Robotic Metamaterials: An Integrated Modular Approach for Users to Create Robotic Applications Hands-on

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Abstract

I propose augmenting initially passive structures with novel active units to enable dynamic, shape-changing, and robotic applications. Inspired by metamaterials that can employ mechanisms, I build a framework that allows users to configure passive, modular structures to perform complex tasks. A key benefit is that these structures can be repeatedly (re)configured and pneumatically actuated by users to turn the passive material into crawling robots, kinetic sculptures, or physical notification interfaces.

To this end, I present a mechanical system consisting of a flexible, passive, shearing lattice structure, as well as a rigid, and an active unit cell to be inserted into the lattice for configuration. The active unit is a closed-loop pneumatically controlled shearing cell to dynamically actuate the macroscopic movement of the structure. The passive rigid cells redirect the forces to create complex motion with a reduced number of active cells. Since predicting the placement of the rigid and active units to produce a desired behavior is challenging, I assist users by contributing an inverse design workflow using a software tool, which optimizes the cell placement to match the macroscopic, user-defined target motions and generates the control parameters for pneumatic control of the active cells.

Acknowledgements

My learning and research experiences during my Master's program have been critical to my academic development. I was shaped and directed by many outstanding researchers at Carnegie Mellon.

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Additionally, I am extremely thankful to Professor Daniel Cardoso Llach. As our program chair, Daniel has offered huge support in encouraging me to prioritize research and offering flexibility to help me achieve my academic goals. Having Daniel on my thesis committee has helped me better incorporate the computational design perspective into my thesis.

Huge thanks to the team Robotic Metamaterials, specifically to my collaborators – Alan Zhu, Joanne Chin, Ziyun Liu, Andy Kong, and Jesse Gonzalez. This thesis is an interdisciplinary work and this research would not be able to cover all the aspects it has right now without their contribution and help. I would like to give special thanks to Professor Scott Hudson for his guidance on this project.

Studying in an interdisciplinary program like Computational Design, I have been constantly inspired by my peers in my cohort. I'm always impressed by how unique everyone's background is and I deeply value the diverse range of perspectives my peers bring into our discussions and conversations.

Lastly, I would like to thank my partner for accompanying me, encouraging me, and accommodating me. I also want to thank Catherine Yu, Daehwa Kim, Vimal Mollyn, Yi-Hao Peng, Andy Kong, and many other of my loved friends for supporting me. There are a lot of precious memories that we share, and I cannot imagine going through this journey without them.

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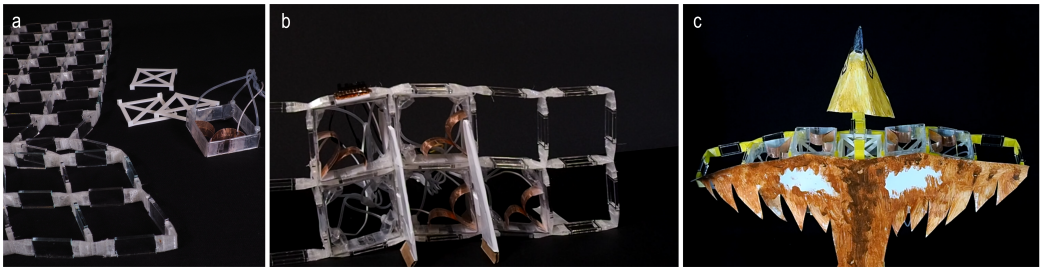


Figure 1: (a) The initially passive metamaterial can be configured with active elements to implement robotic function such as (b) a crawling robot or (c) a shape-changing sculpture, here a bird.

1 Introduction[1]

Advancements in digital fabrication technology allow users to create custom objects more easily. To enable users to go beyond static shapes [27, 32], researchers have investigated systems enabling the fabrication of functional and dynamic objects ranging from mechanical objects [35, 12], compliant mechanisms [19, 46, 25], shape-changing interfaces [30, 47], soft robotics [11, 43], to programmable materials [13, 16, 15]. The computational power injected to these programmable materials allows complex dynamic behavior of materials [18, 15, 13], automated architectural assembly [34, 40], interactive environments [1, 5], and environmental sustainability [21].

One example of such programmable materials are so-called metamaterials [2], which are artificial microstructures that define the macroscopic material properties. Going beyond designing material properties, researchers started to view metamaterials as machines. Such metamaterial mechanisms are passive materials that can employ mechanical [13] or computational [16] functions and can typically be fabricated in one piece and not need assembly. Taking the complexity of assembly out of the picture can enable novices to make specific custom mechanisms that suit their needs. However, in past work, these have been defined by their designed structure, and cannot be modified after fabrication. Such materials fabricated based on one-off designs are hard to adapt to our changing needs and dynamic everyday interactions. Therefore, there needs to be a new type of programmable material that al-

[1]Parts of this thesis have been submitted to The ACM Symposium on User Interface Software and Technology (UIST 2022), and is under review by May 10, 2022.

lows novices to easily reconfigure for dynamic control of material behavior. In other words, robots or materials can be opportunistically created to span the continuum between materials and robots.

In this thesis, I propose an integrated modular approach to allow users to create dynamic, interactive metamaterials that can provide robotic functions, which can be reconfigured later to change or replace their function. Users can configure an initially passive lattice by inserting actuation units, that I call active cells. Along with passive rigid cells, they provide a modular platform for users to design robotic and shape-changing applications in a hands-on fashion.

This material platform aligns with my vision where users can create dynamic applications or turn passive objects into dynamic ones easily on their own. It informs a future where objects made of passive materials can be made active by very simple configurations, from small objects like a pen, to a tabletop, to large construction like a wall or even a living space. I hope in the future this platform can address a diverse range of everyday challenges and support infinite amount of creativity coming from end users.

1.1 Elements of the robotic metamaterial

The elements of the robotic metamaterial consist of (a) passive shearing cells, (b) passive rigid cells, and (c) active shearing cells, as illustrated in Figure 2. The basic cell system building on a careful placement of shearing and rigid cells is inspired by previous work on Metamaterial Mechanisms [13, 15] where passive shearing cells and passive rigid cells transform input movement into output movement upon external forces.

Figure 2a shows the generic sheet of passive shear cells. Each of these cells implement a four-bar linkage, i.e., a 1 degree of freedom mechanism that enables a controlled directional movement. Users can configure the robotic movement by inserting rigid cells (see Figure 2b), which propagate forces through the material and in concert with the shearing cells implement mechanisms.

I extend the capabilities of such materials by introducing an *active cell* to actuate the material, which I show in Figure 2c. Like the rigid cells, this active cell can also be placed into the passive shear lattice such that users can configure their metamaterial repeatedly to implement desired robotic functions. The active cell is pneumatically actuated.

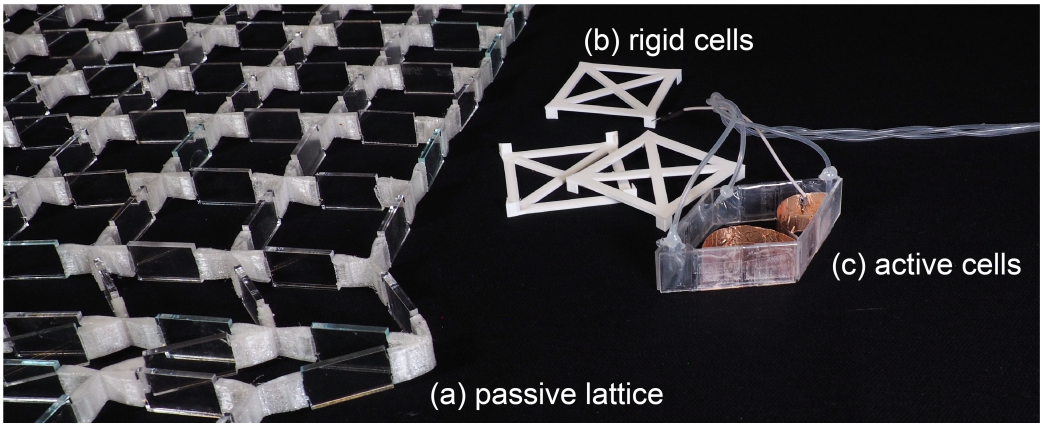


Figure 2: The robotic metamaterial consists of (a) a passive lattice of shearing cells, (b) passive rigid cells and (c) a novel active cell that is (d) pneumatically actuated to enable configurable robotic function.

1.2 Walkthrough

In the following, I showcase how users configure the presented metamaterial to implement a custom material that wakes them up after a power nap.

(1) Design the target motion using a software In the first step shown in Figure 3, users utilize a software tool[2] to compute the number and placement of rigid and active cells within the passive lattice. Users draw the tapping motion in their preferred vector graphics program. Using this tool, users assign the motion to a point on their preferred lattice size. This inverse design tool, which builds on [15], optimizes the cell placement to match the macroscopic, user-defined target motions and generates the control code for the active cells.

