performance are highly promising with significant results as one example can show in *Fig. 10* Various surgical types of equipment and robotics arms are inspired and developed that reduces the part count by 75% which is a significant count when comes to the question of Manufacturing and cost-effective product. The sustainability of these mechanisms as they are made from basic polymer materials and reusable. The material can be recycled using techniques, although it is environment friendly and durable in harsh conditions of the outer atmosphere.[9]

- Highly Compact and tiny
- Geometrical Superiority
- High Energy and work output efficiency
- Force and Displacement Amplifier
- Cost efficiency
- Optimized Design and Topology



(A) (B)

Fig. 10: The application of compliant mechanism at a micro-level (B) shows the strokes multiplier

The Monolithic tools and devices with bi-stable mechanisms are very useful in space applicationswith stable and consistent deflection. Rapid motion is achieved when actuated as the energy release is constant and significant. The permissible stress had a high range that can withstand a million repetitions that would be promising in the further development of aerospace application in monolithic devices. The FEA has shown in *Fig. Number11* represents the deflection and stresses acting as well as the structural and design optimization achieved in this bi-stable

mechanism.InFig. no 12, the release of bi-stable Mechanism in second stable condition can cut a rope with high resultant force; can perform other function just need to be actuated. [10]

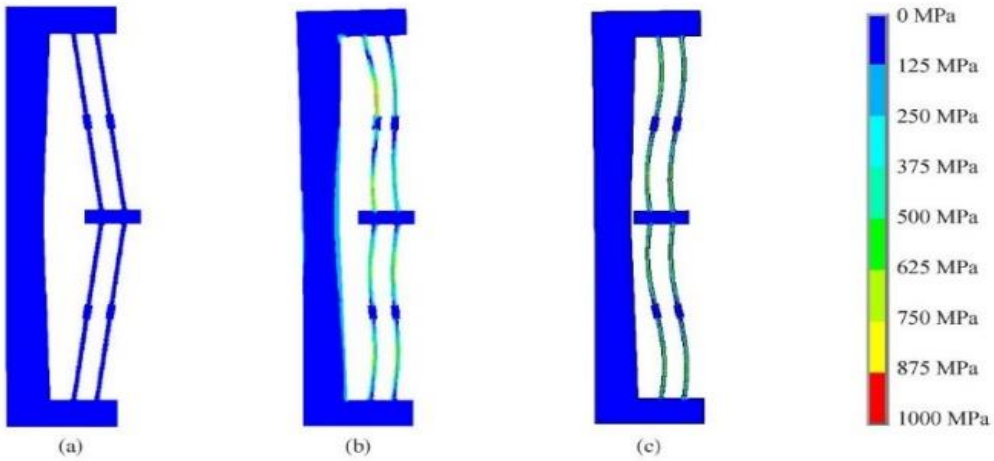
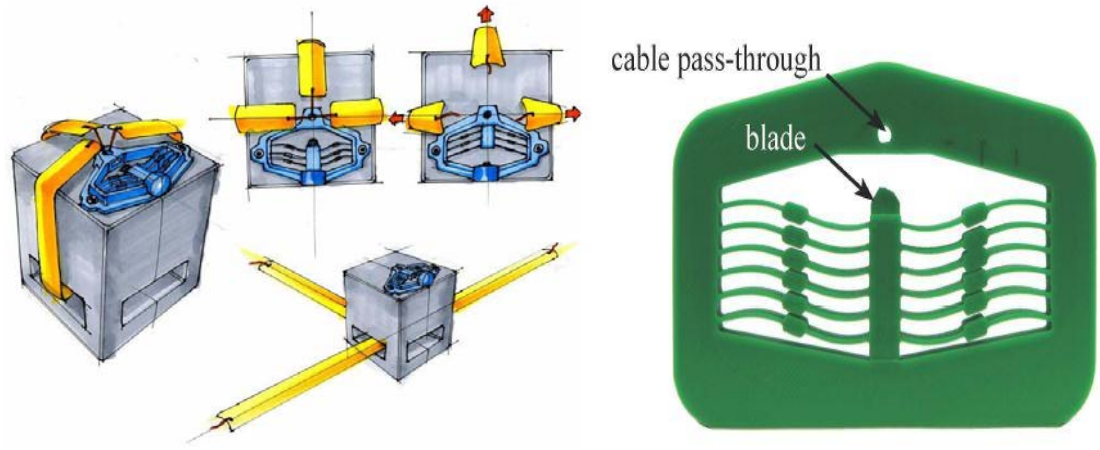


Fig. 11: The bistable mechanism analysis with loaded shows the two stable positions.

