Sparsely Actuated Modular Metamaterials for Shape Changing Interfaces

Ata Otaran*
Saarland University, Saarland Informatics Campus
Saarbrücken, Germany
otaran@cs.uni-saarland.de

Yu Jiang*
Saarland University, Saarland Informatics Campus
Saarbrücken, Germany
yjiang@cs.uni-saarland.de

Jürgen Steimle*
Saarland University, Saarland Informatics Campus
Saarbrücken, Germany
steimle@cs.uni-saarland.de

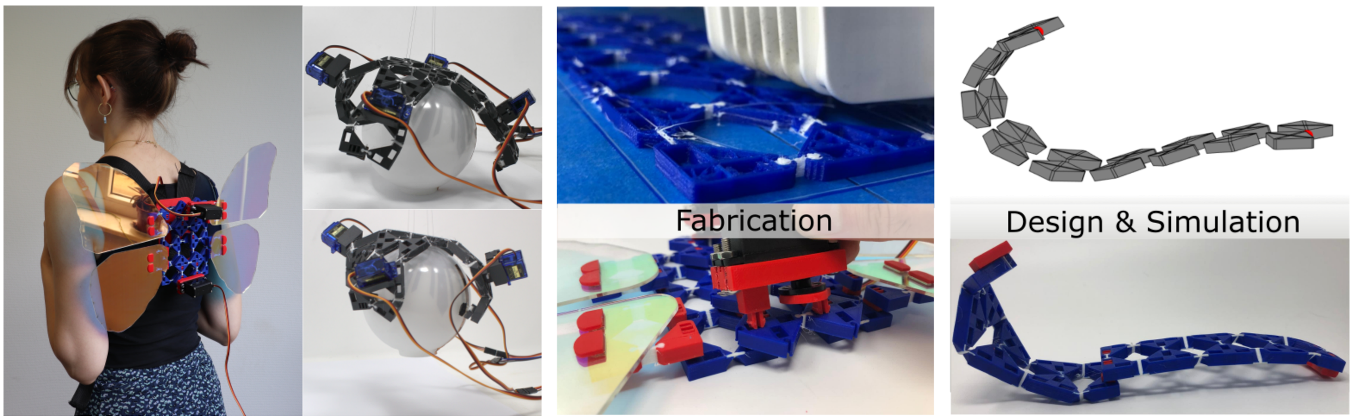

Figure 1: Nature-inspired sparsely actuated metamaterial structures for achieving versatile shape-changing interfaces: implemented example applications (left), fabrication with 3D printing and modular assembly (middle) and a sample instance of a simulated and fabricated deformed interface (right).

Abstract

In the realm of Human-Computer Interaction, the design of physical user interfaces with nature-like movement patterns holds promise for enhancing user experience. A significant factor that affects the functionality and movement properties of natural systems is the specific combination of rigid and flexible elements. While higher rigidity increases stability and dexterity, higher flexibility augments complex curvilinear movements. However, current design tools for shape-changing interfaces do not provide control over the interface flexibility at the design stage. We leverage mechanical metamaterial designs with programmable deformation patterns and implement sparse actuation to afford enhanced shape control and versatility. We present a dedicated design and simulation tool to aid designers in visualizing, customizing, and iteratively refining their shape-changing interfaces. We provide guidelines for the fabrication and post-fabrication customization of the interfaces with modular add-ons, which can augment actuation or combine separate physical structures. We demonstrate the versatility of the approach through various nature-inspired applications.

TEI '25, March 4–7, 2025, Bordeaux / Talence, France

ACM ISBN 979-8-4007-1197-8/25/03
https://doi.org/10.1145/3689050.3704942

Keywords

Metamaterials; shape-change; actuation; 3D printing.

ACM Reference Format:
Ata Otaran, Yu Jiang, and Jürgen Steimle. 2025. Sparsely Actuated Modular Metamaterials for Shape Changing Interfaces. In *Nineteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '25), March 4–7, 2025, Bordeaux / Talence, France.* ACM, New York, NY, USA, 12 pages. https://doi.org/10.1145/3689050.3704942

1 Introduction

Flexible structures enable complex and nature-like shape-changing interfaces [27, 41] that make interactions more versatile and engaging [8] compared to fully rigid interfaces. With the increased accessibility of fabrication methods and materials, the fabrication of custom flexible shape-changing interfaces has become more accessible and relevant to HCI research [33, 40]. Flexible shape-changing interfaces are emerging as a significant interest within HCI, despite the challenges in designing these soft structures. Various toolboxes have been developed for creating various flexible interfaces made of plastic polymers [15, 26, 35, 42, 48] and textiles [1, 17, 24, 25]. Presented tools provide building blocks for design but lack insight into how the degree of internal flexibility of the interface affects the resulting interface deformations.

In this work, we present a toolbox for generating and controlling sparsely actuated shape-changing interfaces with adjustable internal flexibility made of mechanical metamaterial. Our toolbox enables designers to explore various design parameters: joint kinematics, internal flexibility, and actuator configurations. Designers can iteratively refine their models through reconfiguration and simulation cycles while discovering new opportunities along the process.

We propose configuring the internal flexibility of the metamaterial structures by controlling the size of their flexible joints and driving the structure with locally attached servo motors. Metamaterial structures are repeated cell structures, arranged in a grid or lattice form. They can be programmed to exhibit specific deformation patterns by configuring their individual cell structures. Due to the repeated cell structure of metamaterials, their joints are distributed across their structure. Therefore, interface flexibility can be locally controlled across the structure through individual joints. We build on single-degree-of-freedom mechanisms presented by Ou et al. [34] whose cells can be configured to exhibit different movements such as shearing, out-of-plane bending, or twisting. The increased joint flexibility allows movements in higher degrees of freedom. This allows the actuation of the shape-changing interface using sparsely placed servo motors. Using multiple actuators that are placed away from each other can cause local deformations, thereby increasing the versatility and complexity of the shapes that can be achieved.

The proposed shape-changing interfaces entail two main design challenges: First, designing the metamaterial structure to exhibit the desired global deformation requires kinematic understanding and computation for each cell mechanism. We propose a visual design approach to automatically assign cell configurations for a user-defined global deformation. The second challenge is predicting the effect of joint flexibility and sparse actuation (location and magnitude) on the deformation patterns in real-time. To tackle this problem, we implement a simplified energy minimization method for fast estimation of the movement of the shape-changing interface for given joint flexibility and sparse actuation configurations. This allows users to iteratively change and test their designs at runtime.

The presented metamaterial structures are fabricated in a single printing pass using a dual-material 3D printer. The presented designs, exemplified in Figure 1, allow customization of the interfaces with modular add-ons which can be plugged across all cells for augmenting actuation or combining separate physical structures. This enables designers to experiment with different sparse actuation strategies and add further functionalities even after the fabrication. The modular design also enables reusing structures in different combinations for sustainability and scaling the designs beyond the size of the print bed of the 3D printer. We provide guidelines for the fabrication and post-fabrication customization of the interfaces. We demonstrate the practical feasibility of the generated models with a set of implemented nature-inspired application examples.

