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Designing and Implementing a Soft Robotics Workshop for Fundamental Robotic Education

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Abstract

This paper explores the potential of using soft robotics as a tool for robotics education, particularly, early in the college-level academic setting. Soft robotics, a subfield of robotics, is concerned with the use of highly flexible and deformable materials in the design and fabrication of robotics devices. Soft robotics designs are frequently considered to simulate the working of muscles of biological organisms (e.g., humans). Whereas traditional robot construction necessitates reliance on rigid components made of materials such as metals and plastics, soft robots rely on components made from silicone, rubber, gels, or other elastic materials. Such materials endow the soft robot with many degrees of freedom that permit them to bend and stretch into different shapes that are often infeasible for the traditional robots to acquire. With such a shape manipulation capability, a soft robotic gripper can safely handle delicate objects with a lower risk of damage, in comparison with rigid grippers.

Traditional robotic systems are often perceived as intimidating by uninitiated, as they involve intricate mechanical structure, myriad electro-mechanical transducers, and complex control algorithms. In contrast, a soft robot, with its flexible construction material and bio-inspired design, has the potential to offer a more accessible and engaging learning approach to fundamental robotics concepts such as kinematics, sensing, and control systems.

This study investigated the potential and benefits of designing and organizing an educational workshop on soft robotics for undergraduate freshmen and sophomore students from mechanical engineering and other disciplines. Incorporating soft robotics topics in the undergraduate curriculum allows students to partake in an immersive and experiential learning experience in the interdisciplinary fields of material science, engineering design, sensing, and health engineering, among others. Such an experience can promote a deeper understanding of robotics principles. The feedback from the student participants indicated that the soft robotics workshop was able to simplify complex robotics ideas, encourage hands-on learning, and stimulate design creativity.

1. Introduction

Preparation and deployment of students and professionals in the rapidly evolving robotics industry pose several challenges to the field of robotics education. The highly interdisciplinary nature of robotics, combining mechanical engineering, electrical engineering, computer science, AI, and more, make it challenging to develop curricula reflective of current trends and emergent needs of industry. Designing curricula for learners of different age groups while ensuring engagement and technical depth is difficult. In addition, educators often lack the necessary technical expertise [1-5] and are unable to keep pace with the ever-accelerating technological change to have confidence to teach robotics effectively. Students often struggle to see the connections between robotics concepts and real-world applications [2,6,7].

Conventionally, robotic courses have included several important elements: kinematics, locomotion, perception, and control. The current practice is to build a hierarchical structure of robotics courses, starting from 3000 level introductory courses to 9000 level graduate projects. Such a learning structure can impart to students a solid foundation in the understanding of design, assembly, operation, and applications of robotics. However, it places a heavy demand on numerous teaching resources, such as, hiring of instructors with specialized skill sets, scheduling of courses, laboratories, and projects, as well as synchronized collaboration between several departments such as mechanical, electrical, and computer engineering, among others. While such complex operations can be choreographed at a large university with abundant resources, students enrolled at smaller universities or community colleges may find it infeasible to obtain a sufficiently deep level of robotics learning experience. In response, this paper suggests the design and implementation of an educational workshop on soft robotics that can allow engineering students from various backgrounds to have an authentic and engaging opportunity to learn robotics.

Prior publications have explored the value of project-based learning (PBL) [8-11] experiences in engineering education, including in robotics. In the case of soft robotics, the Soft Robotics Toolkit [12], a Wikipedia style learning resource with a diverse range of information, provides comprehensive information on actuator fabrication. This toolkit allows researchers and students alike to share their project materials so that novice learners can use them to learn the foundational knowledge through hands-on, project-based explorations. This toolkit was introduced to the workshop participants (i.e., students) as part of their literature review process.

Situated Learning Theory (SLT), as articulated by Lave and Wenger [13], posits that socially placed behavior is paramount in the process of learning new information. To effectively convey content information to learners, SLT recommends developing a situational context that is meaningful and relevant to them in real-life situations. Das et al. [14] have identified PBL as a fundamental feature of Education 4.0, providing a compelling framework for implementing SLT. In fact, Das et al. [14] argue that students should be able to use their talents in a range of settings.

