B. TECH. PROJECT REPORT

On

Design, Fabrication and Control of a 3-D Printed SMA Actuated Underwater Robotic Manipulator

BY

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DISCIPLINE OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY INDORE

May 2022

Design, Fabrication and Control of a 3-D Printed SMA Actuated Underwater Robotic Manipulator

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

of

BACHELOR OF TECHNOLOGY

in

MECHANICAL ENGINEERING

Submitted by:

Saurav Kambil

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Guided by:

Professor I. A. Palani

INDIAN INSTITUTE OF TECHNOLOGY INDORE

MAY 2022

CANDIDATE'S DECLARATION

We hereby declare that the project entitled **"Design, Fabrication and Control of a 3-D Printed SMA Actuated Underwater Robotic Manipulator"** 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, Professor, Department of 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.

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<u>CERTIFICATE by BTP Guide(s)</u>

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

Dr. I. A. Palani
Professor
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PREFACE

*This report on "***Design, Fabrication and Control of a 3-D Printed SMA Actuated Underwater Robotic Manipulator***" is prepared under the guidance of Dr I. A. Palani.*

Through this report, we have tried to give a detailed design of an innovative Shape Memory Alloy based Robotic Manipulator for underwater applications and cover every aspect of the new design if the design is technically sound & feasible and cost-effective.

We have tried to explain the content lucidly and in logical order. We have also added tables, plots and figures to make it more illustrative. We hope this thesis helps guide the successive students who wish to take up the project's scope and carry it forward.

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ACKNOWLEDGEMENTS

We wish to thank Dr I. A. Palani for his kind support and valuable guidance. We would also like to thank all the members of the Mechatronics Lab and the Instrumentation & Control Laboratory. Lastly, we would like to thank our respective parents for their constant encouragement. It is with their help and support which we became able to complete the design and technical report.

Without their combined support, this report would not have been possible.

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ABSTRACT

The need for the usage of underwater robotic manipulators has increased proportionally with the attention to environmental challenges and resources, as well as general, scientific and military tasks and missions. 'Underwater robotics' is undoubtedly a rapidly growing study topic and a promising industry. R & D activities in the ROV & AUV communities have risen as advanced computing, new materials, sensory technology, and theoretical developments have been achieved.

There are several underwater tasks that are challenging for direct manual execution. These tasks involve high risk due to the deep, unknown, hazardous territory, require high precision or are repetitive. This calls for a replacement of manual labor in the form of an underwater manipulator.

This paper presents an innovative Shape Memory Alloy based Underwater Robotic Manipulator. Pre-existing study on underwater manipulators primarily uses primitive grippers with three to six degrees of freedom actuated via electric, motor-based or hydraulic means. The presented study showcases a novel design, incorporating a humanoid gripper, fabricated via 3-D printing with the material PLA (PolyLactic Acid) plastic - a highly biodegradable material, with seventeen degrees of freedom. The robotic hand is actuated by Shape Memory Alloy coil springs, the quietest actuation mode, thus ensuring that the aquatic life remains completely undisturbed. Special emphasis has been placed on the underwater feasibility and functionality of the design. As per this project, the adopted control mode for this manipulator is ON/OFF.

Keywords: Robotics, Underwater Manipulator, Mechanical Design, 3-D Printing, Shape Memory Alloy, Control

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Chapter 1

Introduction

1.1 Underwater Robotic Manipulators

Robotic Manipulator Arms are multi-functional mechanical devices that can be reprogrammed easily to suit the requirements of the task at hand.

We tend to neglect the ocean as we concentrate on terrestrial and atmospheric challenges. We have yet to thoroughly investigate the ocean's depths and its vast array of resources. Underwater Manipulation can assist us in better understanding marine and other environmental challenges, protecting and efficiently utilizing the Earth's ocean resources, as well as in performing other essential tasks. However, travelling in the ocean is challenging due to a number of complex challenges caused by the unstructured, hazardous undersea environment. Therefore, robotic manipulators are the best tools for conducting subsea intervention operations.

In the recent decades of research and work on Underwater Manipulation, robotic arms have been attached to ROVs (Remotely Operated Vehicles) or AUVs (Autonomous Underwater Vehicles).

The most commonly used end-effectors as grippers are two/three-jaw, magnetic, vacuum or humanoid grippers. In this thesis, the main focus is on the humanoid (resembles a human hand) end-effector. The primary advantages of the humanoid grippers over their alternatives are as follows: -

a) They can be used to accomplish tasks that require higher complexity.

b) They have a more delicate grasp.

c) They are versatile - suited to a larger variety of shapes to grasp.

Fig 1.1: Humanoid Underwater Robotic Manipulator Arm

1.2 Telerobotics

'Telerobotics' refers to the area of robotics wherein the robot is controlled from a distance, primarily with wireless networks or tethered connections. Some of its chief applications include Space Exploration, TeleMedicine and Marine Exploration & Applications.

ROVs are frequently employed to work in water that is too deep or risky for divers to enter. They perform a plethora of tasks, including offshore oil installations, lifting sunken ships using cables, pipe inspection, valve opening & closing, clearing debris, deep-sea welding, etc. They are generally connected to a surface ship's control centre through a tether.

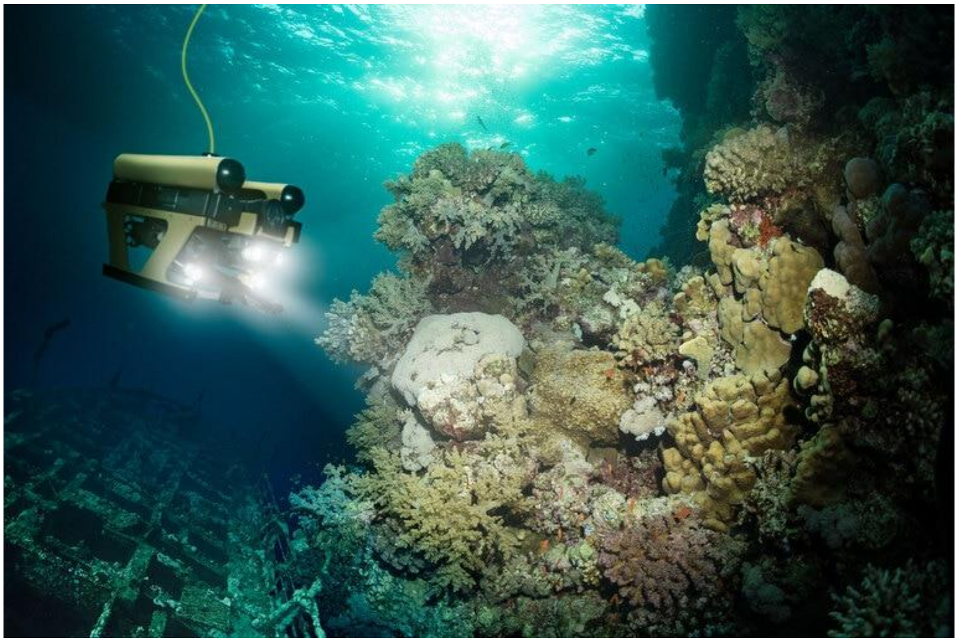
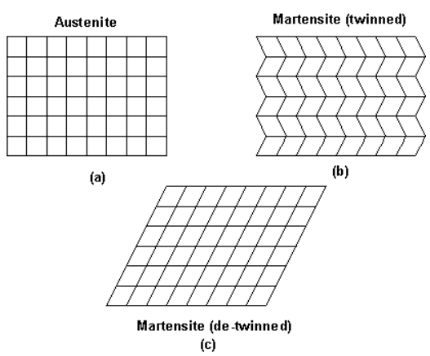


Fig 1.2: Tethered ROV *Courtesy: Power delivery networks for tethered robots | Vicor*

1.3 Shape Memory Alloys and Shape Memory Effect

Shape Memory Alloys are materials (typically wires or springs) that, when subjected to a threshold temperature after their deformation, return to their original shape. These alloys are mainly used as functional materials in actuators and sensors. Shape Memory Effect is observed when the material's crystalline structure shifts between two different phases called martensite and austenite as a result of attaining a set of threshold temperature and stress conditions. The low-temperature phase, Martensite, is relatively soft, whereas the high-temperature phase, Austenite, is relatively hard.