In summary, the main contributions of this paper are the following:

- We introduce metamaterial structures with adjustable internal flexibility that are controlled by sparse actuation for building novel interactive shape-changing devices.
- We develop a custom design and simulation tool for supporting the iterative design process of the presented interfaces *before fabrication.*
- We provide guidance on the fabrication and present a set of modules for customizing the metamaterial shape change and interactive capabilities *after fabrication.*

2 Related Work

Our research builds on prior work on shape-changing interfaces, mechanical metamaterials and compliant interface design and simulation.

2.1 Shape-changing interfaces

Shape-changing interfaces are a diverse class of interfaces that use various actuation techniques to display a physical shape [3]. Such physical shapes produce strong and expressive visual and haptic feedback to the users, beneficial for tangible interaction. A diverse set of mechanisms and actuation methods for shape-changing interfaces have been demonstrated. For example, desktop-based 2.5D shape change interfaces that change surface topologies were presented using pin-based methods [12, 14, 22, 43] where each pin is raised off the horizontal surface by a motor such that a global shape can be generated by a layout of individually actuated pins. These are generally stationary systems, as they require large space for their actuators, and tend to be energy-intensive.

More portable approaches use motor-embedded modular blocks to achieve shape changes and even locomotion in 3D. For example, LineForm [32] and ChainForm [31] offer linear and modular interactive interfaces driven by identical modules capable of sensing and actuation. Such modular approaches improve the scalability of the interface. Linkage-based [9, 47] shape-changing systems have also been demonstrated to achieve diverse shape changes with only one motor or the user's manual input.

However, these shape-changing systems are composed of potentially complex mechanical structures that require assembly. On the other hand, metamaterials recently emerged as shape-changing interfaces that can be fabricated in one go to reduce prototyping effort when creating shape-changing systems. In this paper, we thus explore expanding the shape-changing capabilities of metamaterial structures to demonstrate shape-changing interfaces that are easy to fabricate and can achieve complex curvilinear shapes.

2.2 Mechanical metamaterial structures

Mechanical metamaterials refer to structures whose deformation patterns rely on the arrangement of their interior cell structure rather than the specific material they are made of [6]. Diverse macroscopic behaviors can be achieved by programming the combination of the cell structures. Based on this, past works have demonstrated materials with unique properties or realized certain pre-defined functions that traditional materials cannot achieve. These include auxetic materials that expand in the other direction when stretched [2, 29], locally programmable stiffness in one printed object [38], computational materials that execute logic functions [21, 23, 45], or programming deformation behaviors [7, 13].

Mechanical metamaterials have recently attracted attention in the HCI community as a valuable resource for building shape-changing interfaces through preprogramming the shape change induced by the deformation in the structure. Ion et al. presented a method for controlling the degrees of freedom of a grid structure by selectively constraining its cells [19, 20]. The presented structures have a controllable amount of independent degrees of freedom to achieve a user-defined movement pattern. A recent work presented a pneumatically actuated version of these metamaterial designs [10]. These works focus on planar grid structures that are modeled to have an integer number of unconstrained degrees of freedom. Ou et al. [34] presented a single degree of freedom mechanical metamaterials based on the well-known rotating squares paradigm. They present designs that can perform versatile deformations such as out-of-plane bending, shearing, and twisting which are achieved by changing the joint locations and orientations in the cell structure. Our work uses designs presented by Ou et al. but further explores controlling the cells' internal flexibility to expand the achievable shape space. We achieve this by fabricating the links in the metamaterials with long and flexible material, then control the localized deformation with sparsely placed actuators. Our designs are considered multiple degrees of freedom because of the added joint flexibility rather than unconstrained degrees of freedom.

Accompanying the presented metamaterial-based shape-changing structures, design tools have been developed to support the customization of the shape change. Kulkarni et al. [28] built a design tool that automatically generates custom wrist exoskeletons fitting the user's body measurements. Our cell configuration tool, although using a different strategy, also computes cell configurations from user-given shape input. Our design tool goes beyond solving the rigid body kinematics of the metamaterial structure and further includes user decisions on interface flexibility and actuator locations for the simulation of the interface.

2.3 Flexibility and sparse actuation

The use of flexible joints instead of rigid hinges has been a common method in mass production. As the availability of elastic materials increased, making custom designs with flexible hinges became much easier. In this paper, flexibility and sparse actuation are concepts that essentially go hand in hand. Flexible materials settle at configurations that minimize their elastic energy. This causes the effect of deformations induced by actuators to stay local, as propagating these deformations would mean higher elastic energy. Sparse actuation refers to placing actuators at far enough locations such that the resulting shape of the interface is caused by the localized contribution of a few actuators. This is similar to how several muscles affect one elastic medium at separate locations in nature (e.g., tongue, elephant trunk).

Designing flexible systems is challenging due to the complexity of predicting their movement trajectories. Many researchers presented toolboxes to aid designers in using flexible sections [30, 36, 46]. Various finite element-based methods and tools exist for simulating the motion of thin and flexible strand-like structures [4, 5, 36, 44, 49]. Building onto these models, researchers have developed computational tools for working with deployable grid shells [37], stretched fabric and 3D print combination interface [39]. Relatively faster methods include pseudo rigid body models [18] which discretizes the beam structure even less than the Cosserat rod-based models. Panetta et al. built an optimization algorithm for the location of sparse actuation in grid shell structures and Megaro et al. [30] optimized the flexible structure to meet actuator requirements and avoid material failure. The discrete rod models offer a realistic simulation opportunity, however, they need to minimize an elastic energy function, which poses a highly nonlinear optimization problem that is not fast and stable enough for our purposes. In this work, we find it crucial to enable fast and easy iterations when designing with our metamaterials. Therefore we implemented a simplified elastic energy function which can be solved at one iteration using a Newton Method-based solver. Our algorithm can give the designer immediate visual feedback after configuration.

3 Concept

Our approach enables designers to implement multiple degrees of freedom movement by sparsely actuating 3D printed metamaterial structures. The three novel factors in our approach are: 1) we sparsely actuate a layout of locally deforming metamaterial cells to achieve more complex curvilinear shape-changing behaviors, 2) we provide a design and simulation tool that helps with designing and fabricating such sparsely actuated metamaterials, and 3) we realize shape-changing interfaces based on such metamaterials that

