EE5318: Biomimetic Design

Project Report

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1 Synopsis

1.1 Nature

Many biological beings are equipped with systems for locomotion, defence etc., which are radically different from the mechanisms we would see in mechanical objects around we build. For example, we have wheels for locomotion but whereas the occurrence of wheels around in nature is very fewer. There are several creatures which have capability to do increadible things. Creatures like mantis shrimp, trap jaw ant, froghopper etc. produce tremendous magnitudes of accelerations and speeds just due to elastic deformation of their bodies. With the rise of biomimetic robotics, such mechanisms are crucial and are important to achieve locomotion in difficult terrains, motion during natural calamities or to move or displace objects many times the mass of the robot itself. A mantis shrimp is able to produce such a great force even in water. So, such creatures which manage to generate huge forces many times their own mass and can be an inspiration in designing a mechanism to break space rocks for dust collection.

1.2 Compliant Mechanisms

Most of the devices we interact with daily are mapped to the physical world to complete a job through some mechanism. Most often these mechanisms are built of rigid links and cams connected through rotary, prismatic or any other joint. But if one observes carefully none of these are actually present in the natural systems optimised through evolution. Natural systems achieve motion through deformation of some body components. Such mechanisms which undergo motion through elastic deformation of the body are called compliant mechanisms. These mechanisms have a great advantage over the conventional mechanisms, that they do not have conventional joints. In conventional mechanisms links are connected through joints which are subjected to high wear and tear during relative motion. Such a situation might cause reduction in life of a system. Since motion is achieved through elastic deformation in compliant mechanisms we can improve the life of the mechanism. Fatigue might be a concern in such a mechanism, but limiting the application load frequency would greatly improve the fatigue life of the systems. They carry great potential in space applications as continous supervision for friction and lubication of joints can be prevented. They also provide unconventional mechanism design methods which gives us a larger design space exploration along side the conventional mechanisms.

2 Literature review

The design should accommodate the hard rocks and the available energy in the rover to achieve the required functions. A compliant mechanism is used so that the whole design is compact and free from joints which is crucial for such a purpose. Modeling the mantis shrimp arm and muscle forms an integral part in achiveing the solution. Many attempts have been made to formulate and quantify the nature of mechanisms. S. N. Patek et. al.[1], have tried in modeling the muscle and bone groups using an approppriate four bar mechanisms as shown in the figure. Another study[5] shows how the arm has a kinematic equivalence to the a four bar mechanism.

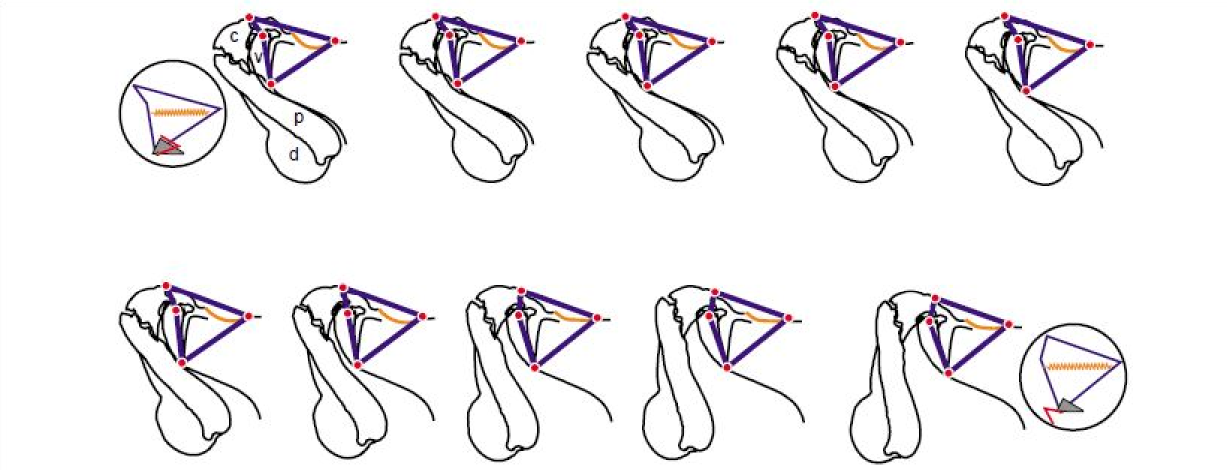

Fig. 8. A tracing of a typical strike sequence from high-speed video images with the links and pivots of a four-bar linkage mechanism overlaid on the tracings. Shown from left to right, images are 0.4 ms apart with the exception of the final two images, which are 0.2 ms apart. The saddle is colored orange; v, meral-v; c, carpus; p, propodus; d, dactyl. Insets illustrate schematically the compression and release of a spring (orange) and the braced and released position of sclerite 2 (red sclerite, gray brace).