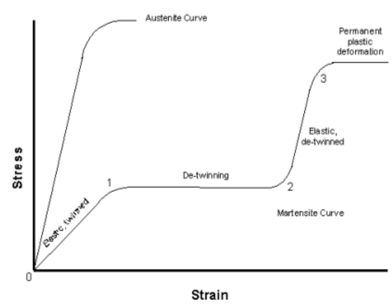


Fig 1.3: Material Crystalline Arrangement During SME | Fig 1.4: Stress-Strain Relationship of SMA [1]

The change in crystalline structure within a Shape Memory Alloy during the Shape Memory Effect is a thermodynamically irreversible process. Internal friction causes energy dissipation and structural flaws. Consequently, temperature hysteresis occurs, as seen in Figure 3a. The substance is 100% martensite starting at 1. The martensite-austenite mixture follows the lower curve while heating. Austenite begins to develop when the temperature reaches the threshold A_S. Austenite continues to form until the material reaches temperature A_F and is entirely austenite. The material composition follows the top curve while being cooled 2. When the temperature goes below M_S, martensite forms and continues to form until the temperature reaches M_F. The material is now reverted to its original state of 100% martensite. The hysteresis in the strain/temperature relationship is precisely proportional to the temperature hysteresis (see Figure 3b). The hysteresis behaviour of an SMA actuator makes developing modelling and control methods difficult. The hysteresis of a given SMA is determined by the alloy composition and manufacturing procedures. With the exception of very wide hysteresis alloys used for joining applications such as couplings, most Shape Memory Alloys have a hysteresis loop width of 10 to 50°C.

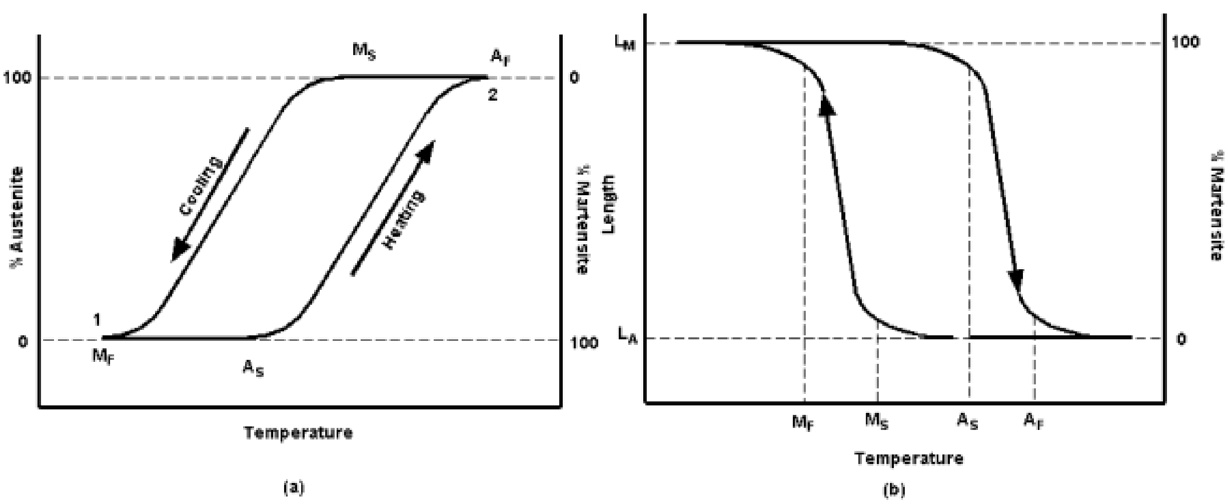


Fig 1.5: Hysteresis Loop in Shape Memory Alloy [1]

1.3.1 Ni-Ti Shape Memory Alloy

The Nickell-Titanium SMA has proven to be one of the most beneficial among all the SMAs in the viewpoint of engineering applications. Further, the Ni-Ti SMA is exceptionally flexible as alloying it with other elements such as Iron, Chromium & Copper can readily change its physical properties to fit demands.

Property	Austenite	Martensite
Melting Temperature, °C (°F)	1300 (2370)	
Density, g/cm³ (lb$_m$/in³)	6.45 (0.233)	
Resistivity, μΩ-cm	Approx. 100	Approx. 70
Thermal Conductivity, W°C/cm (BtuHr°F/ft)	18 (10)	8.5 (4.9)
Corrosion Resistance	Similar to 300 series stainless steel or titanium alloys	
Young's Modulus, GPa (1000 ksi)	Approx. 83 (12)	Approx. 28 to 41 (4 to 6)
Yield Strength , Mpa (ksi)	195 to 690 (28 to 100)	70 to 140 (10 to 20)
Ultimate Tensile Strength, MPa (ksi)	895 (130)	
Transformation Temperatures, °C (°F)	-200 to 110 (-325 to 230)	
Latent Heat of Transformation, KJ*atom/kg (cal*atom/g)	167 (40)	
Shape Memory Strain	8.5% maximum	

Table 1.1: Physical Properties of Ni-Ti Alloy.

1.3.2 SMA in Robotic Applications

Shape Memory Alloy actuators are becoming increasingly efficient in Robotic applications. Their advantages allow robotic systems to be significantly smaller, lighter, and less complicated. SMA actuators have an excellent force-to-weight ratio. Research suggests that an SMA actuator can usually lift an object approximately 78,000 times its weight by 1cm.

The following table shows a comparison of SMA Actuators with their counterparts.

Actuator	Weight	Noise	Actuating Frequency	Force
Electric Motor	Moderate	Moderate	Excellent	Excellent
Pneumatic	Poor	Poor	Good	Excellent
SMA	Excellent	Excellent	Poor	Good

Table 1.2: SMA Actuation compared to its counterparts.

SMA actuation is the most optimal choice, considering the parameters of optimization as cost, portability and noise. Reducing noise is an essential priority because underwater manipulation involves aquatic life, and we aim to avoid the disturbance inflicted upon them.

1.4 Thesis Overview

This thesis is organized into the following sections.

Chapter 2 consists of the section - Literature Review, done to establish the problem statement, highlight the research gap and provide a brief description of the proposed solution and its novelty.

Chapter 3, 4 and 5 consists of the Design section - Mechanical, Actuation and Electronic, respectively. This section elaborates on the design and justifies the design selections. This part covers the most significant portion of the methodology. It includes the performed modelling, testing, fabrication and an overview of the step-by-step assembly. The various challenges faced and key issues followed by the adopted modifications are explained in detail in this part.

Chapter 6 of the thesis deals with the control goals, setup - physical & Arduino, and the final assembly's functionality, working & operation. This part focuses on integrating all the prior sections to present a complete and functional assembly, i.e., a readily reprogrammable robotic arm.