This education workshop involves disciplinary concepts, practices, and skills from: computer-aided design, material simulation, injection molding, and robotic control. The core robotic concepts include forward kinematics, active compliance and human-robot interaction. The workshop lasted for one semester (i.e., 15 weeks), with a weekly two hours schedule. The first month was dedicated to introducing to students the concept of soft robotics and engaging them in literature review. In the second month, some important computer-aided design (CAD) concepts

[15] were introduced to allow the students to design a robot gripper as well as a mold for the same. Pertinent concepts of 3D printing were also introduced in parallel. The next three weeks were devoted to introducing to students the principles of finite element analysis (FEA) and hyper-elastic materials and familiarizing them with COMSOL Multiphysics [16]. The following month was dedicated to FEA simulation and manufacturing of the gripper. This was an in-person workshop and the instructors worked closely with the students. The students did not enroll for any academic credits to participate in this workshop. The end goal of the workshop was that the students must complete the fabrication of a soft actuator that can perform as a gripper to grasp a water bottle. In future, a small kit can be developed for wider adoption and use in enhancing the learning of soft robotics concepts. The kit will not require any complex assemblies and it will be low-cost since various components of the soft gripper robot can be manufactured inexpensively.

2. Methods

2.1. Concept Design

The workflow of the entire workshops is as follows (see Figure 1). At first, the students learned about the concept of soft robotics, for example, what is classified as soft robotics (**SR**) in comparison to conventional robots. Next, the discussion turned to applications of SR in the field of search and rescue (**SAR**), human-robot interaction (**HRI**), and service robot. This was followed by a review of the key characteristics of soft robots. Next, the consideration shifted to the design philosophy that aims to build adaptable robotic solutions by combining flexible, elastic materials and non-rigid components. The design goal of a soft robot is to induce the desired mechanical behaviors of a moving object. For instance, a soft actuator may be developed to mimic the motion of human fingers.