(2) Assemble passive grid Users then assemble the passive lattice[3], as shown in Figure 4, possibly reusing part or all of the grid from a previous design. The passive lattice is designed to be simple to assemble. To configure the grid at the desired size, users can simply attach the rigid members, cut

[2]The software was implemented by Alan Zhu.
[3]The lattice was designed by Samuel Losi.

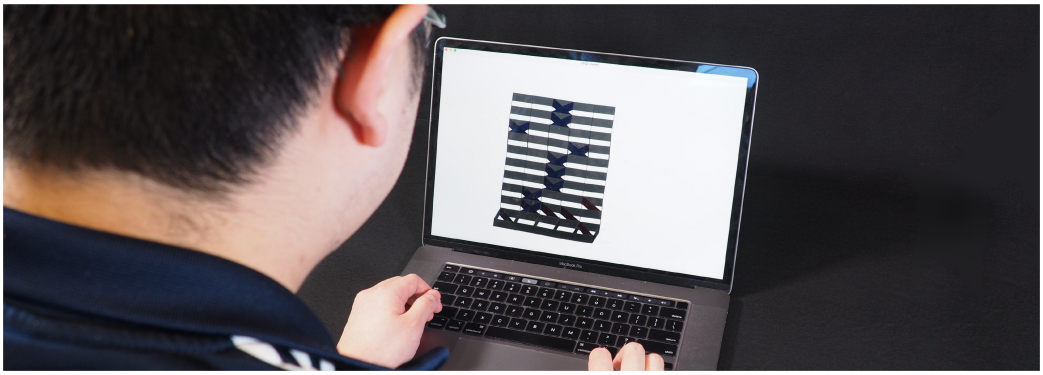


Figure 3: Users specify the tapping motion of their robotic material using the design tool, which optimizes the placement of rigid and active cells, and generates the control code.

from acrylic, into the flexible, snap-fit like joints, 3D printed using the rubber-like off-the-shelf TPU filament (Ninjaflex).

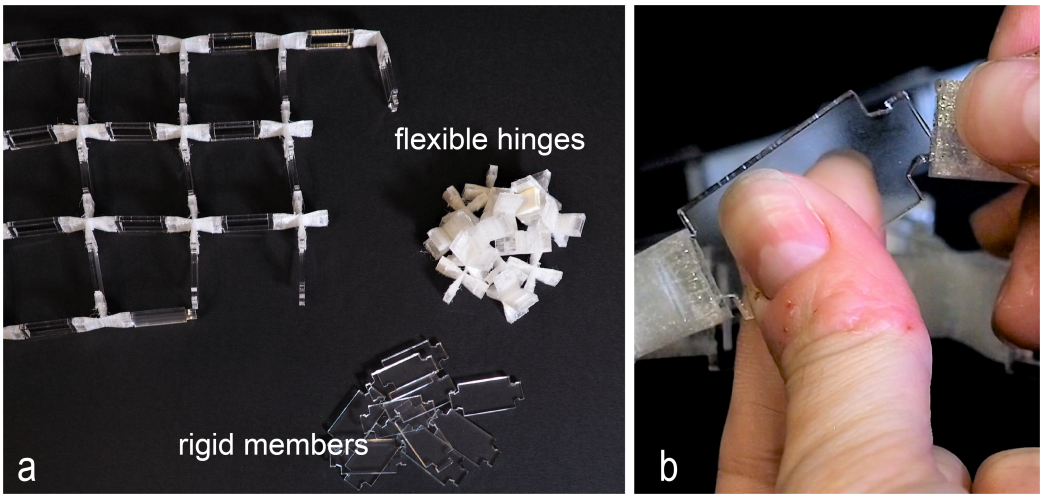


Figure 4: (a) Users can assemble the passive base lattice by (b) simply snapping the rigid members into the flexible joints.

(3) Insert rigid & active cells After users establish the passive lattice serving as the base metamaterial, they insert the 9 rigid and 5 active cells as indicated by the design tool. The cells are designed to be attached with

simple clips to the lattice. Users place the rigid cells first[4]. As shown in Figure 5a, users then insert the active cells, which are the key to creating complex mechanisms. Users attach the active cells and clip the wires and tubing to the lattice to keep it organized. The active cell is designed to be modular, i.e., it is a self-contained unit with the air pockets for pneumatic actuation, and capacitive sensing electrodes for closed-loop control, with the wires, tubes, and circuitry encapsulated. Note that as shown here this is a research prototype, and the fabrication and circuitry can be miniaturized by industrial manufacturing in the future.

Additionally, users can add custom passive parts to the metamaterial to facilitate their specific applications. In this example, users create a custom end-effector, shown in Figure 5b, that taps them on the arm after a power nap. This represents a small trade-off—it makes their designs more customizible, but introduces a specialized part.

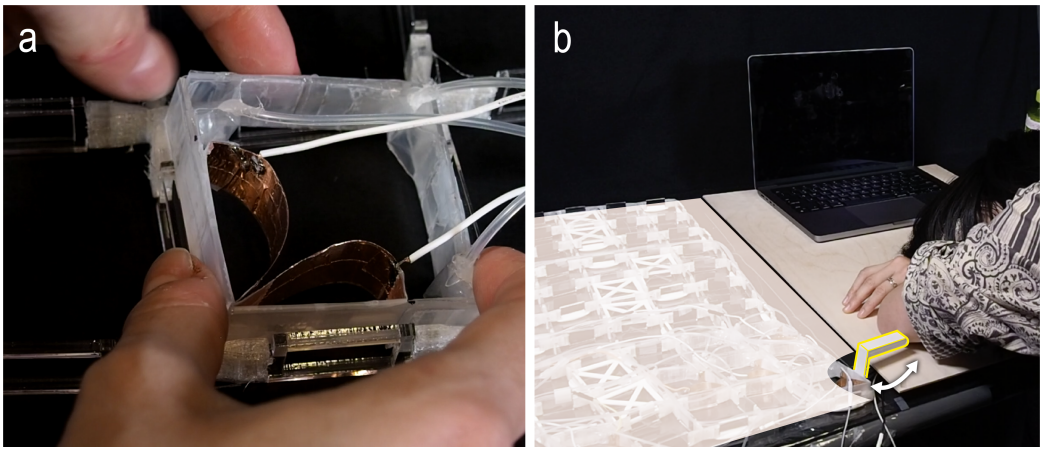


Figure 5: Users insert rigid and (a) active cell modules into the lattice as suggested by the design tool. Additionally, they add (b) an end-effector to their material and integrate it into their desktop.

(4) Upload the actuation code Lastly, users retrieve the control parameters produced by the design tool in step (1), which lists the target angles for each active cell. Users transmit the angle to a preconfigured microcontroller, for which I use an Arduino Mega in my multi-cell prototype. Users

[4]The rigid cells and clips were designed by Joanne Chin.

connect the active cells' control circuitry to the Arduino, to power and to a compressed air source (typically a compressor), making their robotic tapping material ready to go.

In the remainder of this thesis, I will showcase how the robotic metamaterial can be further customized, and show different directional mechanisms as well as robotic applications, as pointed out in Figure 1.

2 Contributions

The main contribution of this work is the concept of dynamically driving metamaterials to perform robotic movements based on metamaterial mechanisms. The specific contributions of this thesis are the following:

1. *Active unit cell.* I develop modular active unit cells to dynamically actuate the macroscopic movement of the structure.
2. *The configurable lattice structure system.* The metamaterial structures can be repeatedly (re)configured by users inserting configuration units to implement their specific applications, making the design reusable.
3. *Inverse design workflow.* I adopt an inverse design workflow, which optimizes the cell placement to match the macroscopic, user-defined target motions and generates control parameters for the active cells.

3 Related Work

This research builds on previous work in the areas of shape-changing interfaces, soft robotics, and mechanical metamaterials.

3.1 Shape-Changing Interfaces

Shape-changing interfaces with pneumatic actuation have been explored in the Human-Computer Interaction field. The project PneUI created pneumatically actuated soft composite materials [47]. Project Sticky Actuators proposed planar soft actuators that can be pneumatically controlled and actuate everyday passive objects [28]. Researchers have also started to transform everyday materials into different shapes and actuation mechanisms. Ou et al. created bending mechanisms that transform inflatables made of various materials into different shapes [30] (Figure 6). Choi and Ishii explored heat-seal patterning that transforms everyday material into DIY inflatables [4]. These techniques, however, offer limited interactivity as it is hard to configure those materials after fabrication. Different from prior work, the shape-changing material in this research can be repeatedly configured after fabrication by end users. This work provides a modular platform to allow users to create interactive materials.