Chapter 7 consists of the obtained final results and the interpretation. In this chapter, the results are presented in an explicit and logical order so as to enable the reader's understanding of the motivation behind each step in the project. This part aims to showcase the results as pieces of a more significant problem that this work was supposed to solve. By combining all of the critical aspects of the original problem statement, a detailed conclusion of the research has been presented.

Chapter 8, the final chapter of this thesis, draws on the conclusion and outlines possible future work in this direction and the contributions of the attempted work to the overall underwater robotics research and its impact on the broad field of engineering.

Chapter 2

Literature Review

The design objective of this project was to design a quiet, light-weight cost-optimized Remotely Operated 'Hand'. The designed assembly may later be attached with a tether to an AUV, provided the disturbance inflicted upon aquatic life remains null. In direct relevance to the current project, the hand can be lowered from the land surface with the help of a tether. Although the shape memory alloy can be actuated in water, its life begins to shorten at a faster rate than usual. Therefore, the remaining assembly - actuator and electronic assembly stay outside the water body.

The grippers currently in use include two-four finger intermeshing/floating jaws, scissor jaws or suction foots.[2] The modes of actuation seen in research are - electric, hydraulic and motor-actuated. The underwater manipulators - both commercially observed and in research are typically designed with three to six degrees of freedom. These manipulators were intended for basic automation tasks. However, the humanoid gripper would be a winner in all scenarios from a higher complexity perspective. Furthermore, an added advantage to higher degrees of freedom is that they can be exploited for obstacle avoidance. Given that the underwater territory is highly irregular, this is an important objective.

Domenico Mura et al.[3] designed a novel motor-actuated soft hand as an end-effector for underwater manipulation. Although the choice of end-effector is optimized in this case, it is actuated by a motor, which makes the functioning quite noisy and disturbing to aquatic life.

Although the electric, hydraulic and motor actuators are efficient in terms of force and frequency of actuation, SMA is the only quiet form of actuation, which is our primary objective in this project.

Combining the best of all scenarios, we proposed a model consisting of a Humanoid (five jaws) end-effector with 17 degrees of freedom actuated by Shape Memory Alloy coil springs through cables drawn from them. The SMA actuators would be used to control both the contraction and protraction of the fingers. Usually, SMA actuated grippers use pseudo elastic springs to aid the fingers' return to their original state. However, our project explores the novelty of using the SMA springs for bi-directional control.

Chapter 3

Mechanical Design

3.1 Mechanical Modelling

3.1.1 Hand

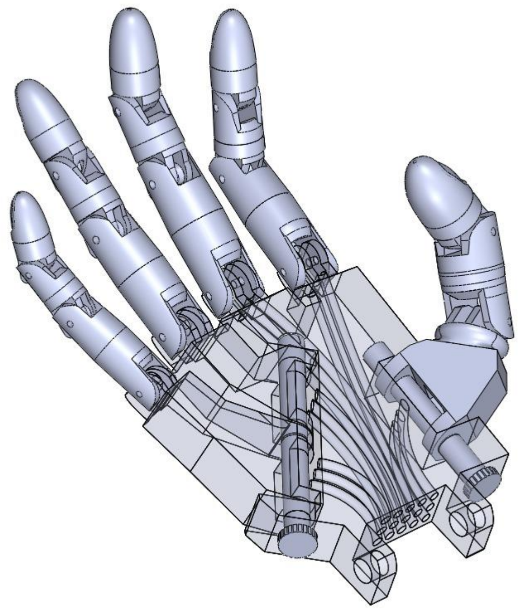


Fig 3.1: SolidWorks[4] design of the hand

The model's dimensions are that of an average male hand. The hand model consists of 17 DoF. As shown in Figure 5, the bio-inspired hand allows free passage of cables from the wrist region to the fingertips, aiding unrestricted individual actuation of each finger. Further, to mimic the capabilities of the human hand to the highest possible extent, the thumb, ring finger, and pinky have an extra degree of freedom in the palm, as visible in the figure.

3.1.2 Double-Deck Plate

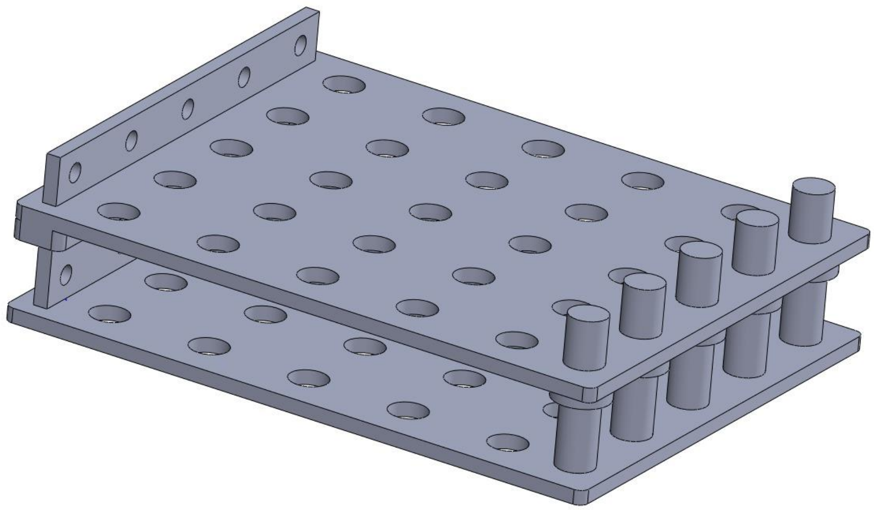


Fig 3.2: SolidWorks design of the double-deck plate

This double-deck plate was designed in order to clamp the SMA coil spring actuators. Since each finger requires two SMA coil springs - contraction and protraction, a total of 10 spaces (5 on each plate) for the spring clamping are provided.

The small holes on the vertical surface of the plate are intended to connect the springs to the hand by passing the cables through them. The larger holes on the horizontal surface are intended to reduce the weight, provide ventilation and also aid in the electronic assembly by providing room for organized connections.

3.2 3-D Printing

3-D printing is the chosen method of manufacturing due to its rapid prototyping capabilities. The cost to manufacture is relatively low, and the 3D print material - PolyLactic Acid (PLA), is one of the most biodegradable materials among all the choices of materials in 3-D printing. This makes the selection of PLA perfect for operation in an underwater environment.

Each part of the gripper was printed in individual segments and assembled together using 2mm diameter dowel pins. The 3D printer was programmed to print at a 0.1mm layer height at 200º Celsius.

Figure 3.3, in the following subsection, shows the assembly of the individually 3-D printed segments.

3.3 Mechanical Assembly

The final mechanical assembly consists of the assembled hand and the double-deck plate, which will serve as the actuator system (explored in detail in Ch 4). The actuator system would be held outside the water body while the hand is immersed with the help of cables (inside a tether for deeper tasks) into the waterbody.