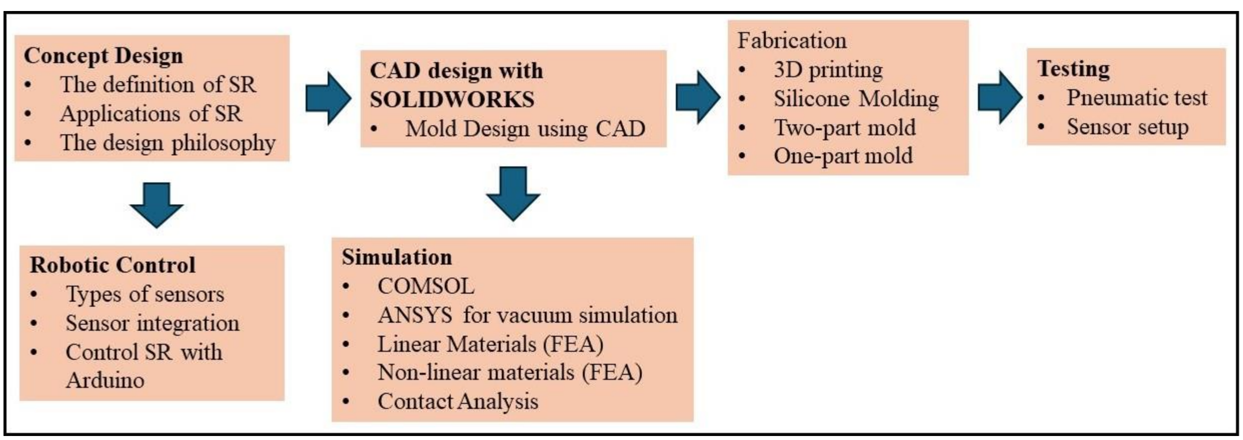

Figure 1: Workflow of the workshop

To introduce the students to the fundamental principles of soft robotic gripper design, the workshop began with a simple demonstration using an uninflated balloon. The students were asked to predict its final shape when inflated, leading to an intuitive understanding that a structure's initial form plays a crucial role in its deformation. Next, a balloon with a different initial shape was inflated, prompting the students to analyze how variations in geometry influence the final expanded form. To bridge this concept with controlled deformation, the students were introduced to a soft pneumatic chamber with an internal divider. When inflated, this chamber expanded asymmetrically, demonstrating how internal constraints can direct motion. Next, a balloon reinforced on one side with tape was used to further illustrate how selective reinforcement affects expansion, reinforcing the idea that structural modifications guide the way soft actuators deform. Finally, the students examined a bellowed soft gripper that bends in a specific direction upon inflation due to its structured features. At this stage, they were able to visualize how air flow interacts with the gripper's geometry, deepening their understanding of how soft robotic actuators can be designed to achieve controlled movement.

2.2. Learning Computer Aid Design (CAD)

CAD involves using specialized software to digitally create, analyze, and modify two-dimensional (2D) drawings and three-dimensional (3D) models of components and subassemblies of products envisioned by designers [15]. In this workshop, the students learned to use SOLIDWORKS as the primary CAD software, with Autodesk Fusion 360 CAD tool introduced for supplementary learning. Figure 2 depicts the CAD model of a soft gripper made by the students using SOLIDWORKS.

For more complex assemblies, the students created individual parts separately before integrating them within the "Assembly" interface. Next, they exported the assembled designs for simulation, allowing for testing and validation of their structural and functional performance.

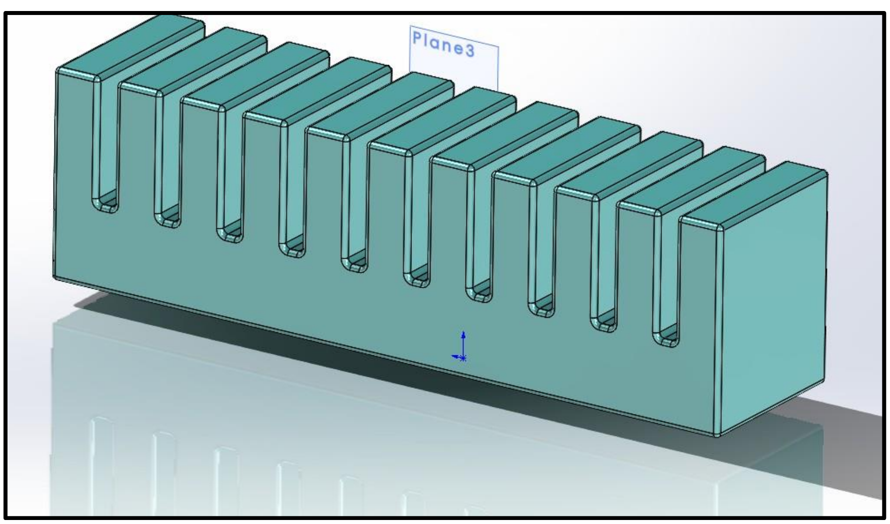

Figure 2: CAD model of a soft gripper created using Sketch, Extrude, Convert Entities, and Filet tools

2.3. Learning FEA Simulation

To test the CAD models of this project, the students learned to utilize the simulation software COMSOL Multiphysics [16] and ANSYS that can be used for simulations and testing. They selected the study type used for simulation to be "Stationary Analysis." This analysis solves rigid conditions and stationary displacements (Stationary Study).

An important part of COMSOL simulations is the "Global Definitions," wherein parameters and materials are set. For the projects of this workshop, the selected parameters included pressure and ramp. The uploaded CAD model then becomes a "Component" in COMSOL whose name could then be changed by the students. The "Component" branch is followed by the "Definitions" branch that utilizes the definitions of functions, variables, and other objects, whose geometric scope is limited to one element (Definitions). Since, the students worked on a soft gripper project, under the "Definitions" branch they needed to define the "Contact Pair" that describes structural contact and multi-physics contact. This contact pair establishes boundaries where the components can come into contact but can't penetrate one another under deformation (About Identity and Contact Pairs). Next, the students defined and selected the source boundaries and destination boundaries in the contact pair function. The "Boundary" system function falls under the "Definitions" branch. On a boundary that is not in line with the global Cartesian coordinate system, students used the Boundary function to apply loads along with other boundary conditions in a normal or tangential direction.