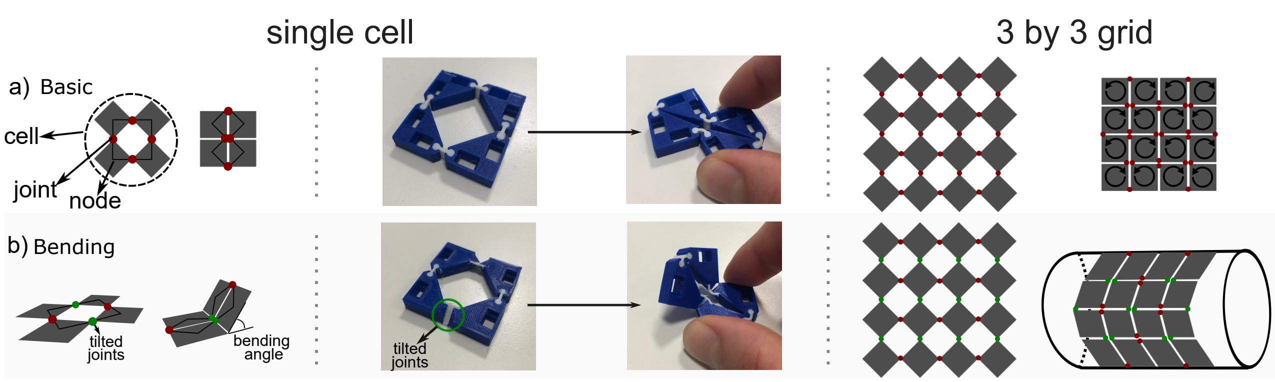

Figure 2: Deformation profiles of the cell structures used utilized for generating the metamaterial base structure. Left: deformation at the cell level; right: macroscopic deformation of a 3 by 3 grid of cells. Non-tilted joints (red) have a rotation axis that is aligned with the surface normal, thus allowing only planar movements. Tilted joints (green) have a rotation axis away from the surface normal, therefore causing out-of-plane bending movements.

can be further reconfigured with a set of pluggable modules to enhance the functionality and customizability. In this section, we describe the basic properties of the primitive cells that constitute the shape-changing structure, and our proposed sparse actuation method.

3.1 Sparsely actuated and locally deforming metamaterials

We base our unit cell designs on Ou et al.'s work which presented cells that contract in-plane and bend out-of-plane when deformed [34]. While Ou et al. used rigid joints that propagate the deformation along the cells, we take a different approach and deliberately use long and flexible hinges. Figure 2 showcases our basic *contracting cells* and *bending cells*. The contracting cells 'close up' linearly when deformed and the bending cells bend out-of-plane by an angle determined by how much the joint is tilted. The long and flexible hinges deform when the cell is deformed, propagating much less deformation to its neighboring cells thus keeping the deformation largely local.

These cells can be flexibly tiled in 1D or 2D, forming, for example, a linear chain, a rectangular grid, or a branched-out structure. This creates a layout in which actuating one cell would only deform its close neighbors. Based on this, we propose to put a small number of actuators within such a layout and at a distance to each other to *sparsely actuate* the metamaterials. The actuators can create local and non-interfering movement patterns which together achieve a global shape change. The flexibility in defining the local deformation and orchestrating the actuation patterns enables complex curvilinear shape-changing behaviors. We demonstrate one such example in Figure 3. The sparsely placed actuators at the left and the right ends can work either in sync or with the same amount of actuation (Figure 3-a) to create a shape that is close to the 1 DOF movement of the base metamaterial structure. Or they can be out of sync and with different amounts of deformation to create movement patterns that expand the shape space, (Figure 3-b and c). Through sparse actuation, complex moving wave patterns can be achieved by moving the motors in basic dynamical motion profiles.

The cell layout can be entirely 3D printed with dual material printing - we printed the rigid parts with PLA or ABS and the flexible hinges with TPU materials.

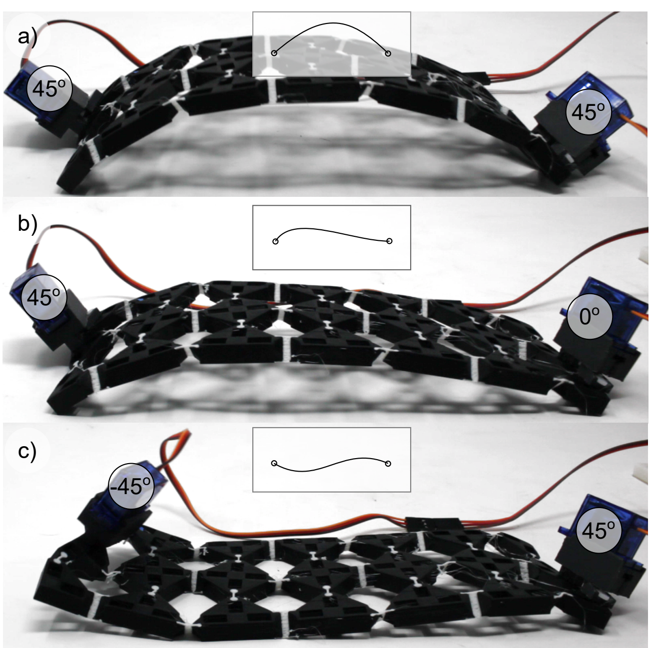

Figure 3: A metamaterial base driven by two motors, showing three different instances of achievable shapes. Degrees written over the motors show the amount of deformation introduced by the specific motor.

3.2 Design and simulation

In this section, we explain how we model the metamaterial structure for the fast estimation of its movements given specified joint flexibilities and actuation amounts.

Every cell is made up of nodes and joints depending on their location in the cell layout. As exemplified in Figure 4, we denote the nodes with the letter N and group the joints into vertical and horizontal joints based on their direction in the original state, and denote them as V and H respectively. Subscript i and j refer to the vertical and horizontal locations of the nodes and joints. Horizontal edge with the subscripts i,j, $H_{i,j}$, combines, $N_{i,j}$ and $N_{i,j+1}$ whereas the vertical edge, $V_{i,j}$, combines $N_{i,j}$ and $N_{i+1,j}$. Every joint is associated with two nodes. Every node is associated with from 2 to 4 joints.

We simplify the movement of all nodes by attaching them a deformation parameter, $D_{N_{i,j}}$, which is in the range of 1 and -1. By this parametrization, the deformation of 0 refers to the original alignment of nodes, whereas 1 and -1 refer to their maximum amount of deformation in either direction.

As shown in Figure 4, the same amount of deformation refers to the rotation in opposite directions for neighboring nodes, which is a requirement of the rotating squares kinematic structure. Nodes whose subscripts add up to an even value rotate on the counter-clockwise direction for deformation of 1 and those that add up to an odd value rotate on the clockwise direction.

The joints force the nodes to follow the kinematic requirements of the structure while also tending to spring back to their undeformed state due to their elasticity. The distribution of the cell deformations is done by minimizing the elastic energy function of the structure. In this work, we defined a simplified energy function that allows designers to quickly simulate the cell deformations.

We define a per-joint energy function as:

$$E_{joint} = (k_1 * (D_{N_1} - D_{N_2})^2 + (1 - k_1) * (D_{N_1}^2 + D_{N_2}^2)) * k_2 \quad (1)$$

where D_{N_1} and D_{N_2} refer to the deformation amounts of the two nodes that share the specific joint. The k_1 parameter is associated with joint flexible length and k_2 is associated with joint thickness. According to Equation 1, having a k_1 value of 1 at a joint refers to completely stiff connections. In this case, deformation at one joint is perfectly propagated to all of the joints regardless of the k_2 values. As the value of k_1 decreases, the per-joint energy function depends more on the individual deformation amounts of nodes.

The total elastic energy function is computed by summing up the energies of all vertical and horizontal joints. Equation 2 shows the computation of the entire energy function. The resulting energy function is a second-degree polynomial function of the deformation amounts of each node:

$$E = \Sigma E_{H_{i,j}} + \Sigma E_{V_{i,j}} \tag{2}$$

The k_1 and k_2 values corresponding to a joint size were found through an empirical evaluation. For this, we printed a set of layouts and defined deformations between nodes with the angular constraints shown in Figure 5. We then computed the best-fitting k values for the given sizes of the flexible joints.

