भारतीय प्रौद्योगिकी संस्थान काशी हिन्दू विश्वविद्यालय
INDIAN INSTITUTE OF TECHNOLOGY
BANARAS HINDU UNIVERSITY

SUMMER INTERNSHIP (ME-497)
PROJECT REPORT

Fabrication, Modeling, and Application of Soft Electrohydraulic Actuators (HASEL Actuators)

Name : **Naman Khetan**

Roll Number : **21135085**

Department : **Mechanical Engineering (B.Tech, part 4)**

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to **Prof. Christoph Keplinger and my mentor Toshihiko Fukushima**, whose guidance and wisdom have been the beacon that navigated me through this project. Their expertise in the design and manufacturing domain of Soft robotics and their unwavering support have been invaluable to the development and continuation of this project.

I am also thankful to **the PhDs and Postdocs of the Robotics Materials Department, Max Planck Institute for Intelligent Systems**, with whom I have had many insightful discussions that helped me to expand my knowledge. I am also grateful to **Janina Schwartz** for the smooth onboarding and management of all the communication, which helped me make my stay in Germany comfortable.

A special thanks to **Dr. Pawan Sharma**, who gave me a letter of recommendation for the DAAD WISE Scholarship program. I am grateful to **DAAD India** for funding this internship.

Finally, I would like to thank my seniors, friends, family, and people who supported me in my efforts during this project.

OFFER LETTER

MAX PLANCK INSTITUTE
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MPI for Intelligent Systems, Heisenbergstr. 3, 70569 Stuttgart, Germany

Prof. Dr. Christoph M. Keplinger
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Managing Director
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Stuttgart, 2023-10-02

Invitation Letter for a Research Internship under the DAAD WISE Program

Dear Sir or Madam,

Mr. Naman Khetan, born on October 16, 2001 is invited to join my department "Robotic Materials" at the Max Planck Institute for Intelligent Systems in Stuttgart, Germany, as a research intern from May 11, 2024 to July 16, 2024. Therefore, he is applying for the DAAD WISE research program.

Mr. Naman Khetan should receive this funding to conduct scientific research in Germany under the supervision Toshihiko Fukushima, Ph.D. student in the "Robotic Materials" department.

We kindly ask for the selection of Mr. Naman Khetan for him to be able to take up the internship.

Sincerely,

Prof. Dr. Christoph M. Keplinger

Director, Robotic Materials Department
Managing Director, Max Planck Institute for Intelligent Systems, Stuttgart
Eminent Visiting Professor of Soft Robotics, University of Colorado Boulder, USA
Honorary Professor, University of Stuttgart, Germany
Co-founder & Chief Science Officer (CSO), Artimus Robotics

INTERNSHIP COMPLETION CERTIFICATE

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Prof. Dr. Christoph M. Keplinger
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Stuttgart, July 17, 2024

Internship Certificate: Mr. Naman Khetan

Mr. Naman Khetan, born on 16 October 2001, has successfully completed an internship at the Max Planck Institute for Intelligent Systems from 13 May 2024 until 16 July 2024. Mr. Khetan worked in the Robotic Materials Department led by Prof. Christoph Keplinger. The internship was related to Mr. Khetan's study program of Mechanical Engineering at the Indian Institute of Technology (BHU) Varanasi in India. Mr. Khetan worked under the supervision of Mr. Toshihiko Fukushima on soft electrohydraulic actuators for soft robotics.

His activities encompassed three main topics: 1. fabrication of the soft electrohydraulic actuators, 2. analytical study of the electrical-mechanical interfacing of the actuator, and 3. development of a robotic application of the actuator. For the first topic, he implemented a semi-mass-production scale fabrication process, producing over fifty actuators using CNC machining, screen printing, laser cutting, and silicone coating. For the second topic, he formulated the relationship between the electrical and mechanical behavior of the actuator using the Lagrangian equation of motion, partially uncovering correlations between these parameters. For the third topic, he developed a bio-inspired active hinge structure. He initiatively presented the idea of the structure and started this project. He prototyped the joint by surveying biological literature and utilizing bio-mimetic design, CAD design, and 3D printing. The joint successfully worked with high-speed reciprocating motion (20Hz), and he demonstrated it to other intern students. He presented these results in a department meeting, gaining experience in structuring academic presentations. Additionally, he attended the EuroEAP 2024 academic conference as an observer and engaged in discussions with various presenters. He also participated in Robotics Institute Germany Interns (RIGI), actively networking with other international interns.