Figure 1: Modeling using four bar mechanism

Since the smallest link is attached to the bone which propels during impact, the orange tissue pushes it using the stored energy and thus achieves the impact force required. In this method the amplification of the force might be described but the true nature of the problem of muscle has not been captured and also have the inherent limitations of any mechanisms like wear, friction etc.

In another study, the mechanical impact characteristics of the mantis shrimp's tendons have been tested by J. R. A. Taylor et. al. This provides a clear picture on the mechanical properties which have been studied under micro-CT scan.

Another important study by the Patek lab has discovered the significance of a saddle like structure on the muscle which is responsible for storing of large amounts of energy and then using it against any prey. This structure has later analysed to lay a starting step to design a mechanism later in the later section of this report. The saddle is modeled as a spring with residual spring force and the others as links are discussed in the above paper as below.

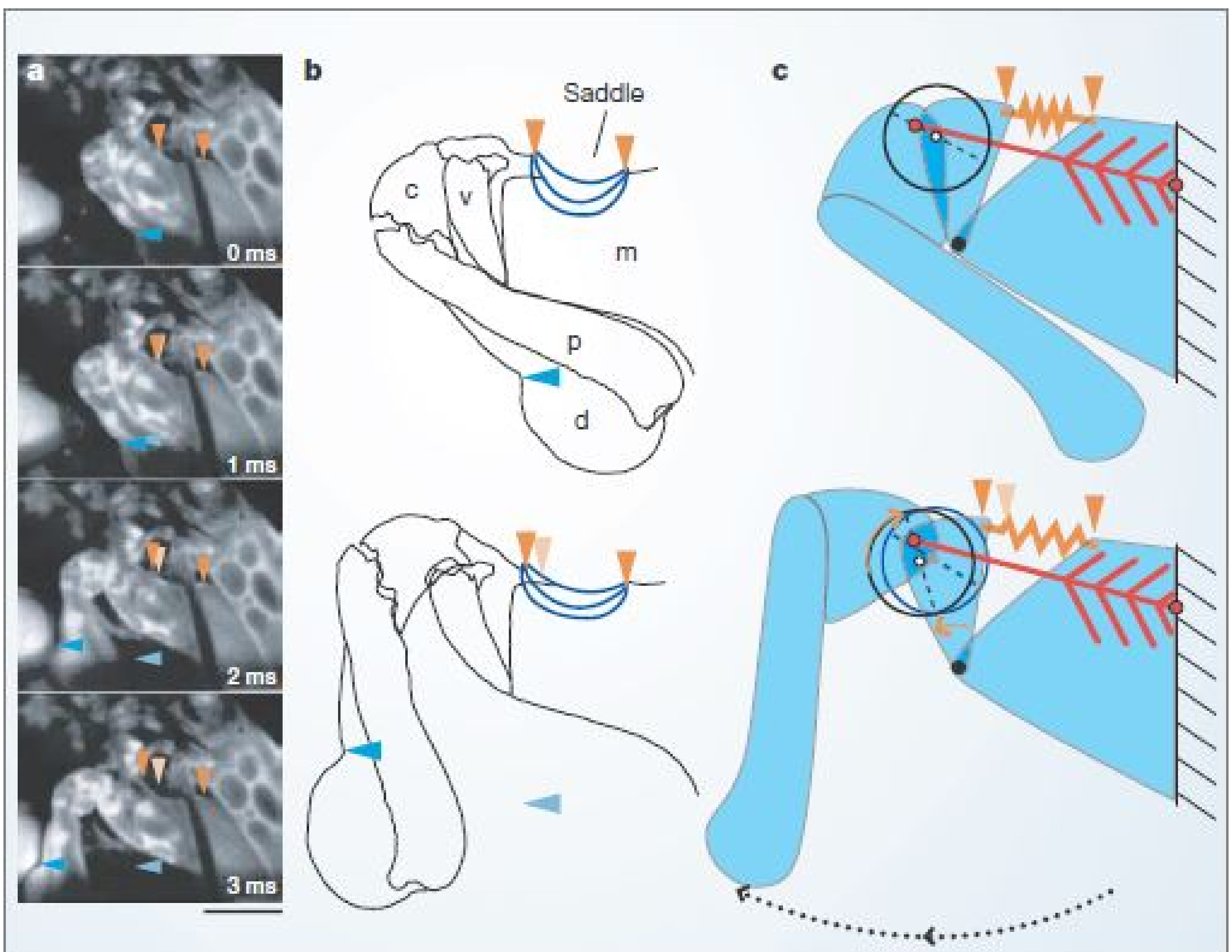

Figure 2:

Another study models the same in a hybrid manner using both the concepts of mechnical links and springs and also using fundamental lever mechanism. This is more near to the practical situation by incorporating a latch, spring and hammer mechanism. The proposed mechanisms is as below.