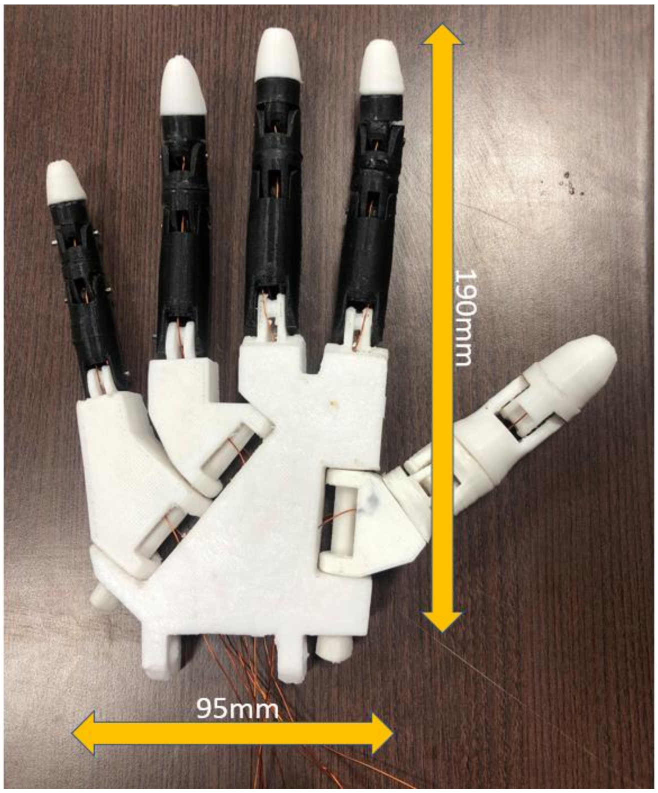


Fig 3.3: Final 3-D Printed Prototype

Chapter 4

Actuator Design Selections

4.1 Introduction

As discussed prior in the literature review, putting together the existing research gap and the objectives of this project, Shape Memory Alloy was the chosen mode of actuation.

$$\rho c V \frac{dT}{dt} = Ri^2(t) - hA(T(t) - T_\infty)$$ [1]

Where ρ - density of SMA; c - specific heat capacity of SMA; V - volume of material; T - wire temperature; t - time; I - current; R - electrical resistance; h - convection heat transfer coefficient; A - surface area of SMA; T - ambient temperature

The dynamics of a Ni-Ti SMA actuator were captured using the temperature-current relationship. In terms of temperature, electrical current, and time, this relationship takes the form of a differential equation (above).

The following sub-sections of this chapter will cover the actuator design selections, testing, and finally, the cumulative setup of the mechanical and actuation units.

4.2 Actuator Design

4.2.1 Copper Wires

In order to connect the actuator system to the hand and actuate the fingers, the cables of choice were copper wires for an array of reasons. Copper wires are heat resistant. SMA coil springs can reach high temperatures, so heat resistance is necessary. They are highly corrosion resistant and ductile, which are vital benefits and reasons for this selection.

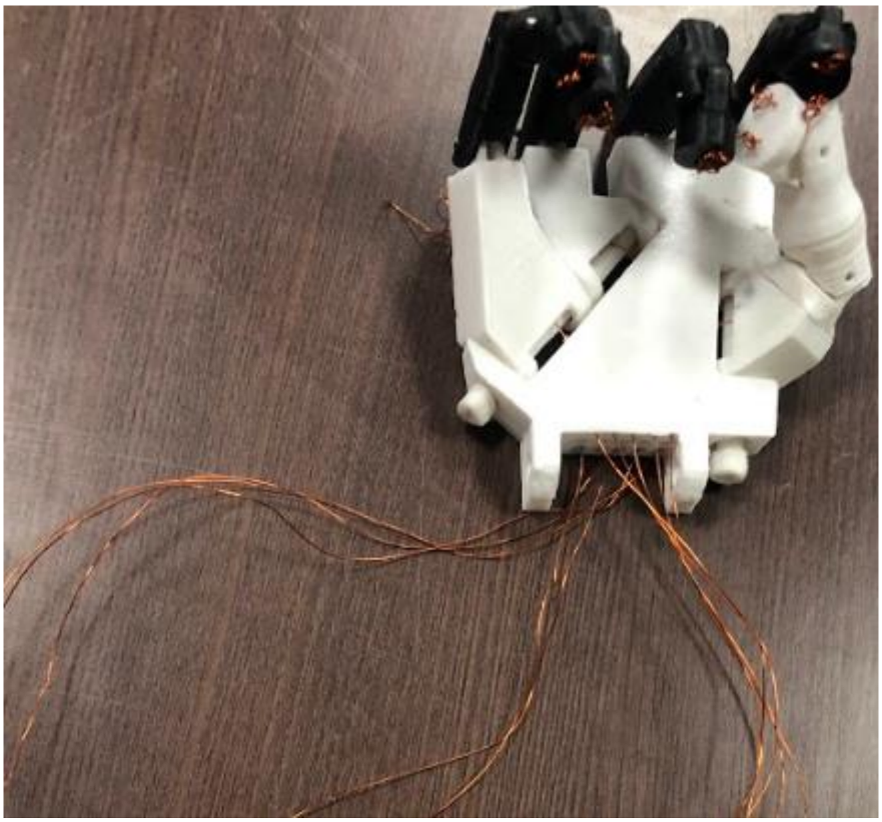


Fig 4.1: Copper Wires

4.2.2 Shape Memory Alloy Coil Spring

Between SMA wires and SMA coil springs, the latter was selected as they have a significantly longer stroke than the former. Nickel-Titanium (Ni-Ti) or Nitinol, being one of the most suitable materials for the application, was the choice for the SMA coil spring.

The Nitinol springs procured had a 0.75mm diameter, were 60-80mm in length in the wound state and contracted to around 15mm when a voltage drop was applied.

4.3 Actuator Testing

The Nitinol coil spring produced approximately 45N of tensile force.

One end of the NiTi spring was clamped, and the other was attached to a pulley system. The counterbalance weight was increased gradually until the system reached equilibrium.

The overall temperature of the spring drastically dipped when they were subjected to pulses of current through voltage drops (duty cycle) compared to a fully ON mode. By manually experimenting, we found that a duty cycle of approximately 66% was optimal in terms of both heat reduction and suitable actuation.