Overall, Mr. Khetan proactively engaged in his internship and stimulated the department with his active discussions. We appreciate his contributions and dedication.

Sincerely,

Prof. Dr. Christoph M. Keplinger
Director, Robotic Materials Department
Managing Director, Max Planck Institute for Intelligent Systems, Stuttgart
Eminent Visiting Professor of Soft Robotics, University of Colorado Boulder, USA
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1. Introduction

Soft robotics represents a transformative approach in robotics, where the focus shifts from rigid, inflexible structures to designs that are flexible, adaptive, and capable of safely interacting with complex environments. These robots, inspired by biological systems, are constructed from soft materials, enabling them to perform tasks that would be challenging or dangerous for traditional robots. A key component in soft robotics is the actuator, which functions similarly to muscles in biological organisms, allowing movement and interaction with the environment.

Among the various actuators developed for soft robotics, the Hydraulically Amplified Self-healing Electrostatic (HASEL) actuator has emerged as a promising technology. These actuators utilize a combination of electrostatic and hydraulic forces to generate movement, mimicking the behaviour of natural muscles. HASEL actuators are characterized by their ability to produce significant strain and force, self-heal when damaged, and adapt to various applications.

This report details the work done during an internship at the Max Planck Institute for Intelligent Systems, focusing on the fabrication, modelling, and application of HASEL actuators. The internship provided an opportunity to engage in cutting-edge research, develop practical skills in actuator fabrication, and contribute to the advancement of soft robotics.

2. Background

The development of soft actuators is crucial for advancing the field of soft robotics. Traditional rigid actuators are often limited by their inability to adapt to complex and unpredictable environments. In contrast, soft actuators offer flexibility, safety, and adaptability, making them ideal for applications in medical devices, wearable technology, and robotics.

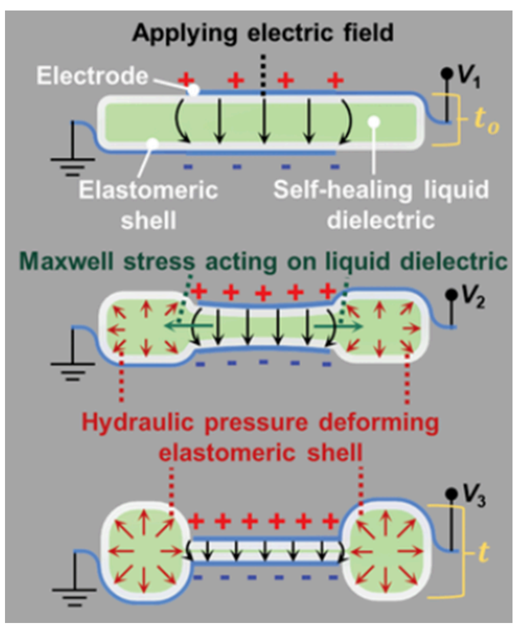

Fig 1: Mechanism of HASEL actuator [1]

HASEL actuators are composed of a dielectric shell filled with a liquid and surrounded by electrodes. When a high voltage is applied, the electrodes generate an electrostatic force, deforming the liquid and causing the actuator to change shape. This deformation mimics the contraction and expansion of biological muscles, allowing the actuator to move. The combination of hydraulic and electrostatic forces enables HASEL actuators to achieve high actuation strains and forces, making them suitable for various soft robotic applications.

The simplicity of their design, combined with the ability to self-heal and operate under a wide range of conditions, makes HASEL actuators a key technology for the future of robotics. Their potential applications span from underwater and aerial robotics to medical devices and prosthetics, where traditional actuators fall short.

