B. TECH. PROJECT REPORT

On

Design and Development of Soft Robotic Systems

BY

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DISCIPLINE OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

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Design and Development of Soft Robotic Systems

A PROJECT REPORT

Submitted in partial fulfillment of the

requirements for the award of the degrees

of

BACHELOR OF TECHNOLOGY

MECHANICAL ENGINEERING

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INDIAN INSTITUTE OF TECHNOLOGY INDORE

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CANDIDATE'S DECLARATION

We hereby declare that the project entitled **"Design and Development of Soft Robot"** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in 'Mechanical Engineering' completed under the supervision of **Dr, I. A.Palani, Head of the Discipline, Mechanical Engineering,** IIT Indore is an authentic work.

Further, we declare that we have not submitted this work for the award of any other degree elsewhere.

Signature and name of the student(s) with date

CERTIFICATE by BTP Guide(s)

It is certified that the above statement made by the students is correct to the best of my/our knowledge.

Signature of BTP Guide(s) with dates and their designation Index

PREFACE

This report on "**Design and Development of Soft Robots**" is prepared under the guidance of **Dr, I. A. Palani**.

Through this report, we have tried to give a detailed design of an innovative way of using SMA Springs and wire in Biomimetic underwater robots, with an intention to mimic the Jellyfish, its motion and material properties of its body. We have tried to cover every aspect of the new design, and to conclude if the design is technically and economically sound and feasible, via conducting necessary experiments and doing detailed study.

We have tried to the best of our abilities and knowledge to explain the content in a lucid manner. We have also added 3D models, reference images, relevant graphs, comparative tables, photos and figures to make it more illustrative.

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ACKNOWLEDGEMENTS

We wish to thank Dr. I.A.Palani for his kind support and valuable guidance. He was always available for the discussion, to answer our doubts and guide us through the different parts of project. He provided an environment, where we were encouraged to discuss the new ideas and our problems.

We would like to acknowledge Mr.Muralidharan M, Mr.Jayachandran S, Mechatronics and Instrumentation Lab and Central Workshop of IIT Indore for providing their sincere cooperation and guidance to carry out this research. It is their help and support, due to which we have been able to complete the design and the technical report of this project.

Without their support this report would not have been possible.

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ABSTRACT

In this report, we aim at developing a Bio-Mimetic Jellyfish like soft robot, utilising Shape Memory Alloy(SMA) as an active actuator. Shape memory alloys has the characteristic Shape Memory Effect(SME) and other properties such as high energy density, Two Way Shape Memory Effect(TWSME) as the most notable ones. These properties make SMA based Actuators as strong contenders to conventional motor-based, pneumatic actuators on various aspects of application.

Designs were made based on two ideas. One utilises SMA NiTi Springs directly with simple flap mechanism, where the flap was meant to be made by medium density ethylene, and the chassis would be fabricated using additive manufacturing (3D Printing). Second utilises a more complex model, where actuator was strained SMA NiTi wire embedded in PolyDiMethylSiloxane(PDMS), a biocompatible material, where the former was active actuator and the latter was passive actuator.

Various experiments were conducted on the SMA Spring and a developed PDMS with embedded strained SMA wire to check the factors and viability of them. Most of the tests done were via the setup created by ourselves and utilising standard equipment whose details and result have been discussed in the report, along with design, fabrication and working.

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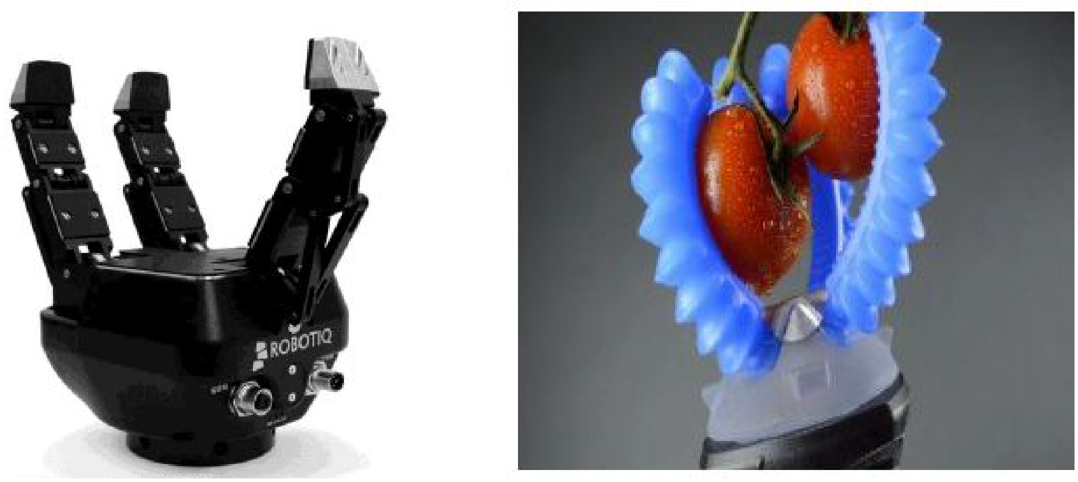
Chapter 1: Introduction

1.1 What is a soft robot?

Soft Robotics is the specific subfield of robotics dealing with constructing robots from highly compliant materials, similar to those found in living organisms

Soft robotics draws heavily from the way in which living organisms move and adapt to their surroundings. In contrast to robots built from rigid materials, soft robots allow for increased flexibility and adaptability for accomplishing tasks, as well as improved safety when working around humans. These characteristics allow for its potential use in the fields of medicine and manufacturing.



(a) (b)

Figure 1:(a) A Hard Robotic Hand

(b) Soft robotic Hand

a. Hard Robots

Hard Robots Or Conventional robots generally consists of mechanical parts linked and actuated with hard actuators such as Pneumatic, Hydraulic, electric Motors etc. the word Hard here aims to bring forward the fact that most parts of a conventional robot are rigid. The rigidity allows better computations of robot and make calculations easier. Figure 1(a) shows a Hard robotic hand made by “Robotiq” the links in the hand are made of hard material and is extensively studied in conventional robotics.

b. Soft Robots

Soft robots are those which are made with highly compliant materials, having properties similar to those of the living organisms. Soft robotics heavily derives its principles from the way living organisms move adapt to their surroundings. Figure 1(b) shows the octopus inspired soft robotic grippers made by a startup from Cambridge University SoftRobotics.INC.

1.2 Drawbacks of the current hard robots and benefits of new soft robots

- Soft robots have inherent compliance with its working environment unlike Hard robots which demands to environment to be adjusted accordingly
- Soft Robots are inherently safe, adaptive and tolerant to operate in unknown environments, especially for human machine interactions unlike hard robots which require application of intricate control measures due to its limited adaptability to unknown environments
- Soft robots are more cost effective and lighter than hard robots due to the nature of materials used for its construction, unlike hard robots which employs connection of rigid using single degree of freedom(DOF) joints

- Soft robots can be manufactured using latest yet simple techniques such as additive manufacturing (3-D printing), mold curing(In case of elastomers)

1.3 What is Shape Memory Alloy (SMA)?

Shape memory alloys (SMAs) are metals that "remember" their original shapes. SMAs are useful for such things as actuators which are materials that "change shape, stiffness, position, natural frequency, and other mechanical characteristics in response to temperature or electromagnetic fields". The potential uses for SMAs especially as actuators have broadened the spectrum of many scientific fields. The study of the history and development of SMAs can provide an insight into a material involved in cutting-edge technology. The diverse applications for these materials have made them increasingly important and visible to the world.

SMAs have two stable phases: the high-temperature phase, called austenite and the low-temperature phase, called martensite. The martensite can be in one of two forms: twinned or detwinned. A phase transformation which occurs between these two phases upon heating/cooling is the basis for the unique properties of the SMAs.

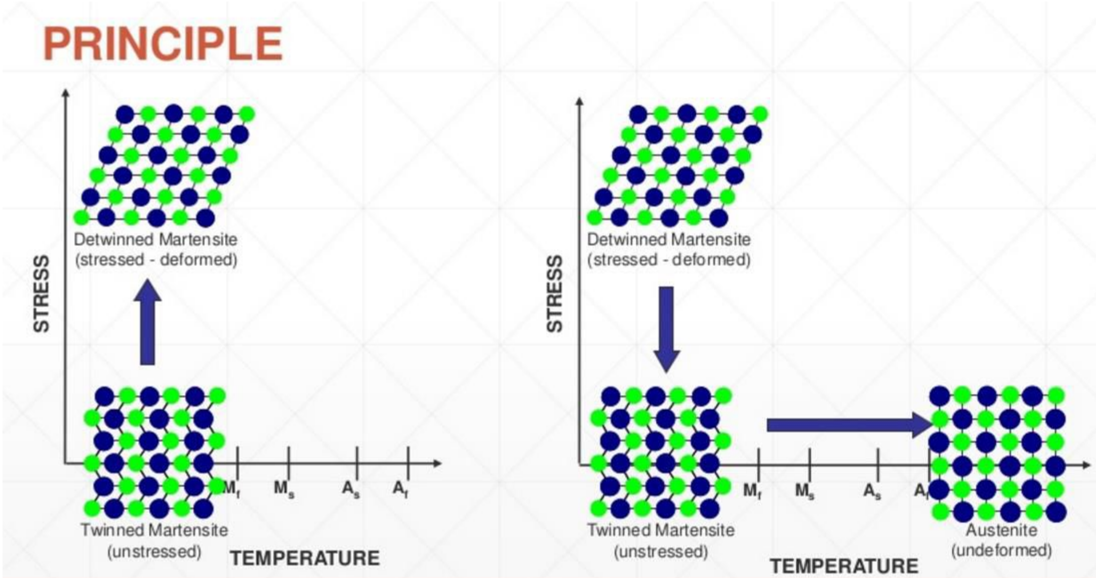


Figure 2:Phase Transformations in SMA

Upon cooling in the absence of applied load the material transforms from austenite into twinned martensite (no observable macroscopic shape change occurs). Upon heating the material in the martensitic phase, a reverse phase transformation takes place and as a result the material transforms to austenite.