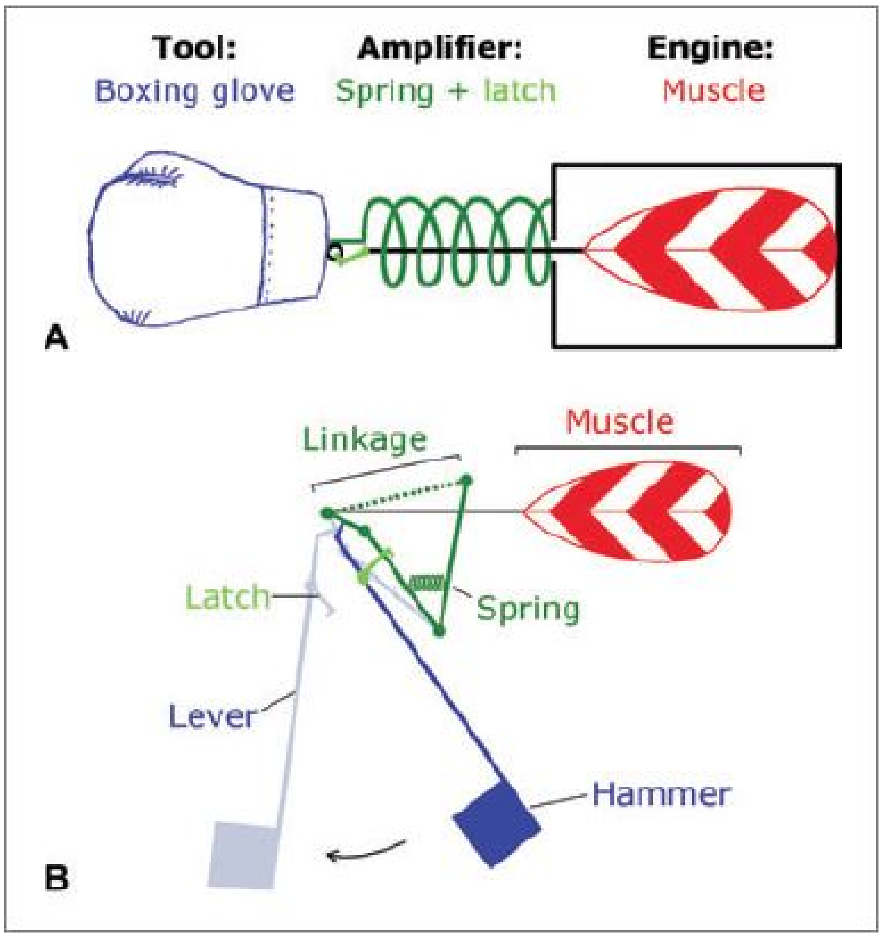

Figure 3: Hammer and latch type mechanism

Another study by S. N. Patek shows the inherent springs involved in the design and has characterised them. Using spring mechanics models they were able to model the loded and inloaded cases of the spring saddle of the muscle. The modeled mechanism is as shown.

3 Problem Statement

3.1 Description of the problem

The field of space exploration has challenges which have a different setting from the conventional problems. One of the major tasks for a space exploring rover is to collect samples of dust, soil and any other required lump of mass on which various tests are done to determine the properties of the material. In the curiosity rover, it is equipped with high energy lasers which blast high energy radiation to burn the lump mass to dust and then collect the dust. This might cause a loss in properties of the material. Compliant mechansims have a major application in space exploration as they do not have any joints and thus no wear and lubrication required. Comsider a situation where a sample might be required from a huge mass of rock. A mechanism which is able to break the lump first and then use the onboard manipulator arm to collect the dust generated would greatly reduce the energy spent on shooting lasers and also would extract the sample without heating and might preserve the properties.