4.4 Setup

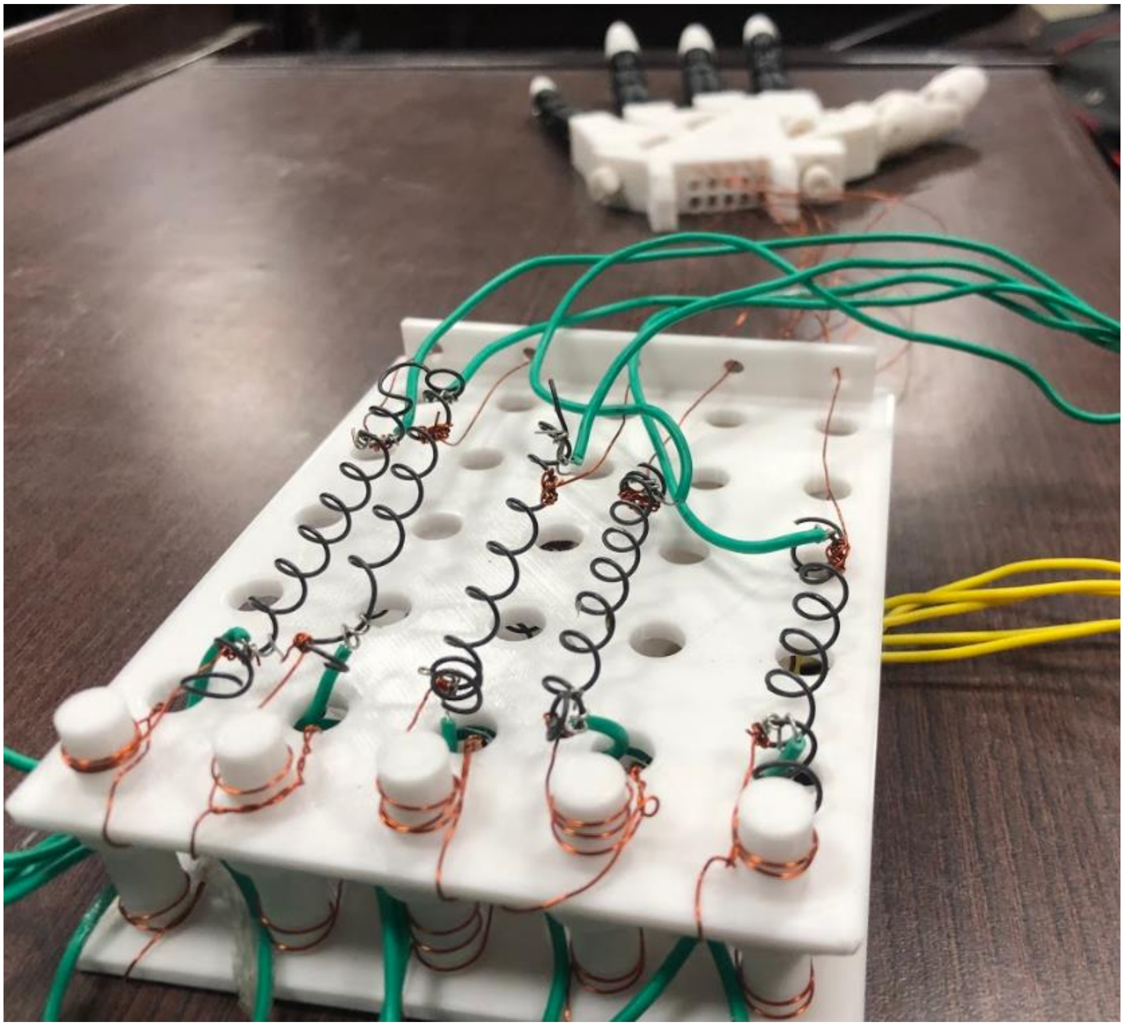


Fig 4.2: Setup - Mechanical + Actuator

The figure shown above shows the actuation system's final arrangement, with the coil springs being well mounted on the double-deck plate. The copper wires, firmly fastened to the coil springs, are then drawn to the fingertips of the hand and are fastened within the distal phalanx of the printed hand.

This assembly, with the help of electronic design & interfacing, this assembly can be deployed as a versatile robotic manipulator on the field, mainly targeted at underwater applications.

Chapter 5

Circuit Design

5.1 Actuation Circuitry

Fig 5.1: Actuation Circuitry

An electrical circuit was designed to deliver power from the source to the SMA actuators in a manner that is controllable by the Arduino Uno microcontroller. The components of the circuit are as follows:

1. DC Power Source 1: 80V 40A
2. DC Power Source 2: 5V 1A
3. 5V Relay module x2

4. Arduino Uno x2
5. Arduino Mega
6. Jumper Wires
7. Single-core electrical wire

We use a high current DC power supply to actuate the SMA wires even though it compromises portability. This was done simply to provide a proof of concept to the prototype. A Li-Ion battery of 10000mAh capacity with a discharge rate of 3C will be able to provide the necessary power for an hour of continuous operation - assuming an operation voltage of 3.7V at 30A.

Power sources 1 and 2 deliver power to the SMAs and the relay modules, respectively. The relay modules are employed to control power to the SMA actuators. The relay modules are controlled by Arduino microcontrollers. The purpose of multiple Arduinos boards employed in the circuit is due to the maximum current draw limit being (20mA) being reached.

Single-core electrical wiring along with jumper wires make the connection to complete the electrical circuit of the actuation setup.

5.2 Circuit Diagram and Breakdown

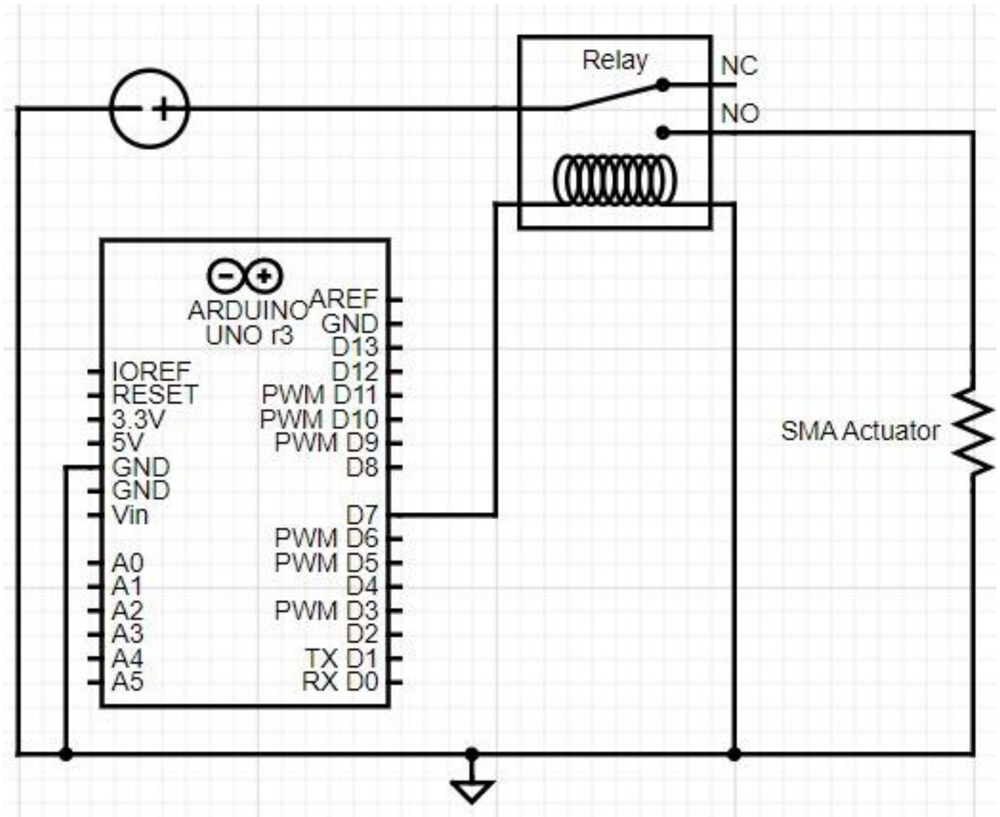


Fig 5.2: Actuation Circuit Diagram

The circuit diagram below shows a schematic of power delivery to a single SMA actuator.

The SMA actuator is connected to the Normally Open (NO) position of the relay. The solenoid of the relay is controlled by the pin D7 of the Arduino Uno. When the Arduino pin gives a 5V signal to the relay, the solenoid activates and switches the terminals from the Normally Closed (NC) to the Normally Open (NO) position. This completes the circuit of the SMA actuator and the DC power source.

Chapter 6

Control of the Manipulator

6.1 Introduction

With the Mechanical, Actuation and the Electronic Design being fully assembled, the final essential portion for completion is the interfacing and overall integration of the setup. This project implements the On/Off control mode. The three other standard modes are - proportional, integral, and derivative.

6.2 Control Goals

In order to minimize heat, the current is fed with a duty cycle of 66%. The primary goal was to provide enough time for the coil spring to both contract as well as reach a threshold temperature in the first ON time. The current was supplied through the voltage drop from the next cycle, only to maintain the heat generated in the SMA spring.

6.3 Controller Setup

As shown in Figure 12, the assembly uses three Arduinos, two 5V relay modules and two power sources. Two of the three Arduinos (Uno) are fed real-time code and readily reprogrammable as required. The other Arduino (AtMega 256) is connected to the PC, mainly to power the relay module. This Arduino Mega does not receive or run any of the codes.