We compute the gradient and Hessian terms for the overall energy function. Due to the nature of the simplified elastic energy function, Equation 1, the Hessian matrix is constant and does not rely on any deformation terms. Therefore the computation of the deformation terms that minimize the energy function are computed at one step, providing a very fast estimation method for the exploration of available shapes.

Placing an actuator on a joint, between two nodes causes that joint to be overridden by the actuator. The deformation amounts of these nodes, therefore, are decided by the actuator. The Newton method minimizes the energy function for the remainder of the nodes that are not overridden by any actuator. Using this method the designer can quickly go through deformation patterns, caused by the specific set of joint flexibilities and actuation amounts.

3.3 Physical design

Following the fabrication of the metamaterial structure, we propose a physical design stage where the user can easily reconfigure the positions of the sparse actuation to try different shape-changing effects.

We designed the structure such that motors can be easily snapped between the nodes. The physical modular connectivity across all nodes of the metamaterial design allows the designer to physically reconfigure the shape change after fabrication by changing the actuator locations. We also provide additional modules for further customization and scaling of the interface. We provide more details on the physical fabrication and post-fabrication modular design procedure in Section 5.

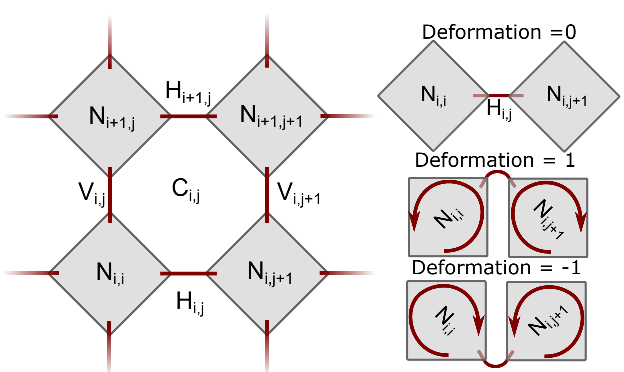

Figure 4: Left: Node and joint naming convention, Right: deformation amount parametrization.

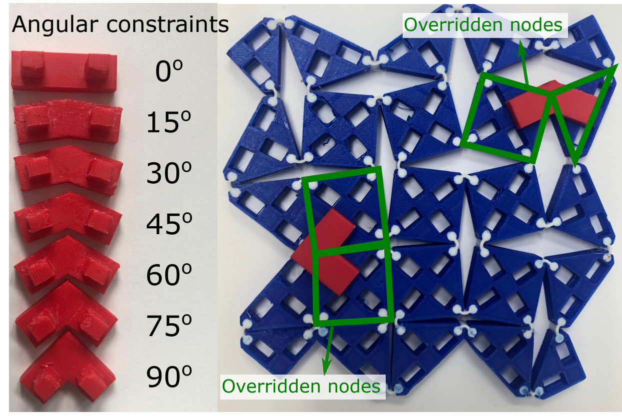

Figure 5: Angular constraints prepared for estimating the coefficients of the simplified energy function

4 Digital design and simulation

Designing sparsely actuated meta-material structures is challenging due to both the complexity of the metamaterial kinematics and flexible joint movement. In this section, we present a walkthrough of the design and simulation tool. We specifically use the swimming fish application example in Section 6 to facilitate a better understanding of the design and simulation stages.

The design and simulation tool offers the user the ability to visually configure the cell parameters (bending locations, bending amounts and structural flexibility), to place servo motors in desired locations, and to simulate the deformation of the structure with the given actuation amounts. The tool is implemented in Matlab and uses efficient algorithms to update visual feedback so that the user can iterate on their design in real-time.

4.1 Designing the metamaterial structure

We used a combined bottom-up and top-down approach. The user defines the number of cells and how they will be placed in the open/flat state. They then define the most actuated shape they would like to achieve. The design tool automatically configures the detailed cell parameters based on the input shape.

In the enumerated list below, we present the design pipeline step by step. Figure 6 demonstrates the main design stages and UI elements for the sample fish application.

(1) **Lay out the grid-like or branched metamaterial structure:** The user creates the desired cell layout by clicking on the button grid, shown in Figure 6-a. The selected cell layout is shown in blue and displayed on the simulation screen after pressing the "Set Structure" button. The cell layout does not have to be a rectangular grid, but every active cell should have at least one neighbor and a closed contour inside the structure should not be created. For the swimming fish example, we define this as a rectangular layout.

(2) **Define the rotary axes:** Once the overall layout is decided, users provide the axes of deformation. Setting the structure

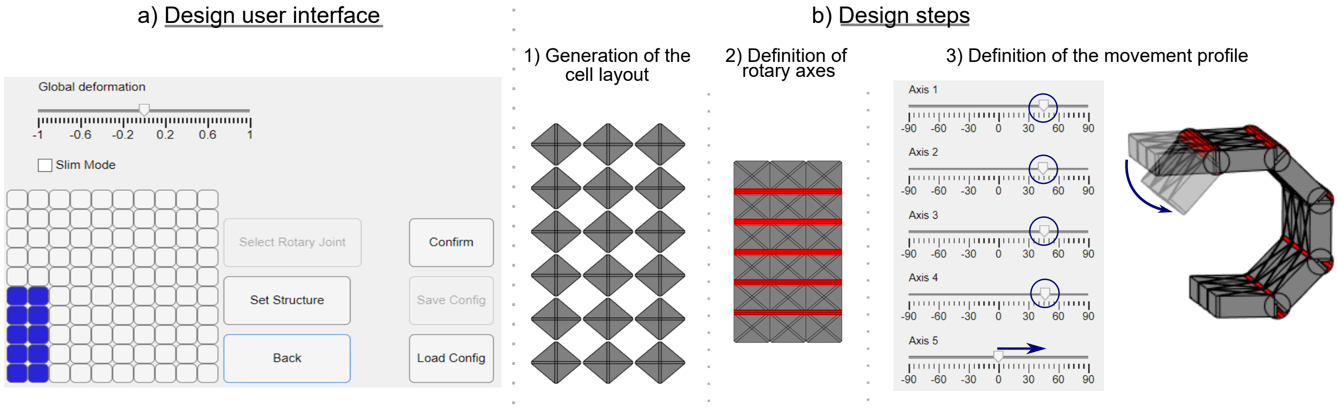

Figure 6: a) Main design user interface and b) design stages of the shape-changing structure. The user 1) provides the cell layout, 2) selects axes of deformation by clicking on possible joint locations, and 3) interactively decides on the shape of the interface in the most deformed form by tuning corresponding sliders.

activates the "Select Rotary Joint" button. Once this button is clicked, the structure goes from an undeformed state to completely deformed state, as shown in Figure 6-b.1 and b.2. The user can simply click and select desired axes on the structure to implement bending. The software imposes two constraints for axes placement: the axes can not cross over and the placed axes continue on the same line until the end of the structure. These constraints are needed because a single cell can not perform the bending effect in two different directions at the same time; and if one cell is bending, its neighboring cell, which is on the same axis as its bending axis, should comply with its motion. For the fish example placement of the joint axes is similar to defining the skeleton of the fish which commands the principle bending axes of the fish body.