If mechanical load is applied to the material in the state of twinned martensite (at low temperature), it is possible to detwin the martensite. Even upon releasing the load, the material remains deformed. A subsequent heating of the material to a temperature above austenite finish temperature (Af - temperature at which transformation of martensite to austenite is complete) will result in reverse phase transformation (martensite to austenite) and will lead to complete shape recovery. The schematic shown above in Figure 3 demonstrate the phase transformation principle involved in the development of shape memory effect in SMA. It shows a variation of stress with temperature. The first graph shows the conversion of twinned martensite to detwinned martensite as a result of development of thermal stresses while the second graph shows the complete austenite to martensite conversion cycle in case of SMA.

SMA remembers the shape when it has austenitic structure. So, if we need SMA to remember and regain/recover certain shape, the shape should be formed when structure is austenite. Reheating the material will result in complete shape recovery. Shape-memory materials behave differently. They're strong, lightweight alloys with a very special property. They can be "programmed" to remember their original shape, so if you bend or squeeze them you can get that original shape back again just by heating them. This is called the ‘Shape-Memory Effect’.

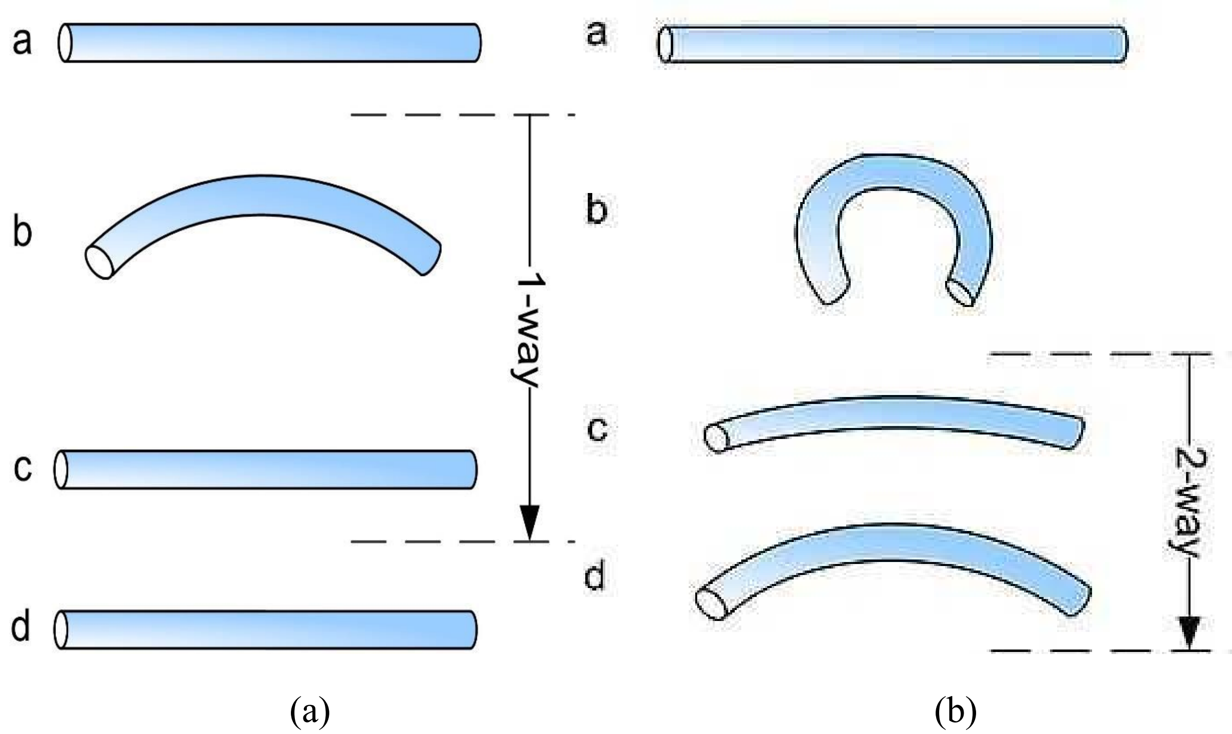


Figure 3:(a)One Way Shape Memory Effect (OWSME)

(b)Two Way Shape Memory Effect (TWSME)

1.4 Shape memory effect

Shape-memory alloys have different types of shape-memory effects. Two common effects are one-way shape memory effect and two-way shape memory effect. The procedures are very similar for both: starting from martensite (a), adding a reversible deformation for the one-way effect or a severe deformation with an irreversible amount for the two-way (b), heating the sample (c)and cooling it again (d).

a) One-way memory effect

When a shape-memory alloy is in its cold state (below As), the metal can be bent or stretched and will hold those shapes until heated above the transition temperature. Upon heating, the shape changes to its original. When the metal cools again it will remain in the hot shape, until deformed again. With the one-way effect, cooling from high temperatures does not cause a macroscopic shape change. A deformation is necessary to create the low-temperature shape. On heating, transformation starts at As and is completed at Af. Figure 4 below demonstrates the One Way Shape Memory Effect (OWSME).

b) Two-way memory effect

The two-way shape-memory effect is the effect that the material remembers two different shapes: one at low temperatures, and one at the high-temperature shape. Such a material shows a shape-memory effect during both heating and cooling. This can also be obtained without the application of an external force (intrinsic two-way effect). The reason the material behaves so differently in these situations lies in training. Training implies that a shape memory can "learn" to behave in a certain way. Under normal circumstances, a shape-memory alloy (SMA) "remembers" its low-temperature shape, but upon heating to recover the high-temperature shape, immediately "forgets" the low-temperature shape. However, it can be "trained" to "remember" to leave some reminders of the deformed low-temperature condition in the high-temperature phases. There are several ways of doing this. A shaped, trained object heated beyond a certain point will lose the two-way memory effect. The Figure 5 above demonstrates the Two Way Shape Memory Effect (TWSME).

1.5 Motivation behind the Project

Increase attention towards soft biomimetic robots.Bridging the gap between conventional robots and natural organisms.Replacing rigid mechanism with soft materials (e.g-Elastomers, gels, fluids,sensors etc). Replacing modular systems (hardware including motor, controller, sensor, etc) with fully integrated material architectures that merges these functionalities.

Chapter 2 : Concept Design

We have decided to focus on applying the concepts of Soft-Robotics for underwater robots. We'll first have to understand the types of motions that can be achieved in the robots that will be manufactured and categorise them for better understanding of its applications and scope. The figure given below shows the same as different swimming nodes.