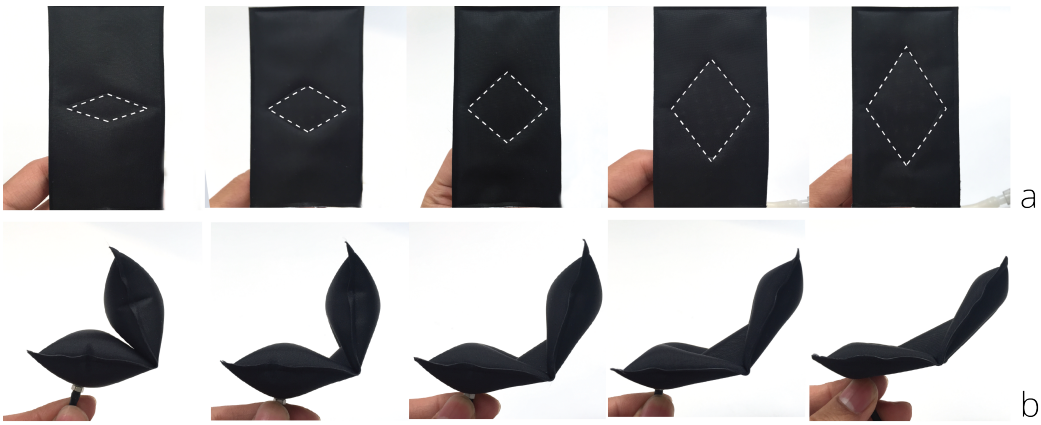


Figure 6: The (a) bending mechanisms on various materials can (b) transform inflatables into different shapes [30].

3.2 Soft Robotics

The domain of soft robotics creates robots from soft components. This is a broad area of work, however, as exemplars, researchers have created pliant structures through programmable composites [22], mechanical structures [48], mechanisms [42], etc. to build soft actuators [26], locomotion robots [41, 10] (Figure 7), etc. Pneumatic actuation is common in soft robotics as it can control complex motion with simple actuation [39]. The proposed robotic material consists of rigid plates connected through flexible joints, making the whole material sheet compliant and flexible. In contrast to actuating the entire material sheets globally, I focus on actuating local areas of the material to trigger the desired global deformation.

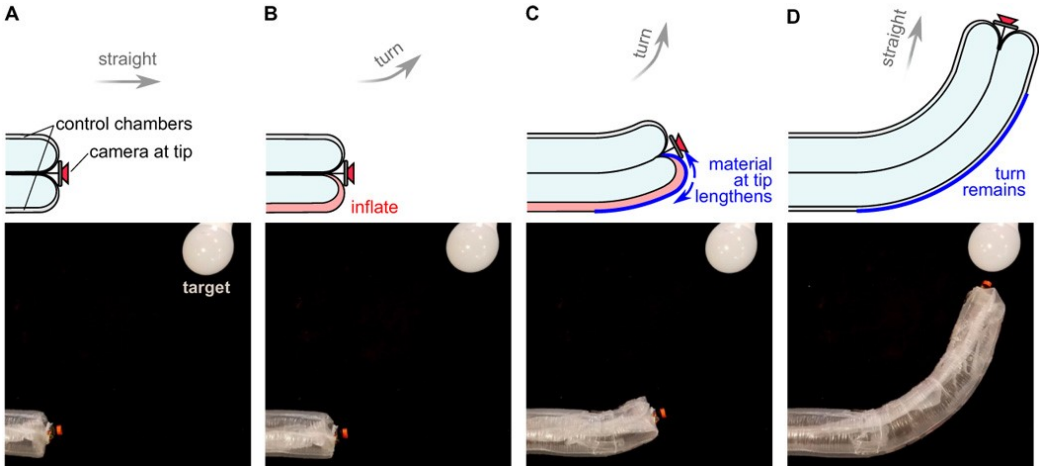


Figure 7: A pneumatically actuated robot can be designed and controlled to reach a target from a distance [10].

3.3 Mechanical Metamaterials

Mechanical metamaterials offer advanced material properties due to their internal mechanical structures. For example, varied internal structures of 3D prints can offer varied elasticity to allow bending and rotation of desired parts [37]. A metamaterial sheet with auxetic structures allows two-dimensional expansion upon a one-dimensional stretch [17, 36], and both planar and spatial transformations [29]. Recently, metamaterials have started to

be understood as devices. Ion et al. implemented mechanisms from metamaterials with repeated shear structures [13] (Figure 8). Shaw et al. made compliant mechanisms from rolling-contact architected structures [38]. Mechanisms can trigger texture change such as the texture on a bike handle [14]. Researchers have also started to integrate circuits into the material [8] and allow in-material sensing capability [6]. Going beyond passive materials that rely on external forces, researchers have started to dynamically actuate materials. Yang et al. implemented an actuated soft buckling mechanisms that can switch between two states under actuation [45]. Overvelde et al. designed a 3D metamaterial that can have multiple degrees of freedom [31]. Yang et al. 4D printed a lattice structure that changes shape under temperature change [44]. Besides the global shape reconfiguration, researchers have also investigated locally reprogrammable materials to offer more material configuration potentials. Chen et al. implemented metamaterials that can be locally reconfigured using a machine [3]. These actuated materials, however, offer limited capacity of shape change and complexity of movements. The robotic metamaterials I propose in this thesis offer high customizability and complexity of shape changing while being easy to reconfigure.

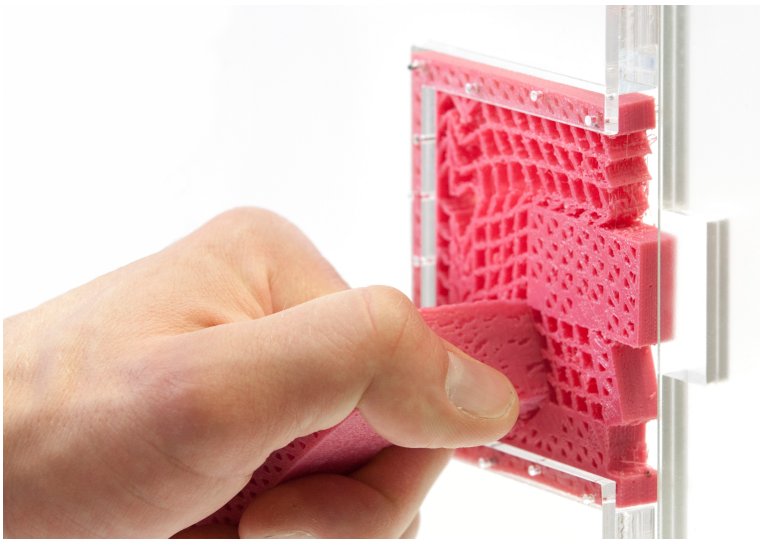


Figure 8: Metamaterials can employ mechanisms, transforming input movements into output movements [13].

4 Implementation: Active Cell

In the following, I describe the core piece of this robotic metamaterial: the active cell that is a modular actuator for this material. It employs pneumatic actuation and capacitive sensing for closed-loop control.

4.1 Pneumatic Actuation

The active cell employs pneumatic actuation. The working principle is shown in Figure 9 and inspired by prior work [13, 31]. The structure of the active cell is a shear cell, i.e., it can change its angle while the opposing members remain parallel. It is a mechanism with 1 degree of freedom. The air pockets for the pneumatic actuation are attached to adjacent corners. When a pocket inflates, the adjacent members are flattened out. To achieve this in both directions, I use 2 air pockets working in opposition within the shear cell.

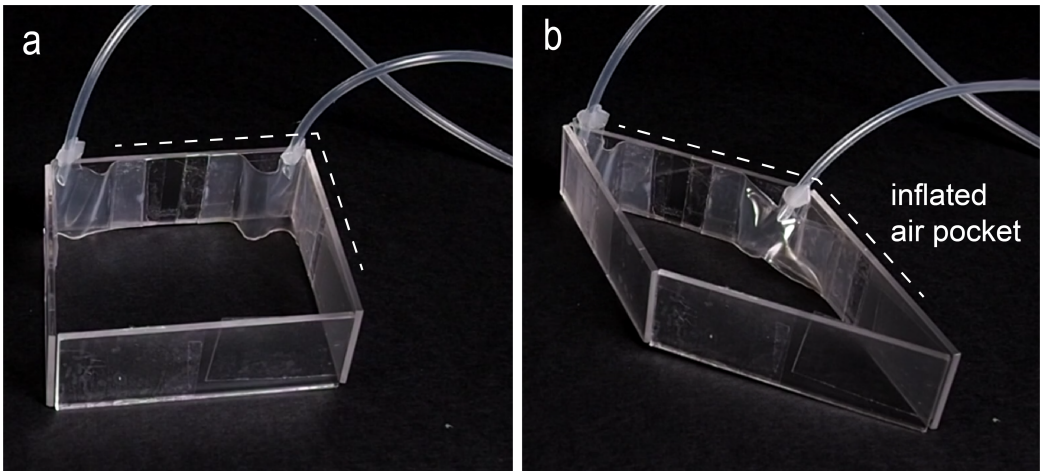


Figure 9: (a) The active cells are actuated by air pockets located in their corners, top left and right in this example. (b) As the air pocket inflates, the angle increases and the adjacent members flatten.