(3) **Definition of movement profile:** Each rotary axis placement creates an axis control slider. Once all of the axes are defined, the user selects the "Confirm" button which enables the axis control sliders. The user can manipulate the structure around the given axes using the sliders. The sliders show the maximum achievable deformation amounts in either direction. The user manipulates the structure to a desired shape in the completely deformed state of the metamaterial structure. We require the user to define the shape of the metamaterial in the most deformed to simplify the user interaction. In this state, cells completely collapse, leaving no gaps, and the user can manipulate the shape similar to folding a sheet of paper. This step can be thought of as visually defining the most deformed/bent state of the fish body in one direction.

(4) **Confirm and inspect:** Once the user confirms the desired maximum deformed state, the metamaterial structure design is completed. Joint locations and deformation amounts are fed to the joint configuration calculation algorithm. The joint parameters for the basic and bending cells are defined on the structure.
Users can simulate the intermediate deformation states of the structure by using the "Global Deformation" slider. This slider operates between -1 and 1, where -1 and 1 stand for maximum deformation in the reverse and forward direction respectively. This slider simulates the structure uniformly, assuming perfect deformation propagation.

Following these steps, the cell configurations are made and the designer can continue with the simulation step.

4.2 Designing joint flexibility and simulating sparse actuation

In this section, we present the user interaction for the simulation of the design and the implementation of the flexible model of the metamaterials. Following the design stage, the joint inclination angles are automatically configured. The designer assigns flexible joint sizes and defines actuators on joints. For the simulation, the user performs the following steps:

(1) **Load the metamaterial configuration** if the metamaterial was not just designed.
(2) **Adjust internal flexibility:** This will automatically assign the joint stiffness, k, values for computation of the simplified elastic energy function.
(3) **Place Motors:** The user presses the "Place Motor" button and selects the desired joint to attach the actuator on. The actuators are presented as red spheres as shown in Figure 7. This will automatically override the deformation of this joint and the connected nodes.
(4) **Simulate motors:** As the motors are placed on the structure, sliders appear on the interface for each motor. We assume that the motors are perfect position sources and that sliders control the deformation amount of the overridden nodes. The deformation amount of the non-overridden nodes is computed to display the resulting shape of the model. Users have the opportunity to iteratively test different locations to inspect which configuration suits their application best before fabrication. For the fish example, we decided to use Configuration 1, as the simulated movements resembled

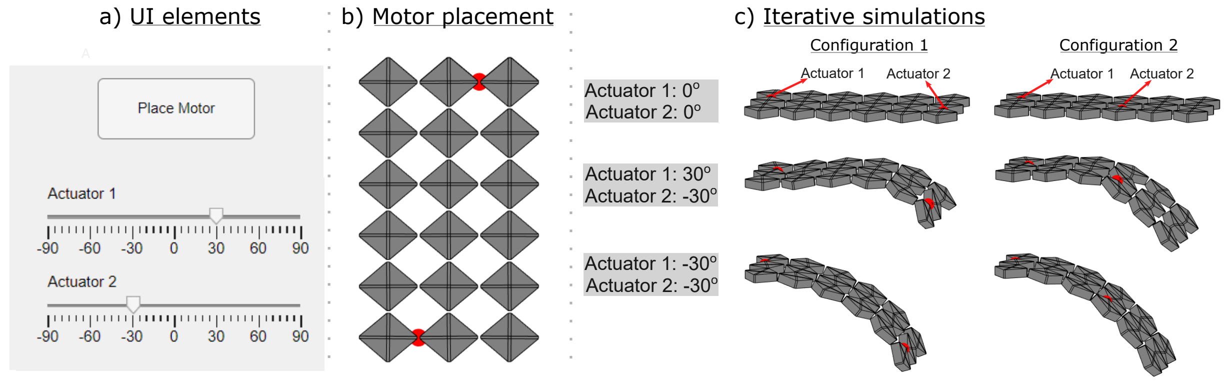

Figure 7: a) User interface elements for placing and controlling motors. b) An instance where the user placed two motors on the metamaterial structure. c) Simulation instances of two motor placement configurations. In the sample, the same metamaterial design is actuated by the same amounts using two actuators. The only difference is the location of the second actuator.

smoother thrusting movements that are more localized on the tail.

5 Physical Fabrication

In this section, we detail the physical fabrication and modular design of the metamaterial structure. In terms of the physical fabrication we found the following challenges important to address:

- Minimizing the assembly time: Using multi-material 3D printing and snap-in modules, the metamaterial structures can be assembled very quickly after the fabrication of individual modules.
- Customizability and scalability: The interfaces allow four connection points on every node along with a diverse set of modules to support reconfigurability, reusability and scalability.

5.1 3D Printing

Our shape-changing base structure designs can be printed in one pass without needing any assembly. We used a dual-material Ultimaker S5 3D printer with a 0.4 mm nozzle width and 0.1 mm layer height. The nodes were printed with PLA/ABS and the flexible joints were with TPU95A. Both when using PLA and ABS for the rigid part, TPU links would occasionally detach from the rigid node. We avoided this by designing the connection points of the TPU sections larger to hook into the rigid structure and resist the longitudinal stress.

The material choice for the stiff and flexible material can be varied, but the important aspect is that the two materials should provide a decently strong connection when printed. Using another flexible material could mean a different elastic modulus, thus changing the ideal values for the deformation propagation function explained in Section 4.2.

5.2 Modular design

Figure 8 shows the fabrication of the example fish application. All applications are first printed as a metamaterial structure and then enhanced through modular add-ons after fabrication. The modules are connected via snap-fit connections for easy attachment and detachment. We used ABS for the snap-fit connections as PLA is too brittle for such bending structures. The modules allow 1) actuator placement for enabling active control, 2) metamaterial combination for scaling or reusability, 3) connection to stable surfaces for grounding or shape attachment and 4) physical enhancing the prototype for desired tasks. In this work, we explored a subset of many possible modular enhancements. The addition of different actuator types, physical enhancements or sensors could unlock many more application possibilities, which we discuss in Section 7.2.

In this section, we present four types of modules that were essential to the applications presented in Section 6.

Servo motors are connected across a joint. The motor connection hubs are designed to align the shaft of the motor at the middle

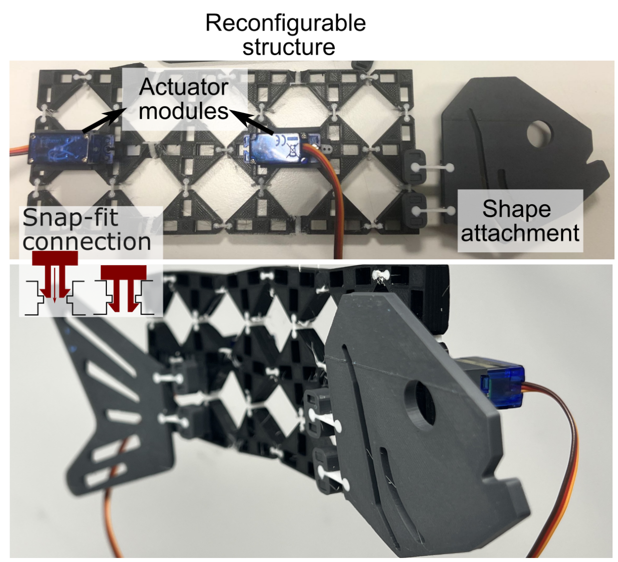

Figure 8: Fabrication of the fish example, including shape attachment and actuator modules added via snap-fit connection hubs.

point of the two actuated nodes. Figure 9 shows our actuator module with snap-fit connections that can be plugged across a joint. When actuated, the motor creates a rotary motion around the joint and actuates the cell.