4 Design

4.1 How does your design solve the problem

Drawing inspiration from the above works, the report tries to overcome the inherent problems of mechanical wear and tear, friction. Also in a space environment assymmetric heating

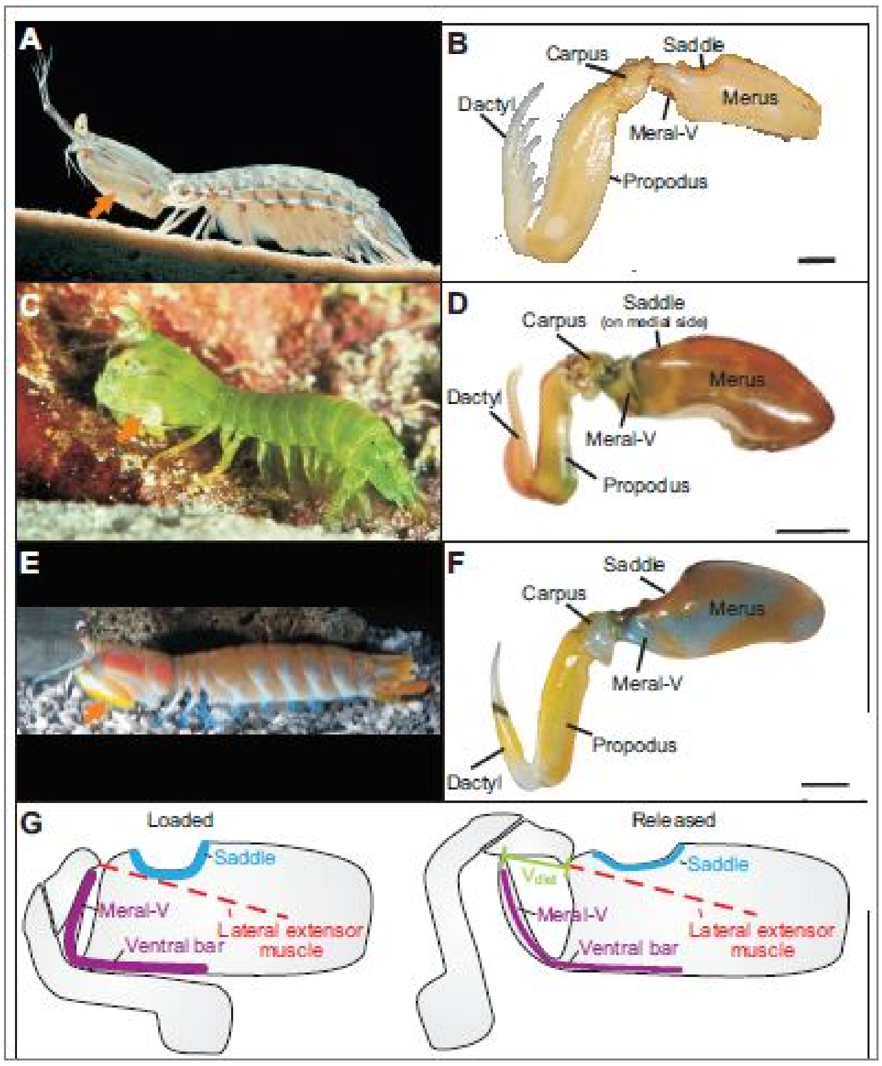

Figure 4: Spring loaded mechanism

of components would lead to ill functioning of the components. Whereas a compliant mechanism would have very less or no assembly and hence would have isotropic expansions. To understand the working of the saddle an FEA has been done in ABAQUS and the results are as shown.