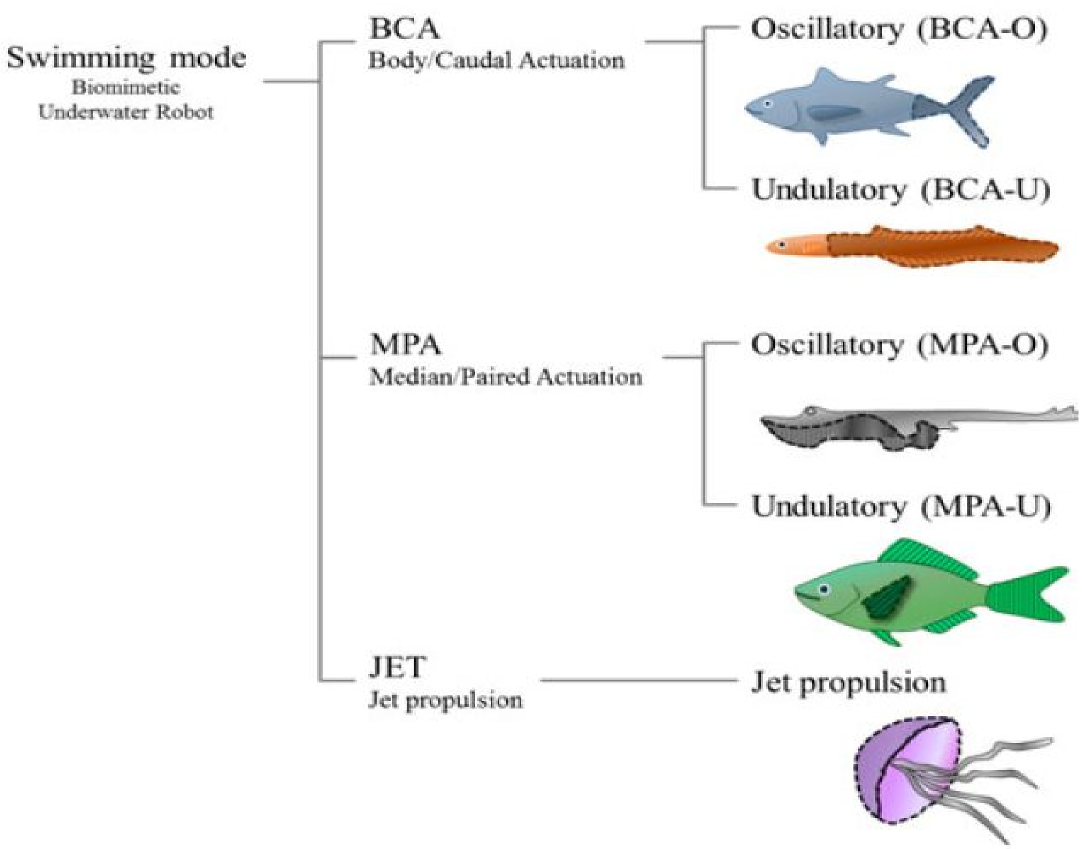


Figure 4:Categorised Swimming modes of Underwater Robots

Once the categorisation was done, three main smart actuators were used, for the fabrication of underwater soft robot, namely Ionic Polymer Metal

Composite(IPMC), Lead Zirconate Titanate(PZT).and Shape Memory Alloy(SMA). Comparative studies of previously done work was done.

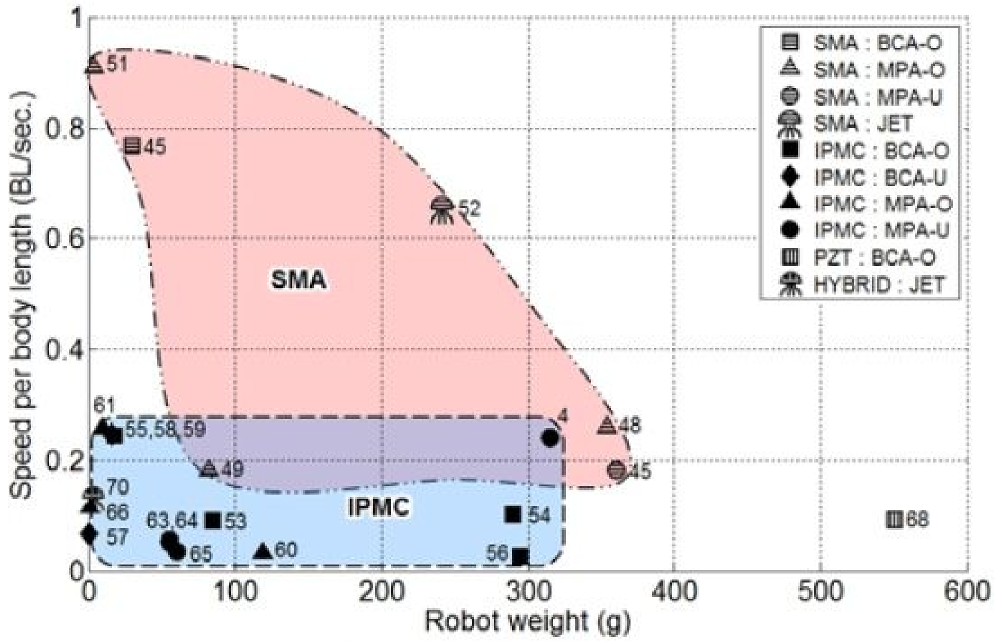


Figure 5: Comparison of different robots using different actuators(speed per unit length VS robot weight)

2.1 Implementation of SMA Actuators in Soft Underwater Robots

The usage of Lead Zirconate Titanate(PZT) if out of question as it needs high voltage for its actuation. We then have come down to the use of either Shape Memory Alloy(SMA) and Ionic Polymer Metal Composite(IPMC). The actuation frequency of SMA stands at 1 Hz and that of IPMC is at 100 Hz. For underwater robotics we prefer use of lower frequencies as faster motion are unnecessary and can disrupt the surroundings of the surroundings. Another aspect to take into consideration the energy.

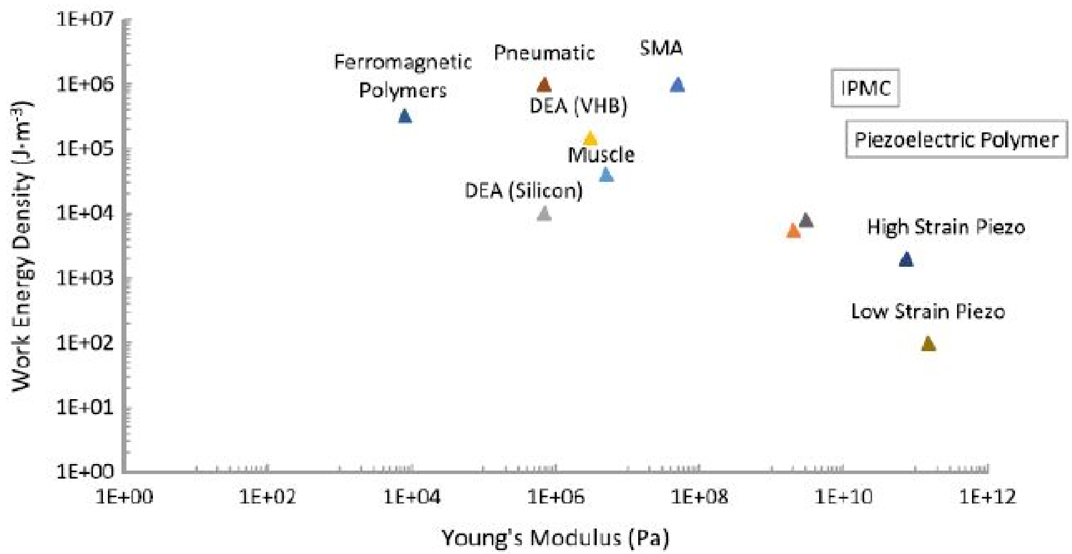


Figure 6:Work energy Density(J.m^{-3}) Vs Young's Modulus(Pa)

As the figures shows, SMA has the highest work energy density when compared to other actuation methods and having moderate Young's Modulus. This is one major factor that makes us move forward with SMA for application with in Underwater Robotics. Other minor factors such as lower environment temperature enabling SMA to cool faster to improve its frequency, repeatability of the actuation over long cycles are also accompanied for its selection.

2.2 Conceptual Design for Incorporation of Shape Memory Alloy spring in Soft Underwater Robot

Various robots have been developed with SMA NiTi spring as a actuators and also some of them have been developed for underwater applications. Some of them have also tried to mimic the jet propulsions one such is show in figure(21312).

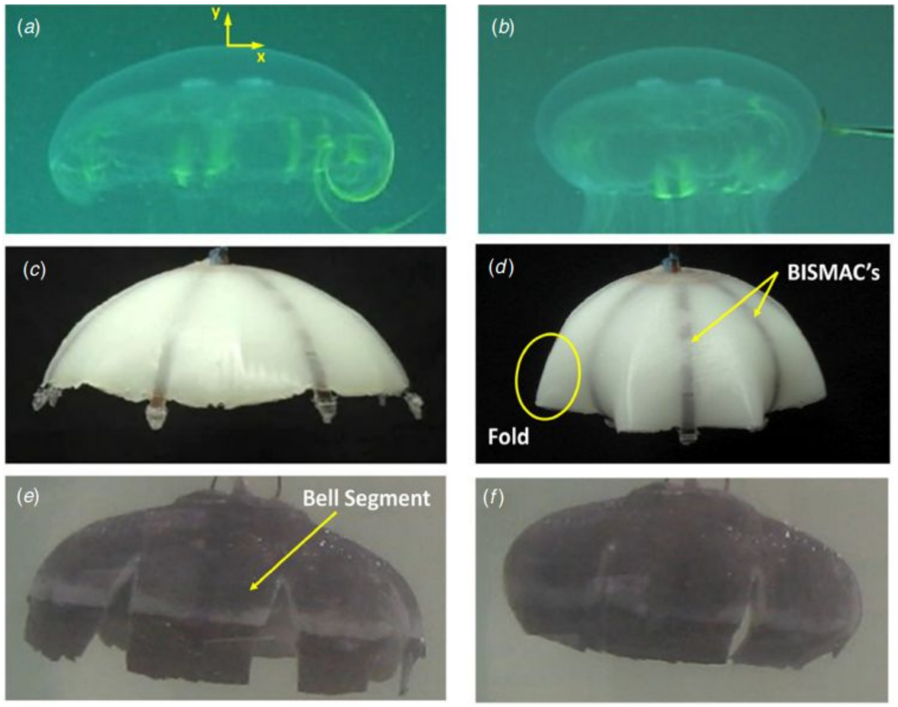


Figure 7: A BISMAC based Biomimetic Jellyfish Robot

Actuator used in the above shown prototypes are named BISMAC. They are basically SMA NiTi wires with metal strip to provide Bias force. But we haven't found any prototype with SMA NiTi SPrings as actuators so we planned to develop one such. Show in here a conceptualized use of SMA Spring for achieving flap motion.