I opted for pneumatic actuation as it yields compliant actuation, making the material conformable and robust against potential impact. Furthermore, it is favored for its potential for miniaturization. While an air supply (e.g., a compressor) is needed, it does not have to be built into the material but can be supplied from a distance. I will elaborate on the ideas for miniaturization and mass-fabrication at the end of this thesis.

The air pockets in the active cell use materials used for inflatable packaging supplies, i.e., thin polyethylene sheets. The pockets are sealed using a laser cutter[5], as shown in Figure 10. The laser is defocused (cf. LaserOrigami [27]) to seal the edges of the pockets before cutting around their perimeter. The silicone tube is sealed into the bag by priming the tube with hot glue shortly before inserting it into the air bag.

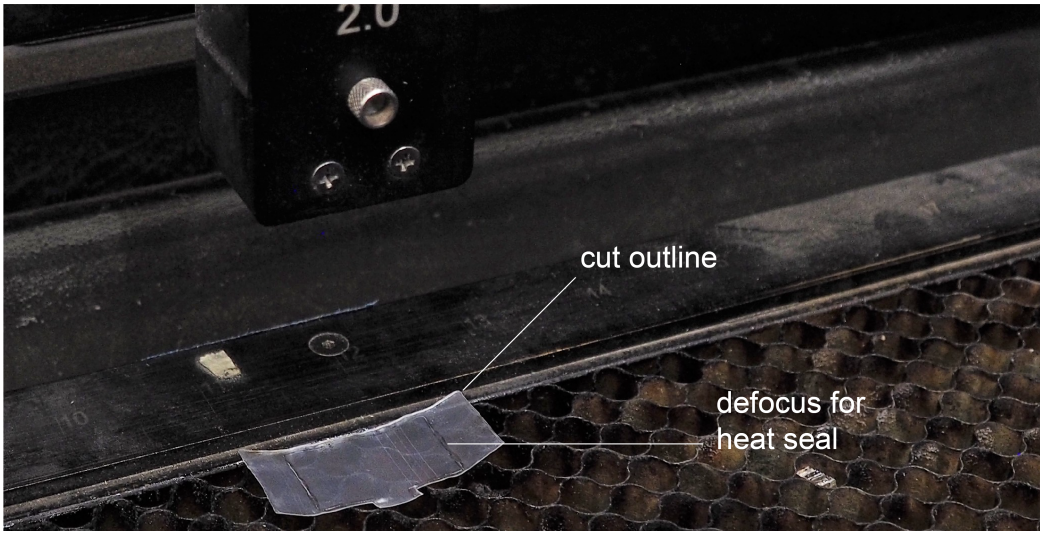


Figure 10: The air pockets are made using a laser cutter by defocusing the laser to achieve heat sealing. For cutting, I use power=37%, speed=18%, PPI=1000, Z=0.116 in; for sealing, I use power=42%, speed=100%, PPI=1000, Z=1 in on a Universal Laser Systems VLS 4.60 (30W CO2) cutter.

4.2 Capacitive Sensing

For reliable actuation, I implement angle sensing to enable closed-loop control. I opted for capacitive sensing as it has good potential for miniaturization and is well understood and robust [9]. I illustrate the novel compliant capacitive sensing geometry in Figure 11.

I did not employ air pressure sensors because the pressure values did not always reflect the mapped angle when the cell is under loads or external

[5]The air pockets were fabricated by Joanne Chin.

forces. I opted for cheaper capacitive sensing boards rather than the board in [6] to make the material more cost-effective. The MPR121 12 channel sensing chip used in the prototype system works well with the sensing geometry.

For many common sensor configurations, changes in angle between sensor elements leads to large changes in distance and produces orientations which make accurate measurement of capacitance difficult. Consider the case of 90°, where the sensing elements would be perpendicular and hence reliable reading nearly impossible. My objective is to find a suitable placement of the capacitive sensing elements that results in a reliable signal across all angle openings in the active shear cell.

We solve this problem by constructing sensor elements in the semi-oval shape shown earlier in Figure 11. This allows them to act as soft springs which maintain proximity throughout the deformation of the cell, but still change proximate area across the entire range of movement. Specifically, the presented capacitive sensor consists of two thin films. I apply copper tape on the inside of the film such that the film separates the sensing elements and acts as a thin dielectric spacer. As the angle of the cell at the sensed corner decreases, the copper sensors will be pushed close to each other, which increases the surface area in close proximity, causing a controlled and reliable change in capacitance across a usable measurement range.

The capacitive sensing technique effectively introduces a spring into the cell, which increases the resistance for actuation at the adjacent corner. As Figure 11 shows, I compensate for this added resistance by adding air pockets to both adjacent corners, which can be controlled by a single multi-way valve. The opposing corner is not affected, and actuation of one air pocket at a time remains sufficient.

Sensing calibration To calibrate the capacitive sensing, I record the capacitance values as I move the cell through predefined angles. I show the setup and results in Figure 12. A wooden handle is used for actuation to not disturb the signal. I model the capacitance value as a linear relationship with respect to the angle of the cell. A shorter form of this calibration is done once for each cell on 5 angles (60°to 120°in 15°increments) to compensate for differences in fabrication. The results in Figure 12 seem to suggest a flat logistic curve—which is expected based on the electrode deformations (see Figure 11)—but the cells are only operated within 60°to 120°, which falls within the linear region.

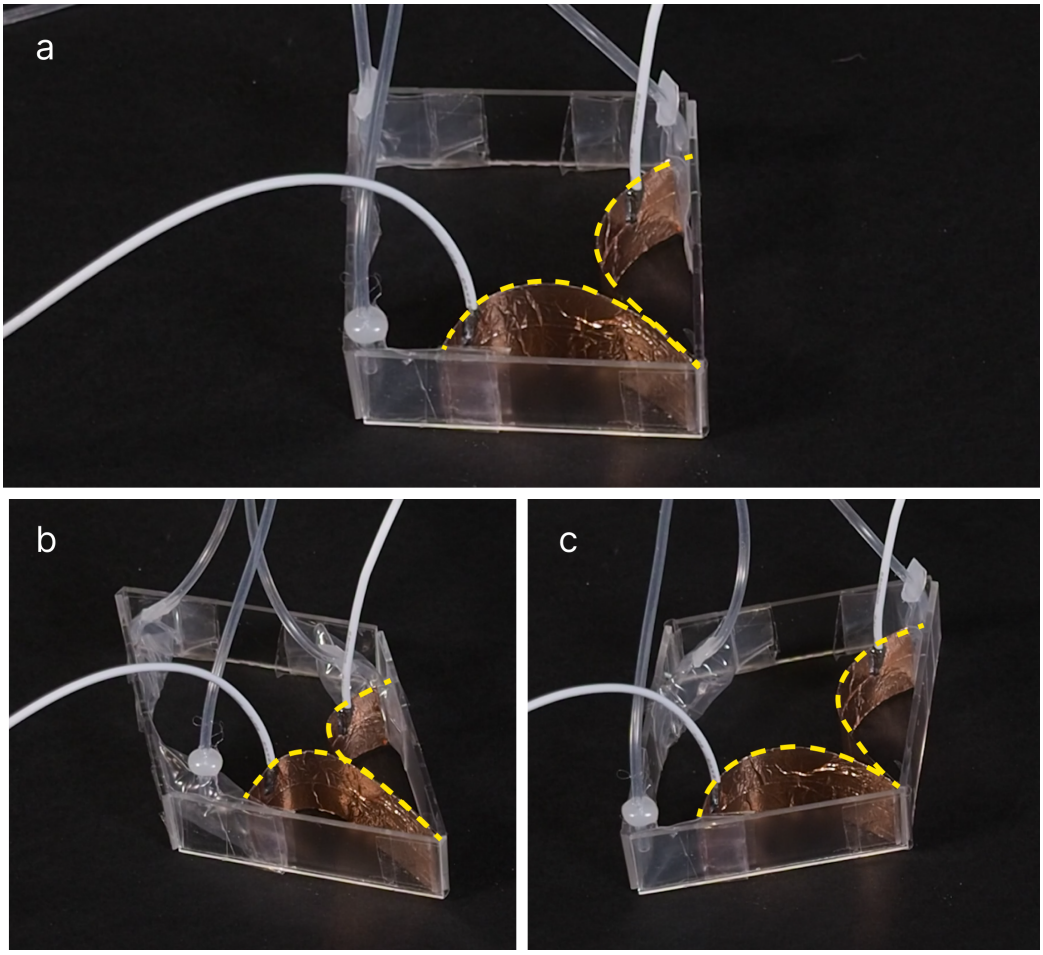


Figure 11: The capacitive sensing electrodes are placed in an semi-oval shape in one corner to sense actuation angle. In the (a) neutral (90°) position, the electrodes touch at their base resulting in capacitance value of 135 units as reported by the sensor. (b) As the angle decreases, the electrodes are pushed together resulting in a reading of 98 at 60°angle at the sensed corner. Conversely, (c) as the angle increases, the electrodes are separated and reliably read 172 units at 120°, providing sufficient dynamic range for robust sensing. These positions are the maximum and minimum that the air pockets can currently achieve.