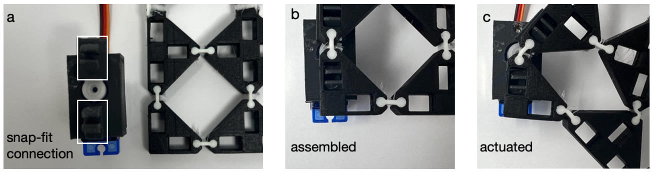

Figure 9: The modular structure that provides housing for the actuators.

Metamaterial connection hub allows transferring the movement of the metamaterial along to another metamaterial structure. This helps generate larger structures that can not be printed at once the design and reusing the same fundamental piece in multiple assemblies. Figure 10 demonstrates two metamaterial structures being combined together by two-way snap-fit connectors. These connectors help rigidly connect nodes of two separate metamaterial structures.

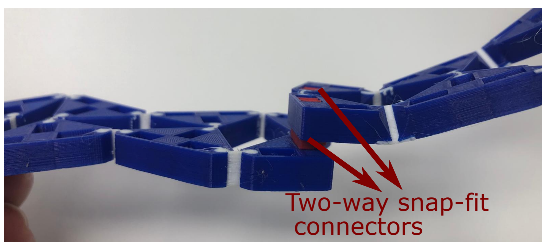

Figure 10: Metamaterials structures are combined through connection hubs. These are two red-colored two-way snap-fit connectors that combine two nodes of two separate metamaterial structures.

Stable connection hubs are used for connecting the metamaterial to a surface to ground it or for connecting a shape that should not be affected by the internal movements of the metamaterial. Figure 11 presents how the stable connection hub is connected to the metamaterial structure and to an external shape. The stable connection hub connects two adjacent nodes of the metamaterial structure to a stable surface through two long flexible beams. This averages out the orientations of the inversely rotating adjacent nodes and keeps the orientation of the external shape unchanged. This is desirable for adding static shapes that are not meant to rotate along with individual nodes during the shape change of the structure.

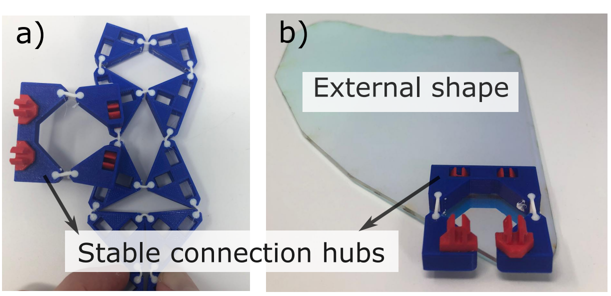

Figure 11: a) Stable connection hub connected to a metamaterial cell. The hub averages out the rotations of adjacent nodes enabling stability of the connected external structures b) stable connection hub connected to one of the butterfly wings for one of the presented applications.

Physical enhancements can be used for enhancing the physical connection of the metamaterial to the environment. In this work, we present friction pads for enhancing higher contact friction with the surroundings. Figure 12 presents a module for adding onto the node which is used for facilitating designs that move across a distance on a surface or grip an object by adding high-friction material onto the connection hub. Section 6.1 and 6.3 present two applications where the use of the friction module plays an essential role.

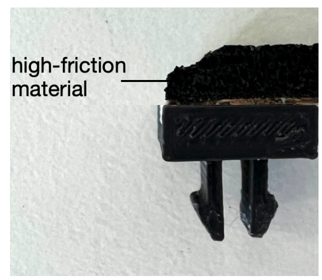

Figure 12: Friction pad module: a physical enhancement module that increases the surface friction of the connected cells.

6 Application cases

The shape-changing features of the presented structures can be utilized in a wide range of applications. We present four example applications, each focusing on a different opportunity offered by sparsely actuated metamaterials.

6.1 Crawling and swimming movement

In this application example, we introduce two interfaces leveraging a common metamaterial base design to execute two distinct natural modes of movement: crawling and swimming. This application demonstrates the efficacy of a simulation tool capable of facilitating iterative exploration across various actuator configurations and actuation signals.

For the crawling worm application, both actuators are controlled to perform sinusoidal movements. By controlling the phase offset between the sinusoidal motor movement profiles we achieve the crawling behavior. Switching the sign of the phase offset causes the direction of the crawl to reverse. The movement of the worm is facilitated by the addition of friction pad modules. As shown in Figure 13, a single crawling motion can cover a large distance thanks to the agile design of the interface.

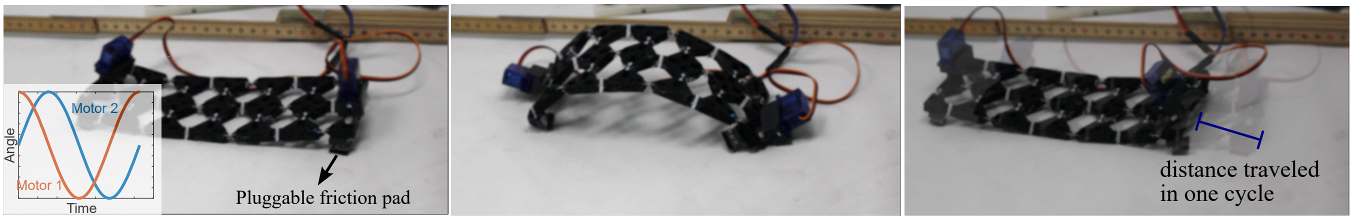

Figure 13: Crawling robot driven by sinusoidal signals applied to the motors with phase difference. In the middle picture, the right-side motor deforms first and starts to slide because the right-side friction module pads are raised off the ground. The crawling robot travels almost one-fourth of its length in one cycle.

In the case of the fish prototype shown in Figure 8, the motor on the tail side of the fish is controlled in a sinusoidal motion profile providing the propelling movement of the fish. The motor on the head side of the fish controls the swimming direction of the fish.

6.2 Wearable butterfly wings

Nature inspiration has been a big part of clothing design. This application was inspired by how the natural flapping motion of butterflies involves the top edge of the wings to lead the bottom edge to be able to push air downwards. Similar to the movement of the crawling worm application, the control of the wings is performed using two motors that move in sinusoidal trajectories that have a phase difference between one another.

In this example, the butterfly model is constructed by combining four separate metamaterial pieces and two actuators, as shown in Figure 14. The building blocks of this prototype can be repurposed for a different design. Through the modularity of the metamaterial structure, the designer can experiment with metamaterial cells with different joint configurations (i.e., print replacement butterfly wings that bend more or less) without needing to reprint one large interface again.

