IGEN 330
Final Report

Project ReMold

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1 Executive Summary

ReMold is an adaptable molding machine designed to revolutionize the composite manufacturing industry by providing a rapid, low-cost, and low-waste prototyping solution. The traditional mold-making process is time-consuming and expensive, with the production of a single mold taking upwards of a month and costing thousands of dollars per hour making rapid prototyping a difficult and costly endeavor. Moreover, the process generates a significant amount of waste at each design iteration, as molds are often discarded after a single use.

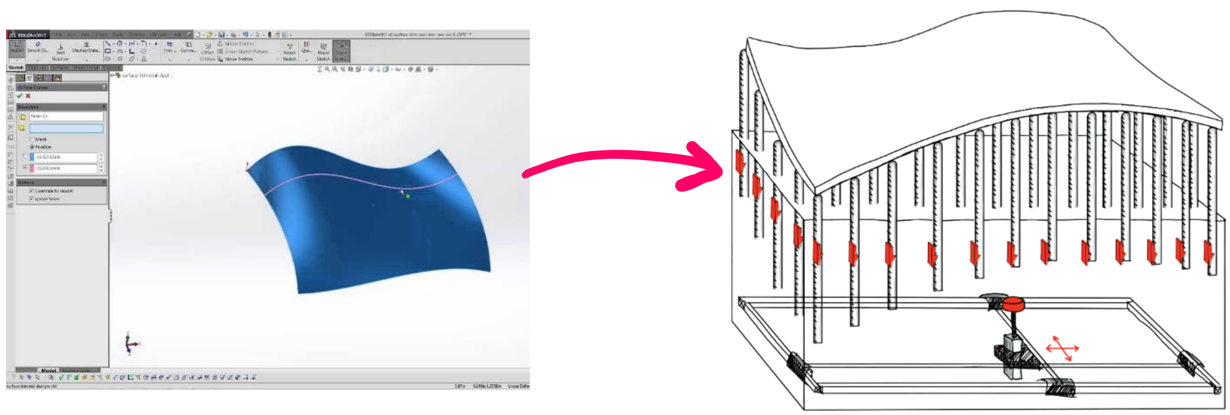
The ReMold machine addresses these issues by providing an innovative solution that utilizes a grid of rods threaded through alignment plates supported by an aluminum extrusion frame. The pins are driven by a gantry controlled with G-Code instructions generated from user-inputted CAD files. The threaded rods support a mesh of wires that provide support for the elastomer/rubber top surface membrane on which the composite parts will be cured.

To ensure that the ReMold machine meets industry needs, extensive stakeholder interviews were conducted. The result was a comprehensive list of quantified requirements for the device. Verification and validation activities will focus on ensuring that these requirements are met. This will involve Gage R&R testing in which archetypal parts will be created on the machine. These parts will be measured for geometric accuracy and used to evaluate the performance, and reliability of the machine. Additional verification is planned for all subcomponents to ensure that they behave as expected.

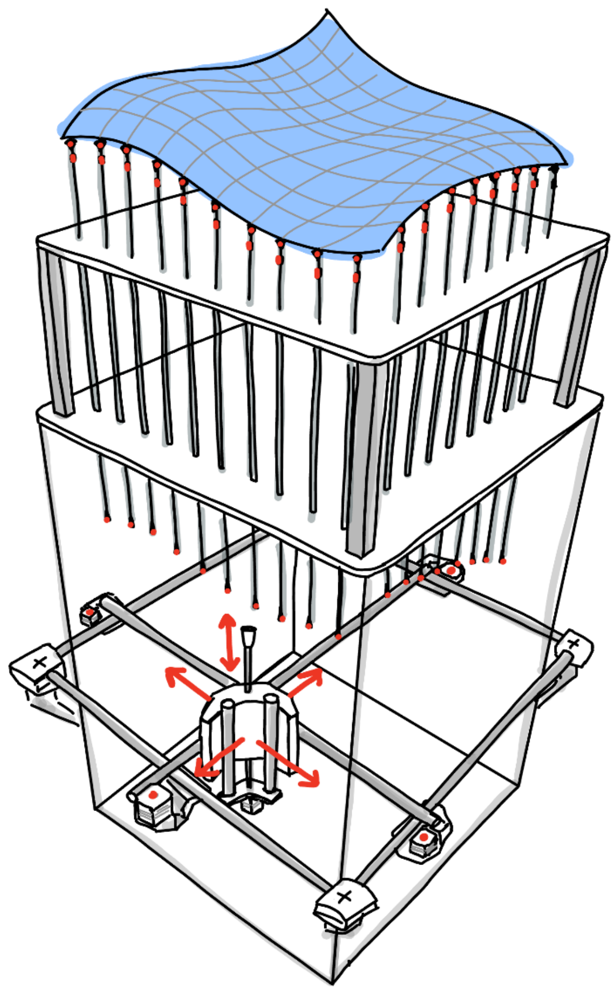
Our socio-economic analysis of the ReMold project reveals that the device has the potential to have a significant impact on the prototyping and composite manufacturing industries. The traditional mold-making process generates a large amount of waste and is expensive, making rapid prototyping difficult. The ReMold machine eliminates waste and reduces costs by allowing for infinite adjustability and eliminating the need for base material to carve out. This has the potential to reduce the environmental impact and economic cost for design teams and composite manufacturers. Moreover, the ReMold machine has the potential to enhance design flexibility and speed, ultimately leading to faster time-to-market for new products.

2 Project Summary

ReMold aims to create a device for rapid, cost-effective, and low-waste prototyping of complex shapes using composite materials. Currently, manufacturing molds for composite parts is time-consuming and expensive, taking upwards of one month and thousands of dollars per hour to produce. The proposed device will recreate a surface modelled in CAD software, allowing for a high degree of accuracy and the ability to create a variety of geometries. This project will improve efficiency and sustainability in the mold making process for low-volume composite parts used in rapid prototyping.



3 Design and Implementation



3.1 Frame and Plates

The frame and plates of the machine were the first components designed as they serve as the base for the rest of the machine. In our initial iterations of designing an adaptable mold machine, we explored various designs including additive, subtractive and castable solutions. However, we ultimately opted for a pin actuation design based both research from similar projects and recognizing the limitations associated with the other ideas such as waste generation, recycling complexity, and restricted availability of materials. Our key design criteria were adaptability, reusability, and ease of use of the machine. These key aspects guided our design into a grid of threaded rods which could replicate surfaces due to a gantry actuating each pin. Using threaded rods allows for setting the heights of the rods without necessitating the use of any latch or clamp mechanism to maintain the desired height.

The decision to use threaded rods also led us to design the base plate and alignment plate which function to confine all degrees of freedom of the rods. The base plate is equipped with ¼-20 threads in a 1.5ft by 1.5ft grid, while the alignment plate, located above the base plate, features through holes with embedded thrust bearings to mitigate rods deflection and wear.

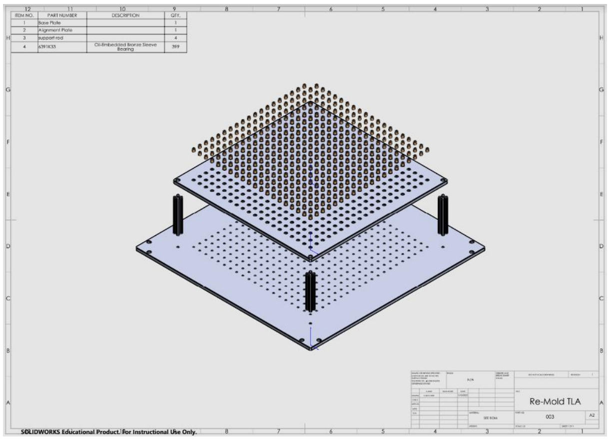


Figure 1: Exploded View of Plate Assembly

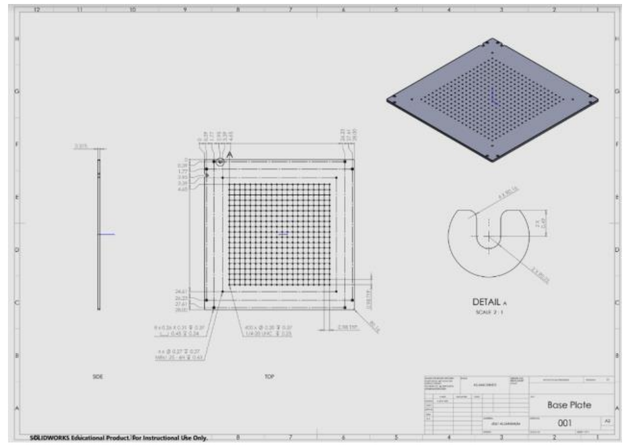


Figure 2: Base Plate

Furthermore, the frame design, which uses aluminum extrude parts, is simple, configurable, and a readily available material for our team. We could easily customize the frame to our designed dimensions and the wide use of the framing in industry makes it highly customizable with off the shelf parts. The frame serves as a base for elevating the pins above the gantry for actuation as well as allowing easy removal of the top plate assembly for placement into an oven, while keeping all the electrical components separated and intact.

3.2 Top Surface

The top surface, which takes the shape of the pins and supports the composite part, is made of a mesh of support wires topped with a layer of high-temperature silicone rubber (40A durometer). The advantages of this compound are that the wires help smooth out curvature and support between wires and the soft silicone forms to the shape of the surface beneath it. In addition, the silicone can withstand temperatures up to 260ºC, the composite part is very easy to demold from the surface, and it is affordable, reusable, and replaceable.

3.2.1 Material Justification Summary

One way we tested different materials was to apply vacuum pressure to a miniature surface of pins to see how the material would deform. Samples of natural rubber, EPDM, polyurethane, and softer silicone were tested. Tensile tests and heat tests were also performed to validate stiffness and temperature compatibility. More details on these tests are outlined below.

In summary, after testing, we found that the increased hardness of the elastomer surface reduces local deformation under vacuum pressure. The medium hardness (40A) was ideal to not show too much detail (or “waffling”). The softer material (10A) deformed too much to the pins, and the harder material required too much vacuum to hold it down. In addition, the rated service temperatures of all materials except for silicone were under 100ºC, which was of concern, as composite cure cycles can go up to 170 ºC. Cost was an important consideration. Soft silicones (10A, 20A, 30A) are significantly more expensive compared to a 40A sheet, being over $100 more for a 2ft x 2ft sheet. With all these considerations, we settled on a 40A durometer high temperature silicone sheet.

3.2.2 Testing and Validation of Materials

First, we selected four different candidate materials based on material selection charts comparing different rubbers. Important properties we considered were flexibility, elasticity, coefficient of thermal expansion, and impermeability. See Appendix A1 to see an example of a material chart used.