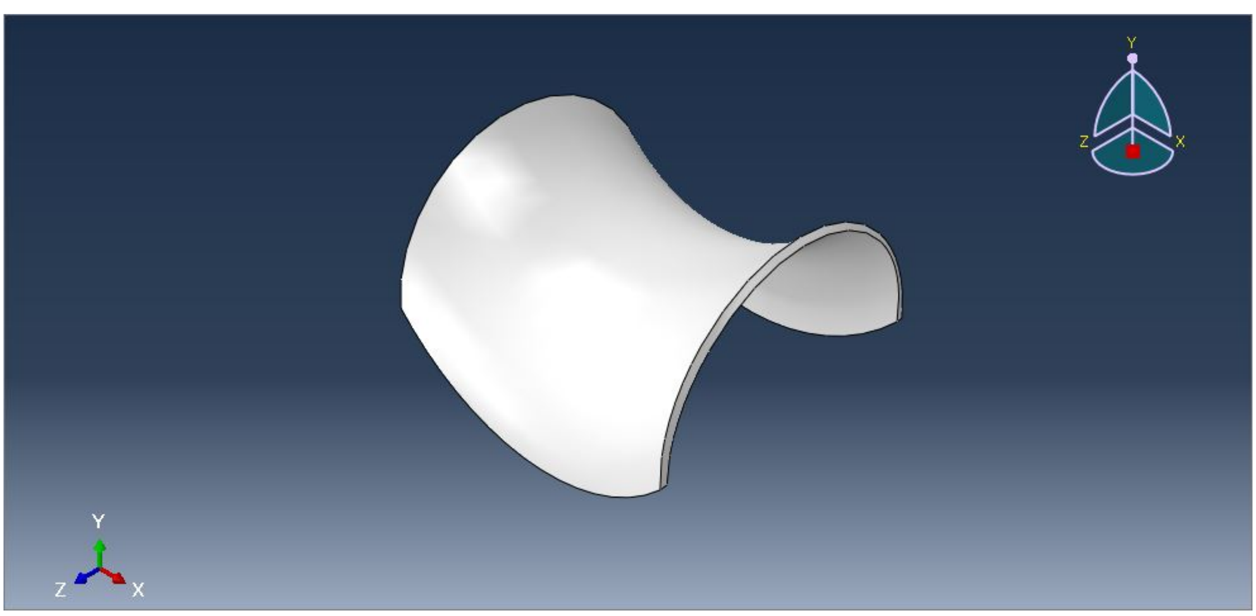

Figure 5: Model of the saddle

A non linear FEA analysis is done as shown. It can be clearly obseverd that the transverse force produces longitudinal strains as predicted by the above paper. Material has been used as ABS as it is well suited for 3D printing.

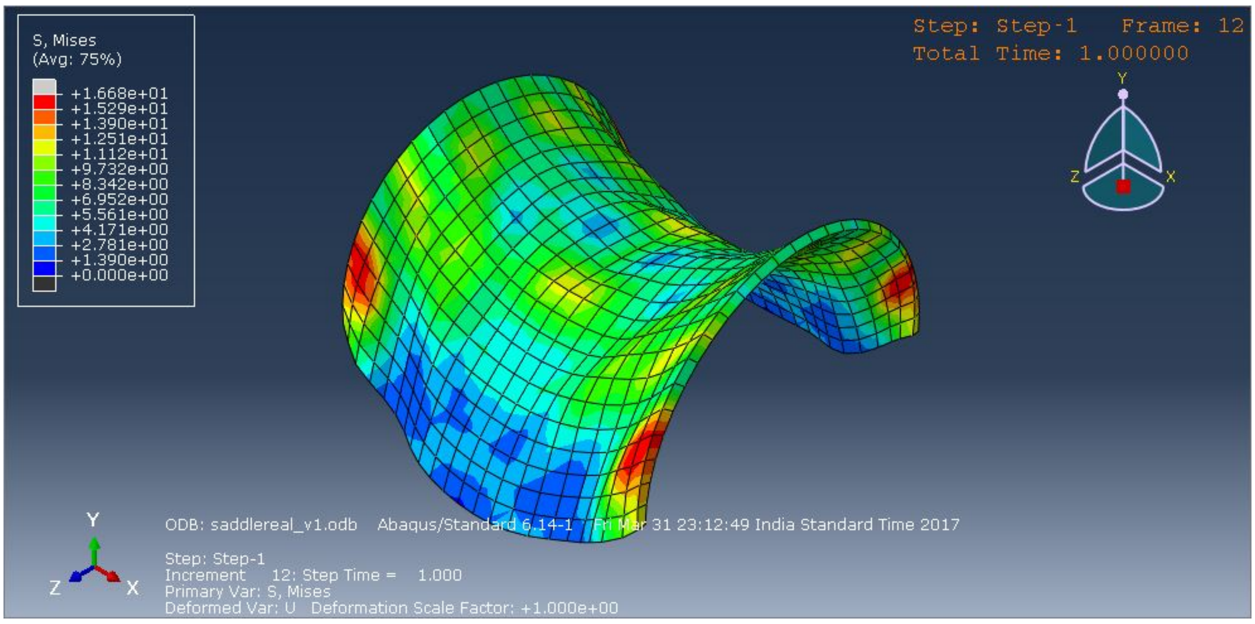

Figure 6: FEA of saddle

4.2 Mechanism Design

So the giudelines for the mehanism is as follows, it should be able to store large amounts of elastic strain energy in a link and should be able to reuse it to propel an arm. So following design is proposed.