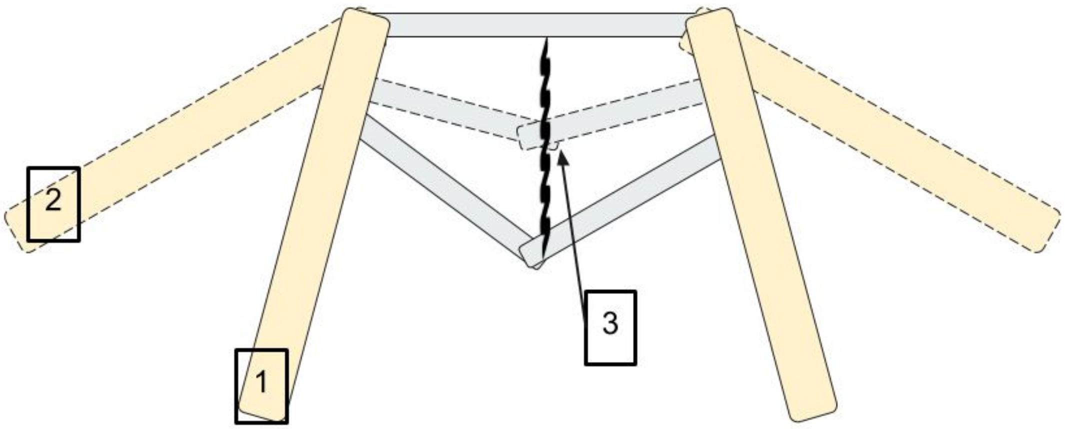


Figure 8:Conceptual design of flapper

The state 1 shows the flapper in relaxed position, as the SMA NiTi spring is actuated the flapper goes up and it flaps and goes to states 2.

2.3 Conceptual Design for Incorporation of Shape Memory Alloy wire in PDMS based actuator for Soft Underwater Robot

It was stated that SMA NiTi is a one way shape memory actuator and needs a restoring force to get back to De-twinned martensite state. Many methods have been applied to make actuators with SMA NiTi and bias mechanisms. One such method is to embed the SMA NiTi wire in to PDMS(PolyDiMethylSiloxane) matrix. Here PDMS acts not only as a restoring agent but also as a actuator. PDMS is one of the soft material that has been studied extensively in soft robotic applications. PDMS is a Visco-Elastic material with the Density (0.965gm/cc) which is slightly lesser than the water. This property highly desirable for our applications of underwater robots. Some properties that may affect the functioning of our model are mentioned below

Property	Value
Density	0.965gm/cc
Tensile Strength	2.24 MPa
Thermal Conductivity	0.15 W/mK
Hydrophobicity	Highly Hydrophobic, Contact Angle 90-120 °C

Table(1) Properties of PDMS

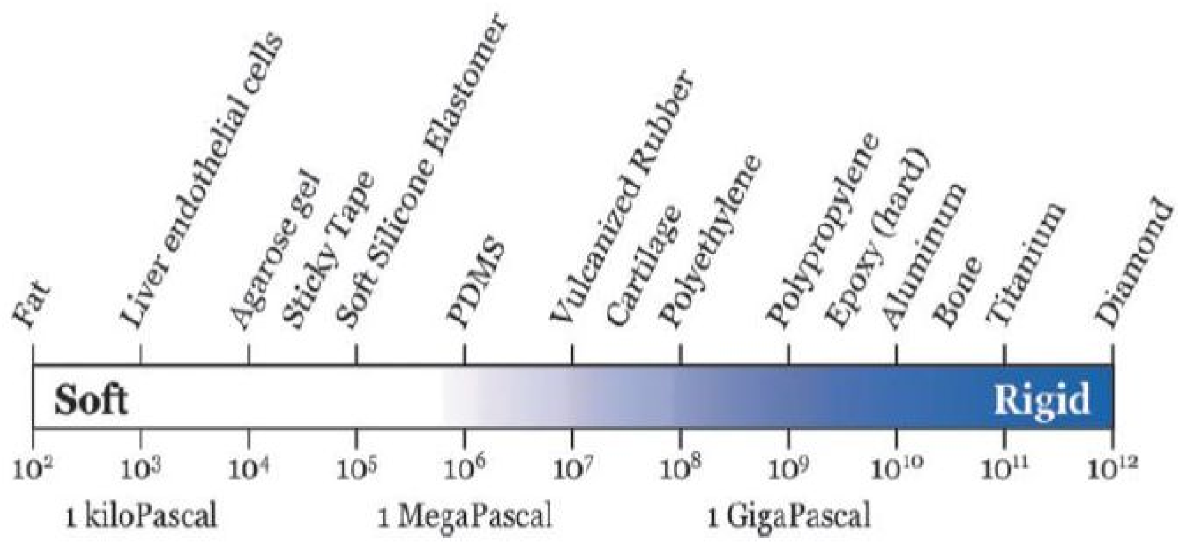


Figure 9: Young’s Modulus comparison of various materials

The figure shows the modulus of elasticity of various materials on same scale. Far right we have Diamond with the highest and far left we have fat with the least. Interestingly we have PDMS in the middle of that which is again a desirable property as we are working with soft materials.

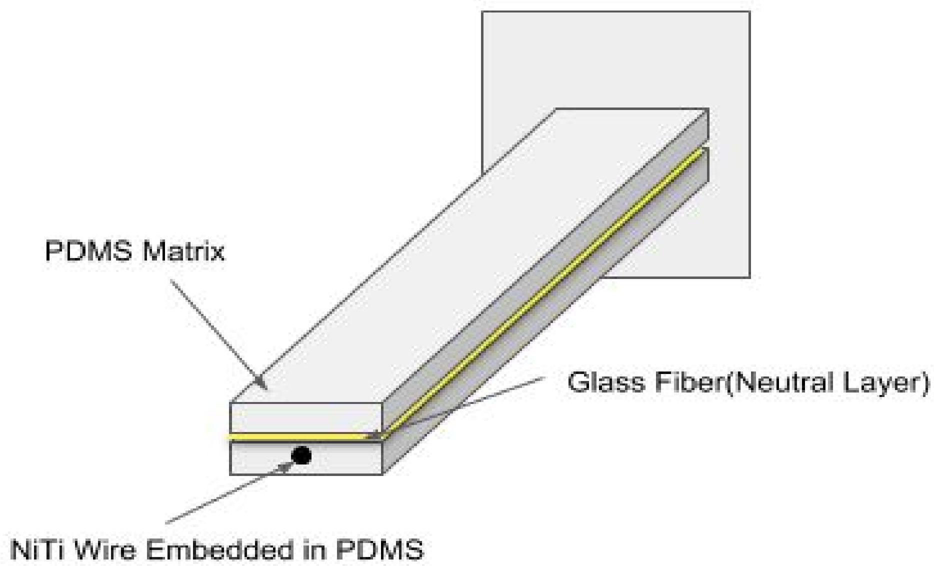


Figure 10: Schematic Diagram of Designed Actuator

Shown in figure is a concept design of PDMS-SMA NiTi based actuator. The two PDMS layer are separated by a Glass Fiber embedded in it. On one side a SMA NiTi wire is embedded.

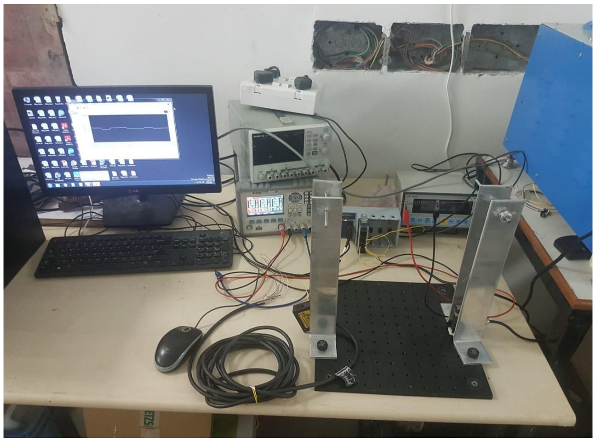
Chapter 3 : Experiments And Analysis

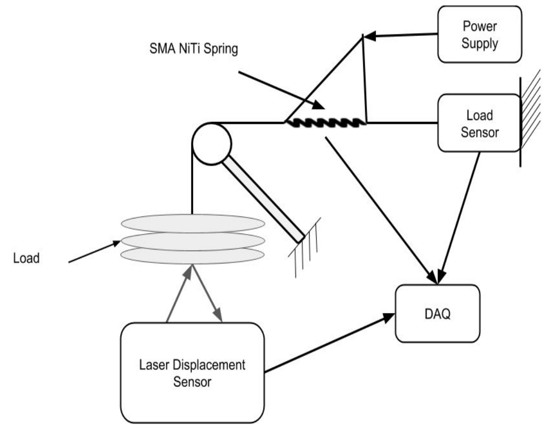
3.1 Development of Setup to appreciate dynamic characteristic of SMA NiTi Spring.