Top four potential materials identified were: silicone, natural rubber, EPDM, and polyurethane. We ordered small samples (6 inch by 6inch, 1/8 inch thick) of these materials to perform physical testing, each with various hardness ratings, which affect local deformation capability.

To achieve quantitative data to compare our materials, we performed tensile testing strips of the rubbers. See Appendix A2 for force vs displacement graphs of silicone and natural rubber. This initial data was useful in showing elastic behaviour of the materials, which shows that at least up to approximately 110N, they will return to their original shape. In addition, it showed that if soft silicone is clamped too tightly, it would be more likely to tear/fail there.

Next, we generated several ideas for how to conform this sheet to the top pin/wire mesh surface. Our main ideas included vacuum forming, using weights, magnets, and Velcro/hooks. Since vacuum forming would apply even pressure on the whole surface, this was the idea we decided to pursue and test. We created a mini vacuum-sealed box to place around 3D printed pins and pulled vacuum within the box to pull the top sheet to the pins/wires. See below for a visual of this setup. A pressure gauge and regulator were used to quantitively adjust how much pressure was being applied.

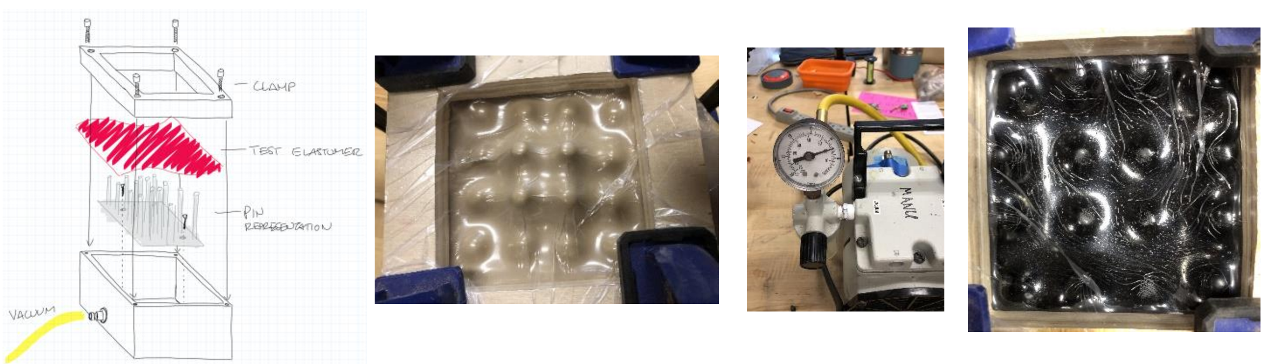


Figure 3. Prototyping setup for vacuum testing.

Lastly, since the rated service temperatures of some materials were under 100ºC, we placed samples in an oven at 107ºC for an hour, which is the curing cycle for our available prepreg. There were no significant changes in the materials, but after some research we concluded it would be too risky to use a lower temperature rated material.

3.3 Vacuum Chamber

The implementation of our vacuum forming setup for the top surface material was through the fabrication of a vacuum chamber.

In order to successfully create a surface in which we could layup a composite part we needed a method to adhere the high temperature silicon sheet to the pin heads and array. Our team experimented with different methods off attachment including magnets, hooks and weights and found that each method was insufficient at equally distributing pressure over the sheet and resulted in a low quality surface. As a result, our team took on the task of using vacuuming the sheet surface to the pin heads.

The initial experiment was a scaled down prototype of the concept of a vacuum box.

Figure 4. Vacuum Box Prototype With Demo Shape

Figure 5. Vacuum Box Prototype with Vacuum Pulled

The figure on the left depicts the constructed vacuum box with a 3D printed prototype of a pin configuration. The figure on the right shows the box under vacuum demonstrating the use of vacuum to adhere the top sheet material to the shape of the pins in the box. These experiments informed our decision to create a full scale version which would enclose our entire pin assembly.

The design for the vacuum box was based on a group brainstorming session in which we decided to manufacture a steel box which would be welded together and sealed.

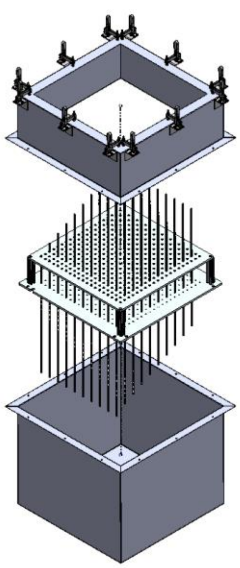


Figure 6: Vacuum Box Exploded View

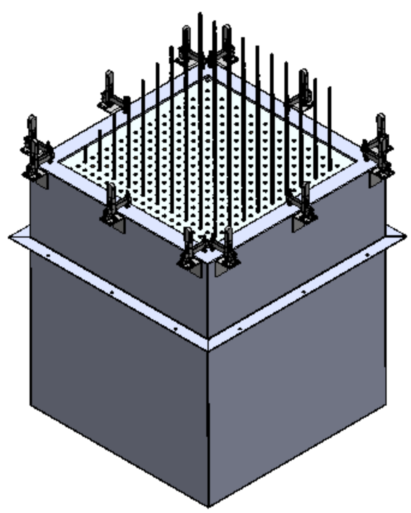


Figure 7: Vacuum Box

This design was decided upon as we could fully enclose the pin assembly inside the box with the top sheet clamped to the top of the vacuum box and sealing the assembly. This design was chosen for the simplicity of it and that we would be able to gather materials and have manufacturing services provided by the Materials Shop.

This design was put together quite hastily as we only had two weeks of the term remaining and we did the welding ourselves and thus did not seal quite as well as expected. The design did work however as we were able to use vacuum sealing plastic and tacky tape to seal the edges which were not airtight and successfully complete multiple layups.

3.4 Pin Actuation

A significant aspect of the project is automatically adjusting the heights of the threaded rods. The group thus needed to determine a way to rotate the bottom of each rod to adjust the height of the array. This section will focus specifically on the vertical actuation itself, while the following section discusses the interface between the pin actuator and the pin itself.

The group's initial idea was to implement two independent processes – one to turn the threaded rods and one to move vertically up and down. The system, after navigation to the correct X/Y location, would first extend the pin actuator to the bottom of the pin to be actuated. Upon meeting the pin and interfacing with it (think "latching on"), some part of the device would rotate the pin. Since rotating the pin moves it vertically, the vertical actuator would need to move up or down at the same speed as the pin to maintain contact with the pin. This plan has a few problems: first, is it difficult to create something which can both rotate and move up and down (not to mention the fact that this assembly needs to mount to an X/Y gantry). The electrical connection for either the rotator or vertical actuator would need to be routed through a slip ring and it would be very bulky to mount. The second problem was that the vertical speed of the vertical actuator would need to precisely match the vertical speed from rotating the pin. Any variation in speed and the two would either detach or bind.

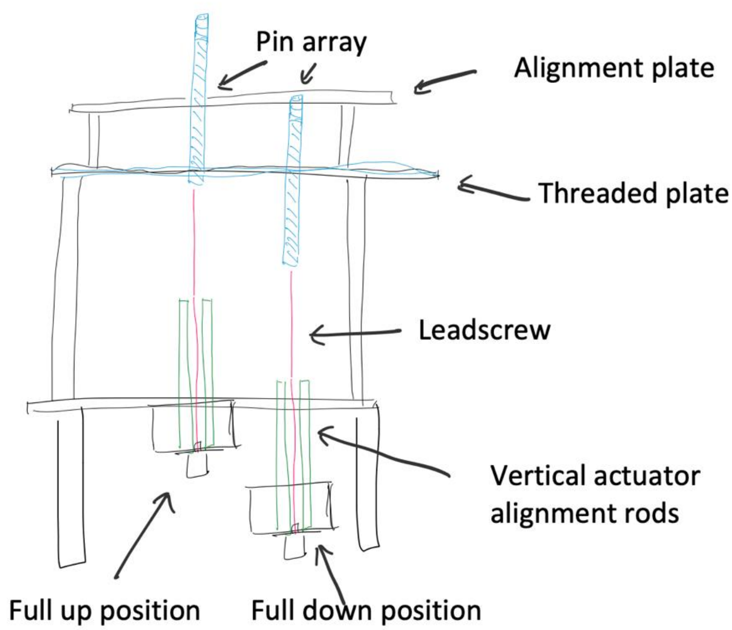


Figure 7: Diagram of the Z actuator system

The group's second and ultimately chosen approach, is to use only one motor. A stepper motor is attached to a long lead screw, threaded with the same pitch as the pins in the array. This way, if the rotation speeds are the same, the vertical speeds will be the same (underscoring the importance of matching the thread pitches). First, the X/Y gantry is positioned below the intended pin to be actuated. The stepper motor will then spin until it reaches the bottom of the desired pin at which point it will interface with the pin (see following section for details) and continue to rotate. The two will rotate up or down together until the desired position is reached, at which point the two will decouple and the actuation pin will retract to move to the next pin. The challenge in this design is in the pin-actuator interface, but the obvious advantage is in that it only uses one stepper motor, negating the need for complicated mechanisms which can grip, spin, and move up and down in a small space. Further, the group's existing gantry has a toolholder which can be adapted with a longer setscrew to suit our purposes making design and fabrication easier.

3.5 Pin-Surface and Pin-Actuator Interaction

These two interactions are critical to both ensure that our mold surface smoothness is acceptable to layup directly on, and ensure that we can reliably and repeatably actuate each pin with precision and accuracy.

3.5.1 Pin-Actuator Interaction

The pin-actuator interaction has several requirements: Each pin needs to move both up and down, independently of all others, in dimensionally controlled manner. Pins must be driven up to their final height in stages, and pulled back down after a user is done with a mold geometry. To accomplish these requirements, we settled on a design whereby the Z-axis of our gantry will move up to the bottom of the pin, latch onto the pin, and then drive it up/down. When done, the actuator will unlatch and retract.