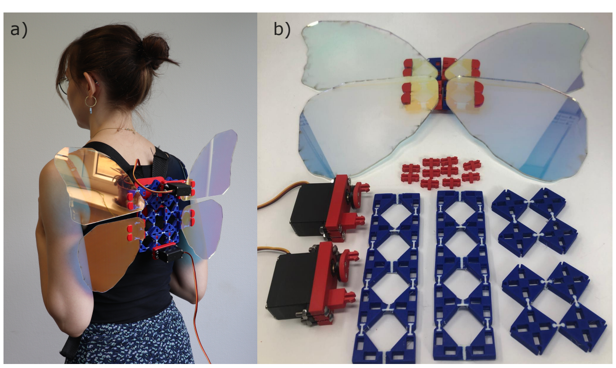

Figure 14: a) Butterfly-inspired wearable shape-changing interface. b) Disassembled form of the interface, showing two 4 by 1 bending cell arrays, two 1 by 1 basic cells, two motors, four wings connected by shape stabilizers, and metamaterial basic connection elements.

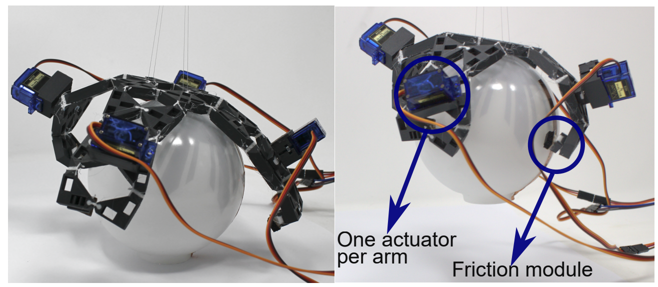

Figure 15: Gripper design actuated with four motors, using friction pads as pluggable modules for grasping objects.

6.3 Shape adaptable object gripper

Our sparsely actuated metamaterials provide more flexibility to traditional mechanical structures, for example, a gripper. Instead of having binary closing and opening-up states in a gripper, having a few actuators allows us to control each arm of the gripper separately. The flexibility also allows the links of the gripper to conform with the shape of the object better than a stiff gripper would do. These enable the gripper to produce more fine-tuned motion, enabling more complex functionalities such as adjusting the gripping size based on the object, and selectively opening up arms to control the releasing direction of the object.

6.4 Umbrella holder

With this application, we demonstrate that the simulation of sparse actuation does not need to only model the use of multiple actuators on one interface. Angular constraints, presented in Figure 16, can be used alongside actuators to simulate a constant local deformation. In this application, we present an umbrella-holding mechanism that is already curved in the rest state due to the angular constraint connected over its joint on one end. A motor on the other end of the structure is actuated to fully close the holding mechanism once the user places the umbrella. The grasping style of the umbrella holder was inspired by octopus tentacles. Along these lines, augmenting the umbrella holder with additional friction or suction by providing modular add-ons could increase the grasping quality for various other objects.

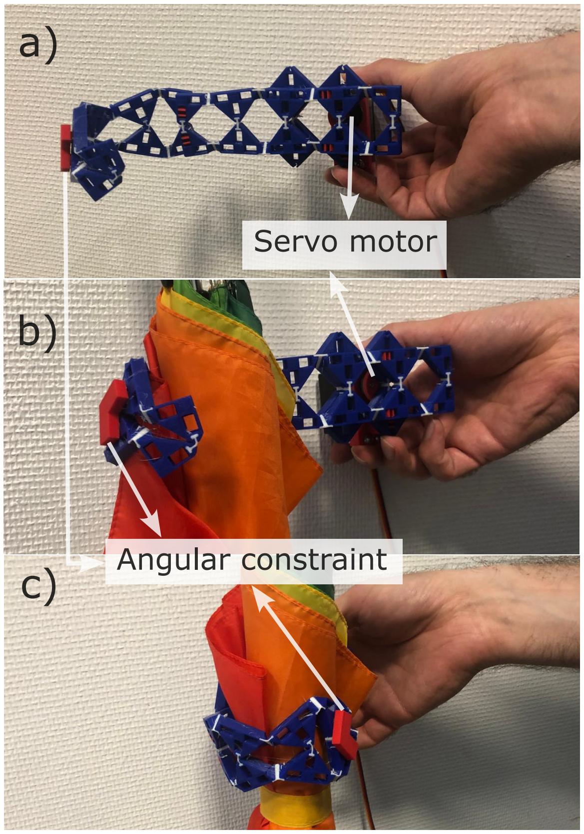

Figure 16: a) The umbrella holder is at its rest state deformed on one side due to the angular constraint module to support the umbrella when placed. b) The umbrella is placed on the holding mechanism and the motor deforms the metamaterial. c) The shape-changing interface bends completely to securely hold the umbrella.

7 Limitations and Potential Extensions

In this section, we briefly discuss the limitations and share insights on our experience with the design of the proposed structures and potential avenues of extensions.

7.1 Simulation

Our deformation approximation algorithm is a simplified energy function and it relies on certain assumptions to expedite its simulation. The approximation generates a good enough estimation of the actual deformation behaviour. This, however, can be further improved by using a physics-based method to simulate more accurate and realistic deformation behaviour which can incorporate interactions with the environment. In this paper, we focus on providing the designer with a fast enough algorithm to support their shape exploration. A slower but more accurate simulation could follow the existing one after the designer experiences real-time exploration and finishes the parameter refinement. We leave the implementation of a more physics-based approach to future work.

7.2 Modular enhancements

One benefit of our approach is that its modularity enables further extending many aspects of our method. This can lead to tailored solutions and more functional metamaterial structures in terms of hardware setup, actuation method, etc. The most basic extension based on our current structures is to expand our current set of modules to incorporate sensing (e.g. magnetic, capacitive) for achieving modular interactive displays. The combination of the flexible nature of the structure with internal deformation sensors could provide us with opportunities for active kinesthetic feedback during tangible interactions with the shape-changing interface. External sensing methods can be helpful in interactive applications such as adding proximity sensors to presented gripper applications for object detection. Embedding conductivity in the 3D printed structure [16] can provide more ways of implementing sensing capabilities or seamlessly embedding external sensors. In this work we only presented a friction module as a physical enhancement module. Other types of passive modules such as magnets [11] or suction cups can be added to increase the environmental interaction capabilities of the cells.

7.3 Primitive cell types

Our designs consist of two types of cells: basic and bending cells. Ou et al. [34] presented additional kinematic configurations such as shearing and twisting cells. For this work we decided to work with a smaller group of available primitives to explore wider into what is possible with only these two, since the versatility of our interfaces is not due to the type of movements we can offer but due to the range of movements provided by the joint flexibility and sparse actuation. Expanding into the cell would without a doubt expand the set of achievable shapes.