The solid mechanics interface of COMSOL computes results such as displacements, stresses, and strains. As the students worked on their soft grippers project, "Linear Elastic Material" was used since it helps with incorporating external stress, external strain, and plasticity of the component (Linear Elastic Materials). In COMSOL Multiphysics, under the "Solid Mechanics" branch, there exists the interface for the "Hyper-elastic Material" that enables the definition of material properties and the application of boundary conditions and loads. The students were also introduced to nonlinear materials at this stage. Most strength of materials courses only introduce linear elastic materials that depict very low strain, but the materials used for soft robot fabrication can undergo large strains without plastic deformation of fracture [17]. These materials do not have a linear stress strain relation and thus need specialized hyper-elastic material models where the strain energy is expressed as a function of the strain. Figure 3 depicts the comparison of the mechanical properties of a linear elastic material with a hyper-elastic material. It is critical for students to gain familiarity and working experience with the aforementioned tools for designing and analyzing components for soft grippers as flexibility and durability are key requirements (Hyper-elastic material).

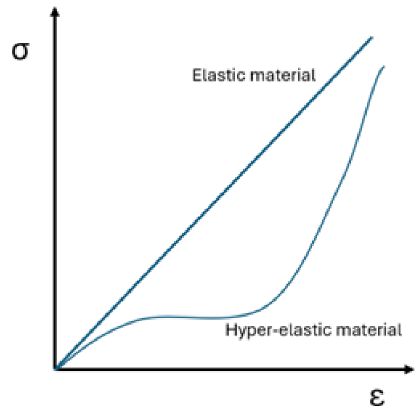

Figure 3: Stress-strain relation of linear elastic material compared to hyper-elastic material

The students used the "Fixed Constraint" node to set all displacements on the selected component to zero. Then they used the "Boundary Load" to divide the force by the thickness of the component. Additionally, they used the "Mesh" function, an important aspect of COMSOL, to define how the geometry will be solved. The "Mesh" function determines important factors including how the geometry is divided, the shape and type of elements used, the size and density of these elements, and their quality. The students gained an understanding of how these aspects directly impact computational efficiency, memory use, solution interpolation, and accuracy, influencing both the time required and the reliability of the results.

To study the soft grippers for this project, as discussed above, the students performed a stationery study and defined parameters to be used. After performing the study, the students visualized (see Figure 4) the impacts and deformations caused by the earlier defined stress and boundary loads. The simulation is an essential part of this project as it provides students a visual understanding

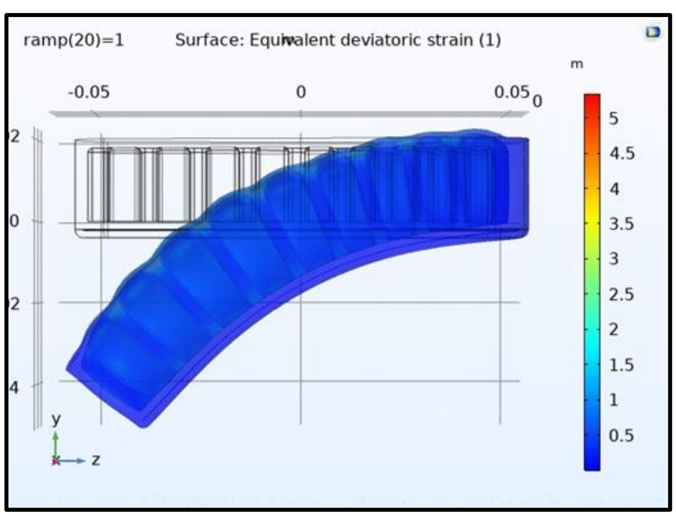

Figure 4: Simulation of a gripper in COMSOL Multiphysics

of the amount of load that could be carried by the designed soft gripper, which is important for enhancing the quality of the grippers and making them as efficient as possible.