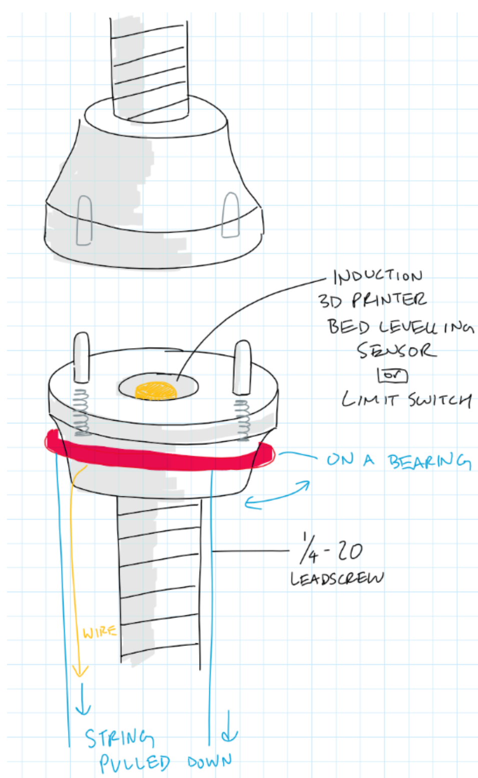


Figure 8: Diagram of pin-actuator interface

The proposed design uses a ¼-20 leadscrew so that the axial movement per rotation of the leadscrew matches that of the ¼-20 pins. The end effector of the leadscrew will have a few spring-loaded pins which will latch into holes in the bottom of each pin. The pieces at the bottom of each pin can be FDM printed and the end effector can be resin printed. We hope to integrate an induction bed levelling sensor normally used for 3D printing inside our end effector, which we can use to detect how far away we are from the pins above when we latch. The most critical feature of this design is that we hope to be able to retract these spring-loaded pins so that we may un-latch. This is a challenge we have considered several solutions for, including a string running to a motor in the gantry core which can pull down, an electromagnet which can pull the pins down, or potentially a small servo on the end effector. We are aiming to reduce the amount of bulk on the effector as much as possible, so are trying to integrate the string idea.

3.5.2 Pin-Surface Interaction

The pin-surface interaction is a challenging problem as well, with the following requirements:

- The pins must support the surface while maximizing surface smoothness
- They must be able to support a membrane of wires or another similar membrane which adds reinforcing inter-pin support for the top sheet
- They must be able to accommodate a 45-degree angled top surface
- They must be temperature-resistant up to 80 degrees C minimally
- They must be unconstrained from rotating with the pin's axial rotation

Initially, we experimented with the idea of a ball-joint pin head with two wires passing though each head in x and y. These wires would help add inter-pin support for the top surface. However, this design created a poor surface finish at each pin due to the way that the center of the pin protrudes up above the wires. Additionally, these ball joint components are complex and would require custom machining.

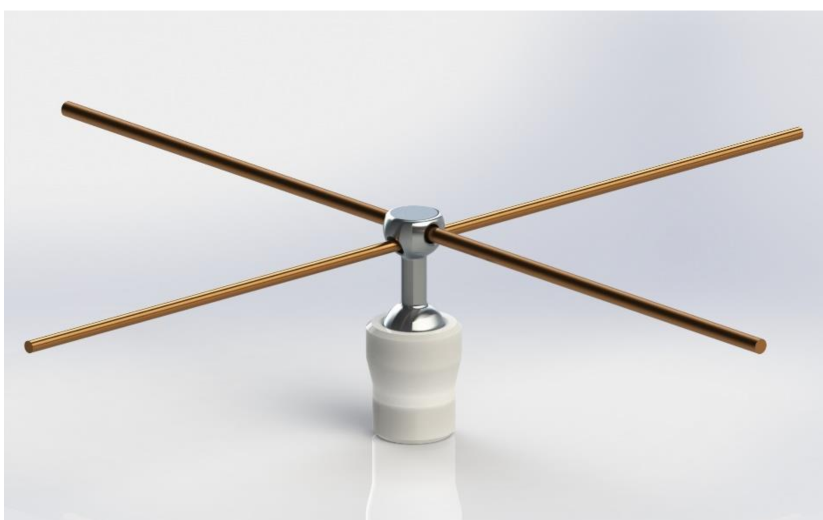
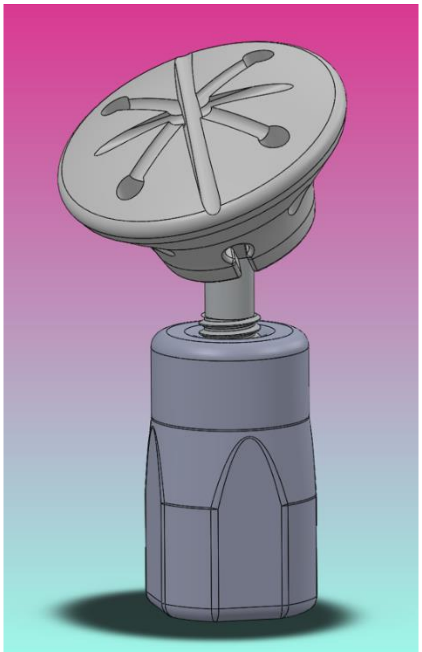
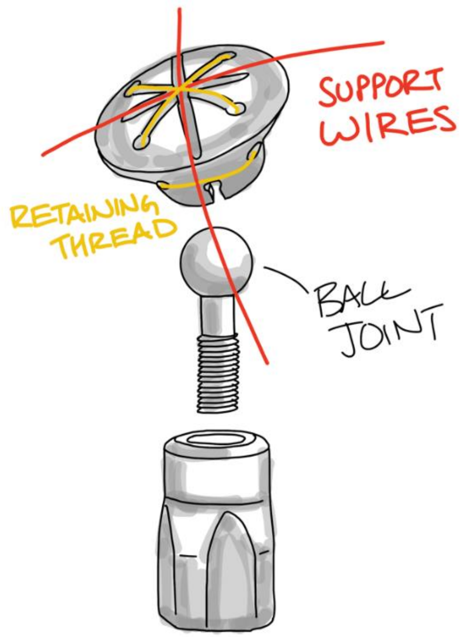


Figure 9, rendering of initial pin head design

Next, we designed a version using off-the-shelf ball joints for RC car suspension, which were perfectly low-profile for our application. We switched from having the wires pass through the pin head to having the wires rest on top of the head. Each major pin has ABS printed caps that support two wires, as illustrated in this rendering:





Figures 10 and 11, Rendering and diagram of pinhead

Additionally, after discussing how each pin intersection with overlapping support wires would lead to cross-shaped ridges, we have settled on a design where the wires are held down in recessed grooves with two loops of Kevlar string wound into two loops holding the wires inside these grooves, similar to the way a button works. This holds down the steel wires without wire ridges on the surface.

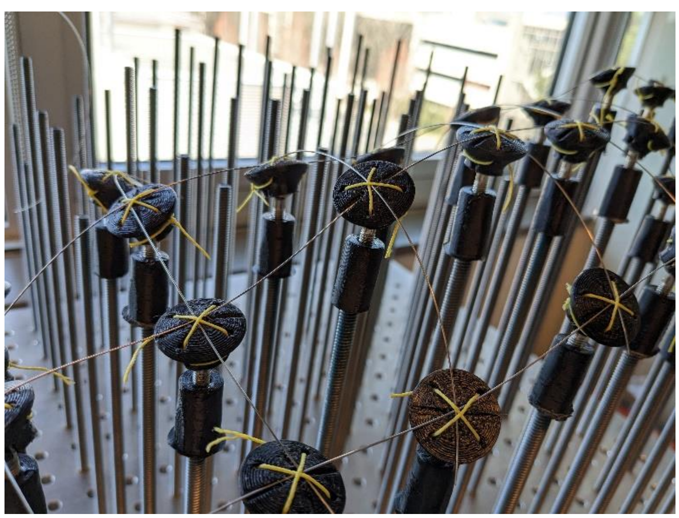


Figure 12, Pinheads and wires

3.6 Firmware

Marlin firmware was selected for controlling our adaptable composite mold machine due to its flexibility and compatibility with various hardware components. Its open-source nature enabled us to modify and customize the firmware to meet our project's specific requirements as we developed and refined our design. One such customization involved configuring custom boot screens, which allowed us to tailor the machine's startup sequence and display project-related branding. Another key feature we implemented was servo control for Z-axis actuation, ensuring precise and reliable movement of the mold during the production process.

Throughout the project, we benefited from Marlin's robust community of users and developers who provided invaluable support and guidance as we encountered challenges during the development process. In the end, Marlin offered a solid foundation for controlling our adaptable composite mold machine, successfully implementing the features needed for an efficient and accurate molding process.

3.7 Software

The primary function of our software system was to translate CAD designs into a set of G-Code instructions executable by the machine's control board. To achieve this, we developed a software system that enabled users to select an .stl file (inches, ASCII, or Binary) and convert it into a list of triangles that were passed through processing filters. These filters rotated, flattened, translated, and adjusted the mesh resolution of the part, facilitating its conversion to a 2.5-dimensional depth map. Ultimately, a G-Code file was generated, instructing the machine on the height adjustments required for each threaded rod. Users could then send the file to the machine control board via a serial connection or an SD card.

We opted to work with .stl files because they are a prevalent file format in manufacturing and computer-aided design. .stl files represent 3D geometry as a mesh of triangles, which are easily parseable, allowing for efficient extraction of the necessary information to generate G-Code instructions. Our software accommodated both binary and ASCII format .stl files, providing flexibility to users.

Although our software was primarily designed for use by trained professionals and students, we acknowledged the importance of providing an accessible and efficient experience. Since we did not develop a dedicated graphical user interface, users needed to examine the output depth map directly within their code to confirm the numbers were reasonable. They could also select and deselect filter methods and set rotation angles in the code, which they could determine from their modeling software.

For the end-user experience, we relied on the popular software Pronterface to communicate with the machine through a serial connection. However, other similar software could be used just as effectively. Through Pronterface, users are able to load the generated G-Code file and send it directly to the machine. This approach ensured that even without a dedicated user interface, trained users could still efficiently operate the system and achieve accurate mold geometry.