The design has a cylindrical rubber reservoir which stores the energy in it and is released into the links when required in a controlled process or for a rapid impact. So when the rubber cylinder releases energy the free link moves forward guiding the bigger arm through contact. This contact is necessary as it increases the lever advantage of the mechanisms to provide maximum output amplification. The design gives flexibility in terms of the arm amplification by the lower arm. The lower arm length can be modulated based on the requirement of the force. The body connects to a spring type cylinder which compresses as the arm retracts back and then releases whenever necessary.

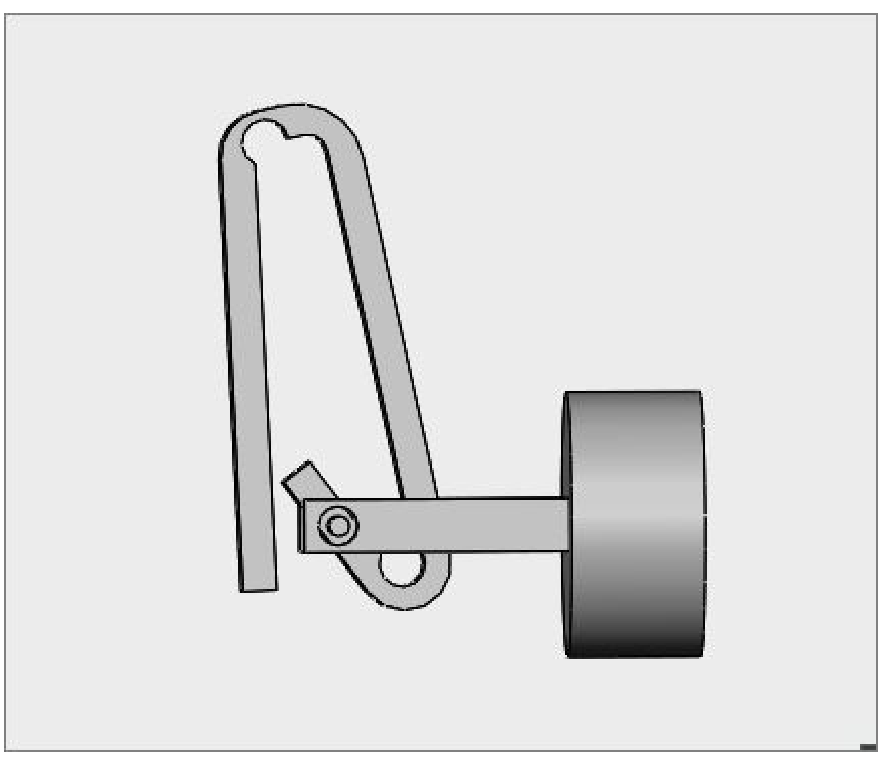

Figure 7: Mechanism-1

4.3 Proof of concept

The working of the concept is tested by performing an FEA in ABAQUS under nonlinear geometry. The results are as shown below.