2.4. Learning Mold Design

Based on the fabrication requirements, the students 3D-printed either the final part or its mold. Since the soft robotics workshop adopted silicone molding as the primary fabrication technique, the students worked on designing molds in SOLIDWORKS for relevant parts of their soft robot. The mold design process exposed the students to the "Tool → Combine → Subtract" feature in the "Part" control of SOLIDWORKS. Typically, the student-designed molds featured an exterior box structure, such as a cuboid, for simplicity and accessibility. A rectangle sketch was extruded by the students to a depth of at least 15 mm around the part, forming the mold's outer shell. Moreover, to create the mold, the students extruded the box over the part and saved the file as a separate body (unmerged). Next, in the "Combine" submenu, they set the box as the main body from which they subtracted the part to form the negative space. For complex designs, they split the mold into multiple accessible parts before 3D printing to facilitate easy removal of the cured silicone (Figure 5).

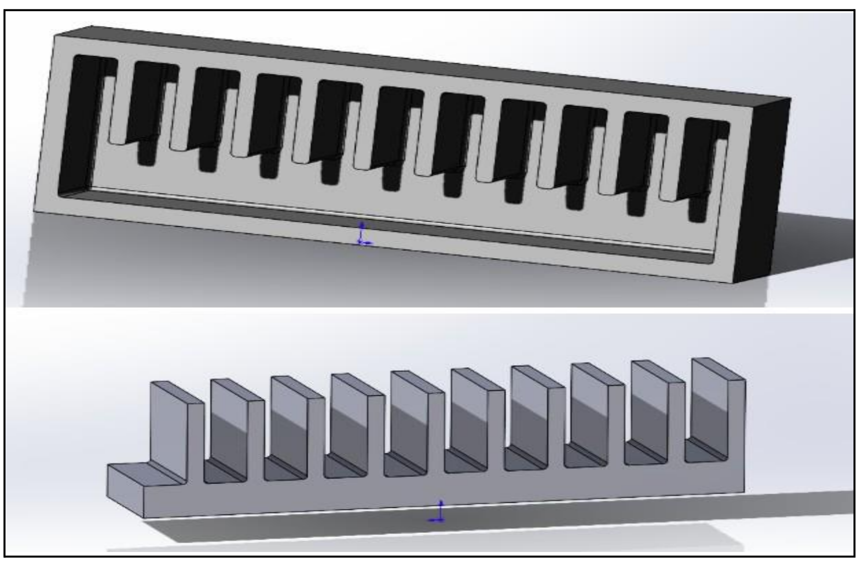

Figure 5: Soft gripper side (Top) and CAD model of the mold (Bottom)

2.5. Learning 3D Printing

Student participants of the workshop performed all 3D printing tasks in the university's Makerspace using the Ultimaker and advanced 3D printers. They had to first complete the mandatory training to operate the various 3D printers. The PRUSA i3 — a fused deposition modeling (FDM) printer was the primary advanced 3D printer used by the students (Figure 6).

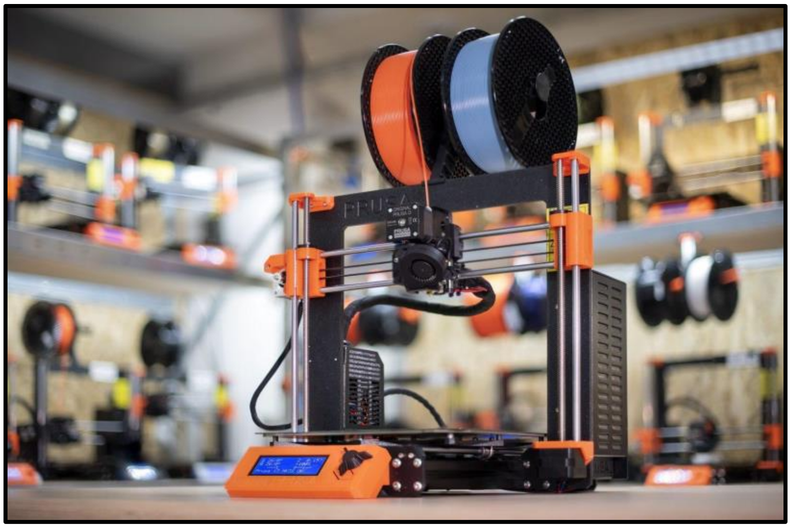

Figure 6: Original PRUSA i3 MK3S+ [18]