3. Motivation

The motivation for developing HASEL actuators stems from the limitations of conventional actuators, which are typically rigid and require complex mechanisms to achieve movement. In contrast, HASEL actuators offer a more straightforward, efficient, and adaptable solution, capable of producing muscle-like movements with fewer components and greater flexibility.

Furthermore, the versatility of HASEL actuators makes them ideal for various applications. Whether in a robotic arm, a wearable device, or an autonomous robot, the actuator's ability to adapt to its environment and perform complex tasks significantly advances over traditional technologies.

4. Objectives

The internship at the Max Planck Institute for Intelligent Systems aimed to achieve the following objectives:

1. **Fabrication of HASEL Actuators**: Implementing a semi-mass-production process to fabricate over fifty actuators, using techniques such as CNC machining, screen printing, laser cutting, and silicone coating.
2. **Modelling of HASEL Actuators**: Developing an analytical model to describe the relationship between the electrical input and the resulting mechanical behaviour of the actuators using the Lagrangian equation of motion.
3. **Application of HASEL Actuators**: Designing and prototyping a bio-inspired active hinge structure to mimic the movement of a dragonfly wing, demonstrating the potential of HASEL actuators in aerial robotics.

These objectives were chosen to provide a comprehensive understanding of the fabrication, modelling, and application processes involved in developing HASEL actuators to contribute to the broader field of soft robotics.

5. Work Done

5.1 Fabrication of HASEL Actuators

The fabrication of HASEL actuators involved a series of carefully planned steps, each designed to ensure the production of high-quality actuators suitable for research and application. The process began with **heat sealing of films** using a heat extruder head mounted on a CNC machine to seal films together for the actuators. These heat-sealed films were then used in a **screen-printing process** to apply conductive layers in carbon ink. Then, **dielectric liquid like silicon oil is filled** in these films through tiny pores using syringes. These pores are then **heat-sealed using soldering iron**.