My sensing technique works robustly in my prototypes with unshielded wires. In my experience, even noise in the signal caused by users' hands

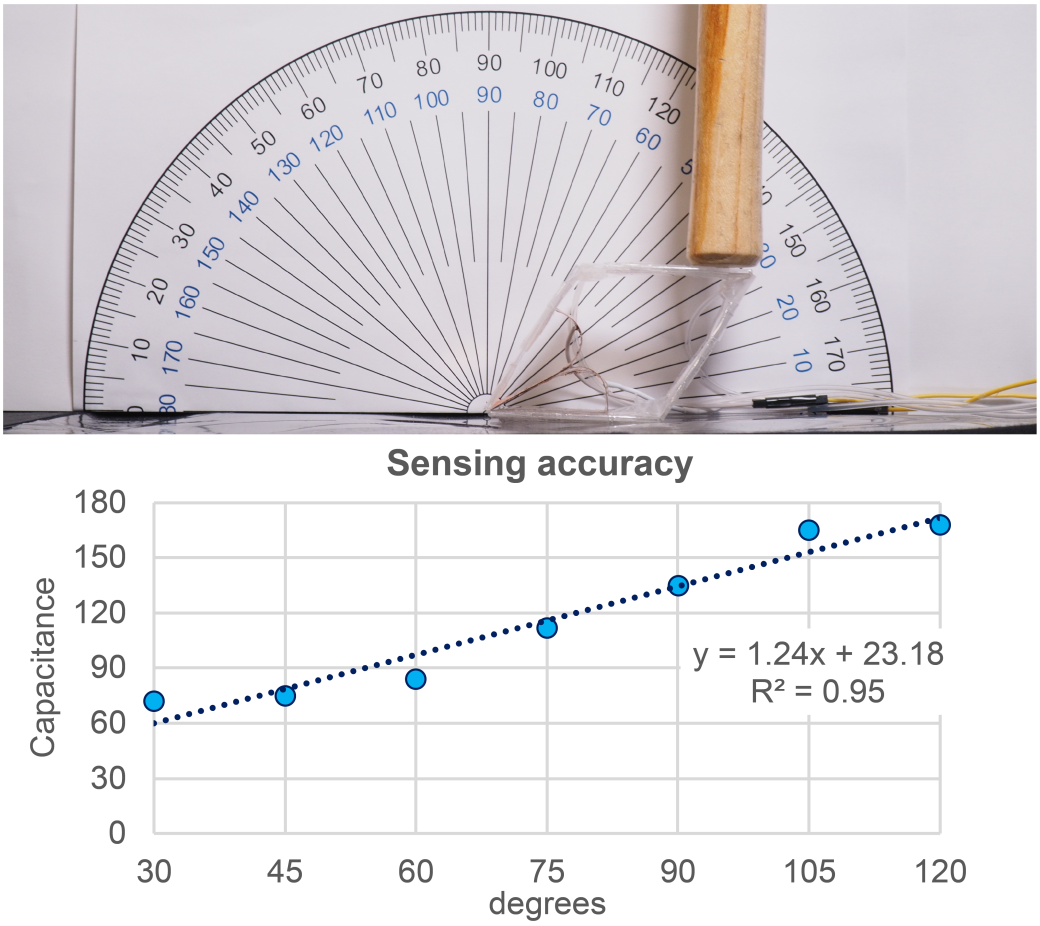


Figure 12: I record the capacitance values after moving the cell to a defined angle and use the linear relationship to model the angle sensing.

touching the wires will not cause significant fluctuation in the signal readings. I will show in Section 7 how users can move the active cell to record an input motion without disturbing the sensor readings.

4.3 Closed-loop Control

I use the capacitive sensor data to implement closed-loop control for the pneumatic actuation. Each active cell is controlled by 2 valves, i.e., one valve per actuated corner. I use simple 2-position 3-way solenoid valves in my prototypes (FA0520E). I implemented a PID (Proportional Integral

Derivative) control loop that uses the capacitive sensor data to drive the valve open/close states of the valve in a course PWM (Pulse Width Modulation) fashion.

The solenoid valves I used are digital with only open and closed states while the compressor is always on during the actuation. When the valve re-opens after closing, the higher pressure air that is introduced will be suddenly released and create shock, which would end up in a non-smooth, bumpy motion on the cell. To mitigate that, a pneumatic buffer (a small reservoir) is added in each feed line. This buffer, as shown in Figure 13, is a hollow ball (diameter 50 mm) in my prototypes. The buffer serves as a smoothing filter (much like a typical filter capacitor in an electrical circuit) and temporarily absorbs rapid changes in pressure, releasing them into the line over a slightly longer time period. The larger the ball, the larger the smoothing effect. This also creates small but manageable delays to inflation. The ball sizes and tube lengths are kept consistent across cells to allow synchronization of air travel.

To drive active cells, users connect the driver modules to the global power source (6V DC) and air supply (Master Airbrush Cool Runner II, 57psi compressor). An Arduino Mega drives the valves for each module based on the sensor data on the capacitive sensor boards (based on the MPR121 12 channel touch sensing chip). In my current prototypes, I need at most 10 psi from the air supply to drive the active cells effectively.

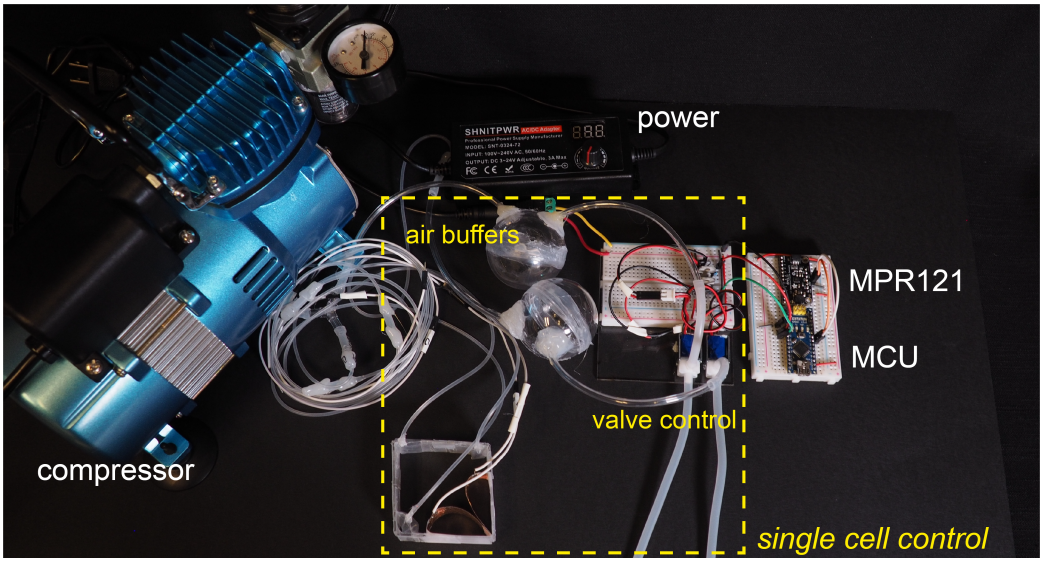


Figure 13: The entire circuit includes valves and air buffers for each active cell and shared power supply, compressor for air supply and microcontroller.

5 Technical Evaluation[6]

To characterize the active cell, three evaluations were performed to assess its actuation accuracy and performance under loads.

5.1 Actuation accuracy

In the first evaluation, the aim is to assess the actuation accuracy. The setup and results are shown in Figure 14. The movements of the active cell are video-taped as the cell is actuated to nine different angles, i.e., from 40°to 120°incrementing by 10°. The results show a relative error over all data points of 7.59% (SD=8.82%).

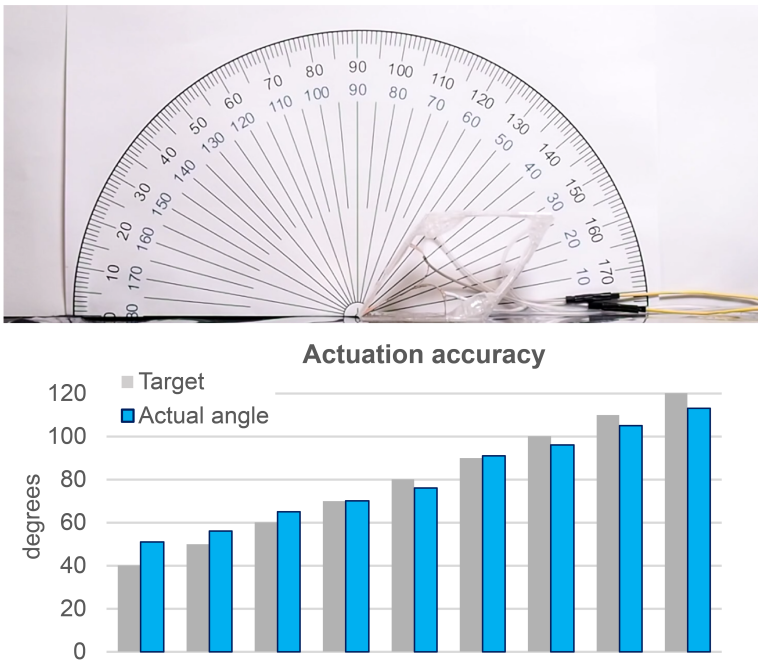


Figure 14: The actuation accuracy of the active cell is measured.