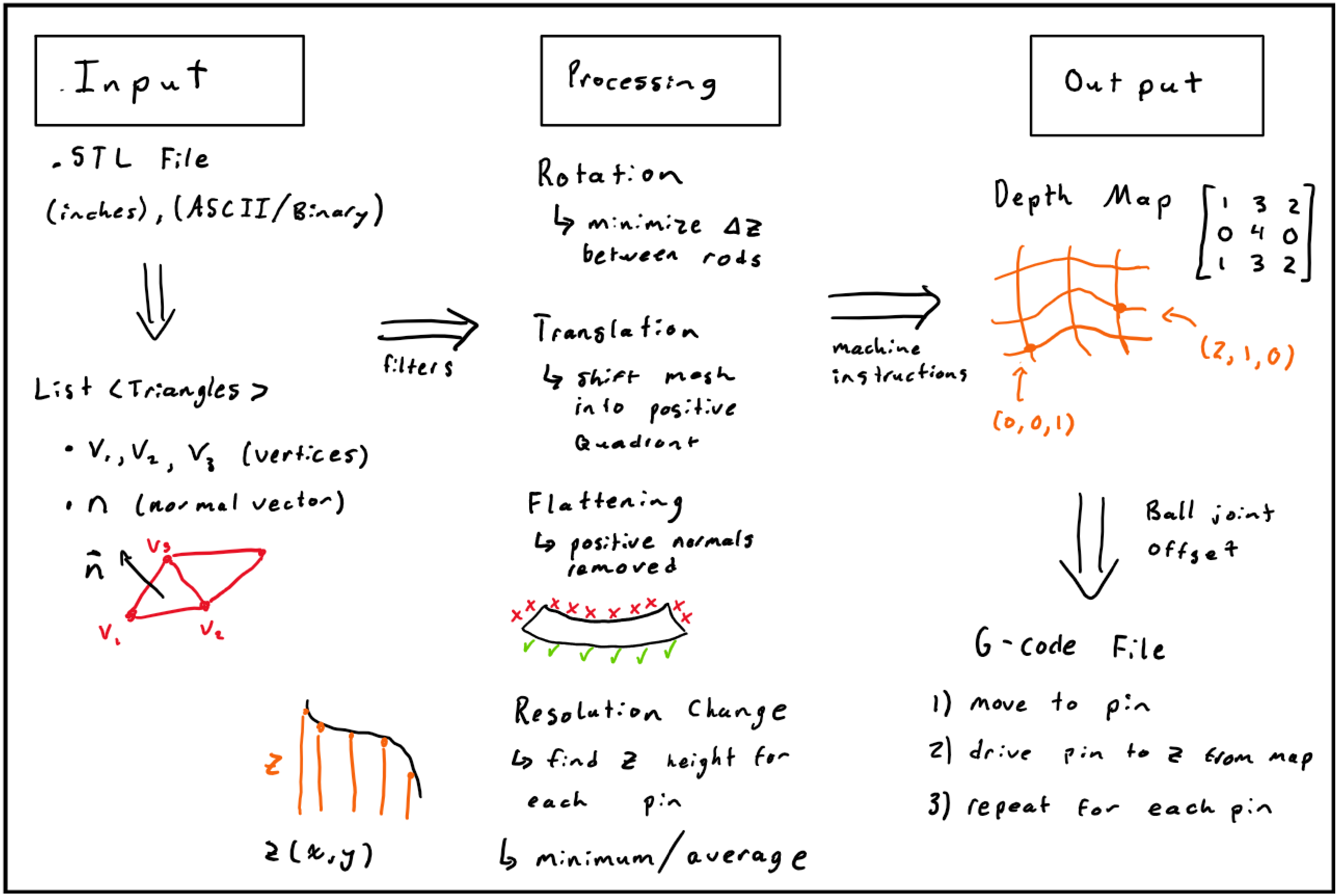


Figure 13. Code Flow Diagram

4 Validation and Verification

4.1 Software and User Experience

The software component of the Re-Mold project underwent rigorous verification and validation to ensure it met project specifications and stakeholder needs.

For software verification, we developed a comprehensive test suite that covered all aspects of the software. The test suite achieved the desired 100% branch coverage and >90% line coverage, indicating that all possible paths through the code were executed and that almost all lines of code were tested. Automated testing tools and techniques were employed to ensure the software was thoroughly and consistently tested.

During software validation, we conducted functional tests based on sample .stl files, including semicircles and quarter pipes. Although functional coverage for Z actuation was not completed, our tests provided insights into the software's performance under various input parameters. The use of Pronterface for G-Code communication to the machine proved seamless and well implemented, validating the end-user experience

Since a graphical user interface was not developed for the project and users were expected to have training and expertise with the machine, we did not conduct formal usability testing.

4.2 Mechanical Validation & Verification Methods

To validate the mechanical components of ReMold our team validated the machine through the parts it produced. By examining the parts produced by a machine, we could identify any defects or deviations from expected specifications. This process involves a thorough analysis of each component, including its size, shape, and overall quality. Through this analysis, we can determine if the machine is functioning properly or if adjustments need to be made to ensure consistent and reliable production. Ultimately, validating a machine through the parts it produces helps to maintain high levels of quality and productivity, while minimizing waste.

4.3 Composite Layup Verification

The main purpose of our device is to be used in composite manufacturing to prototype complex shapes. We verified our device by manufacturing a carbon fiber and a fiberglass part. The top surface shape and manufacturing process were unique for both parts. This validated that our device could be reused for different configurations and sustained different manufacturing processes for composites, which was our goal.

The pins were adjusted to the right heights for the part. The wire surface provided a stiff surface for the silicone membrane to be put on and did not deform under vacuum pressure. More wires were added diagonally for our second fiberglass part. When vacuum pressure was applied, the wire surface was still visible as can be seen in the pictures. However, the surface finish on the parts—especially the fiber glass part—were smooth. Getting rid of the extra bumps would be a next step in improving our device.

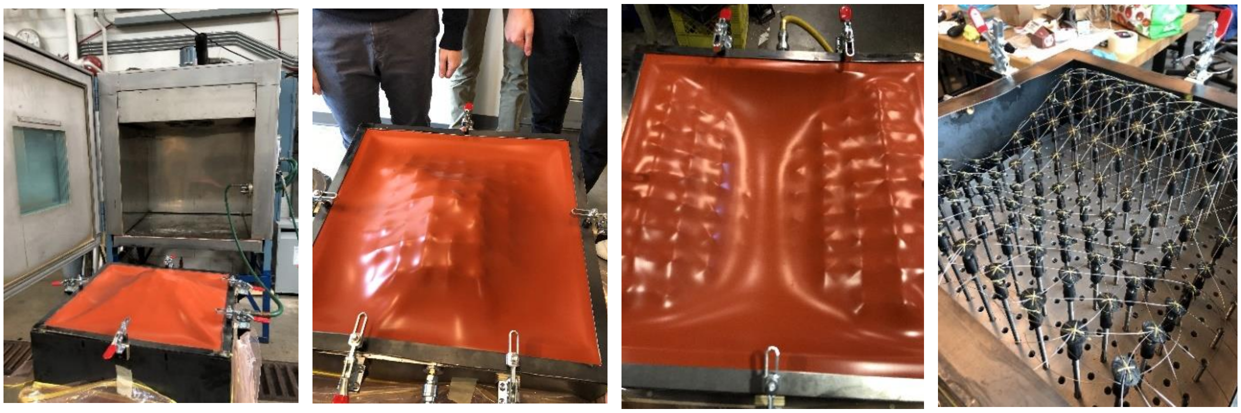
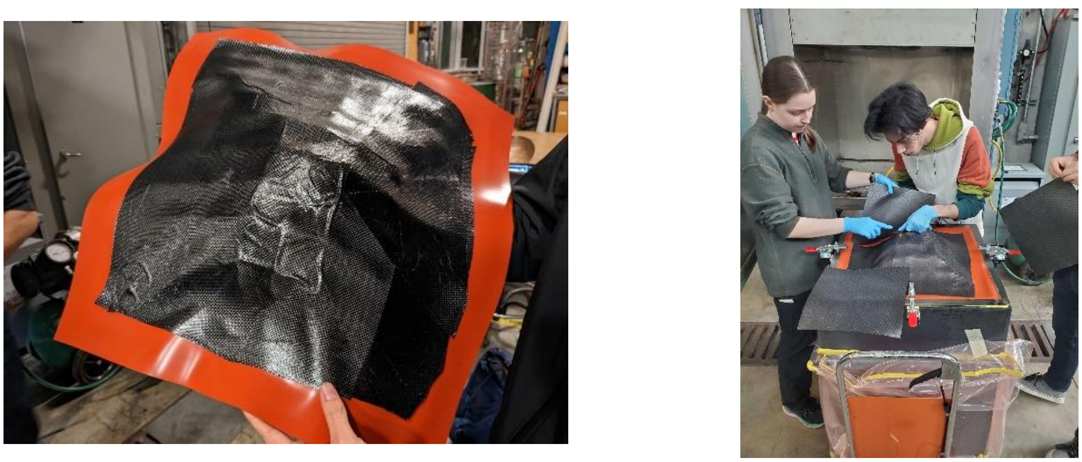


Figure 14, Photos of the layup process

Part 1 – Carbon Fire Prepreg Hand Layup

The carbon fiber part was manufactured using prepreg and put in the oven for 6h at 95ºC. The geometry of the part showed the variety angles that our machine could achieve and was mainly convex. This test also verified that our vacuum chamber held the surface in place with vacuum pressure and was able to withstand high temperatures. The part was very easy to demold.



Figre 15, Finished part and laying up carbon fibre

Part 2 – Fiberglass Wet Layup

For our second composite layup, we did a fiberglass wet layup that cured at room temperature. We attempted to recreate a half pipe shape on our mold, which demonstrated that our device could create concave parts, where the top sheet is pulled down below the highest pin height. More wires were used on the surface, and this significantly improved surface finish. In addition, apart from some defects, the surface finish was much smoother and consistent than the carbon fiber part.

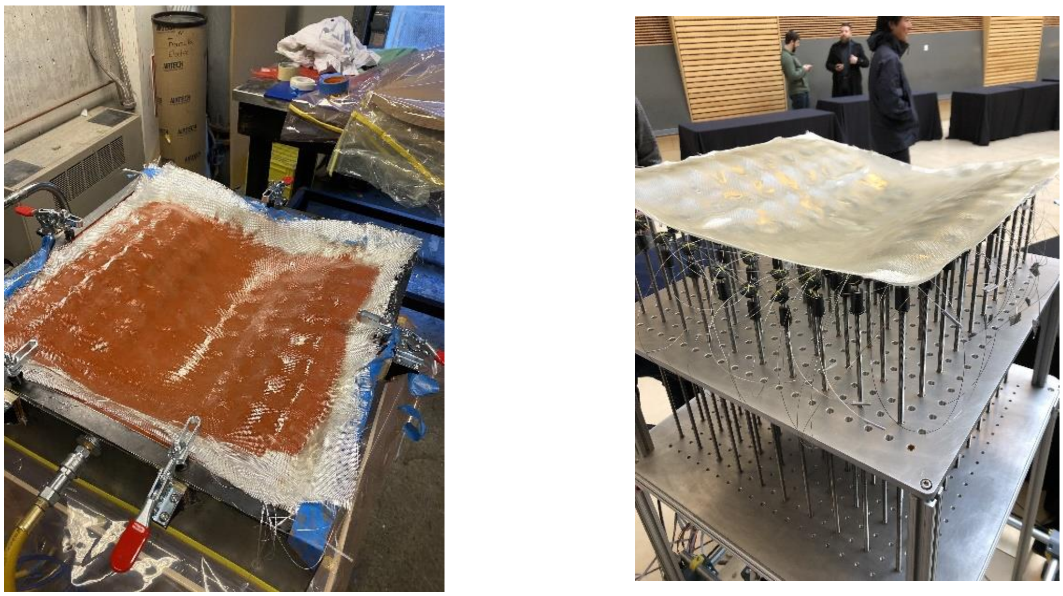


Figure 16, Layup and finished fibreglass product

5 Socio-Economic / LCA / Stakeholder Investigation

Two of the primary functions of the product is to reduce the amount of waste generated and costs required in the traditional mold making process. As previously discussed, the typical mold making process involves a subtractive process – starting with a large piece of material and removing excess until it has the desired shape. No matter the type of material used, this generates a large amount of waste – by definition, the process requires removing excess material. Further, typical mold materials, such as insulation foam or MDF wood, are harmful to the environment to create and dispose of [citation needed]. Examples of foam and wood molds, from the team's research and stakeholder interviews, can be seen below:

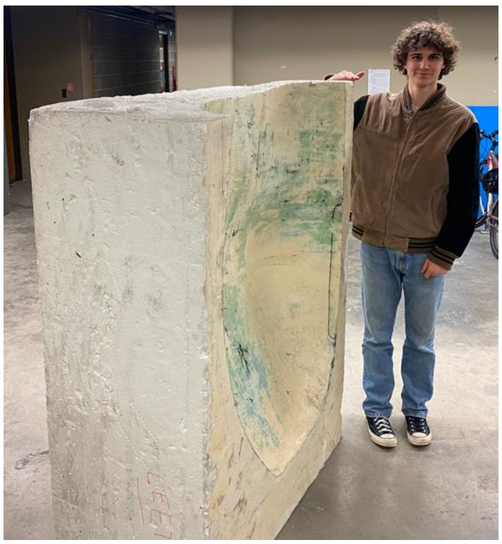


Figure 17. Evan with a foam mold, found in the garbage on UBC campus

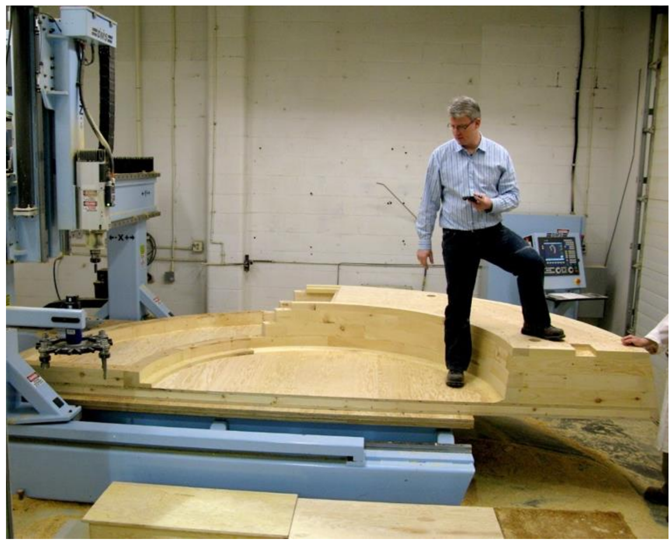


Figure 18. Tim Olson of Adanac Patterns, machining solid wood molds (From Adanac Patterns website)

This has a significant cost, both monetary and environmental, especially in the prototyping space when small adjustments to the mold may necessitate cutting a whole new mold, causing the old one to be thrown out.

Project ReMold negates both issues. From the environmental waste aspect, since the project has infinite adjustability, there is no single use component to it and no waste generated. Each iteration only requires a small adjustment to the existing surface. This correlates to a monetary advantage as well. Since there is no base material to carve out, there's no material to buy for each mold.

ReMold could have a significant socioeconomic impact in any workplace. Take for example UBC's Engineering Design Centre (EDC), where student teams work on their projects. Many projects require composite parts involving extensive prototyping. Typically, foam molds are cut on a local CNC, going through an enormous amount of mold material, and accruing a significant cost. ReMold would reduce the EDC's environmental impact and economic cost for design teams and any other composites company.

6 Budget and Project Work Summary

6.1 Budget

Our total budget was $2400, with $400 from IGEN and $2000 from AMS Sustainability Project Fund.

6.1.1 Materials Engineering Shipping and Receiving

Shipping and tax are not included in purchases from Materials Engineering Shipping and Receiving.

Order 1 – November 2022 – McMaster-Carr

Item	Price	Currency
Sleeve bearings – 110	$ 62.7	USD
Steel threaded rod – 110	$ 148.5	USD
T-slotted framing – 12 ft	$ 68.06	USD
Various stainless steel wire	$ 29.49	USD
	$ 412.99	**CAD**

Order 2 – February 12, 2023 – McMaster-Carr & Amazon

Item	Price	Currency
Natural Rubber Sheet, 1/8" thickness, 12" x 12", 40A durometer	$ 15.88	USD
Polyurethane Rubber Sheet, 1/8" thickness, 6" x 6", 40A durometer	$ 16.41	USD
Silicone Rubber Sheet, 1/8" thickness, 6" x 6", 10A durometer	$ 22.09	USD
EPDM Rubber Sheet, 1/8" thickness, 6"x6", 60A durometer	$ 6.65	USD
Limit Switches	$ 11.76	CAD
Adhesive weights	$ 1.15	USD
Stepper motor drivers	$ 22.00	CAD
Externally threaded nut	$ 23.66	USD
1018 Carbon Steel Precision Acme Lead Screw (3 ft)	$ 48.36	USD
Total	**$ 213.27**	**CAD**

Order 3 – March 20, 2023 – McMaster-Carr & Amazon

Item	Price	Currency
40A Silicone 24"x24", 1/8" thickness	$ 114.93	USD
40A Silicone 6"x6", 1/8", 1/8" thickness	$ 20.75	USD
High-Temperature Soft Silicone O-Ring Cord Stock	$ 24.10	USD
Extrusion 2-3m	$ 66.60	USD
1/4 inch Ball bearings for Z assembly	$ 12.99	CAD
Total	**$ 323.13**	**CAD**

Order 4 – March 30, 2023 – McMaster-Carr

Item	Price	Currency
Gasket Material (2" x 36")	$ 33.24	USD
Toggle Clamps	$ 40.04	USD
Total	**$ 98.93**	**CAD**

Total through Materials Shipping & Receiving = $1048.32

6.1.2 Other Purchases

Vendor	Item	Price	Tax/shipping	Currency
AliExpress	Ball joints	$ 129.11		CAD
Arif	Gantry	$ 730.25		CAD
Amazon	JST Adapter Cable Connectors	$ 14.99		CAD
	Kevlar String 200ft	$ 18.99		CAD
	Mini Push Switch Button	$ 10.52		CAD
	LCD Graphic Smart Display Control Board	$ 25.99		CAD
Home Depot	Husky ¼ inch male connector	$ 7.53		CAD
	Husky ¼ inch female connector	$ 8.29		CAD
	Black spray paint	$ 14.36		CAD
Lee's Electronics	4 conductor cables 24ft	$ 19.00		CAD
	Misc JST connectors	$ 8.00		CAD
Stevenston Marine	Waxed Thread	$ 15.00		CAD
Coe Lumber	Silicone sealant	$ 14.00		CAD
	Plywood sheet	$ 14.00		CAD
Amazon	Hold Down Toggle Clamps Set	$ 32.99	$ 3.96 tax $ 0 shipping	CAD
	High Temperature Gasket	$ 17.18		CAD
	Inside corner bracket gusset	$ 25.49		CAD
	Hold Down Toggle Clamp Set	$32.99	$ 8.72 tax $ 0 shipping	CAD
	Total	**$1138.68**	**$12.68**	

Total for other purchase = $1151.36

Purchasing Summary

Purchase through MTRL store	$1048.32 (not including tax and shipping)
Purchase outside of MTRL store	$1151.36 (some including tax and shipping)
Total	**$2199.68**

6.1.3 Services provided by the Materials Engineering Machine Shop

1. Machining top plate with 100 through holes and base plate with 100 threaded holes
2. Cutting steel plates for vacuum box

All metal for these jobs was provided by the machine shop. See Appendix B for photos and drawings of the pieces done by the machine shop.

6.2 Project Work Summary

Project planning process

Name	Main Responsibilities	Other main tasks accomplished
Arif	• Design, manufacturing, implementation of pin heads • Fabrication and assembly of all gantry parts • Fabrication of pins (welding) • Composite Layups (prepreg and fiberglass) – preparation and manufacturing	• Shared design and implementation of actuator-pin interface • Design for adapting stock Z actuator to increased range for our application • Various manufacturing and design support throughout (welding, printing, design for manufacture)
Arthur	• Adapting stock Z actuator to increased range for our application • Partial design and implementation of actuator-pin interface, including CAD of part and design of servo to detach from pin • Fabrication of vacuum box	• Assisted with layup and monitored cure • Assembly of gantry • Review of drawings and CAD • Various other fabrication (vacuum test box, frame, pin-actuator interface, gantry)
Evan	• Marlin Firmware configuration • Software development • Electrical wiring • Assembly and repair of printed pin heads	• Gantry sizing, installation, and testing • Assisted in manufacturing and assembly of machine • Assisted with layup and monitored cure
Kayla	• Design, CAD Modelling, and drawings in SolidWorks for the frame, plates, vacuum box and assemblies. • Communication with Materials Shop for manufacturing of design • Assisted in manufacturing and assembly of the machine	• Fibreglass layup with Rachel • Construction and prototyping of the scaled down vacuum box • Design and Manufacturing of electrical enclosure • Assembly Drawings for Z Actuation and Pin Heads • Sealing of vacuum box
Rachel	• Top surface material selection and validation • Composite layups (prepreg and fiberglass) – preparation and manufacturing	• Purchasing through MTRL store and keeping track of budget • Booking and managing oven at CRN • Vacuum chamber building and sealing • Assisted in manufacturing and assembly of machine

7 Project Wrap-Up

As our Re-Mold project reaches its conclusion, there are a few remaining tasks for the team to complete following the submission of the Final Report. Namely:

- Return of borrowed equipment and resources: Throughout the term, our team gratefully borrowed various tools and supplies from Baja, MANU, IGEN, and Formula, with permission. We have already returned the majority of these items and will ensure that the remaining items are returned over the coming days. Consumables borrowed from design teams will be replaced with any remaining project budget.
- Further demonstration and reporting of results: Our team is committed to writing a project closeout report for the AMS Sustainability Fund by April 30th. This report will provide a summary of our project outcomes and findings and will be tailored according to the specific requirements for large projects (2-3 pages maximum). We will submit this report online and send any PDF versions to sustainability@ams.ubc.ca.