6.4 Operation

```
digitalWrite(springPin1, LOW);
delay(4000);
digitalWrite(springPin1, HIGH);
delay(2000);
digitalWrite(springPin2, LOW);
delay(4000);
digitalWrite(springPin2, HIGH);
delay(2000);
```

Fig 6.1: Arduino Code Snippet

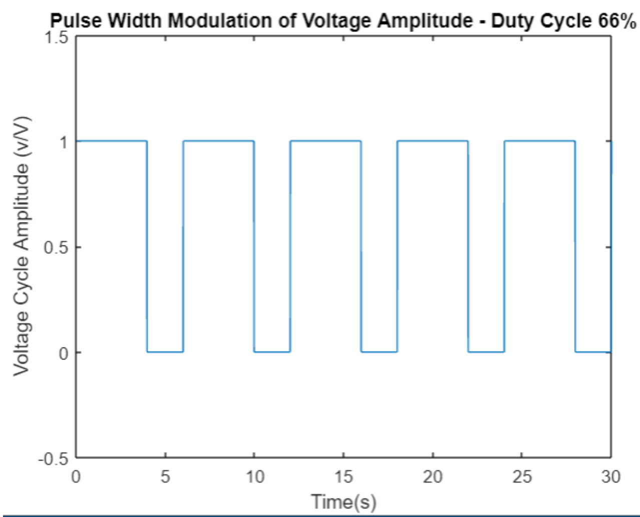


Fig 6.2: Voltage Cycle Amplitude - Time (Plot)

From Figure 13, we can observe that for every six seconds, the actuator receives a drop for 4 seconds, which is 66% of the cycle, as illustrated in the Duty Cycle plot in Figure 14.

6.5 Final Assembly

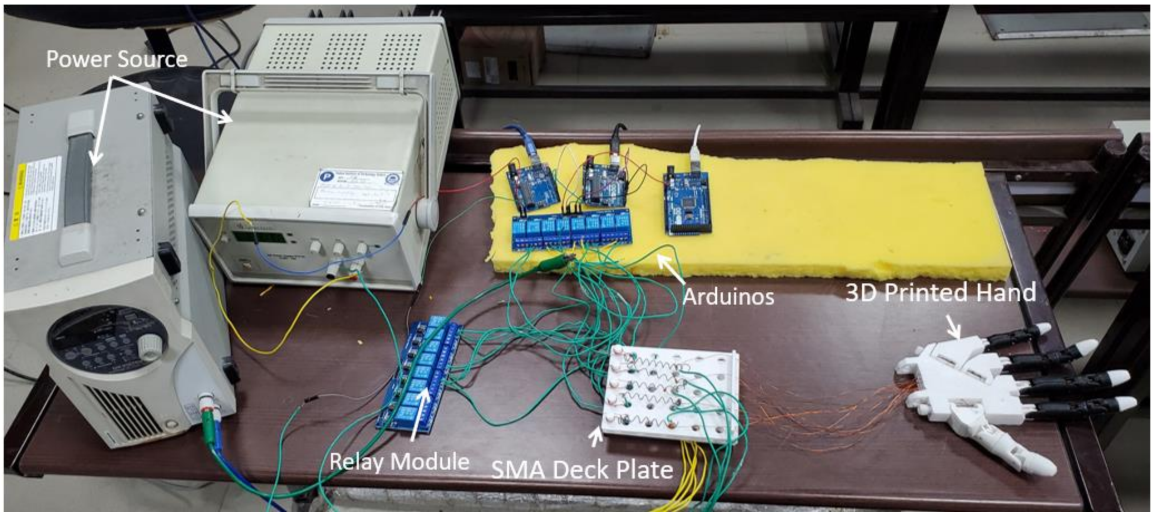


Fig 6.3: Final Assembly

The above figure (Fig 6.3) shows the final assembly of the project. The two power sources working alongside the Arduinos and Relay modules provide the voltage drop to the Nitinol springs, in turn contracting the springs of choice, thus actuating the hand appropriately.

Chapter 7

Results and Discussion

7.1 Mechanical Design

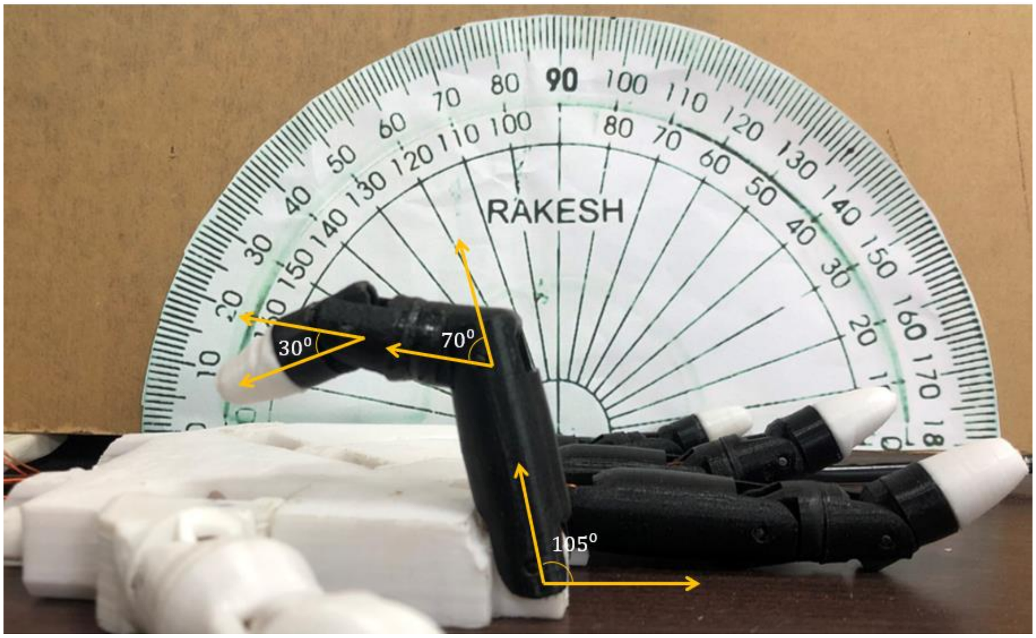


Fig 7.1: Angle Traversed by Index Finger

Parameter	Index	Middle	Ring	Pinky	Thumb
Length(mm)	93	95	93	77	85
Rotation(degree)	205	205	295	295	210

Table 7.1: Finger Dimensions & Extent of Actuation in terms of Rotation

7.2 Grasping Capability and Actuation

Fig 7.2(a) & (b): Manipulator Grasping Tools

7.2.1 Grasping Force

A load of 0.70N was hung from the fingertip of the index finger. Gradually, the load was increased until the finger, while being actuated, failed to lift the load. Hence, the actuation force of one finger is 1N.