Many setups have been designed in past for computing various parameters of SMA NiTi coil springs. Many follow a pattern of a dead load a restoring force for detwinning the martensite. Almost all have considered the dead weight as the intantenoues or the peak force applied by the SMA NiTi coil spring in that configuration. While some have appreciated the fact that the force applied by SMA NiTi coil spring was not the weight of dead weight used. One such setup have been developed which is simple and also easy to make.

a. Setup Design

One such setup have been developed which is simple and also easy to make. The schematic and setup is shown in figure.





(a) (b)

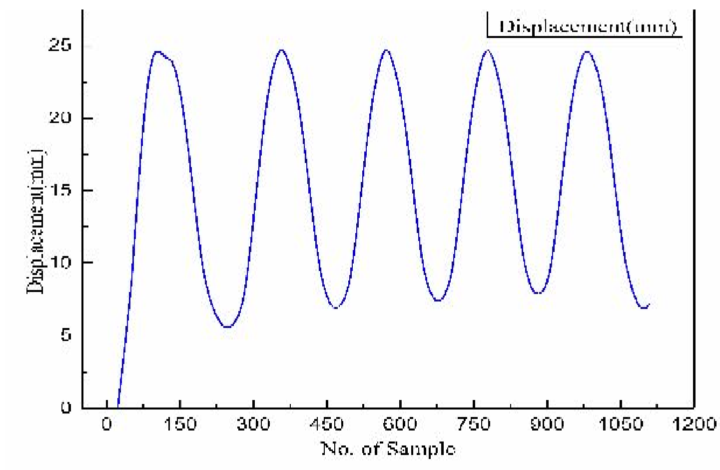
Figure 11: Experimental Setup for studying SMA Spring Actuation Cycle

(a)Actual Photo

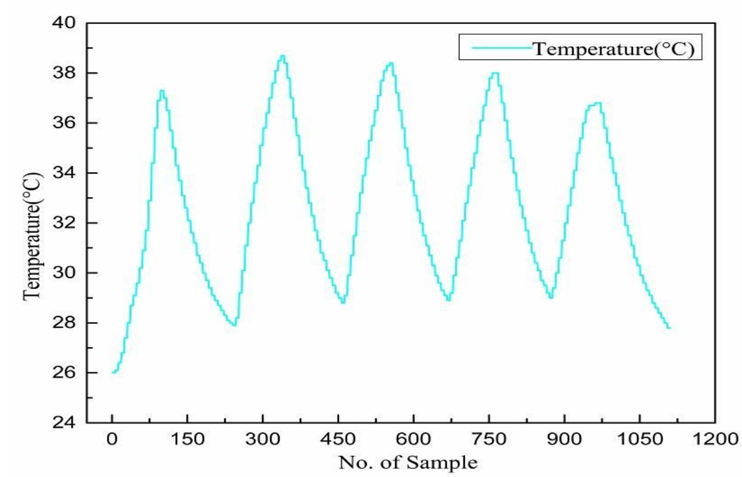
(b)Schematic Diagram

b. Results from dynamic analysis

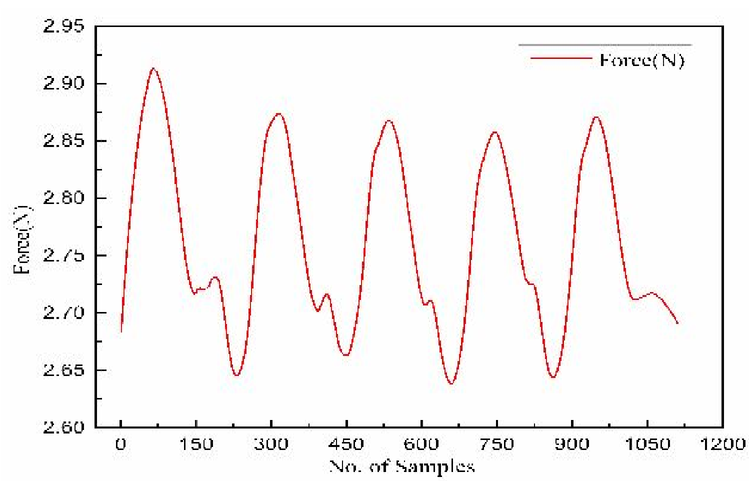
After performing the experiment on SMA NiTi coil springs the results of Temperature and Displacement were as expected and have been identical to most literatures on SMA. the important point here to observe is the fact that force measured was neither constant not linear. However the force was proportional to the temperature which is expected as the actuation was a atomic phenomenon completely dependent on temperature. Due to complexities involved in the behaviour we restricted our analysis here and didn't tried to find any relation between the temperature and force. Still with general observation we can say that maximum force was achieved at max temperature.


Displacement(mm)
Displacement(mm)
No. of Sample

(a)


Temperature(°C)
Temperature(°C)
No. of Sample

(b)


Force(N)
Force(N)
No. of Samples

(c)

Figure 12: Various Parameters of SMA NiTi Spring during actuation cycles

(a)Displacement Vs Number of cycles

(b)Temperature Vs Number of cycles

(c)Force Vs Number of cycles

The results yielded have confirmed that the force applied by SMA NiTi Springs was not Constant and have a nonlinear nature however the deflection was minor(0.25 N) for our application. But can be helpful while working with precise and sensitive projects involving SMA NiTi coil spring.

3.2 Design of SMA embedded in PDMS actuators

The concept design of PDMS SMA NiTi has been tested by many have achieved desirable results. So we went ahead with the design and started working on the mould to fabricated the actuator.

3.3 Design of mould for SMA embedded in PDMS actuators

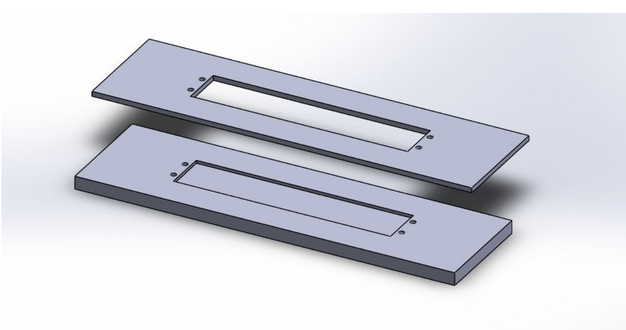
Various Authors previously worked on PDMS based actuators and fabricated such actuators. Many configurations have been tried for SMA NiTi wire to produce different type of actuations. These include bending, twisting flapping etc. In General while fabricating a PDMS based actuator a mould has to be prepared and actuating elements here SMA NiTi wire is held between supports and then cavity is filled with mixture. The complete setup then is allowed to cure. For PDMS(syl 180) the curing time at room temperature is 48 hours. The curing time can be reduced easily by increasing the temperature however increasing temperature beyond 52 degree celsius will start the actuation in SMA NiTi.

Many researchers have used 3D printed moulds for fabrication which is great as mould can easily be designed and manufactured. While 3D printed moulds have this advantages they are fragile and also deformable, over this they are not good conductors of heat. The biggest disadvantage of 3D printed mould as we found that one mould can only produce one type of actuator and cannot be used for next actuator. This make they one time moulds. Following are the requirements we kept for us while designing a modular mould.

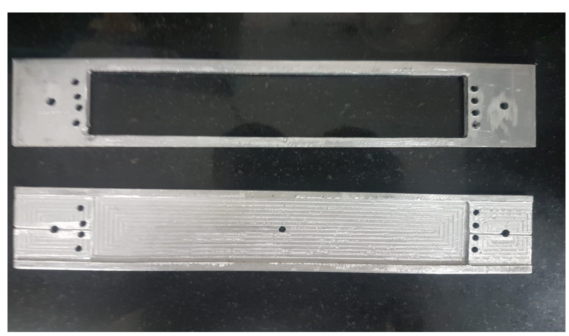
1. It should be Reusable.
2. It should be Good conductor of heat
3. It should be modular
4. It should be rigid and sturdy.

a. Design of moulds with fixed dimensions

We started with a simple design to understand the complete process from a practical perspective.we designed a simple Cope and Drag type Mould. First SMA wire have to be placed on Drag and then Cope has to be fixed on it. Later the setup is placed in oven and the PDMS mixture is poured in it. Next it is allowed to cure.