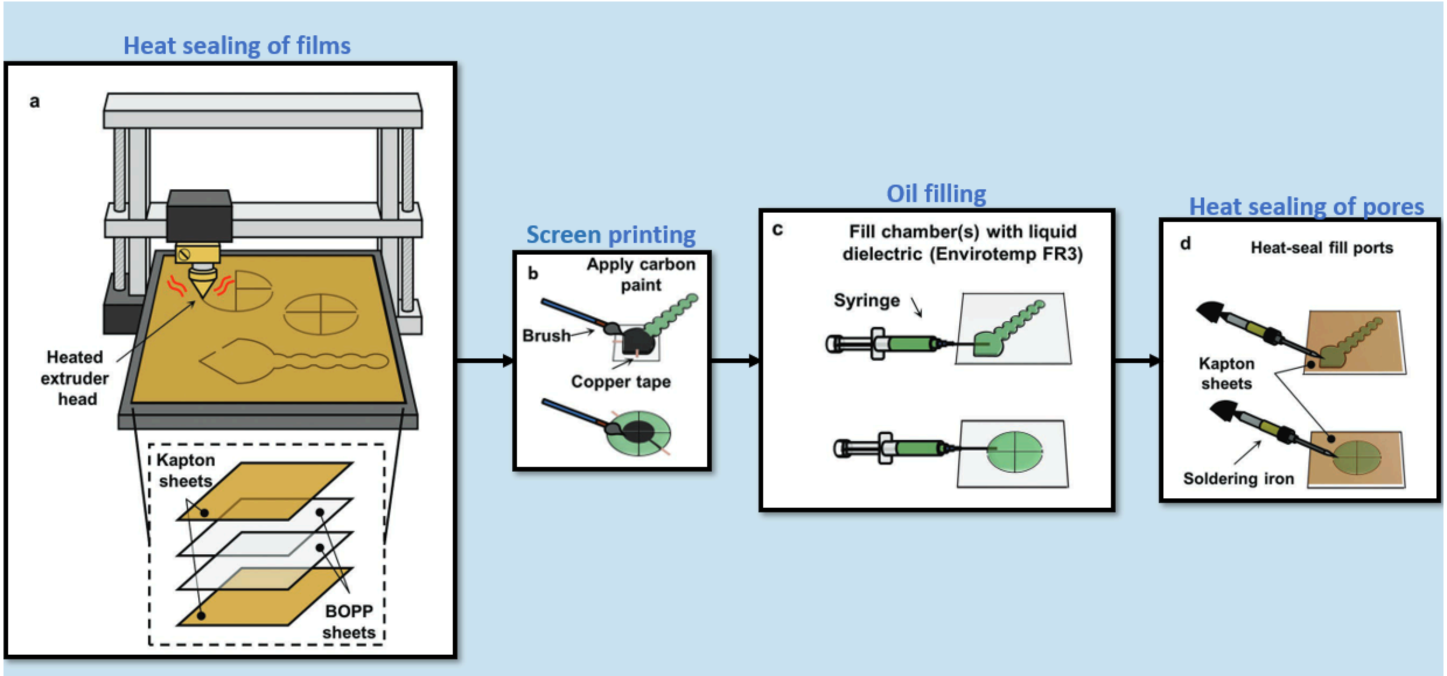

Fig 2: Step-by-step fabrication of HASEL actuators [1]

Once the basic structure of the actuator was formed, the next step involved silicone coating to enhance the actuator's durability and performance. Over **fifty actuators were produced** through this semi-mass production process, demonstrating the feasibility of scaling up the production of HASEL actuators for larger-scale applications.