[6]In collaboration with Alan Zhu, Andy Kong.

5.2 Holding loads at an angle

To understand the performance of the cell under loads, weights were added on the cell after it reached the target angle unloaded, using the same setup was used as before. The results are shown in Figure 15. 5 different weights were used, from 20 g to 90 g. The cell had more difficulties holding its angle under load when it was closer to 90°, resulting in failed trials (i.e., oscillation around target angle resulting in dropped weights) for larger loads. This is likely due to each bag not being able to be inflated fully. The relative error is 3.52% (SD=4.45%).

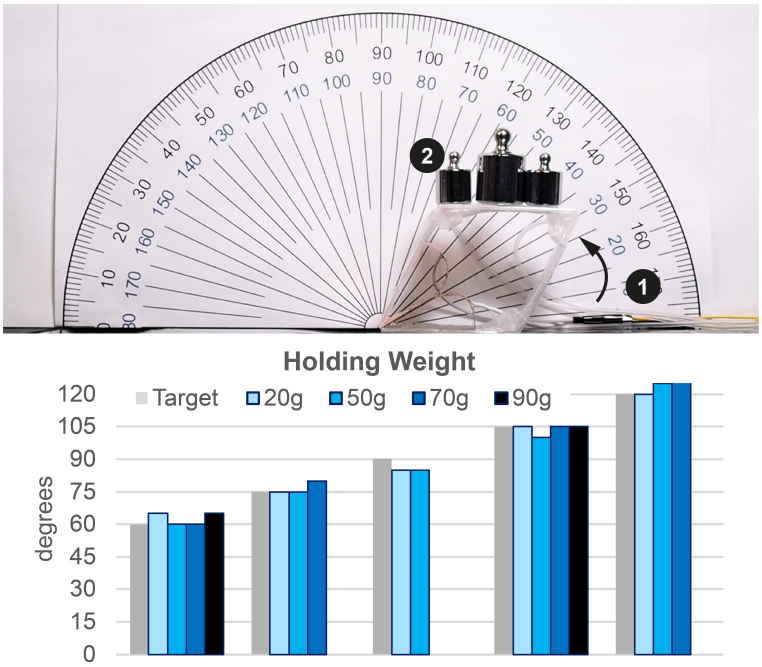


Figure 15: I measure performance under load, where the cell is actuated to the target angle unloaded and added weights at the target position. Missing data points indicate failed trials, discussed above.

5.3 Lifting loads to an angle

Lastly, the active cell's performance when lifting loads is characterized. The results are shown in Figure 16. In this setup, weights were added to the cell

first before the cell was actuated to its target angle. Similarly to the previous evaluation, actuation around 90°is more challenging compared to the more extreme angles. This can have implications, like trying to avoid dwelling on such angles, which could be implemented into computational design tools in the future. Lifting loads yields a relative error of 7.28% (SD=7.29%).

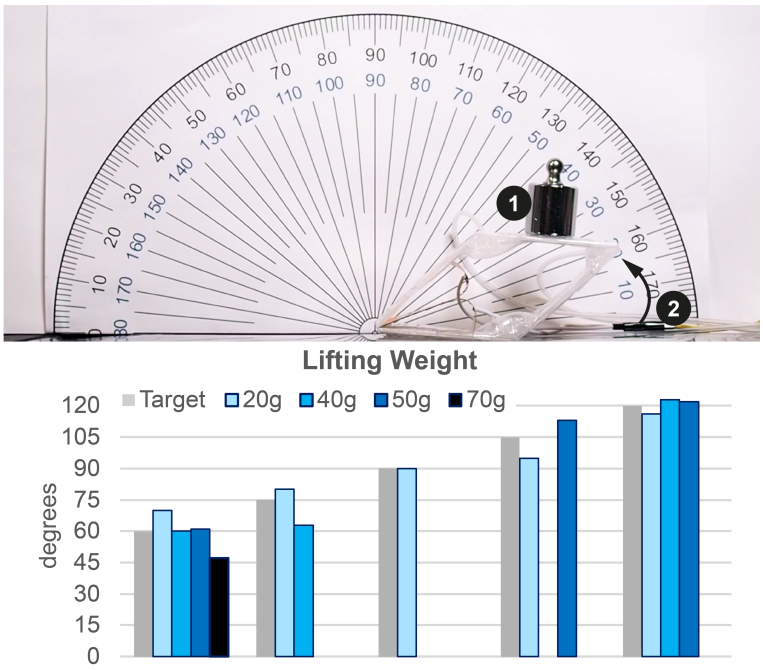


Figure 16: The performance of lifting loads to a target angle is measured.

6 Inverse Design Workflow[7]

To assist the cell configuration design of robotic metamaterials, I adopt an inverse design workflow using a software tool implemented by Alan Zhu. The tool builds on the algorithms proposed in [15]. As an example, in order to find a configuration for a 2×8 cell crawling robot, users need to specify the following parameters:

(1) Grid dimensions. First, users need to specify the number of rows and columns in the grid. In this case, the dimension is 2×8.

(2) Anchor points and vertices. Users specify the anchors that fixate the grid and vertices that trace out motion paths.

(3) Motion paths. Then, users need to draw the motion paths for the vertices to trace out.

(4) Accuracy and complexity. The path accuracy reflects the difference between the target path and the path that the current grid can achieve. The complexity of assembly is governed by the number of active cells to assemble into the physical grid. A lower number of active cells typically yields more rigid cells and lower path accuracy.

(4) The number of iterations. In general, the larger the grid, the larger the number of iterations. More iterations lead to a more optimal configuration, which also takes longer to run.

(5) Adding a ground in the visualization. Some applications such as the crawling robot need to interact with the ground. This option allows users to add a ground in the visualization. Note that the ground is only for visualization purposes as this tool only simulates kinematics.

(6) Simulation. After everything is specified, users run the tool to view the simulation (Figure 17). The simulation shows the rigid cell and active cell locations. The tool also outputs lists of angles for active cells, marked with cell numbers, shown in Figure 18a.

[7] In collaboration with Alan Zhu.

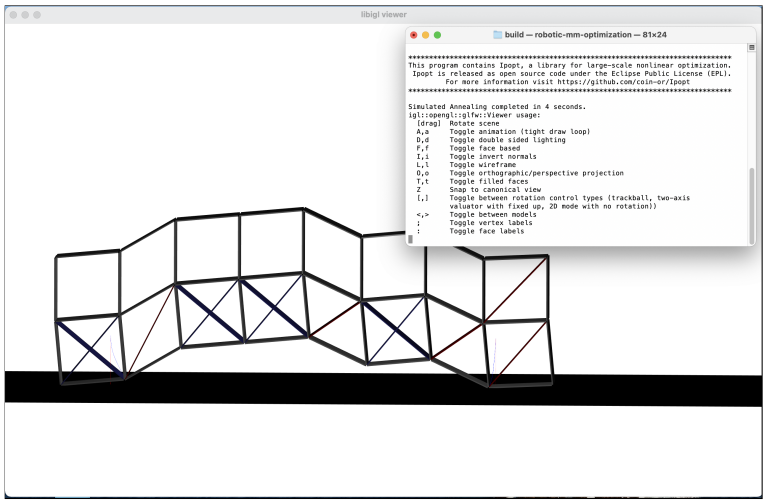


Figure 17: The simulation for the 2×8 crawling robot.

(7) Run the Arduino program with target angles. Finally, to test the configuration on physical prototypes, users place the active and rigid cells on the grid as suggested by the simulation. Then they transmit the angle lists (Figure 18a) to Arduino and actuate the active cells to the target angles (Figure 18b).

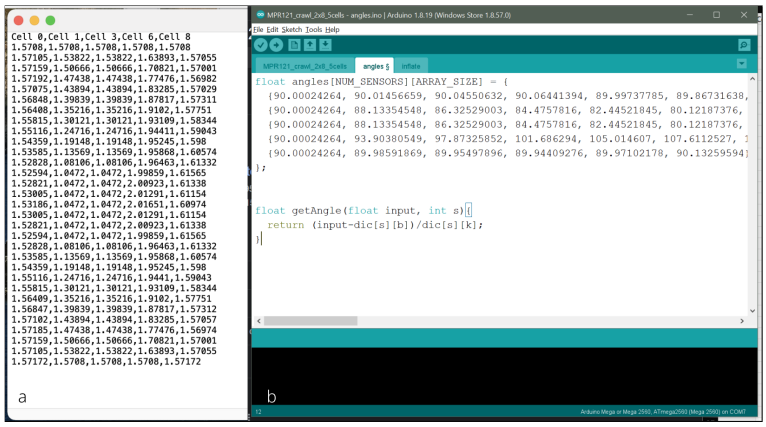


Figure 18: (a) The simulation outputs angle lists for active cells. (b) The lists will be read by Arduino to run the actuation.