7.2.2 Actuation Time & Cycle Time

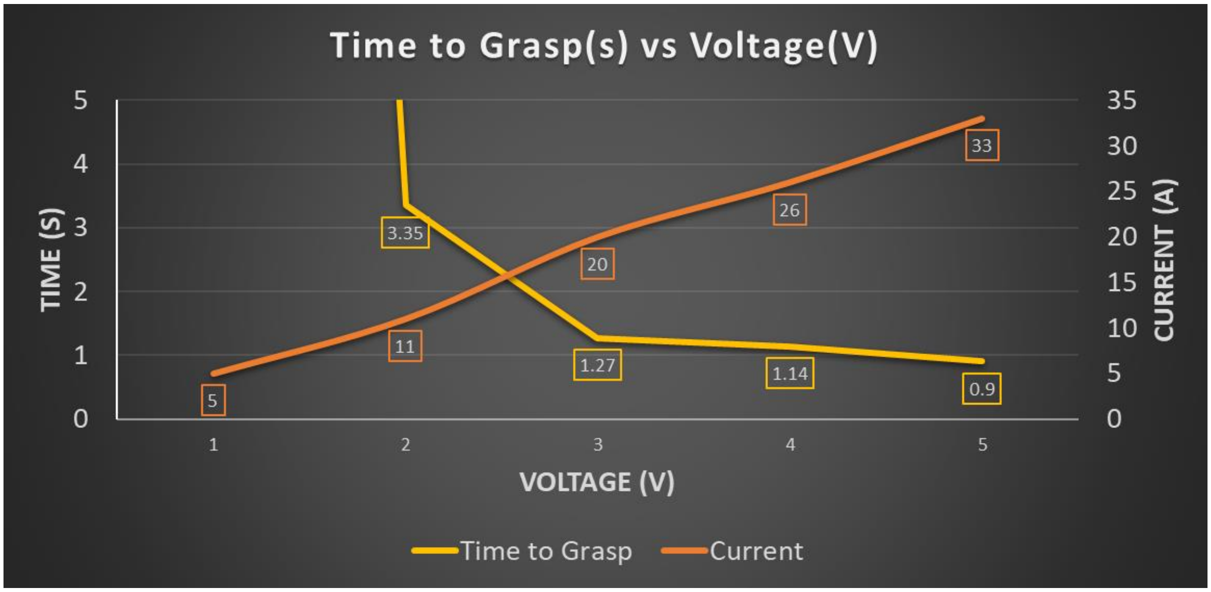


Fig 7.3: Time to Grasp & Current - Voltage Plot

The above plot illustrates the variation of the hand's time to grasp with increasing voltage. At 1V, the actuator drew a current of 5A but took over 50 seconds to actuate fully. As the voltage approaches 3V, we can observe that the time to grasp drastically reduces.

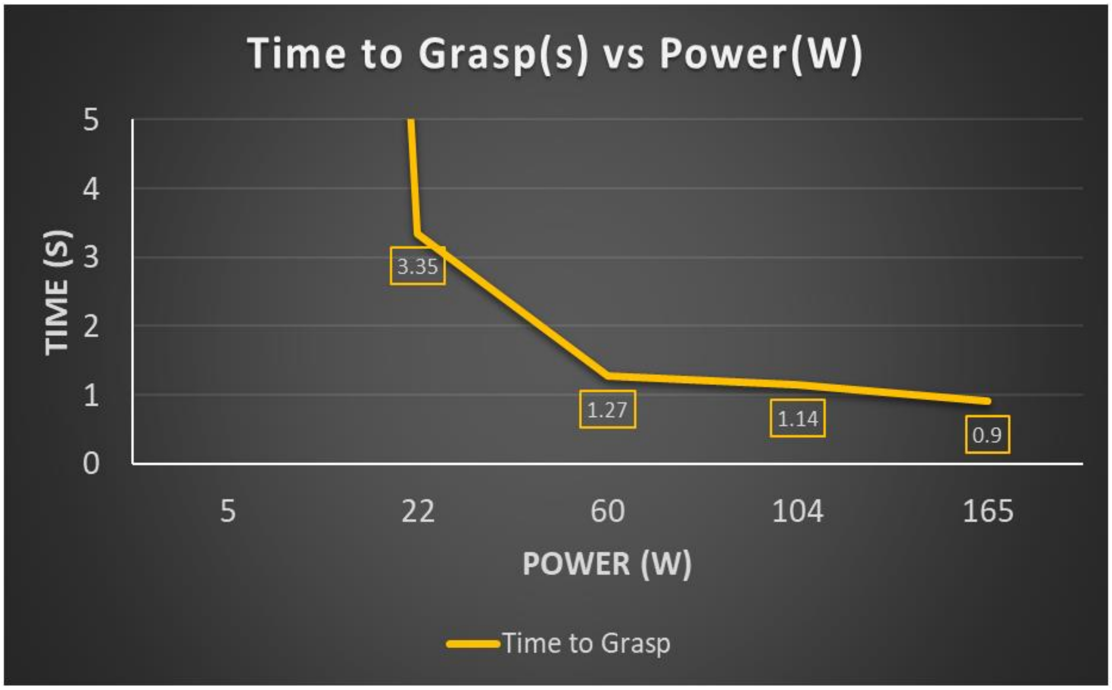


Fig 7.4: Time to Grasp -Power

Figure 19 is a cumulative plot representation in Fig 18. The ideal actuation scenario is observed at the supply of 50-60W to the actuator.

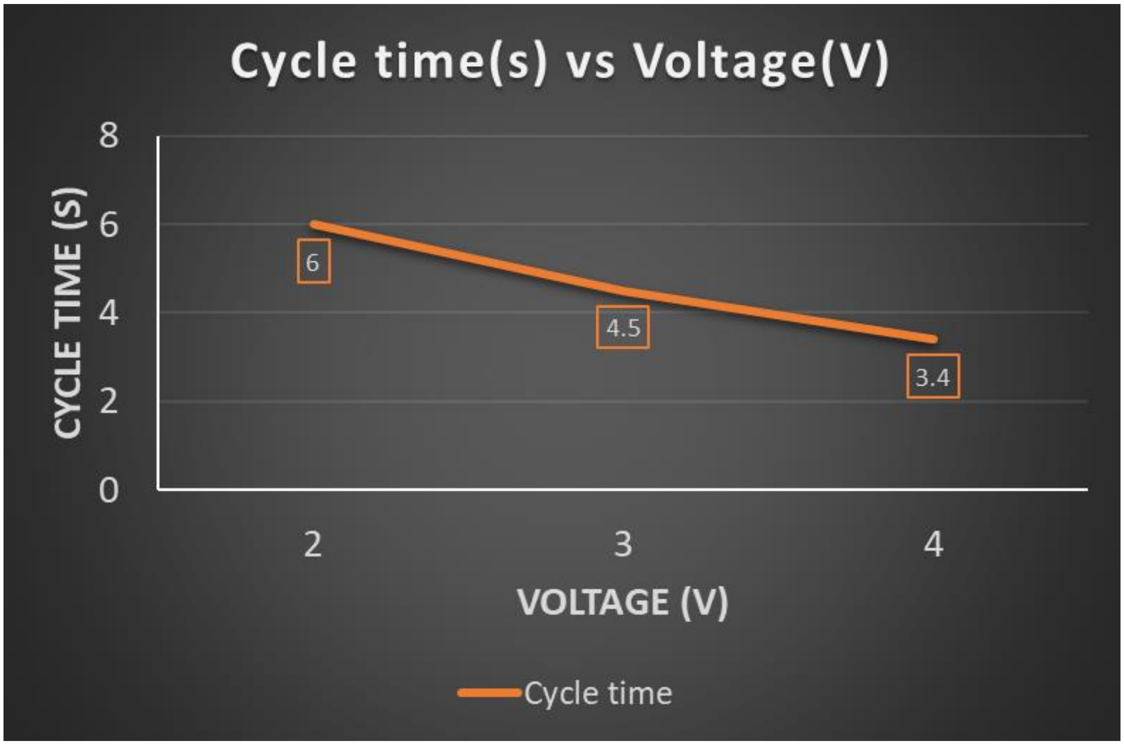


Fig 7.5: Cycle Time - Voltage

Cycle time in this plot is defined as the sum of times taken to contract, protract, and the wait between the two events to partially reset the tension in the copper wires caused by the first set of actuators (contraction).

In conclusion, operating the actuator at a voltage drop of approximately 3V produces the most optimum results.