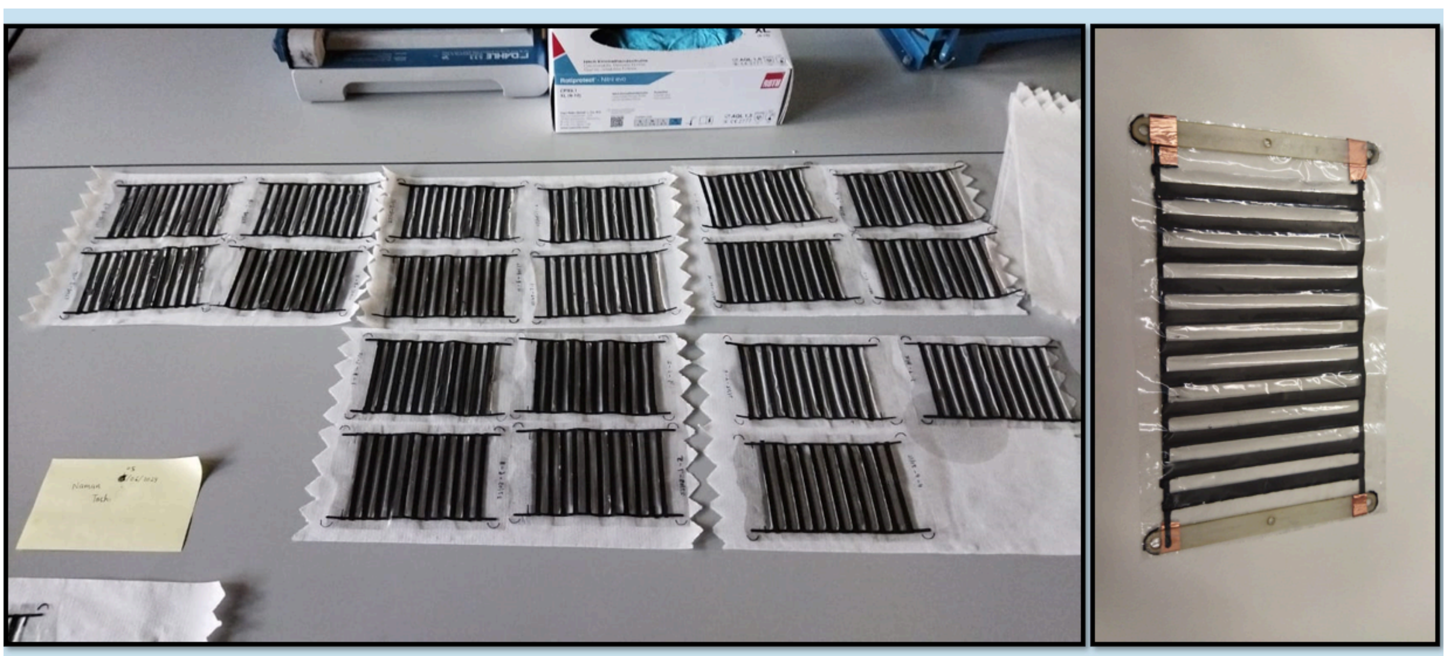

Fig 3: Manufactured HASEL actuators

Challenges encountered during the fabrication process included maintaining consistency in actuator performance and ensuring the reliability of the actuators under various operating conditions. These challenges were addressed through iterative testing and optimization, resulting in a set of actuators that met the desired specifications for further testing and application.

5.2 Modeling of HASEL Actuators

A critical aspect of the work was developing a model to describe the relationship between the electrical input and the resulting mechanical behaviour of the HASEL actuators. This model was based on **the Lagrangian equation of motion**, which provided a framework for understanding the dynamics of the actuator's movement.

The modelling process involved formulating equations that captured the interplay between the electrostatic forces generated by the applied voltage and the resulting mechanical motion of the actuator. This included accounting for factors such as the actuator's geometry, material properties, and the characteristics of the liquid inside the dielectric shell.