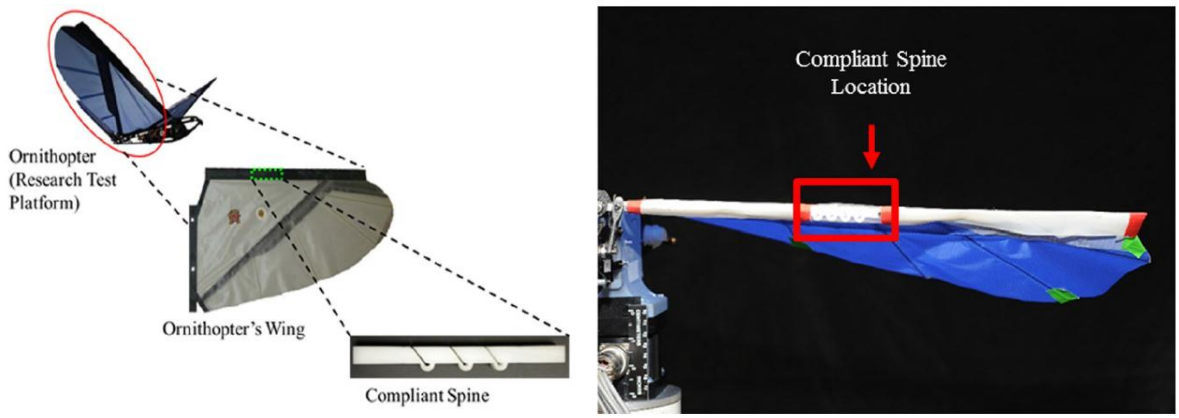
The Cubesatesatellite used very complex mechanisms for the deployment of solar panels arrays, in *Fig. 12* shows the release of flexural material with internally stored energy which is released when the bistable Mechanism's blade moves it to its second stable position cuts the string resulting in the deployment.



(A) (B)

Fig. 12:(A) The application of a Bistable wire cutter device applied to a satellite for the deployment of segments. (B)Bistable Mechanism device used for cutting wirewith added more strands on either sides.

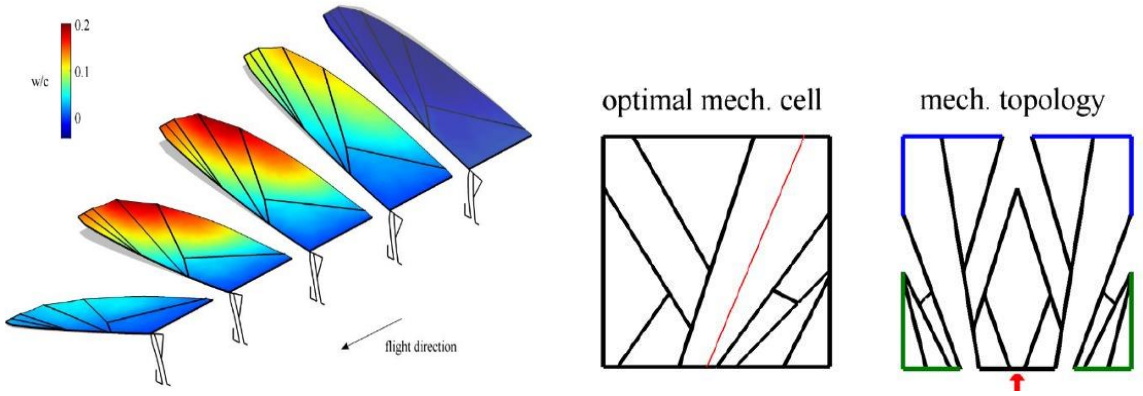
The Fabrication of ornithopter is challenging as well as time-consuming; the basic problem encounter with the development of ornithopter is the lift to weight ratio, the flap's deflection doesn't promise the life requirement Cd value is significant to counter this problem they develop heuristic optimization algorithm which is an optimal iterative solution to a problem. The Compliant spine (CS) is incorporated in the span with two compliant joints as relaxation of stresses during flight as well as maintain the lift with structural reliability as shown in *Fig. 13*, the polyamide thermoelastic polymer material is used for fabrication, for example, Delrin, Kapton not cheap but can tolerate the -360 to +360 degree Celsius temperature. The bistable also helps to bring down the expenses of the manufacturing process with less eco-friendly materials.It is reliable to manufacture and sustainable in every approach to an extent. [11]



(A) (B)

Fig. 13: (A) shows the compliant spine used in Ornithopter (B) shows the location and overview of it.