To print their mold designs on the Ultimaker 3D printers, the students started by exporting their CAD model as an STL file and saving it to a shared Google Drive. Next, they downloaded the STL file onto Makerspace computers and opened in the slicing software Cura, where they made necessary adjustments for alignment, support structures, and resin thickness. Once sliced, Cura provided an estimated printing time, which was recorded along with the student's netID. The students also had the ability to save the sliced file on an external USB drive or send it over the network to a printer.

To print mold designs on the PRUSA i3 3D printer, students had to transfer the sliced files using an external USB drive since this printer is not connected to the network. The printer's filament was encased to prevent stringing, and students carefully calibrated its settings before initiating printing.

2.6. Learning Silicone Molding

The workshop exposed the students to several key steps of the silicone molding process that are required to produce a high-quality molded part. First, they determined the part's weight using the CAD model to calculate the precise amount of silicone required, ensuring efficient use of materials. They observed mandatory safety precautions by wearing nitrile gloves. Before the molding process the students cleaned the molds with iso-propyl alcohol to ensure that there was no contamination. Next, they applied a thin layer of mold release agent to the mold to prevent silicone from adhering to the surface. Since the release agent is flammable, students were asked to wear a face mask and perform this step in a well-ventilated area, such as outdoors.

Next, the students learned to carefully mix the ingredients that make up the silicone mixture.

Specifically, Portlife and Theolife served as the base materials for the silicone mixture. There were two parts to be used for fabrication. Part A component contained vinyl functional silicones and the platinum catalyst, whereas Part B contained vinyl functional polymer, hydrogen-functional crosslinker, and cure inhibitor. The students began the process of creating the silicone mixture by adding the specified weight of Part B, followed by 1–2% of its weight in an anti-catalyst or retardant to moderate the reaction speed. This catalyst was used so that the silicone curing process did not start until the degassing process was completed. Then, they added a calculated amount of Part A, along with 2–3 drops of silicone dyes for visual uniformity. Next, they thoroughly mixed the ingredients to ensure consistent color and proper integration of all components.

To remove trapped air and prevent defects, the students placed the silicone mixture in a vacuum chamber for approximately 10 minutes, allowing air bubbles to escape (Figure 7). Then, they poured the degassed silicone into their previously 3D printed molds. The silicone was poured very slowly in the mold while trying to maintain a constant flow rate to prevent the formation of any additional bubbles. To create a stable base, the students immersed an index card or paper (at least 1 mm thick) in the mold that limited bending in one direction and improved the grippers structural integrity. Prior to the workshop, the instructors had meticulously tested and documented each step to ensure the mold's durability, accuracy, and functionality. The top and the bottom halves of the gripper were fabricated separately. After both the parts were cured, a thin layer of silicon was applied in between the two parts to create a seal between them.