7 Application Examples[8]

I illustrate how the robotic metamaterial can be configured to employ traditional robotic functions, act as an input device, and interact with the user. My prototypical implementations are designed to showcase the potential of such materials.

7.1 Locomotion robot

In Figure 19, I show how the robotic metamaterial platform can employ conventional robotic functions, specifically locomotion. The crawling robot uses only active cells due to the simplistic nature of the movement. In this example, I used only a single layer for the crawler and 3D print feet to clip on. This represents a small trade-off—it makes the material simpler, lowers assembly effort and reduces the number of actuators needed, but introduces a specialized part.

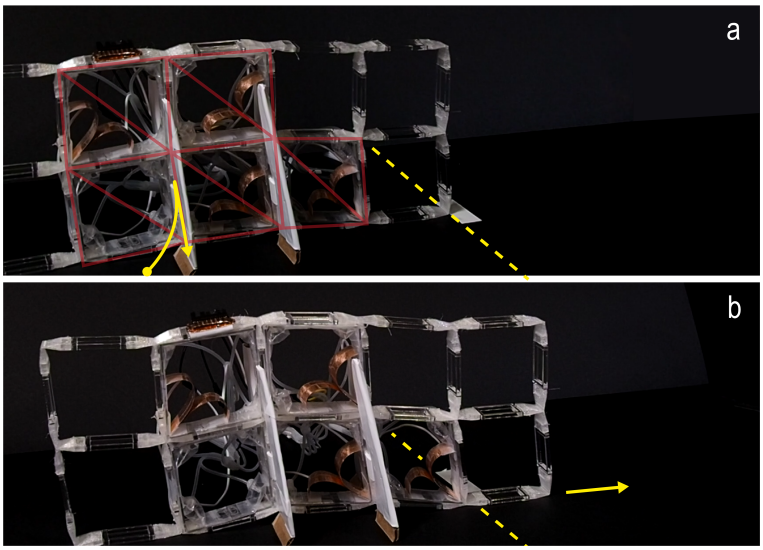


Figure 19: I show a compliant crawling robot made out of a 2×5 grid using only active cells (no rigid cells). Users clip on small legs to provide differential friction. The lifting motion and the locomotion direction are annotated in yellow and the active cells in a muted red.

[8]In collaboration with Joanne Chin, Alan Zhu, Ziyun Liu

7.2 Shape-changing installation

I explore how the robotic cells can be used for more artistic and organic applications. As shown in Figure 20a, a bird that can flap its wings is made from the robotic metamaterial[9]. Additionally, I explore how users can adopt my system as an input device. I show in Figure 20b how users move the cells manually to record the wing's motion. The screen in the background shows the real-time signal. The capacitive sensors are not disturbed by the proximity of the hands.

The fact that users can adopt the system as an input device showcases a forward design capacity of the material. The recorded sensed angles during users' experimentation can become the target angles for actuation that plays back users' input.

[9]The bird was designed by Joanne Chin

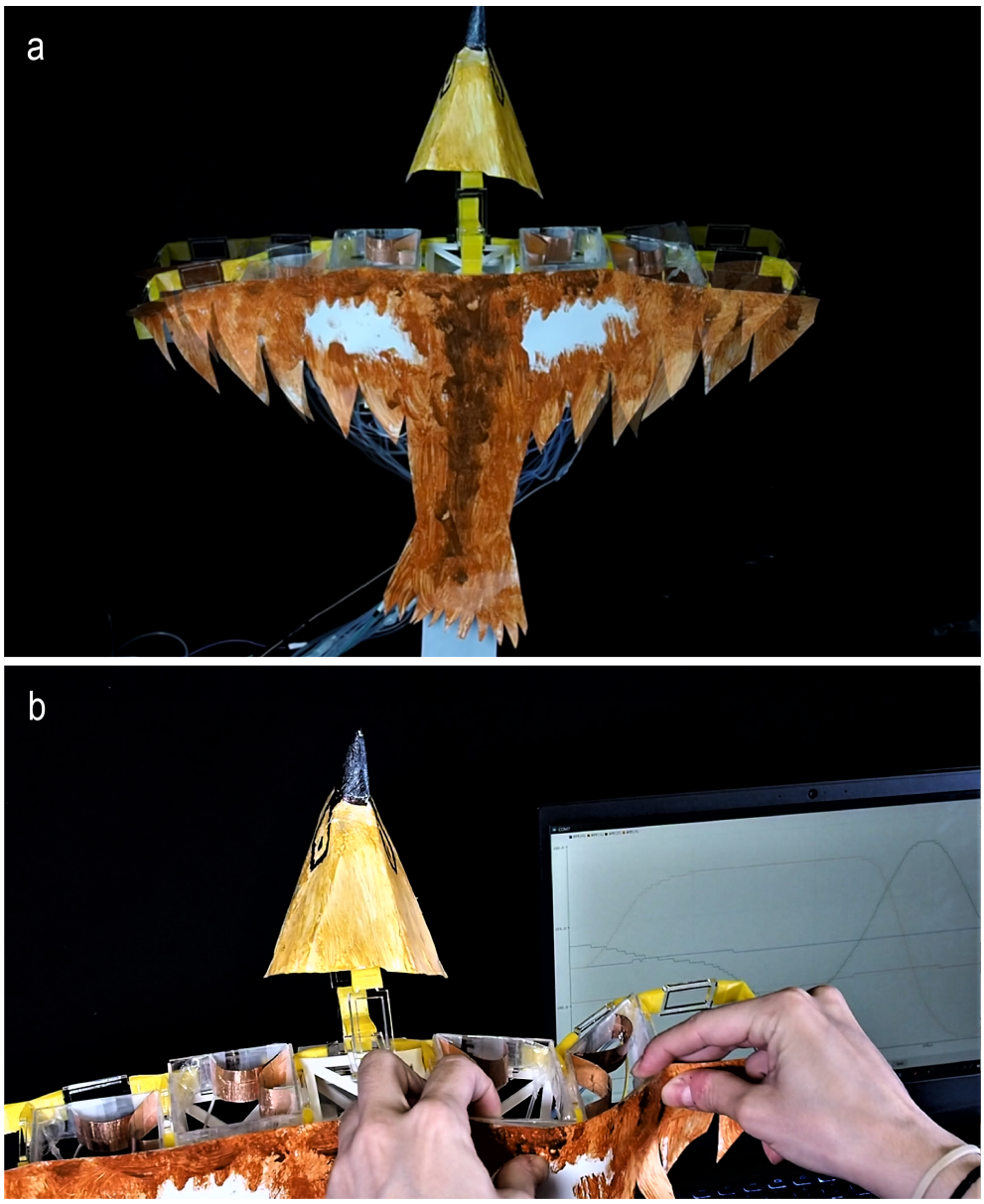


Figure 20: The robotic metamaterial platform can be used for actuated kinetic sculptures, (a) here a bird, and how the cells can also (b) serve as a platform for input.

7.3 Integrated desktop notifications

In this application example, I explore how such robotic metamaterials can interact with users. Figure 21 shows an example where the material is configured to wake users after a short power nap[10]. The material holds a simple end-effector at the bottom right corner, which taps the user's arm to wake them. It uses a combination of rigid and active cells to implement the motion across the 5×10 cell lattice.

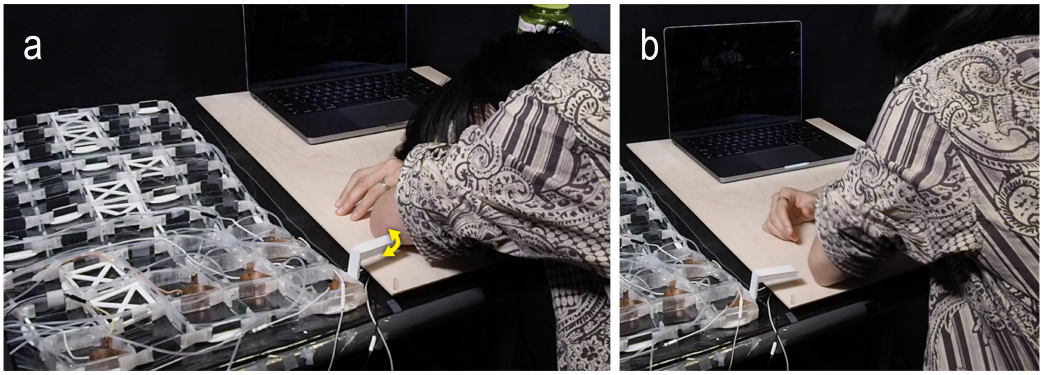


Figure 21: In this example, the material interacts with the user. It is designed to wake them after a power nap by tapping them on the arm.