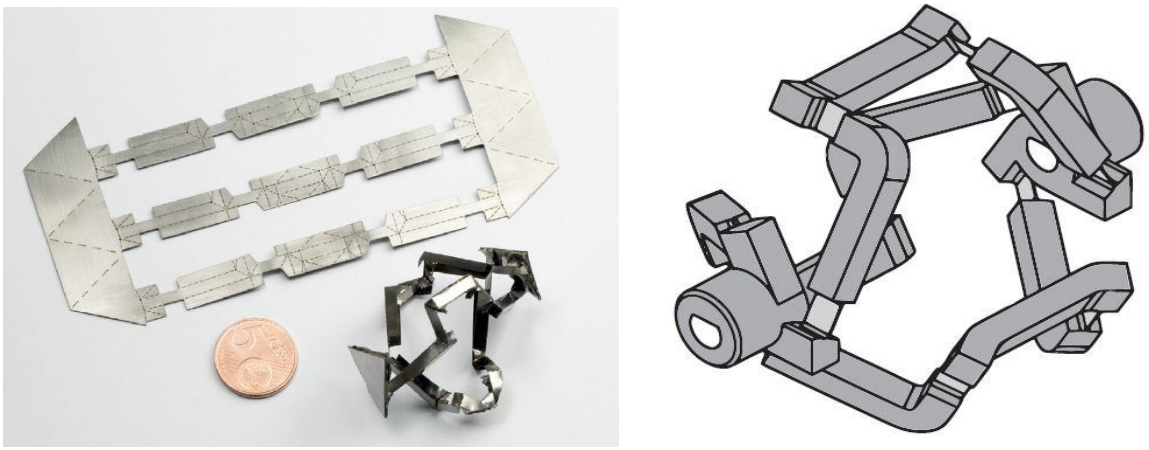
The Compliant Spine is attached to the ornithopter as can see in the picture, the author also did load and stress analysis for further development. The concept of Orinithopters came from that era of Leonardo the Vinci & Sir George Cayley and early researchers think about such an object that can attain a flight. A similar thought is being processed with a flapping wing with topology with optimized design; by using the compliant mechanism, bends the linear wing to get the patterns and constraints as shown in *Fig. Number15* theAeroelastic deformation causes an increase in a swept angle (flapping angle) that increases lift and enhances aerodynamics performance is observed. [12]



(A) (B)

Fig. 14:(A) Shows the analysis of the Aeroelastic deformation that causes an increase in a swept angle. (B) depicts the optimal topology of wing.

Compliant Homokinetic Coupling has stupefied application in space flights as we know thrusters are used to propel the spacecraft in space but the spinning motors and complex machines behind the thruster come with a pretty huge budget and R&D. this coupling is recently created and used to transfer the motion between two angled axis, this folded mechanism made with origami and complaint mechanism can be incorporated with only two motors to propel the thrust in every possible direction for maneuver. The part count and capital expenditure reduces to half and thereby make every space flight inexpensive and reliable. In Fig. 15 showcases the folded origami pattern with the compliant mechanism. The Complaint linkages emerging from the 2D cut out as seen in the Fig. are having a high aspect ratio and have very little error in the crease folding pattern. The coupling is reliable and design optimized. Sustainability comes into the picture when dealing with sheet metal and scrap produces during manufacturing, the scrap is generally recycled and smelted again to roll into new sheets. [13]



(A) (B)

Fig. 15 (A) shows the small structure made by origami as well as compliant mechanics and use for thruster navigation and shows the application in space and planetary science (B) graphics design of Homokinetic coupling.

The fabrication of solar panels with linkages and the use of origami is delicate work with precision and time-consuming. In this paper, the author made the fabrication of bulletproof foldable sheets using fibers or Carbon fiber with epoxy resin transfer into it with vacuum pressurization technique. At foldable gaps will allow the assembly and sandwich structure is made similar concept can be implemented in solar panels fabrication with polymer tapes and other sandwich material like Delrin, nylon and other polyamides material which clears the parameters.[14] In Fig. 15 the fabrication process is displayed.