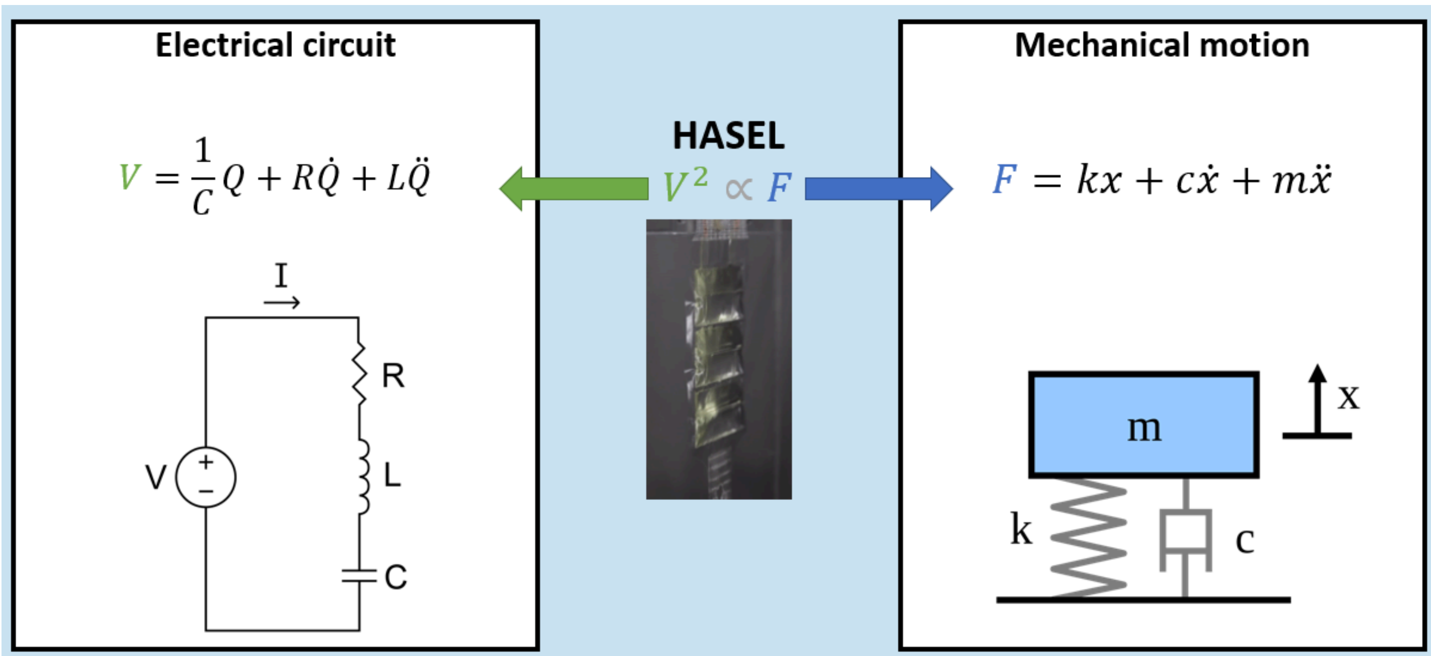

Fig 4: HASEL connecting electrical parameters to mechanical properties [2]

The resulting model provided valuable insights into the actuator's behaviour, highlighting the correlations between electrical input parameters and mechanical output. These insights optimised the actuator's performance for specific applications, such as developing a bio-inspired active hinge structure.

5.3 Application of HASEL Actuators

The final stage of the project involved applying the fabricated and modelled HASEL actuators to a specific robotic application. The chosen application was the development of a **bio-inspired mechanism designed to mimic the movement of a dragonfly wing**.

This application was selected due to the complexity and precision required to replicate the wing's movement, making it an ideal test case for the HASEL actuators. The design process began with a review of biological literature to understand the mechanics of dragonfly wing movement. This information was then used to create a CAD model of the wing structure, prototyped using 3D printing.

The fabricated wing structure was integrated with the HASEL actuators, allowing it to achieve high-speed reciprocating motion. The system was tested at various frequencies and voltages, with the results showing that the wing's movement closely matched the specifications of an actual dragonfly wing, particularly at a **frequency of 20 Hz**.