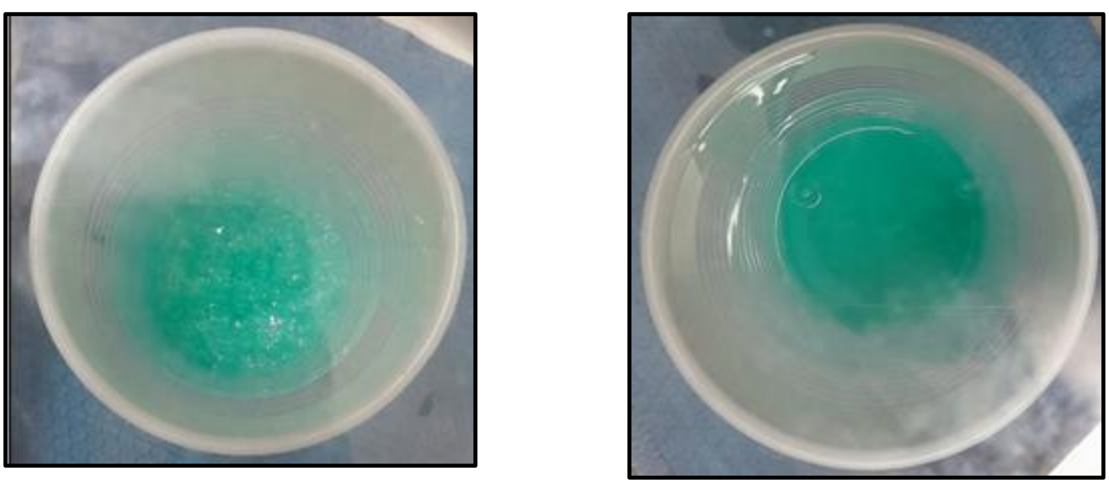

Figure 7: Before (Left) and after (Right) degassing in a vacuum chamber

2.7. Final Assembly

The instructors distributed the assembly tasks to the student groups in a streamlined process. One student group worked on material mixing, then the mixture was passed onto the next group for degassing in a vacuum chamber. Meanwhile, one student group worked on mold printing. After all the materials were prepared, the students started pouring the silicone gel into the mold and let it fully cure for four hours. Figure 8 describes the manufacturing process in a sequential order. Figures 9 and 10 show the final results of the soft robotic finger. It can be observed from Figure 9 that the bending angle is around 48 degrees, this can be calculated by basic trigonometry. This result is further validated in prototype testing. The fabrication of the gripper started with the 3D printing of the molds, continued with the two-step silicone molding, and then finally testing the gripper. The entire process on average took seven hours. Table 1 lists the breakdown of time required for each step.

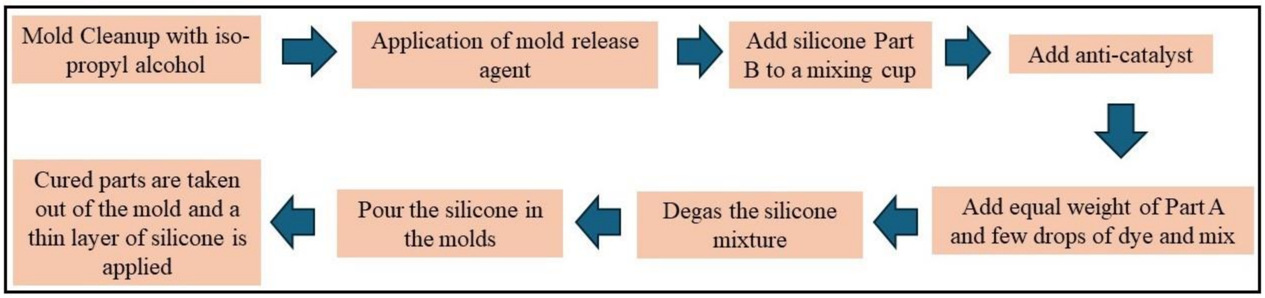

Figure 8: Flowchart of gripper manufacturing process

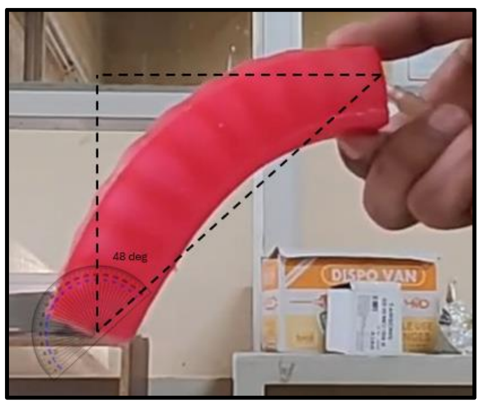

Figure 9: Gripper under actuation

Figure 10: Final Product

Table 1: Time to manufacture each gripper

Process	Time
3D printing molds	Two hours
Silicone molding	30 mins (mold preparation + degassing) + Four hours (curing step 1) + One hour (curing step 2)
Testing	30 mins

3. Results and Discussion

Overall, among the 13 workshop attendees, there were 9 freshmen and 4 sophomores. A survey was carried out at the end of the semester. The students' perception of workshop difficulty level is shown below in Figure 11. Moreover, Table 2 shows examples of student feedback. Most of the students confirmed that they received hands-on experience in soft robotics, either dealing with electronics or mechanical assembly, and they found the workshop met their expectations.