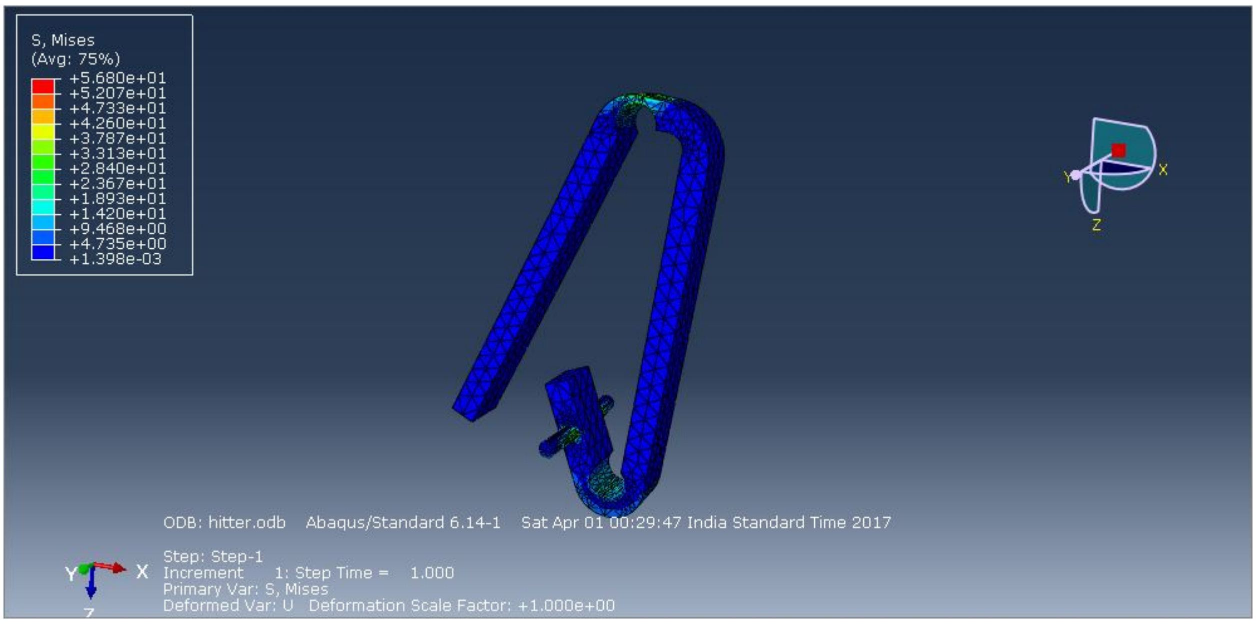

Figure 8: FEA for actuated arm

It can be seen that there is no stress in the body of the mechanism but some stress accumulation in the compliant joint or the live hinge is as low as 40 MPa. Such a force can be easily accommodated by spring steel. But the hitting arm can be made of special hard materials with modified microstructrure. The microstructure can be mimicked from bones microstructure. The construction for the arm would consist of hard steel in the outer periphery whereas much spongy steel in the deeper cores. This construction can also be seen in the Japenese katana.

But such a mechanism would be inherently limited by its contact friction and also deformation in the contact link. Also the guidance and the path traversed by the end link is also not so specific. A guiding mechanisms neednt be implemented. Once the mechanism is actuated it needs to deliver a lot of energy to the arm which should amplify the force. One more important thing that can be noted it that the impact phase is more important than the recoil phase. Since as shown in a study[4], the velocity os the arm increases and completes the impulse and then comes back slowly again. Considering all the above possibilities it is then seen that a compliant bistable mechansism would provide an innovative way to both actuate and store energy and provide the same output as required. Also such a mechanism would allow us to use more energy which unloading but lesser energy to reload the spring. This also draws inspiration from a saddle but in a modified shape. The conceptual model of such a design is as shown.

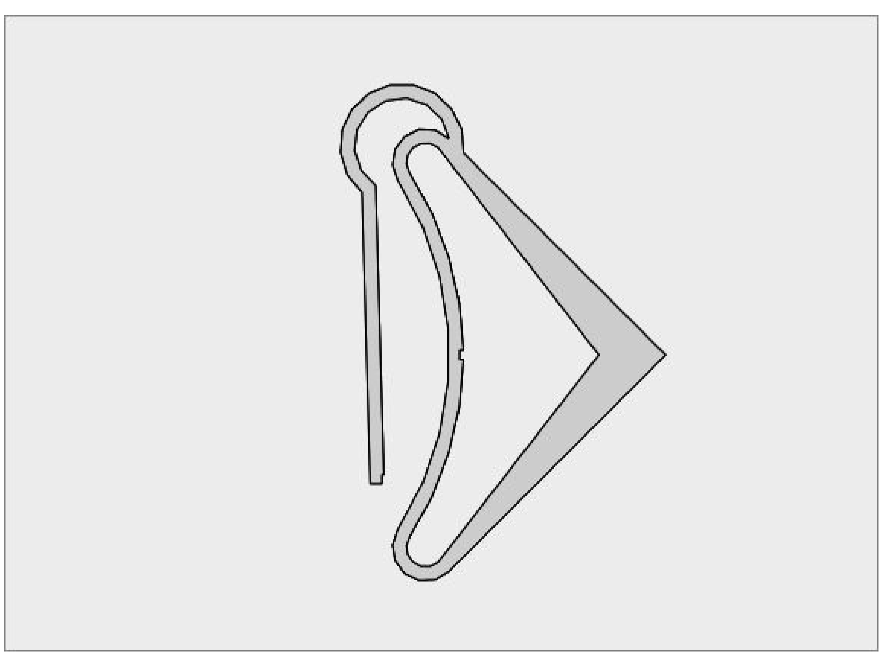

Figure 9: Underformed bistable mechanism

So the above mechanism illustrates the conceptual design of the proposed bistable mechanism. The curved beam being compliant can be designed in away where it is not just bistable but stores some inherent elastic deformation energy which can be imparted to the arm once it clicks to the other stable state. This would be a unibody design eliminating any requirement of assembly.