Our team is incredibly interested in the future development of the project; however, we have conflicting availabilities over the summer including work terms and travel and the majority of members are not planning enrollment in an x30 project or NVD in the following year. We have decided that the project will be stored personally by Arthur until a future decision is made. We hope that the project may be continued at a later date by an IGEN x30 team in Fall 2023 interested in our work or by any of our team members in a 430/NVD project in Fall 2024.

Rachel will be responsible for completing expense reimbursements on behalf of the team, following the procedures outlined on the IGEN website

8 Recommendations

8.1 Recommendations for Future Validation and Verification

The mechanical system of Re-Mold consists of the frame, plates, pins, and pin heads of the machine. To verify the mechanical design, the machine will go through Gage R&R (Reproducibility and Reliability) this process ensures that the given design input yield the same design output when reproduced over time. Our team would recommend in later stages of the machines life that this process be carried out to ensure the quality of the machine and parts produced.

In order to carry out a Gage R&R study, we must have known operators of the machine, known inputs and collection of the machine output. In our case we will be carrying out a crossed study meaning we will have two operators A & B who will each perform the same input of our two archetypal parts and then cross compare the output of the machine. The repeatability of the machine is the variation due to gage, that is, how much variation is due to the machine. Where as, the reproducibility is the variation due to the operator either A or B in our study.

Example of GageR&R data collection:

Run Order	Part Configuration	Operator	Response
1	Part-1	A	Co-ordinates1.cvs
2	Part-2	A	Co-ordinates2.cvs
3	Part-1	B	Co-ordinates3.cvs

Using data collection we can compare the co-ordinate output data, the ‘Response’ to the original input and the output data for the same part to determine the repeatability of the machine.

Source	Standard Deviation	Study Variation (6 * SD)	%Study Variation (%SV)	% Tolerance (SV/TOL)
Total Gage R&R				
Repeatability				
Reproducibility				
Operators				
Part-to-Part				
Total Variation				

8.1.1 Pin Height Validation:

For validating the position of each pin our team researched the ideas of digital image correlation as well as other methods such as a probe which may check the height of each pin as ensure it’s correct position.

Digital image correlation is the less invasive method which only requires that a camera be mounted above or below the pins and use a grid warping method to determine the displacement of each pin. This method may provide feedback more quickly than using a probe which needs to individually check each position while imaging allows us to view the entire assembly at once.

Probing the pins is another method in which we can verify the accuracy of the machine to output the correct displacement of the pins based on input geometry.

8.2 Top Surface Improvement:

Currently the top surface is relatively bumpy due to the pins and wire surface under the silicone membrane. In addition, some geometries may not be accommodated if there is a large variation in adjacent pin height, which would create a large angle. Some recommendations to improve the top surface include:

1. Purchasing and testing different thicknesses of silicone material and determining which material would be ideal depending on the geometry of the part. For example, for softer curves, a thicker material should be used, but for smaller/sharper geometries, a thinner sheet would be ideal.
2. Improving the wire mesh surface to reduce "waffling" and bumps. For example, increasing the number of wires would help to some degree. In addition, exploring the possibility of using a flexible/porous fabric under the silicone to smooth the surface.
    a. Increasing the number of wires may include adding inter-pinhead wires which would need to be weaved between the major wires
    b. Wire stiffness could also be increased with a different material choice. We would like to experiment with superelastic nitinol wires at greater diameters which would have greater stiffness but also greater displacement before plastic deformation.
3. Introducing the ability to include machined or 3d printed detail features on top of the created surface to accommodate creases or mounting features in a mold

8.3 Software Implementation Improvement

To address the current shortcomings of the software implementation and improve its usability and accessibility, we recommend developing a complete application that features an expanded graphical user interface (GUI). This GUI would allow users to interact with their .stl files visually, making the software more intuitive and user-friendly. The complete application would integrate key functionalities not currently implemented including:

1. Visualization of .stl files: The GUI should provide a 3D visualization of the .stl file, allowing users to inspect and manipulate the model before processing. This would help users to better understand the input geometry and identify any potential issues in the output.
2. Manual face selection: Users should be able to interact with the 3D visualization to manually select the face they want to mold, providing greater control over the final output. This feature would empower users to customize the molding process according to their specific needs and requirements.
3. Parameter adjustment: Users should be able to adjust processing parameters such as pin configuration, height determination method, and other relevant settings through the interface. Offering this functionality within the GUI would enable users to optimize the molding process more easily and efficiently.
4. G-Code sender: Integrate a G-Code sender similar to Pronterface within the application, allowing users to send G-Code files directly to the machine via a serial connection or other compatible communication methods.
5. Progress monitoring: Develop a progress monitoring feature that provides users with real-time feedback on the status of the molding process, including estimated completion time and potential issues.

By developing a complete application with an expanded GUI, the Re-Mold project's software will become more accessible and user-friendly, catering to both experienced professionals and novice users alike. This comprehensive solution will also eliminate the need for multiple software applications, streamlining the entire process from .stl file input to machine communication and control.

8.4 Z Actuation Improvement

A current shortcoming of the Z actuation system lies in its integration and reliable use. The system is currently able to navigate to a pin, move the Z actuator up to the pin base, and rotate it to the desired position. The system can also retract the pins, by following the same process as extending them, just rotating them in the other direction once the bottom of the pin is reached. The difficulty lies in reliably detaching the Z actuation system from the pin which is being actuated. The following recommendations can thus be implemented:

1. Redesign of “pin capture device” which more securely and reliably holds the pins, in both up and down movement. The mesh between pin and actuator sometimes doesn’t connect well enough to reliably move the pins down so a more secure capture would be essential for reliable operation
2. Redesign of the “pin release device” to allow for more reliable release of pins. Not a complex problem, but the spring loaded pin release device doesn’t have enough travel to clear the bottom of the pin and thus doesn’t reliably let go. Implementing this and the previous point would allow for truly hands-off operation.

9 Risks and Safety

User safety can be broken up into mechanical, electrical, and training and maintenance hazards.

Mechanical hazards: as a dynamic machine our project poses a multitude of mechanical hazards that may affect the user or others in the area.

Hazard	**Cause of Hazard**	**Description**	**Mitigation options**
Pinch point	Adjustable height threaded rods	Due to the spacing of rods in higher density grid, if the user were to reach in while actuation was occurring there's possibility of pinching	• Light curtains • Cover for finger safety (acrylic cover with mounting to frame) • Clear pinch point warning labels • Safety interlock switches • Emergency Stop
Pinch point	Gantry	Gantry moving on X, Y axis can cause pinching if easily accessible.	• Machine guarding to be inaccessible without a tool • Clear moving parts and pinch point warning labels • Emergency Stop
Laceration or Punctuation	Threaded rod ends / sides	Threaded rods pose a possibility of puncture, and the sharp ends may cause laceration.	• Cover for finger safety (acrylic cover with mounting to frame) • End caps on the threaded rods • Deburr ends of threaded rods
Crushing	Frame / machine falling over	If improperly anchored to the ground with a high center of gravity can topple over hurting user or others around	• Mounting feet/L-brackets at corners of frame to provide anchoring for machine • Weights to bring down centre of gravity of machine
Laceration or Punctuation	Top-surface recoil / snapping	Overstretching of the top surface may result in snapping or projectiles of the top surface	• Acrylic cover to enclose area • User requirement for safety glasses
Blast injury	Vacuum chamber	Evacuated chamber has many points joining accessories or parts of chamber together and may implode	• Incorporate safety factor in design and testing • Users must wear eye protection • Users must repressurize unit when not in use

Electrical Hazard: Machine is hooked up to standard power outlet as supply to move motors.

Hazard	**Cause of Hazard**	**Description**	**Mitigation**
Electrical Shock	Improper Grounding	If the circuit is improperly grounded this can result in voltage travelling through the user	• Grounding wires for enclosure, frame, base plates • Continuity checks
Fire	Exposed Wire / Improper grounding	Exposed wire or improper grounding can generate heat or arc and cause fires.	• Insulation Resistance tests using Fluke or equivalent
Burn	Incorrectly sized wires / Overheating of motor	Under sizing power cables can result in increased resistance coming off as heat	• Power calculations for wire sizing
Tripping	Electrical wires / cords on ground	Electrical wires running from outlet to machine can be a tripping hazard	• Duct taping cods to ground with bright colours. • Running cords outside of walking areas

Training and Maintenance: the machine is designed to be used in a busy industrial environment and as such must include consideration to inexperienced operators and maintenance technicians

Hazard	Cause of Hazard	Description	Mitigation
Failing parts	Wear on bolts, threaded rods, moving parts	If not properly maintained and replaced parts will fail due to cyclical loading	• Keeping a maintenance log • Spare parts on hand • Maintenance manuals write up
General user harm	Improper knowledge of tool use	If not properly trained on machine can result in injury due to combination of moving parts, power, heat and heavy components	• Operating manuals write up