7.3 Control

On/Off control mode was implemented for the actuation of the SMA actuated hand. The fingers of choice (fed via code) actuated fully by default, given a voltage drop. Due to time constraints, experimentation for other modes of control could not be conducted. Section 8.2.1 elaborates on the future scope and improvements that can be made to the control sector of this project.

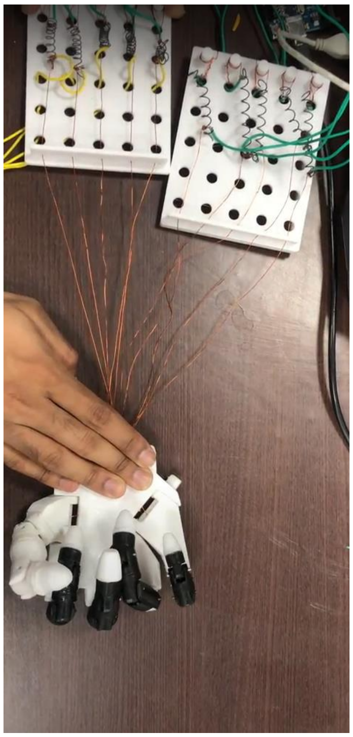


Fig 7.6: Fully Actuated State of the Hand

7.4 Underwater Valve Experiment

Fig 7.7 (a), (b) & (c): Valve Opening

The above figures show the hand grasping the valve, followed by the opening and rest position.

Figure 7.7(b) shows that the actuation system and electronic assembly reside just outside the tank's surface. The hand was lowered with the help of the double-deck plate and the cables (copper wires) until the hand reached the valve. Upon powering up the system, the hand grasped the valve and consequently created a torque that enabled the opening of the valve.

Note: To maintain the tension in the cables, the double-deck plate was pulled upwards so as to continue translating the SMA contraction directly to the fingers to be actuated.

Chapter 8

Conclusions and Scope for Future Work

8.1 Mechanical Design

8.1.1 Soft Robotics

Incorporating a softer finish for the hand constituting flexible joints, i.e., its compliance being concentrated at its joints, would be mechanically better.[2] A softer hand can adapt better to further irregularly shaped objects and grasp them much more effectively, with relatively better-grasping force control.

8.1.2 Other Modifications

Exploiting Underactuation: The simplest case of underactuation is when the DoF exceeds the number of actuators. Underactuated systems have the advantage of causing relatively lesser harm on impact and have also proven to be more tolerant to cases of actuator failure.

Self-balancing: Since the Remotely Operated Hand will undergo several hydrodynamic forces while suspended by a tether, it is essential to ensure that the hand does not drift off from the task region. It would be rather uncomfortable to employ extra effort in manually correcting its position constantly. Including a control system that reduces the hand’s deviation from its preset trajectory can solve this problem.

8.2 Control

8.2.1 Alternate Types of Control

This project designed a manipulator wherein the actuation system is functional until complete grasp. There is no state between a full grasp and a freely suspended state. To achieve complete control, PID control can be employed. Further, the grasping force can also be a control target by simultaneously actuating the contraction and protraction springs appropriately.

8.2.2 Tele-Operation

Once the control mode is made multi-dimensional, a user can be equipped with EMG sensors. The signals are amplified and transmitted to the receptors attached to the hand; thereby, the hand would mimic all the user's actions. A camera can be attached so that the user receives visual feedback from the Remotely Operated Hand.

8.2.3 Sensors & Feedback

For tasks requiring high sensitivity and complexity, the previously mentioned subsections would be insufficient. Added sensors and real-time feedback are essential in this case. In this scenario, incorporating haptics would greatly benefit the cause, as kinesthetic feedback is most relevant to the type of task and the hand mode

8.3 Conclusion

A highly dexterous five-fingered (17 DoF) humanoid gripper with underwater operation capability was designed. The gripper was 3D printed from PLA biodegradable plastic.

A rotation angle of 205º was achieved in the index finger. The actuation force of one finger was 1N, i.e., the gripping force of the fingertip was measured to be 1N.

The index finger’s actuation time was 0.96s, and the overall cycle time was measured to be 3.4s.

The underwater valve operating experiment was performed to demonstrate the design viability of the manipulator.

The 3-D Printed SMA Actuated Underwater Robotic Manipulator adhered to the initial objectives of being perfectly quiet and cost-effective and also was able to supply sufficient force to perform a moderately difficult task underwater.

References

[1] - Invited Chapter in Automation, Miniature Robotics and Sensors for Non-Destructive Testing and Evaluation, Y. Bar-Cohen Editor, April 99 | Constantinos Mavroidis, Charles Pfeiffer and Michael Mosley Robotics and Mechatronics Laboratory Department of Mechanical and Aerospace Engineering Rutgers University, The State University of New Jersey

[2] - Sivčev, Satja; Coleman, Joseph; Omerdić, Edin; Dooly, Gerard; Toal, Daniel (2018). Underwater manipulators: A review. Ocean Engineering, 163(), 431–450. doi:10.1016/j.oceaneng.2018.06.018

[3] - Mura, Domenico; Barbarossa, Manuel; Dinuzzi, Giacomo; Grioli, Giorgio; Caiti, Andrea; Catalano, Manuel (2018). A Soft Modular End Effector for Underwater Manipulation.: A Gentle, Adaptable Grasp for the Ocean Depths. IEEE Robotics & Automation Magazine, (), 1–1. doi:10.1109/MRA.2018.2871350

[4] - https://inmoov.fr/

Yuh, J.; West, M. (2001). Underwater robotics. Advanced Robotics, 15(5), 609–639. doi:10.1163/156855301317033595

Xiu Fen Ye, ; Ya Nan Hu, ; Shu Xiang Guo, ; Yu Dong Su, (2008). [IEEE 2008 IEEE International Conference on Mechatronics and Automation (ICMA) (Formerly ICIMA) - Takamatsu, Japan (2008.08.5-2008.08.8)] 2008 IEEE International Conference on Mechatronics and Automation - Driving mechanism of a new jellyfish-like microrobot. , (), 563–568. doi:10.1109/ICMA.2008.4798818

Diolaiti, N.; Melchiorri, C. (2002). [IEEE HAVE 2002 - IEEE International Workshop on Haptic Virtual Environments and their Applications - Ottawa, Ont., Canada (17-18 Nov. 2002)] IEEE International Workshop HAVE Haptic Virtual Environments and Their - Teleoperation of a mobile robot through haptic feedback. (), 67–72. doi:10.1109/have.2002.1106916

El-Ghazaly, Gamal; Gouttefarde, Marc; Creuze, Vincent (2015). [IEEE 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) - Hamburg, Germany (2015.9.28-2015.10.2)] 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) - Hybrid cable-thruster actuated underwater vehicle-manipulator systems: A study on force capabilities. , (), 1672–1678. doi:10.1109/iros.2015.7353592

Lin, Maohua; Vatani, Morteza; Choi, Jae-Won; Dilibal, Savas; Engeberg, Erik D. (2020). Compliant underwater manipulator with integrated tactile sensor for nonlinear force feedback control of an SMA actuation system. Sensors and Actuators A: Physical, (), 112221–. doi:10.1016/j.sna.2020.112221

WANG Yang-wei, LAN Bo-wen, LIU Kai, ZHAO Dong-biao. Modeling and experiment of flexible manipulator actuated by shape memory alloy wire[J]. Journal of Zhejiang University(Engineering Science), 2018, 52(4): 628-634.dx.doi.org/10.3785/j.issn.1008-973X.2018.04.003

https://www.vicorpower.com/industries-and-innovations/robotics/robotics-tethere