(a)



(b)

(c)

Figure 13: (a)Design of Simple Cope and Drag type Mould

(b)Fabricated Mould

(c)Drag with SMA NiTi wires fixed

b. Design of modular mould for actuators of variable dimensions

The results from our previous experiments where satisfactory and we had successfully fabricated a actuator. Incorporating modifications to make the mould perfect we designed a modular mould. Figure shows the conceptual design of the Modular Mould.

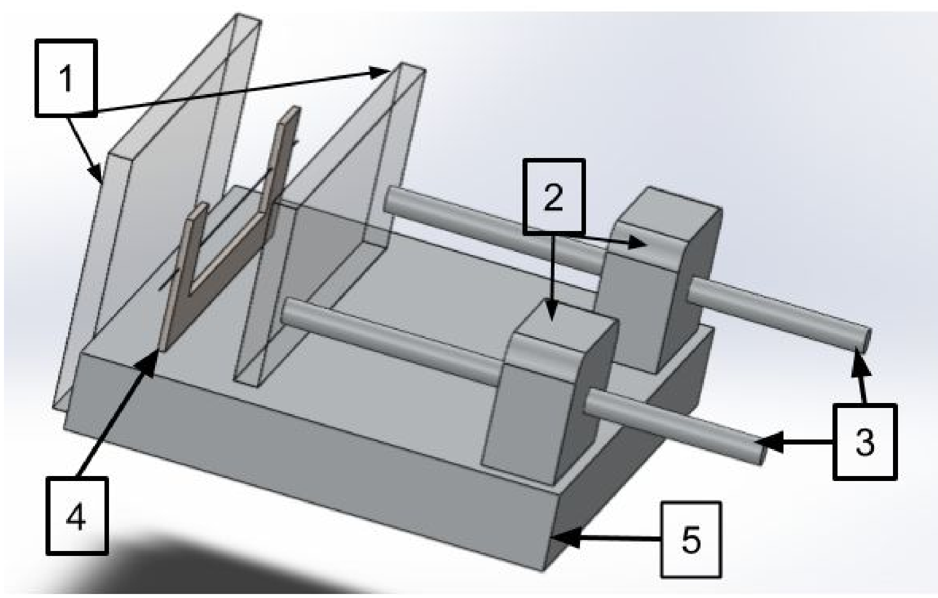


Figure 14: Conceptual Model of Modular Mould

(1) End supports (2) Nut (3) Lead Screw (4) Thin Metal plates (5) Metal Base

Concept of modular mould is that (1) these are two end support in between these two we will place a thin sheet (4) which will have SMA NiTi wire in it. (2) and (3) is a Lead Screw and Nut assembly this will maintain the pressure on two supports and prevent leakage. The size of plate (4) is the determiner in size of actuator and hence the mould can be used of fabrication of mould of different sizes without making new moulds. A large metal base(5) is proposed to have stable temperature of mould. To test this new concept of mould for PDMS we made a simpler version of mould. Complete process of fabrication has been depicted in Figure .

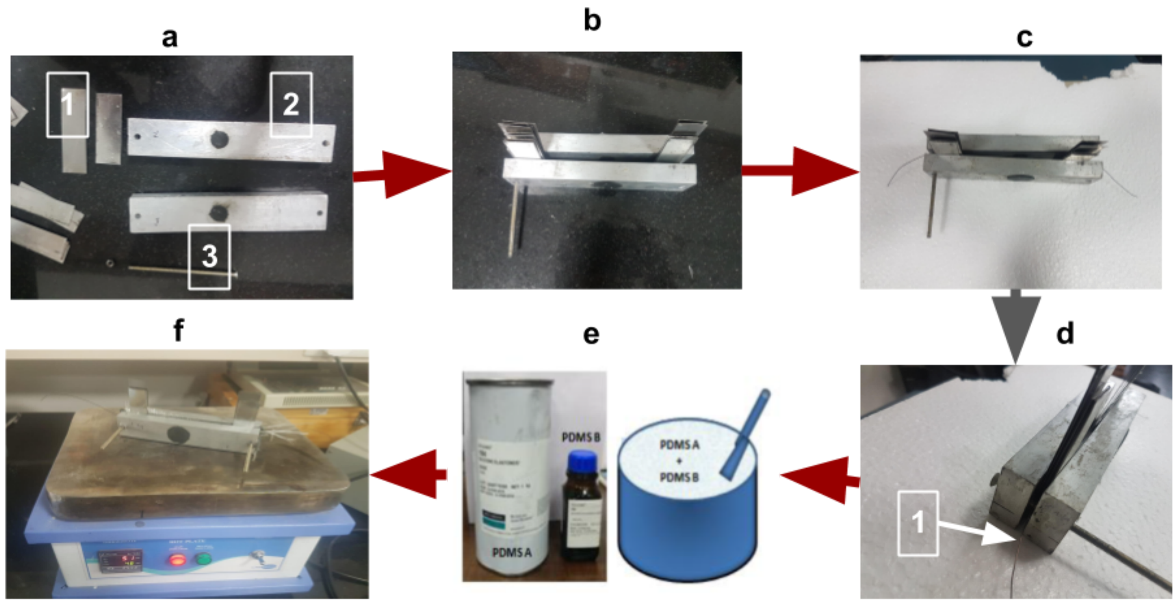


Figure 15: Fabrication process(a) Shows all parts of mould (b) Assembly of mould
 (c) Assembly of wire(Top view) (d) Assembly of Wire(Side view)
 (e) Mixing of PDMS solution (f)PDMS poured into mould on Heated bed for Curing

3.4 Fabricated actuators

We fabricated 4 actuators with the previous mould. Two of which are shown in figure. The actuators retained the dimensions of mould we made all actuators of thickness 3mm and they had same dimension.however we have seen that after mixing the PDMS it has to be degasified or the air bubbles will remain trapped and will affect the final actuator.

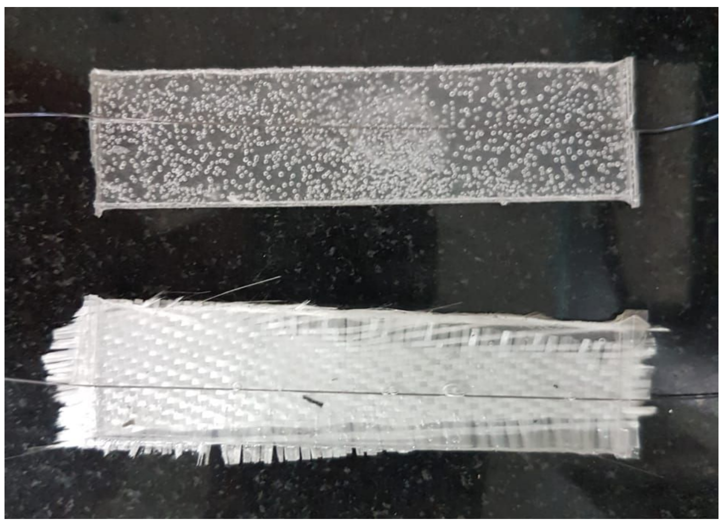
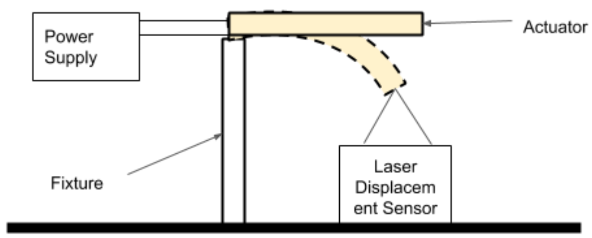


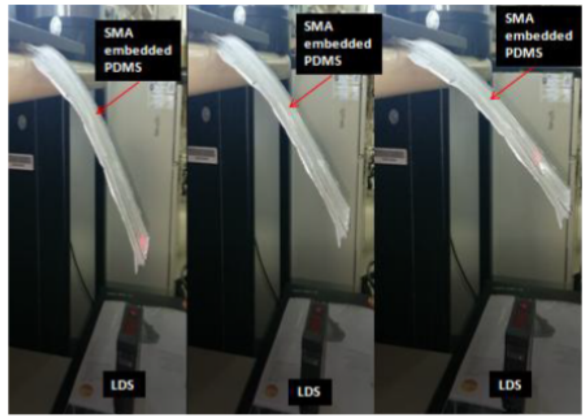
Figure 16:Top-Actuator without degasification of PDMS Solution
Bottom-Actuator with degasification embedded with glasswire

Shown in Figure two fabricated actuators. The one on top is containing ar bubbles which were trapped during the mixing. The one at the bottom has a Glass Fiber in between and contains no air bubbles.

3.5 Time Variations for cooling and heating for SMA embedded in PDMS actuators

To find time variations for Cooling and Heating of fabricated actuator a setup was designed. Schematic and actual setup is shown in figure.