The same material can be configured to perform another function shown in Figure 22, i.e., to remind them to drink water. This scenario illustrates how this material can be augmented with traditional mechanisms. I show a simple pulley-style system that is actuated by this metamaterial and connected with a string to a pendulum[11]. The pendulum provides visual notification by moving the blue indicator and audible signals by pinging the cup.

Note that I did not implement automatic triggers for my prototypes at this stage. Given the computer-controlled nature of my metamaterial, connecting the applications with a timer or calendar app would be trivial after enhancing my control circuit with wireless communication modules, e.g., Wifi or Bluetooth.

[10]In collaboration with Joanne Chin and Alan Zhu
[11]The pendulum was designed by Joanne Chin

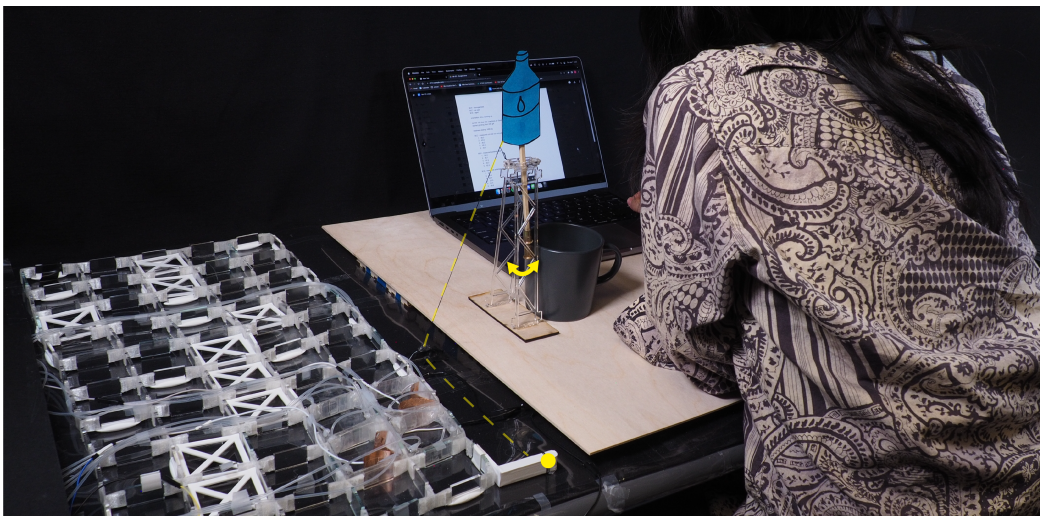


Figure 22: The robotic metamaterial can be augmented with traditional mechanisms for additional configurability. I show a pulley-style motion redirection from the integrated material to a user-designed desktop notifier to remind them to drink water.

8 Discussion & Limitations

The active cell design, the inverse design workflow, and the exploration of applications that I present in this thesis are an important contribution towards exploring robotic materials. The scope of this thesis yields limitations to the proposed systems and opportunities for future work.

My vision of achieving small scale, autonomous, robotic metamaterials has the potential to create complex robots from passive bulk material. One example could be a robot that is specifically made for disaster area exploration. It can be configured to walk, crawl, fold and roll through cavities, or even implement material properties such as damping. All these functions could be integrated into the passive material ad-hoc and controlled remotely.

I will discuss the next steps for this research agenda in the following.

Miniaturization To move closer towards robotic materials, I wish to miniaturize our design. Recent work showed fabrication techniques that build on lamination processes to create millimeter scale metamaterials [24] or robots [23]. The approaches are promising for our passive base structures.

Autonomous robotic metamaterials The challenging part to miniaturize is the active unit cell. However, I did design it with miniaturization potential in mind. The air pockets could be included in a layer-based lamination process, based on evidence on fabrication of small-scale pneumatic or hydraulic pockets [20]. Capacitive sensing lends itself well to miniaturization as it is used extensively in everyday mobile and wearable devices. The circuitry components and wiring can be integrated into the semi-rigid members during the layer-based fabrication process.

The most challenging components to integrate the valves and air supply. Here again recent work on layer-based valve systems [7, 33] point towards feasibility for mass-fabricatable, small-scale valves to integrate in this metamaterial. The last challenging component is the air supply. I plan to investigate distributed air buffers throughout the material such that they can store air with minimal leakage, which can then be distributed to the target cells using small-scale pumps (e.g., Piezoelectric Pumps[12]. In summary, the manufacturing of such small scale robotic metamaterials is not trivial, but

[12] `https://www.piezodata.com/precision-piezoelectric-air-pump/`

seems feasible. A draft design is shown in Figure 23[13] for a layer-based active cell that embeds valves and electronics.

3D robotic metamaterials The structures I investigate in this thesis are limited to 2-dimensional lattices. 3D bulk materials are beyond the scope of this thesis, and I wish to investigate them in the future. 3D structures would allow for more integrated and complex robotic materials. The configurability becomes an interesting challenge in that interior cells become difficult to reach to insert modules or connect tubing. One solution that comes to mind is to create *potentially* active cells everywhere and route the wiring and tubing towards the outsides of the bulk material.

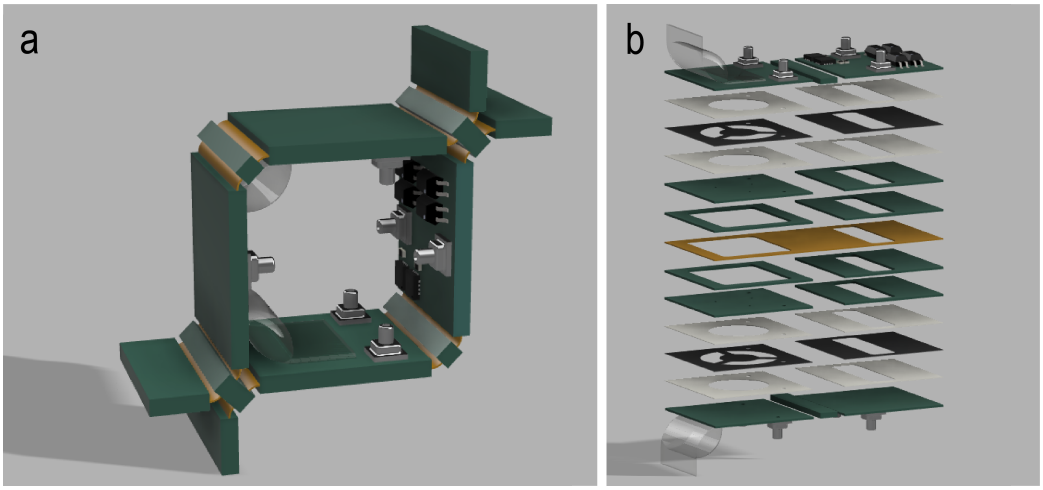


Figure 23: (a) The concept of an active cell sized at 20 mm and based on (b) layered construction.

Future robotic materials advanced by the potentials listed above can allow the material to perform more complex motions, be untethered and autonomous, and go beyond 2D sheets. I believe that the robotic metamaterials contribute to a more dynamic world that is shapeable by individual users. Empowered by such active materials, users can have the opportunity to redefine their relationship with the originally passive materials and objects.

[13]The visualization was created by Jesse T. Gonzalez

9 Conclusion

In this thesis, I presented a novel actuated material based on metamaterial mechanisms. The material can offer shape-changing and robotic capabilities and high customizability, while being modular. I demonstrated its potential by illustrating distinct application scenarios, including a crawling robot, a bird-themed kinetic sculpture, and a desktop ambient notification systems that can be integrated into the desk. I believe that this material presents a first step towards user-configurable complex robotic materials. In the future, I seek to expand from the 2D grid to a 3D space and allow more sophisticated actuation and deformation. I also aim to miniaturize the fabrication and explore how users can configure systems with hundreds or thousands of cells.

Collaborator acknowledgements

I would not be able to cover all the aspects this thesis has now without contributions from my collaborators and important unofficial advisors.

I would love to give huge thanks to Alan Zhu for implementing the algorithm and CLI of the optimization tool and all his proactive efforts in conducting evaluations and building applications. I am also feeling extremely lucky to have Joanne Chin to help with the material element design, sensor element fabrication, and application building. Her creativity has added a lot to the applications. I'm also really grateful for having Ziyun Liu in dividing the workload of sensor fabrication with me, which would have been impossible for me alone. Lots of thanks to Andy Kong for helping with the cell evaluation and Jesse Gonzalez for his visualization of the miniaturized active cells.

I am also extremely fortunate to work with Professor Scott Hudson. Scott has been highly knowledgeable in sensing and actuation and has given me a lot of guidance that unstuck me.

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