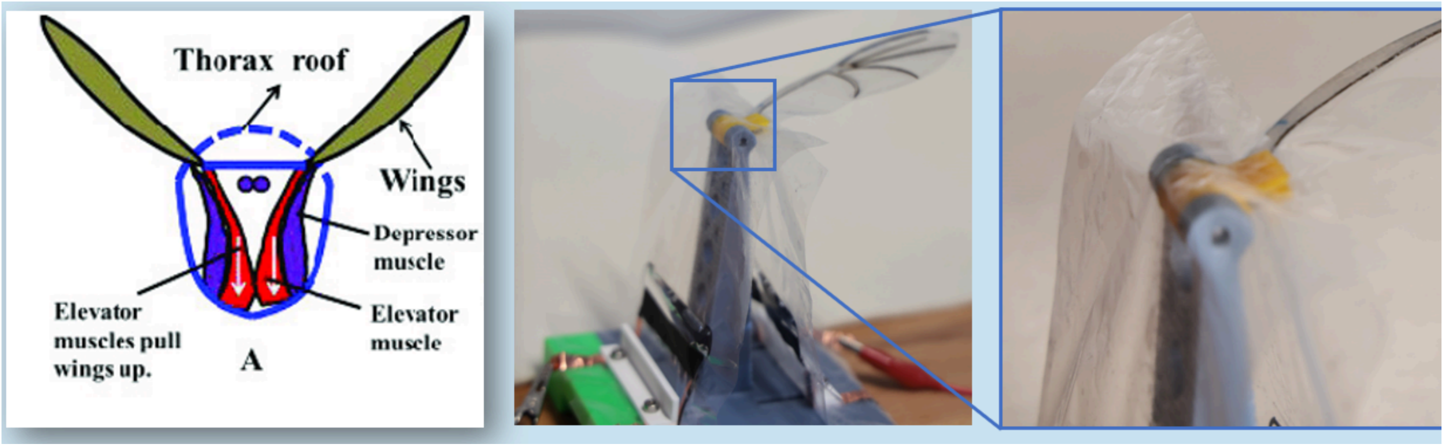

Fig 5: The dragonfly wing mechanism and its replication

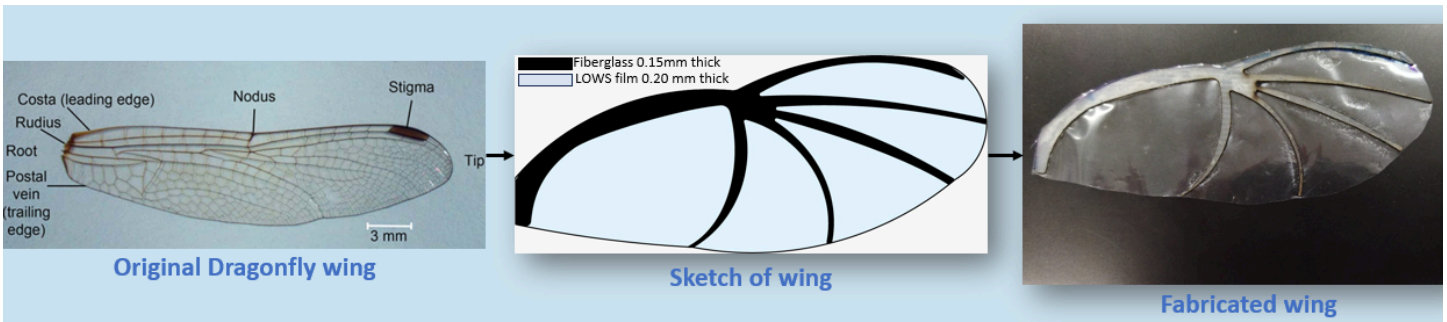

Fig 6: Original dragonfly wing and the fabricated wing [3]

This successful application demonstrated the potential of HASEL actuators in aerial robotics, particularly in developing lightweight, efficient, and adaptable flying robots. The work also provided a foundation for future research, with the potential to further refine the actuator design and explore additional applications.