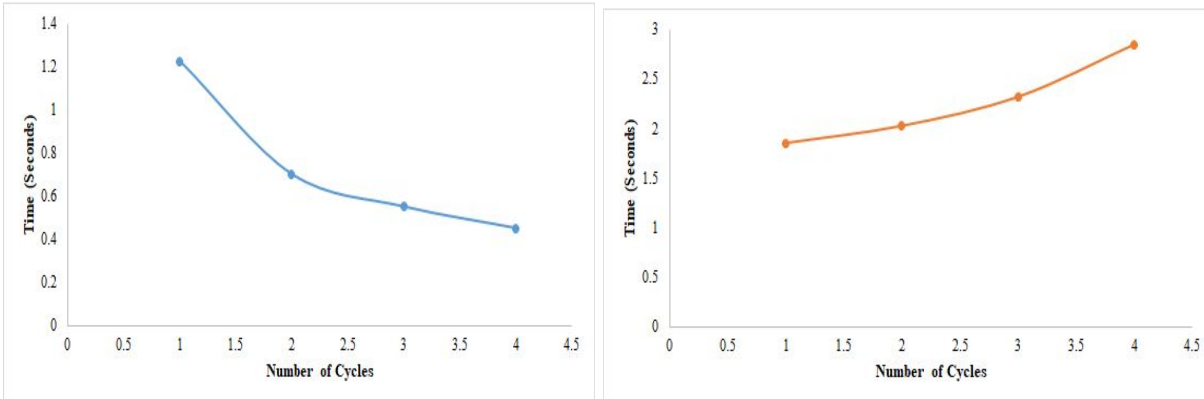
(a) (b)

Figure 17: Experimental Setup for Displacement of Actuator

(a)Schematic Diagram

(b)Actual photo

With help laser displacement sensor we calculate the displacement of tip. For our experiment we noted two extreme values of displacement and used them to state the actuator states as fully actuated for maximum displacement and relaxed for minimum displacement. The data of the experiment was recorded with NI compactDAQ and was exported to MS Excel and calculations were done to get values of heating time and cooling time.



(a) (b)

Figure 18:Changing parameters SMA wire during cycles of actuation

(a) Heating time vs Number of cycle (b) Cooling time vs Number of cycle

It was observed that the heating time was decreasing with each cycle this was due to the fact that the local volume around the SMA NiTi wire was at a high temperature even though the surface temperature of actuator was not that much. And with each cycle the local temperature was going high and this was decreasing the time required for actuation. With this same observations we can predict the nature of cooling time with number of cycle. The cooling time was increasing with each cycle. Again local heating was the reason behind this.

3.6 Frequency Measurements for Developed SMA embedded in PDMS actuators

A real jellyfish usually moves only upwards and floats with waves. For which it only flaps around a frequency of 0.2-1.2 Hz. These numbers are just an observation and used here for calculations. We previously seen that a jellyfish actuates with a complex mechanisms which is not understood by researchers. But considering it for a simple flapping mechanism for our calculation and the least frequency be 0.2 Hz.

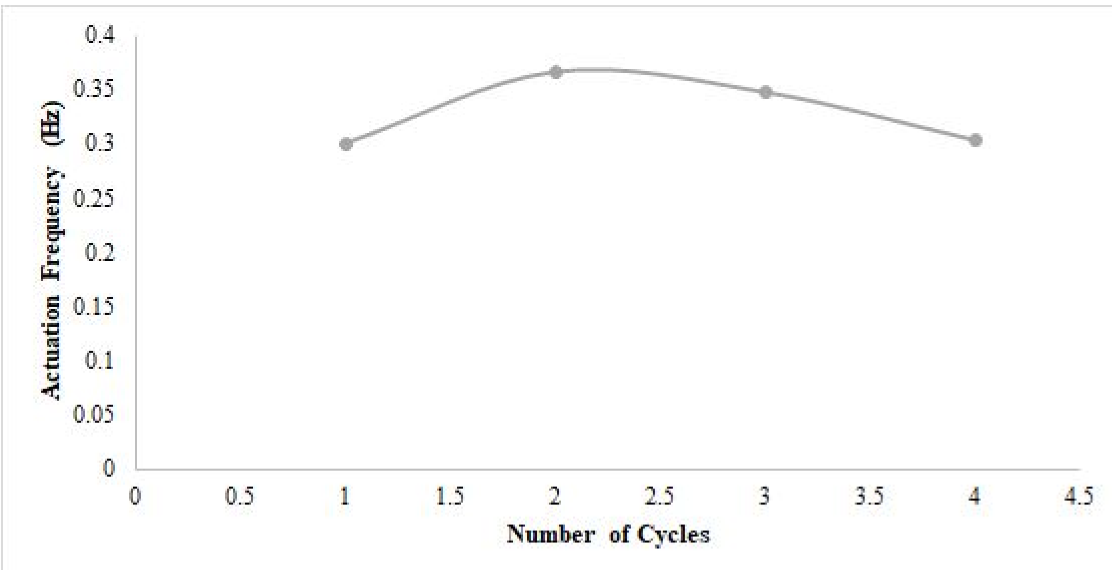
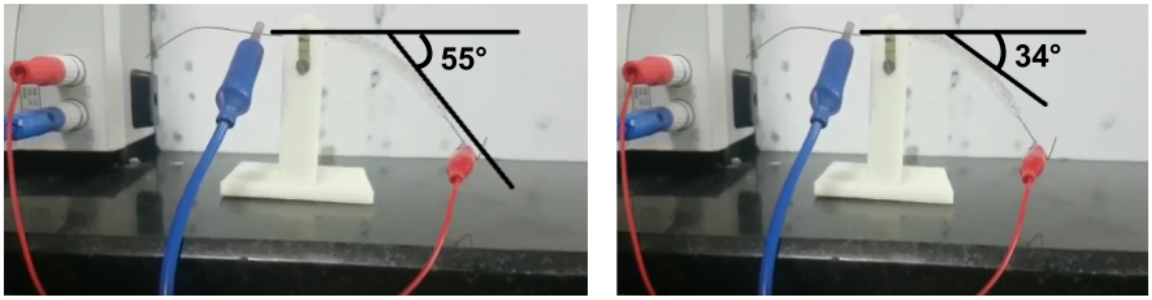


Figure 19: Actuation frequency vs Actuation cycle

The actuation frequency first increases with number of cycle but later started decreasing and decreased continuously. The maximum actuation frequency we achieved was 0.36 Hz. the Actuation frequency can further be improved if the same experiment is carried out in water.

3.7 Maximum bend angle for Developed SMA embedded in PDMS actuators



Maximum Bend Angle(degrees) at Tip

Maximum Bend Angle(degrees) at Midpoint

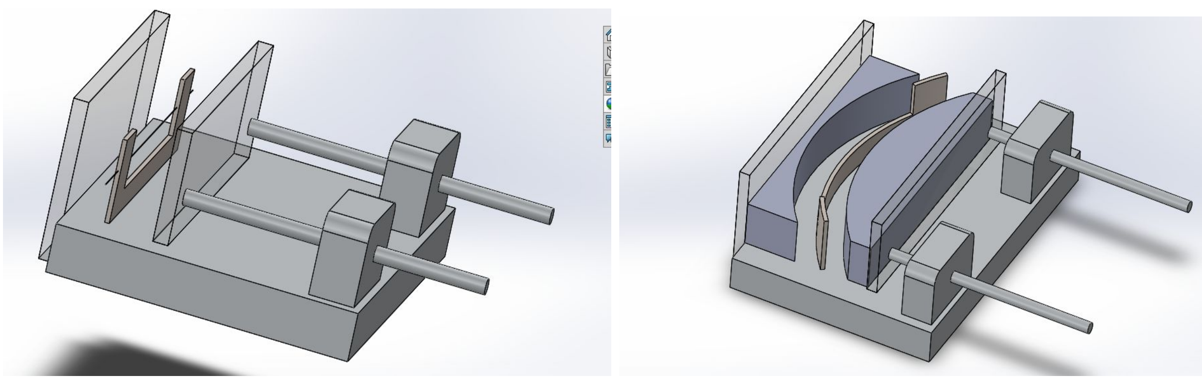
Figure 20: Bending angle of actuator at 2 points

We have also studied the angle with the actuators can bend. We have observed that that maximum bend angle at tip was 55 degree and at mid point 34 degree.

Chapter 4 : Finalized Design

4.1 Final Mould for SMA embedded in PDMS actuators

We have fully tested the concept of new moulds in chapter 3 section 3.4. All required parameters for aimed actuators were achieved with mould. Hence we went ahead with the concept and designed two moulds out of that.



(a) (b)

Figure 21: (a) Modular Mould for straight actuators
(b) modular Mould for Curved actuators

Mould for curved actuator was designed to make curved actuators that can be used in our final Jellyfish prototype shown in next section.