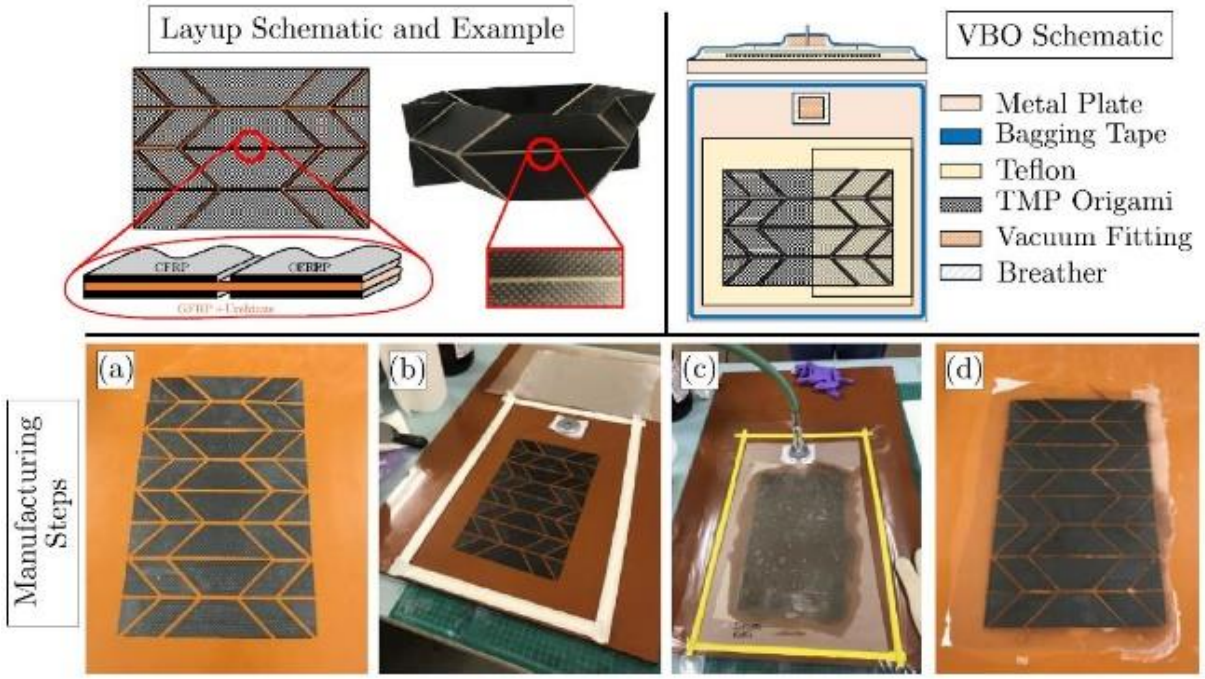


Fig. 16: The fabrication process for origami with creases and assures the foldability of a sheet.

3. Critical Analysis

We think technology develops astime passes and now is the perfect timing for the implementation of technologies which is reliable, sustainable, and more efficient with less failure percentage. As the work done by several authors and researchers on compliant and origami applications, the mechanisms are very structurally sound and restraining the kinematic behavior. The thermoplastic material has flexibility and ability the to retain its shape after deformation. The Bistable mechanisms havetheir significance when comes to solve the deployment problems. The authors also put efforts to meet the global sustainability and growth of the future. They made it sustainable and quite reliable with promising performance meeting with parameters of space application and efficiency.

4. Inference

Nature is being always a compliant ever since we know science and mathematics, for example, the wings of a bird to the flexible muscles that help to perform various activities. The compliant mechanisms are guiding the future on the path of sustainability. The cutting technologies make it possible to cut out the layout turn it into folding prototypes rather than using conventional methods leads to errors in dimensional accuracy. The primary objective here is the modification results in existing models are astonishing. Further various analytical tools are used, for example, tape spring's thickness, youngs modulus and other parameters are taken into consideration. The morphing wing results in performance and vibration damping in space application (Softride). The fabrication is also reliable and when comes to meet the criteria, it is very promising. Reduces time, labor hours for making complex rigid mechanisms that required various expensive tools and machines. Origami shows its compactness and durability of linkages could bring the path to sustainability and cost-efficient space programs.

5. Conclusion

Compliant Mechanics and Origami has a wide range of applications in Aerospace and Space. In recent years reveals the importance and urgency to keep the R&D ongoing. With enhanced use in space applications of these different mechanisms can makes a difference. Compliant joints and linkages are found promising in the field of biosciences, Aerodynamics, space dynamics reduces the part count makes it simpler and enhances the performance of the mechanism. The rigid origami structures are developing with the hope of better performance and brighter future technologies. With a novel and scalable approach to the design of wings and space application, it would bring revolutionary changes. The benchmark study of fold compliant mechanisms brings new possibilities in design and fabrication. We proposed some of the literature to showcase the applications and benefits as well as the favorable conditions. The more and more usage of origami and compliant mechanism in space and aerospace applications is another revolution or another step for moving ahead with technology because everything is possible with technology.The origami and compliant mechanisms are studied in graph patterns to analyze their resulting motions. The deployable solar arrays with the least thickness could mark the path to high deployed diameter panels.

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