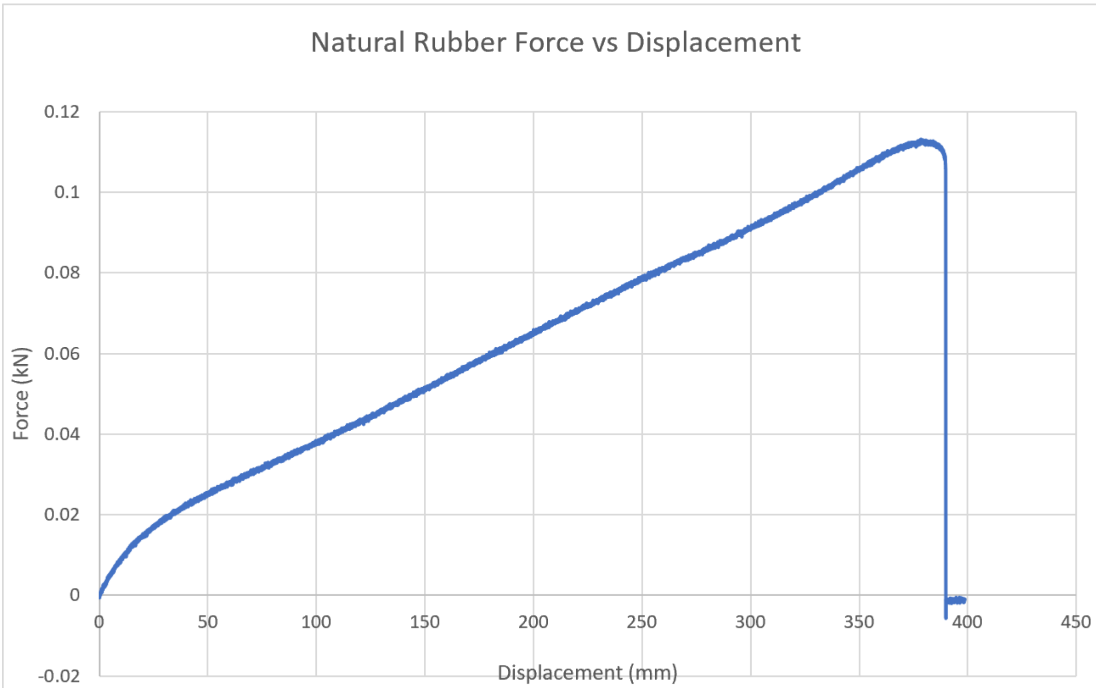
10 References and Appendix

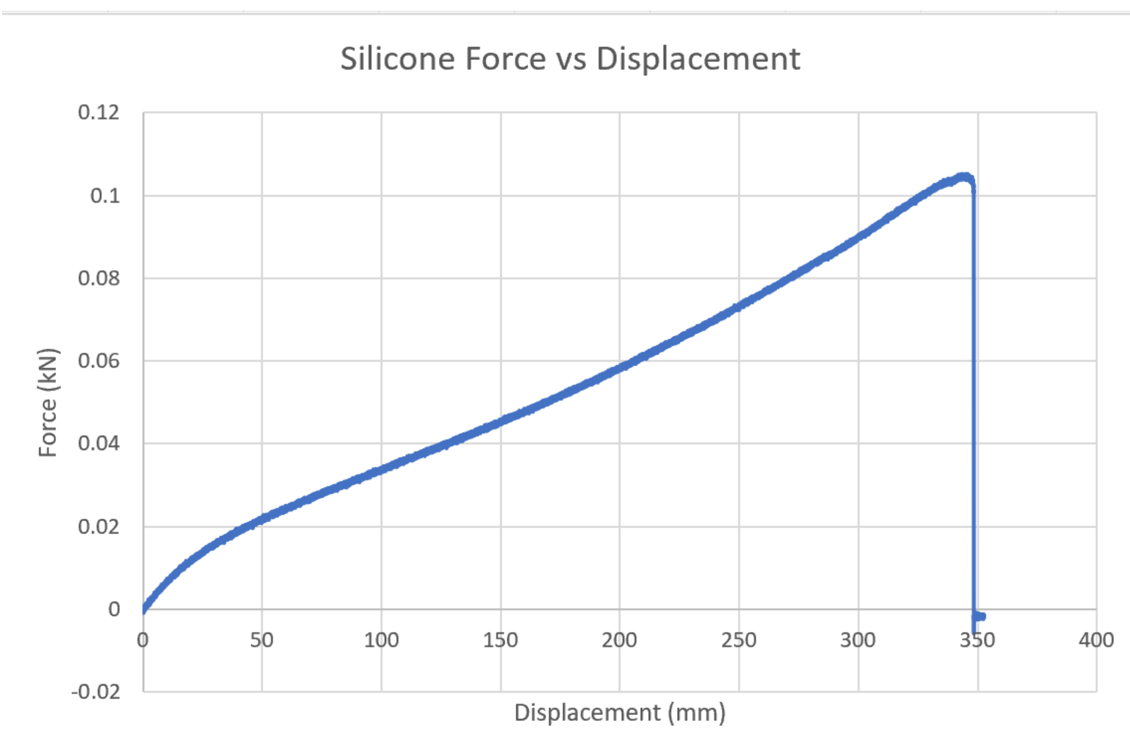
Appendix A

A1. Example of material chart comparing different rubbers

Commercial name		APTK			Polyurethane	Silicone	SBR
	Epichloro-hydrin rubber	EPDM Ethylene-propylene-diene rubber	Fluorinated rubber	Polyboron rubber	Polyurethane	Silicone rub-ber	Styrenebutadi-ene rubber
	Low gas permeability, very good low temperature properties, good resistance to mineral oils, ozone and high temperatures.	Versatile in use, very good flexibility, resistant to abrasion, resistant to wear and tear, resistant to ozone and weather, resistant to low temperatures. Can be used to protect against washing and spraying agents, excellent for profile cords not usable in conjunction with petrol, solvents and mineral oils.	Hexafluoropropylene vinylidene fluoride copolymer. Resistant to extreme temperatures even over 200°C. Very good mechanical properties and high resistance to tearing even at high temperatures. Excellent for exposure to sun-light, ozone and weather. Not recommended for use in conjunction with esters and ketones.	High mechanical strength, medium resistance to oil, good resistance to ozone. Flexibility and damping properties can be varied as required, excellent resistance to water, slight permanent set.	Excellent resistance to wear and tear, best flexibility with high shore hardness of all the elastomers, good resistance to oil, not resistant to hydrolysis.	Resistant to high temperatures, odourless and tasteless, non-toxic, can be sterilised in accordance with foodstuffs regulations. Resistant to sea water and corrosive salt solutions, not to be used in conjunction with steam, concentrated acids and alkali, swells strongly under the effect of aromatic solvents.	Similar to natural rubber, resistant to abrasion, rubbing in, good resistance to high temperatures and cracking, resistance to extreme low temperatures, not resistant to petrol, benzene, greases and oils.
International designation	ECO	EPDM/EPM	FPM	PNR	PUR	MVQ/SI	SBR
Hardness available	50 - 90 Shore A	30 -90 Shore A	65 - 90 Shore A	10 - 80 Shore A	55 - 98 Shore A	40 - 80 Shore A	35 - 95 Shore A
Temperature resistance	-40°C to 130°C	-40°C to 150°C	-30°C to 225°C	-40°C to 80°C	-30°C to 80°C	-70°C to 180°C	-30°C to 110°C
Short-time peak temp	150°C	180°C	350°C	100°C	100°C	225°C	150°C
Tensile Strength (N/mm²)	17	20	20	17	30	8	25
Tensile elongation (%)	150 to 500	450	400	300 to 700	800	250	450
Properties							
Abrasion	moderate	good	moderate	good	excellent	moderate	very good
Resistance to flex cracking	good	very good	good	moderate	-	bad	good
Elongation/Tensile strength	good	good	good	good	excellent	bad	good
Flexibility	moderate	good	moderate	as required	good	good	good
Notch strength / strength of structure	good	moderate	almost good	moderate	excellent	moderate	good
Resistance to light	good	excellent	excellent	good	good	excellent	moderate
Resistance to oxidising	good	excellent	excellent	good	good	very good	moderate
Resistance to ozone	very good	excellent	excellent	good	good	excellent	moderate
Resistance to wear/tear	-	good	almost good	good	excellent	bad	very good
Weathering effect	good	excellent	excellent	good	moderate	excellent	good
Resistance to							
Alkali	bad	excellent	very good	moderate	not suitable	not suitable	good
Petrol	good	not suitable	excellent	not suitable	very good	not suitable	not suitable
Benzole	good	not suitable	good	not suitable	not suitable	not suitable	not suitable
Foodstuffs	not suitable	suitable	not suitable	not suitable	not suitable	excellent	suitable
Solvents, aliphatic	good	bad	very good	not suitable	very good	not suitable	not suitable
Solvents, aromatic	good	not suitable	good	not suitable	moderate	not suitable	not suitable
Solvents, halogen	not suitable	not suitable	good	not suitable	bad	not suitable	not suitable
Oils and greases	very good	bad	good	conditional	very good	good	not suitable
Acids	moderate	very good	very good	moderate	not suitable	not suitable	conditional
Water	moderate	very good	good	excellent	not suitable	good	very good

A2. Force vs displacement graphs for natural rubber and silicone.