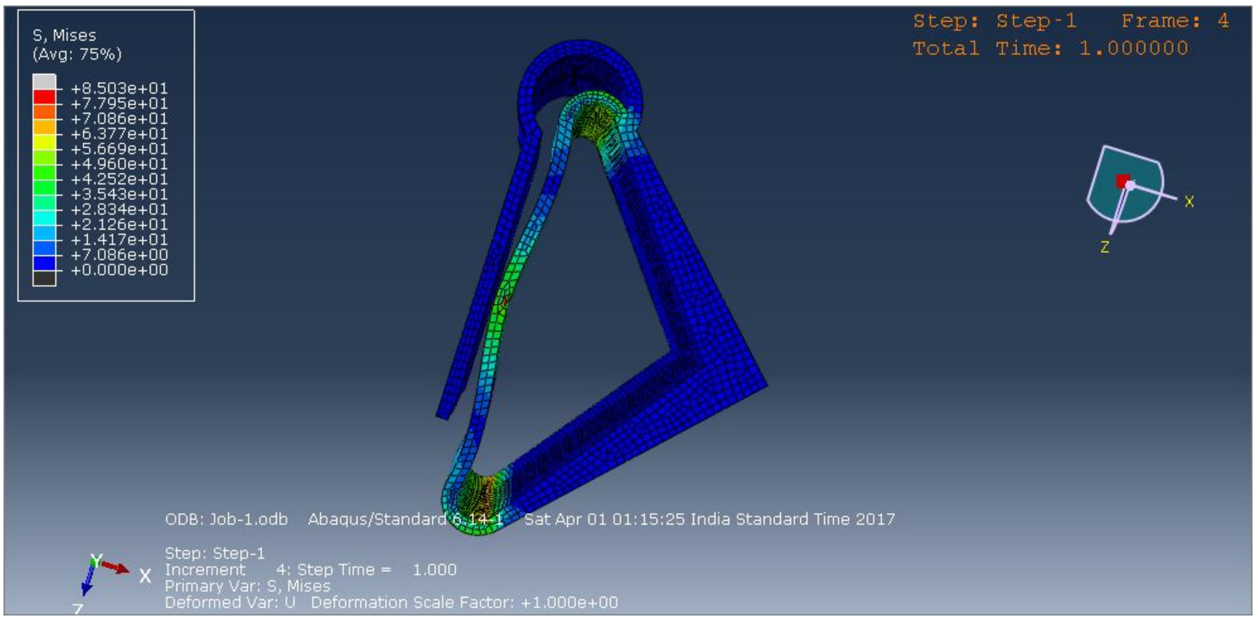

Figure 10: Deformed state or second stable state of the mechanism

An FEA simulation shows that peak stresses in such a design wouldnt exceed the yield strength of the material and thus can be effectively used as a substitute. This design is better than the previous design in terms of compactness and simplicity of the deisgn. Compared to a 4 bar mechanism a bistable mechanism provides much higher impulses. Though the freedom of amplification of forces interms of link length manipulation is lost, it is translated into a single parameter of curvature of the bent shell.

So once a stimulus is given to the other side of the bent sheet, the sheet switches stabile modes from one to the other imparting a huge impulse to the arm which in turn breaks the rock. Again the microstructure can also be played with to get optimum design. The amplification can be played with by changing the symmetry of the bent sheet.

5 Futurework

Only a preliminary study and proof of concept are provided on the use of compliant mechanisms as a substitute of conventional mechanisms. A detailed study might be done on the analytical formulation of the curvature of the beam vs impact force generated should be done. Also ABS is used for analysis as it is 3D printable and light weight yet hard, but based on the strength of the rocks we need to break we can have the bent sheet made by that. Many more alternatives using the saddle type structure itself may be explored as a design alternative for a beam based bistable mechanism. There are many other high impulse generating creatures like the trapjaw ant, which can also be explored as apotential venue to draw inspiration from.

6 Conclusion

Organisms being optimized to a wide range of atmospheres are a trasure for inspiration. They have some of the finest techniques to complete a task. They are also capable of superhuman capabilities like achieveing many magnitudes of g's of acceleration like in the trap jaw ants defence jaws or in the matis shrimps arms. One of such biomechanical system of a mantis shrimp is taken in this report. The saddle which is the most important in deformation is analysed and the directions of strains is observed. Also a pure live hinge based design with a rubber spring reservior as a design is proposed and analysed for failure. A better alternative for impulse which is a bistable mechanism is proposed and is analysed. In both the cases the stresses induced for a required amount of deformation is much less than the yield stress of the material, and hence can be an alternative for conventional mechanisms.

7 References

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