4.2 Final model of SMA NiTi Spring based model

From chapter 3 section 3.1 we have came to a conclusion that SMA NiTi Spring can be used for actuating the Flapper like Jellyfish Figure () however that was just a conceptual design and a proper design has to be made. Here we tried to make full Jellyfish which can be actuated by SMA NiTi spring. We designed our Jellyfish with 6 fins(flappers or anything can be used for that). SMA NiTi springs(4) are placed between the Head(1) and the mid plate(3) shown in figure . actuation of SMA NiTi spring moves the mid plate up and down which in turn produces a flapping motion. The frequency here in the case of SMA NiTi spring can easily be controlled by change in actuation power.

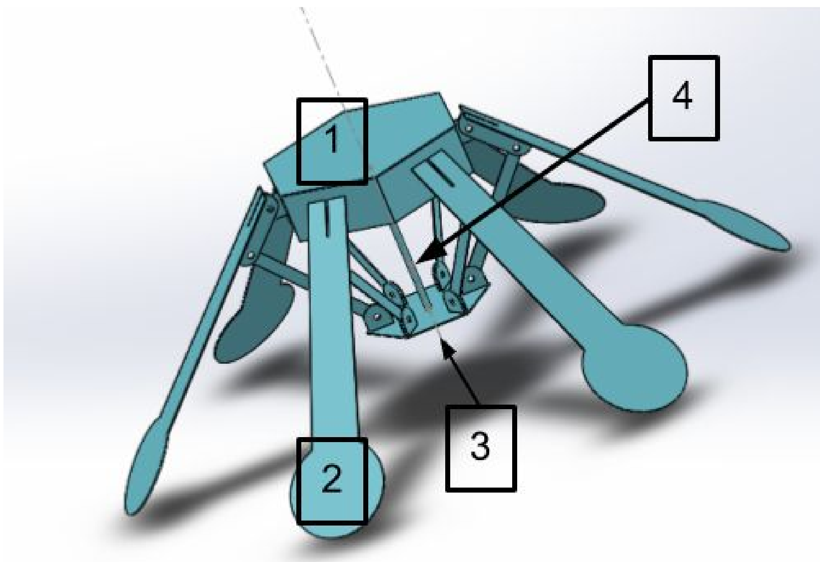


Figure 22: Model of Jellyfish utilising SMA Spring

We planned to make the fins(2) of Jellyfish with medium density Polythene, the head(1) and other(3) parts with thick Acrylic sheet. A fin was also fabricated with laser cutting and is shown in figure .

4.3 Final model of SMA embedded in PDMS actuators based model

After achieving a desired frequency for the fabricated actuators we went ahead for design of Jellyfish. Also for this we aimed to have 6 curved actuators(2) to actuate the robot.

A central control system(3) is designed for jellyfish placed in the middle. The final design is shown in figure . The rest of the body(1) will be made of silicone rubber.

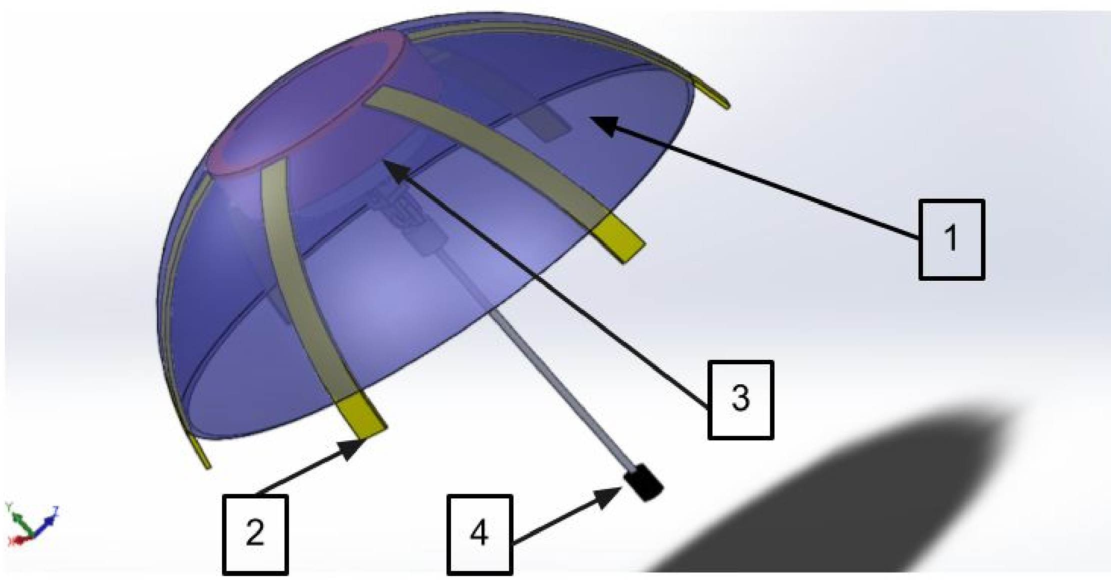


Figure 23: Model of Jellyfish using Specially designed actuators

In previous work we found that no mechanism to control the direction of Jellyfish was proposed and this hinders the use of such robots for surveillance and monitoring purpose. Here in our design we have proposed a simple yet effective mechanism to control the direction. A control rod(4) is placed below the fish, the rod is capable of tilting in any direction.

Figure 23:Illustration of control rod utilisation for directional control

Whenever the rod is turned in any one direction the whole body of jellyfish reacts to counter torque and orients itself in opposite direction. Which effectively controls the direction of motion of jellyfish.

Chapter 5 : Conclusions and Future Scope

5.1 Conclusions

In this work, Dynamic characteristics of SMA NiTi coil springs were studied and deflection on force applied by spring were calculated. For this purpose a new and easy to make setup was Developed. A design based on SMA NiTi spring was also made.

The Modular Mould was designed to make Actuators of variable Thickness have been tested and found that they were leak proof and the final actuator was accurate. A nitinol SMA wire of 0.5 diameter embedded in a PDMS based soft actuator is developed. The developed soft actuator is actuated using Joule heating with varying parameters and its actuation characteristics are studied.

The proposed SMA embedded PDMS soft actuator showed a Maximum Bend angle was Observed at the Tip 55° and Maximum Bend Angle at midpoint was 34°. It was observed that the Cooling time was reduced and heating time was increasing with each consecutive actuation cycle. Although the surface of actuator was not heated significantly.The maximum surface temperature is around 67ºC during the actuation.

More importantly Maximum Actuation Frequency 0.36 Hz was achieved which validated our choice to use SMA embedded in PDMS for jelly fish like under robots.

5.2 Future Scope

We have validated two actuators for application in jellyfish like robot. Further work can be done in analyzing the dynamic characteristics of SMA NiTi embedded in PDMS actuators.

The robots fabricated can be used for surveillance or collection of meteorological data and have infinite possible applications due to its energy efficiency. Work can be done to test these prototypes in real waters or local water bodies to optimise the design for real conditions. More data can be collected on dynamics of robot to control the movement speed and maneuverability.

5.3 Publications

- "Design and Development of Polydimethylsiloxane (PDMS) Based Smart Flexible Soft Robotic Actuator Driven by Shape Memory Alloy Wire", full paper accepted for presentation at International Conference of Advancements in Automation, Robotics & Sensing(ICAARS) 2018.
- "Investigations on Shape Memory Alloy Based Smart Prosthetic Hand for Upper Limb Handicapped", full paper accepted for presentation at International Conference of Advancements in Automation, Robotics & Sensing(ICAARS) 2018.

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2. Reena Disawal, Tameshwar Nath, Shashi Prakash, I.A.Palani, "Life cycle analysis of Electrically actuated SMA spring using Talbot Interferometry" uploaded in Applied Optics (IF: 1.650)
3. A Biomimetic Robotic Jellyfish (Robojelly) actuated by Shape Memory Alloy composite actuators, IOPscience, Institute of Physics.
4. Embedded SMA wire actuated Biomimetic Fin: A module for Biomimetic Underwater Propulsion, IOPscience, Institute of Physics
5. A Bio-Inspired Shape Memory Alloy Composite(BISMAC) Actuator, IOPscience, Institute of Physics
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8. http://www.mit.edu/~6.777/matprops/pdms.htm
9. Softer is Harder: What differentiates Soft Robotics and Hard Robotics?, Gursel, ALICI. ARC centre of excellence for Electromaterials Science, University of Wollongong,Australia

Image Sources

Figure:1(a) - Robotiqq.com

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Figure:2 - Google Images

Figure:3 - (a),(b) - Google Images

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Figure:6 - Stephen Coyle et al (2018), Bio-inspired soft robotics. Material Selection, actuation and design, Extreme mechanics letters.

Figure:7 - Embedded SMA wire actuated Biomimetic Fin: A module for Biomimetic Underwater Propulsion, IOPscience, Institute of Physics

Figure:9 - Carmel Majidi (2014), Soft Robotics: A Perspective—Current Trends and Prospects for the Future , Soft Robotics Journal