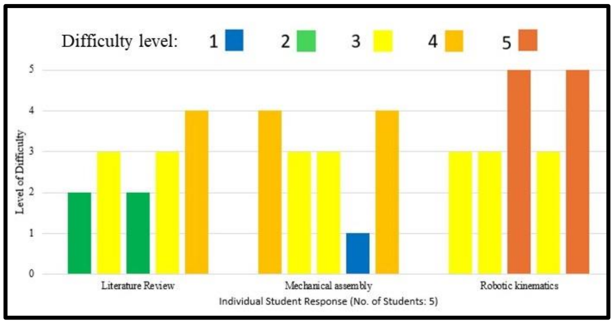

Figure 11: Survey evaluating the level of difficulty about the workshop

Table 2: Student learning feedback on the workshop

Please describe your achievement(s) this semester.	**Did the assignments meet your expectations?**
I introduced new team members to the pump station and how it worked. ***I led the team to create a system that could actuate one finger and stop actuation when force was detected on the finger.*** I handled some of the wiring of the system, Arduino to Jetson communication, and troubleshooting/debugging the robotic system.	Yes, I am ok with the assignments.

I gained decent knowledge about CAD and through using the mode I could make one finger of the hand we wanted to make ultimately.	No.
For this semester, I worked on understanding the CAD model of soft grippers and learning about the COMSOL Multiphysics software. The software was new to me, so for most of the semester I worked on understanding the software and the value of using it to perform analysis and testing. ***I performed trial*** testing ***to be able to perform real*** testing ***and analysis on the actual grippers.***	Yes, I am ok with the assignments
I learned more about soft robotics grippers for agricultural and mechanical engineering. I learned more about the fabrication, design, and materials used in soft robotic grippers. ***This semester, I learned computer aided design and Autodesk Fusion. I learned silicone molding and heat shrink. I also learned about 3D printing and how that can be used to create the mold of the grippers. I helped create two silicone grippers.***	Yes, I am ok with the assignments
We were able to create the CAD design of our soft robotic finger. In addition, we were able to 3D print that design into a mold. This allowed us to create silicone prototypes with two different materials.	Yes, I am ok with the assignments

4. Workshop Limitations

There were several issues in the execution of the workshop. First, the students felt that they were struggling at the stage of simulation. To address this, the students were given more than two weeks, beyond the original schedule, to complete the simulation training. Second, the students needed to have certain pre-knowledge about computer-aided designs, i.e., they needed to learn how to use SOLIDWORKS before they could start the designs of soft gripper and the mold. The future plan is to implement a pre-workshop training on COMSOL simulation and SOLIDWORKS design, perhaps with the adoption of video tutorials and some pre-workshop assignments.

The workshop primarily focused on the design and development of soft grippers. Hence, sensor integration and controls were out of the scope of this workshop due to time constraints. Future workshops will include a pre-workshop survey to get a better understanding of the students' existing skills and their expectations from the workshop. However, since most of the students had little to no prior mechanical engineering experience and were oblivious to soft robotics concepts, this survey was not conducted.

5. Conclusion

The students were able to develop flexible, pneumatic-actuated grippers. Through iterative design, computer-aided modeling, simulations, and fabrication, the team tackled challenges that advanced both technical expertise and collaborative problem-solving. Highlights included mastering silicone molding techniques, learning COMSOL simulations and Prusa i3 operations, refining CAD mold designs, and 3D-printing prototypes, all of which contributed to the study's mission of creating innovative robotic systems for industrial and educational applications.

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