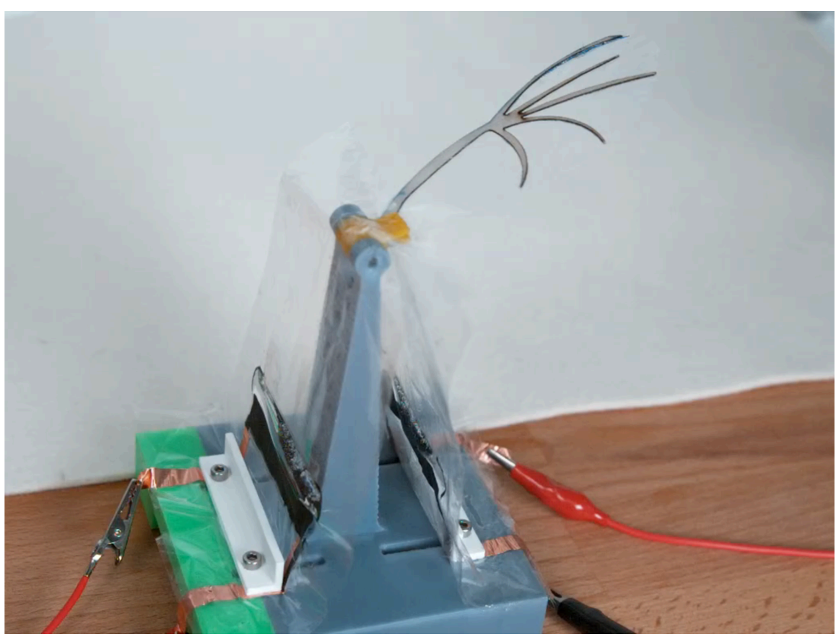

Fig 7: The experimental setup along with HASELs muscle mechanism

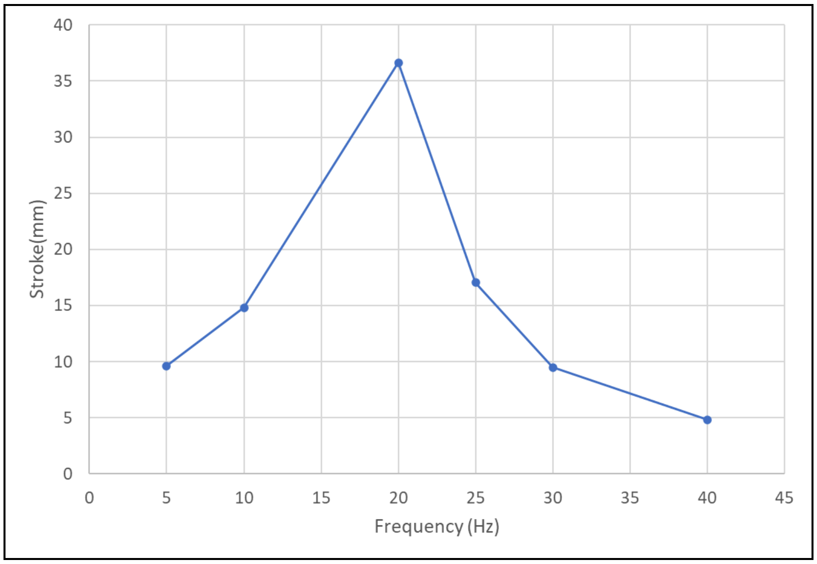

Fig 8: Graph of Stroke of wing vs Frequency

The observations from the graph in Fig 8 are as follows:-

1. The **highest stroke at 20 Hz** may be due to the resonance at this frequency.
2. An actual dragonfly wing usually has a 20 to 40 Hz frequency and 20-40 mm wing stroke, so at 20 Hz, 6kV, step input, the developed wing **matches the specifications of an actual dragonfly wing**.

Component	Specification
Wing dimensions	10 cm
HASEL pouch	6 cm*2cm
Stroke by HASELs	1mm
Stroke of wing	35 mm
Moment arm length	5 mm
Operating Voltage	6kV
Operating Frequency	20Hz

Table 1: Summary of all specifications of Dragonfly wing mechanism

6. Conclusion

The internship at the Max Planck Institute for Intelligent Systems provided a valuable opportunity to engage in cutting-edge research on HASEL actuators. The work carried out during the internship contributed to the broader field of soft robotics, advancing the understanding of actuator fabrication, modelling, and application.

The successful fabrication of over fifty HASEL actuators, the development of an analytical model to describe their behaviour, and the application of these actuators in a bio-inspired active hinge structure demonstrate the potential of this technology to revolutionize robotics. The ability to create actuators that mimic biological muscles, self-heal, and adapt to a wide range of conditions represents a significant advancement in the field.

The insights gained from this work will inform future research and development efforts to further enhance the performance and versatility of HASEL actuators. As soft robotics continues to evolve, technologies like HASEL actuators will play a crucial role in enabling the next generation of robots to interact with the world in new and innovative ways.

7. Future Work

The work done during the internship has laid a strong foundation for further research on HASEL actuators. My work during the internship has future scope focusing on the following areas:

1. **Integration into Untethered Flying Robots**: Further research is needed to integrate the developed wing mechanism into an untethered flying robot, exploring the challenges and opportunities of achieving autonomous flight with HASEL actuators.
2. **Optimizing Actuator Performance**: There is potential to achieve higher frequencies and greater stroke lengths with the same size of HASEL actuators. Future work will explore materials and design optimizations to enhance the actuator's performance.
3. **Noise Reduction**: Reducing the noise the actuators generate during operation is crucial for applications requiring silent operation. Research will focus on identifying and mitigating noise sources and improving the actuators' overall user experience and functionality.
4. **Exploring New Applications**: The success of the dragonfly wing application suggests that there may be other areas where HASEL actuators could be effectively utilized. Future research will explore additional applications, particularly in wearable devices, medical robotics, and underwater exploration.

8. References

1. Adv. Mater. 2021, 33, 2003375
2. 2024-04-19_Toshihiko_Fukushima_HASEL_legs
3. J. Sun, B. Bhushan / C. R. Mecanique 340 (2012) 3–17