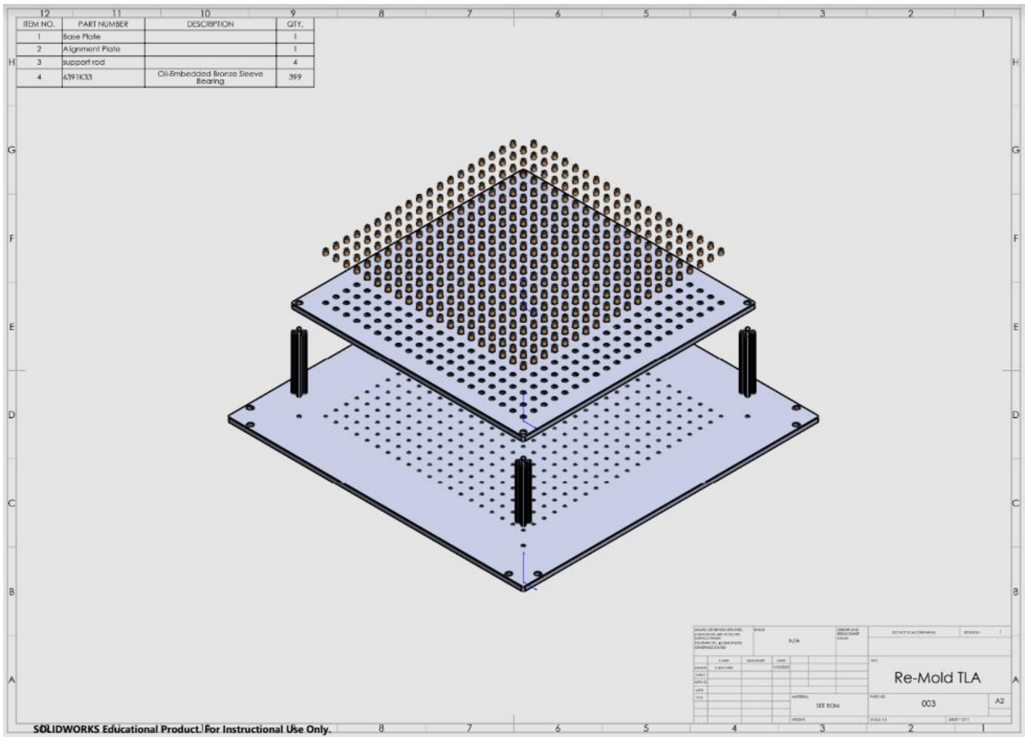


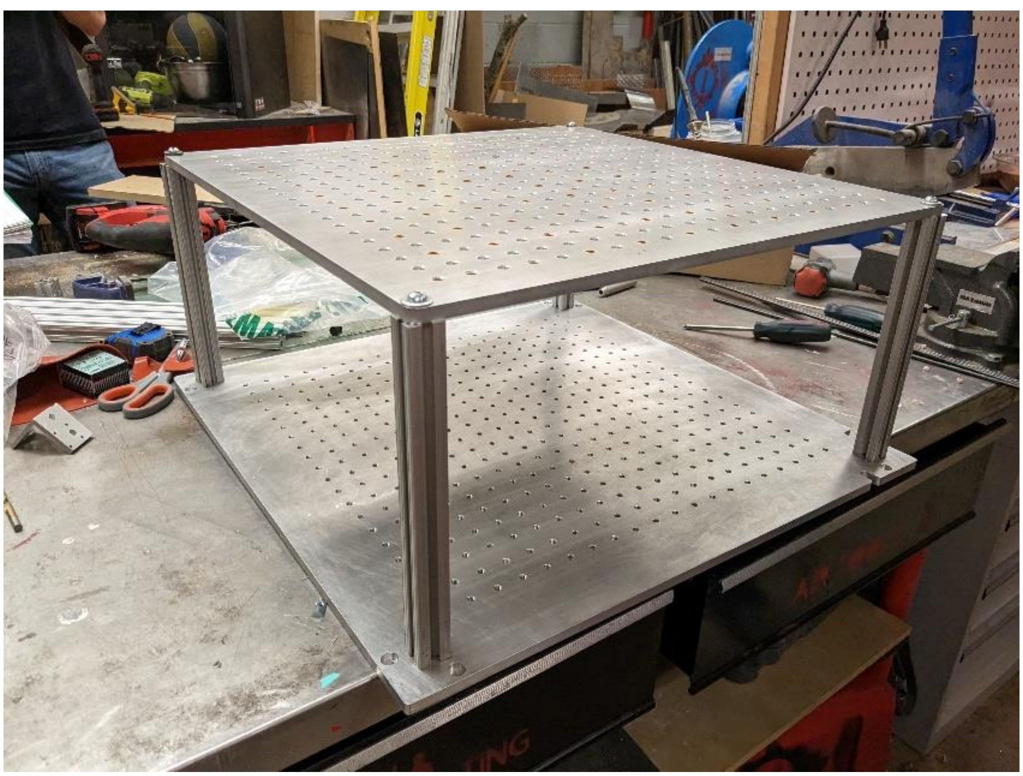


Appendix B

Parts manufactured by MTRL shop

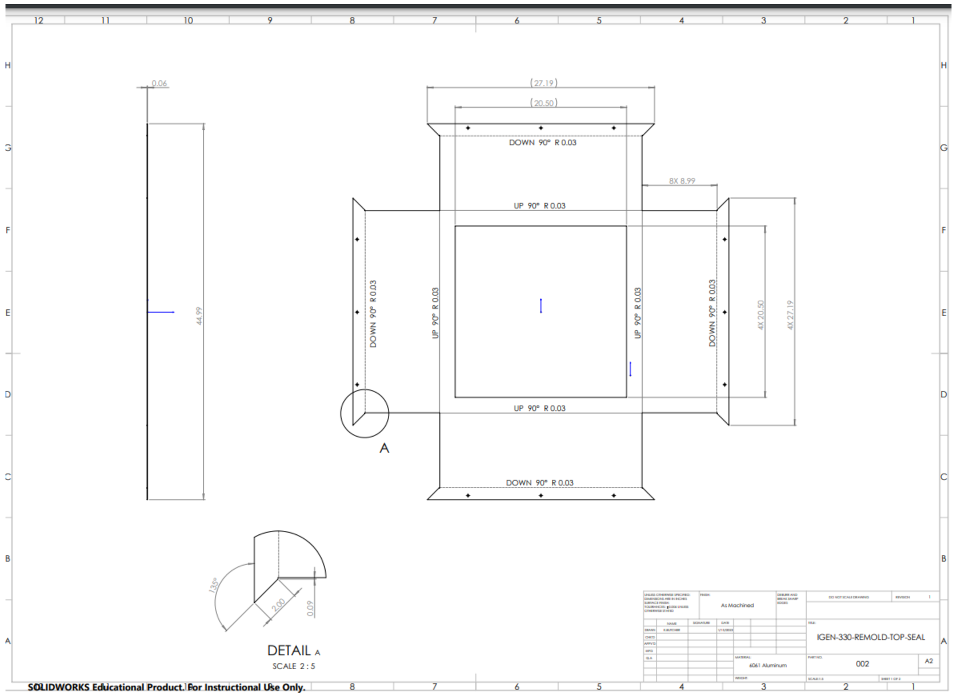
B1. Top Frame Assembly – top and base plate



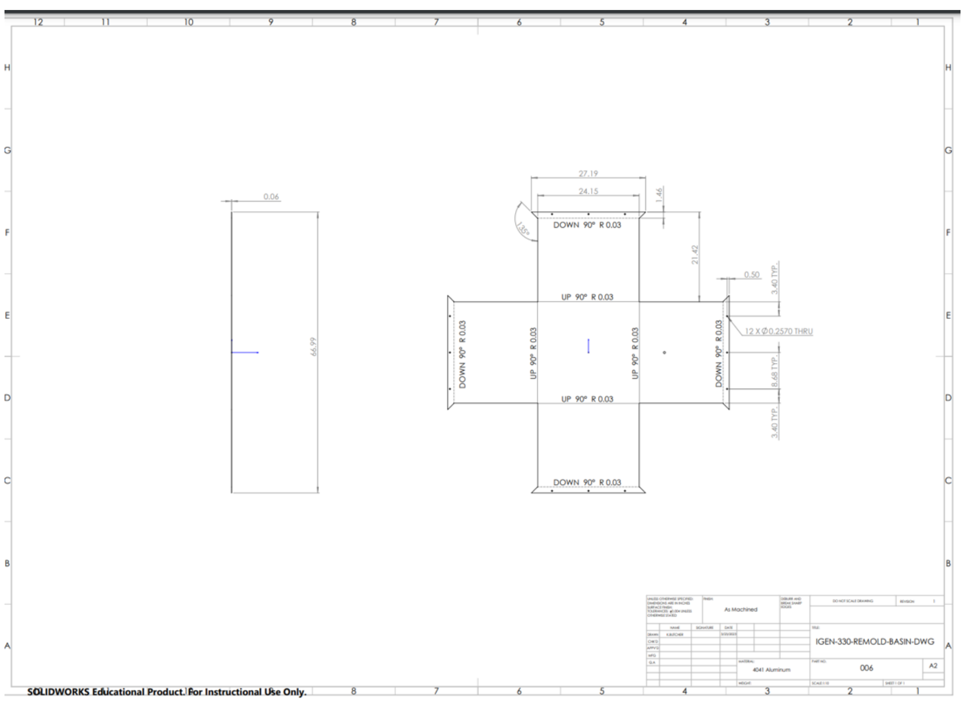


B2. Vacuum box drawings

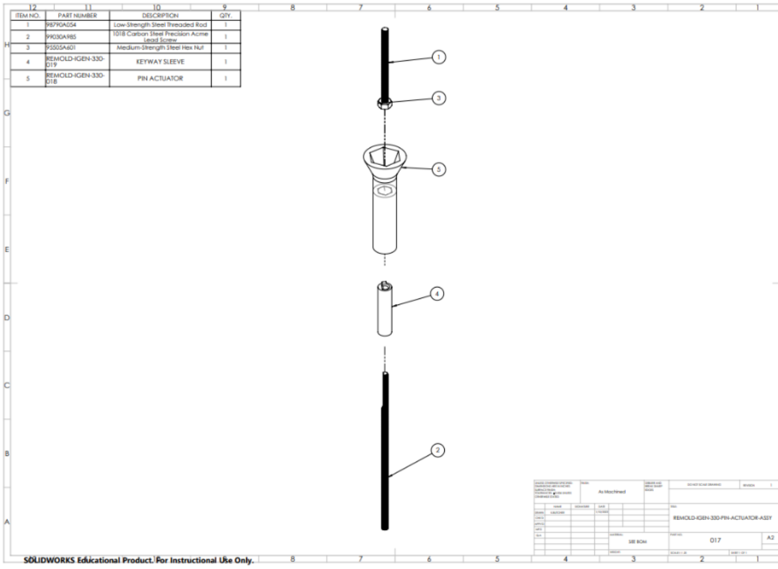
Top Seal

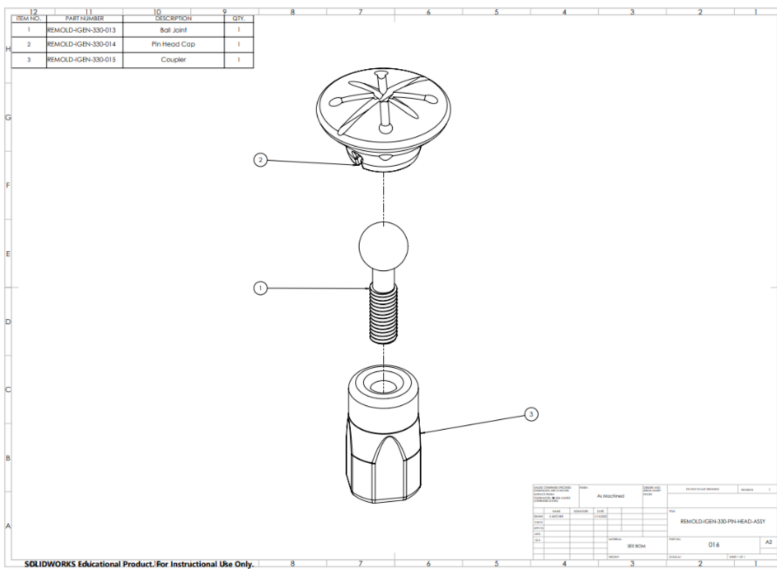


Basin



Assembly Drawings for Z Actuation and Pin Heads





Appendix C

Software Project Breakdown

- **Main.java**: The main class that handles user input, file selection, and coordinates the processing of STL files and G-code generation.
- **stl4j package**
  - **STLParser.java**: A class responsible for parsing STL files and converting them into a list of Triangle objects.
  - **Triangle.java**: A class representing a single triangle in the 3D model. It stores vertex coordinates and provides methods for calculating properties, such as normal vectors and barycentric coordinates.
  - **Vec3d.java**: A class representing a 3D vector. It provides methods for vector operations like addition, subtraction, scalar multiplication, and dot product.
  - **Plane.java**: A class representing a plane in 3D space. It stores the plane's normal vector and a point on the plane. Provides methods for calculating properties and intersections with the plane.
- **gcode package**
  - **GCodeWriter.java**: A class responsible for generating G-code instructions based on the depth map data. It can write the generated G-code to a file.
- **util package**
  - **DepthMapUtil.java**: A class that provides utility methods for generating depth maps from a list of triangles, interpolating z-coordinates, and calculating pin heights for an adaptable molding machine.
  - **TriangleFilterUtil.java**: A class that provides utility methods for filtering triangles, such as removing triangles with outward-facing normals or that are outside a specified region.