7.4 Actuation

We used lightweight and small DC servo motors to actuate the cells because they are attainable and fit the requirements of the cell actuation (-90 to 90 degrees movement range). A problem with these motors is that they suffer from higher noise levels than more expensive ones. We observed that the inherent elasticity of the system works as a dampening factor and the structure does not vibrate as much as a rigid structure would. Still for achieving higher torques and more stable actuation, bigger and higher quality motors can be used. Additionally, other actuation methods such as pneumatics or shape memory alloys can be an interesting extension to this work although the simulation tool would need to be adjusted for it. We believe that shape memory alloys complement the lightweight nature of the metamaterial-based structure for applications where their lower actuation speed is not a problem.

7.5 Structural considerations

During our actuation tests, we did not observe any significant material failure or plastic deformation. These tests included running presented movements for the application cases for extended repetitions. When using angular constraints for a long duration, as in the umbrella holder application, the joints that are most affected by the constraint did not fully bounce back to their original straight form after the removal of the angular constraint. In time they straightened further but a partial deformation was sustained. This deformation due to persistent stress, also known as creep, did not cause failure and the affected joints still operated. This effect can be further studied for analyzing the reusability extent of the presented structures.

8 Conclusion

In this paper, we propose adding sparse actuation into mechanical metamaterials with flexible joints. Instead of producing only one pre-programmed movement, these can achieve multi-degree-of-freedom movement out of one fabricated structure, making such structures more functional for interactions. We provide a design tool for automatic configuration of metamaterials, and a simulation tool to enable previewing the resulting shape-changes before fabrication. The presented design and simulation tool is made available as open source[1]. We present a set of pluggables, which allow users to easily plug in, remove, and reconfigure actuators, combine separate metamaterials and augment physical properties (e.g. add friction) for different application scenarios. Finally, we showcase the capabilities of sparsely actuated metamaterials, using several examples of applications that were inspired by nature.

Servo motors are ideal off-the-shelf components as they generally work in a 180-degree range, the same as the actuation range of the cell joints, and provide high enough torques to deform the flexible structure. For future work, we believe that shape memory alloys will be promising in complementing the lightweight property of the metamaterial-based structure for applications where their lower actuation speed is not a problem.

References

[1] Lea Albaugh, Scott Hudson, and Lining Yao. 2019. Digital Fabrication of Soft Actuated Objects by Machine Knitting. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300414

[2] A Alderson and K L Alderson. 2007. Auxetic materials. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 221, 4 (2007), 565–575. https://doi.org/10.1243/09544100JAERO185 arXiv:https://doi.org/10.1243/09544100JAERO185

[3] Jason Alexander, Anne Roudaut, Jürgen Steimle, Kasper Hornbæk, Miguel Bruns Alonso, Sean Follmer, and Timothy Merritt. 2018. Grand Challenges in Shape-Changing Interface Research. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3173574.3173873

[4] Miklós Bergou, Basile Audoly, Etienne Vouga, Max Wardetzky, and Eitan Grinspun. 2010. Discrete Viscous Threads. In *ACM SIGGRAPH 2010 Papers* (Los Angeles, California) *(SIGGRAPH '10)*. Association for Computing Machinery, New York, NY, USA, Article 116, 10 pages. https://doi.org/10.1145/1833349.1778853

[5] Miklós Bergou, Max Wardetzky, Stephen Robinson, Basile Audoly, and Eitan Grinspun. 2008. Discrete Elastic Rods. In *ACM SIGGRAPH 2008 Papers* (Los Angeles, California) *(SIGGRAPH '08)*. Association for Computing Machinery, New York, NY, USA, Article 63, 12 pages. https://doi.org/10.1145/1399504.1360662

[6] Katia Bertoldi, Vincenzo Vitelli, Johan Christensen, and Martin Van Hecke. 2017. Flexible mechanical metamaterials. *Nature Reviews Materials* 2 (2017). https://doi.org/10.1038/natrevmats.2017.66

[7] Bernd Bickel, Moritz Bächer, Miguel A. Otaduy, Hyunho Richard Lee, Hanspeter Pfister, Markus Gross, and Wojciech Matusik. 2010. Design and Fabrication of Materials with Desired Deformation Behavior. *ACM Trans. Graph.* 29, 4, Article 63 (jul 2010), 10 pages. https://doi.org/10.1145/1778765.1778800

[8] Anke Brocker, Jakob Strüver, Simon Voelker, and Jan Borchers. 2022. SoRoCAD: A Design Tool for the Building Blocks of Pneumatic Soft Robotics. In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI EA '22)*. Association for Computing Machinery, New York, NY, USA, Article 330, 7 pages. https://doi.org/10.1145/3491101.3519770

[9] Stelian Coros, Bernhard Thomaszewski, Gioacchino Noris, Shinjiro Sueda, Moira Forberg, Robert W. Sumner, Wojciech Matusik, and Bernd Bickel. 2023. *Computational Design of Mechanical Characters* (1 ed.). Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3596711.3596799

[10] Zhitong Cui, Shuhong Wang, Violet Yinuo Han, Tucker Rae-Grant, Willa Yunqi Yang, Alan Zhu, Scott E Hudson, and Alexandra Ion. 2024. Robotic Metamaterials: A Modular System for Hands-On Configuration of Ad-Hoc Dynamic Applications. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 326, 15 pages. https://doi.org/10.1145/3613904.3642891

[11] Himani Deshpande, Bo Han, Kongpyung (Justin) Moon, Andrea Bianchi, Clement Zheng, and Jeeeun Kim. 2024. Reconfigurable Interfaces by Shape Change and Embedded Magnets. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 325, 12 pages. https://doi.org/10.1145/3613904.3642802

[12] Aluna Everitt, Faisal Taher, and Jason Alexander. 2016. ShapeCanvas: An Exploration of Shape-Changing Content Generation by Members of the Public. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 2778–2782. https://doi.org/10.1145/2858036.2858316

[13] Bastiaan Florijn, Corentin Coulais, and Martin van Hecke. 2014. Programmable Mechanical Metamaterials. *Phys. Rev. Lett.* 113 (Oct 2014), 175503. Issue 17. https://doi.org/10.1103/PhysRevLett.113.175503

[14] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. InFORM: Dynamic Physical Affordances and Constraints through Shape and Object Actuation. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology* (St. Andrews, Scotland, United Kingdom) *(UIST '13)*. Association for Computing Machinery, New York, NY, USA, 417–426. https://doi.org/10.1145/2501988.2502032

[15] Kristian Gohlke, Eva Hornecker, and Wolfgang Sattler. 2016. Pneumatibles: Exploring Soft Robotic Actuators for the Design of User Interfaces with Pneumotactile Feedback. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction* (Eindhoven, Netherlands) *(TEI '16)*. Association for Computing Machinery, New York, NY, USA, 308–315. https://doi.org/10.1145/2839462.2839489

[16] Jun Gong, Olivia Seow, Cedric Honnet, Jack Forman, and Stefanie Mueller. 2021. MetaSense: Integrating Sensing Capabilities into Mechanical Metamaterial. *UIST 2021 - Proceedings of the 34th Annual ACM Symposium on User Interface Software and Technology* (2021), 1063–1073. https://doi.org/10.1145/3472749.3474806

[17] Alice C Haynes and Jürgen Steimle. 2024. Flextiles: Designing Customisable Shape-Change in Textiles with SMA-Actuated Smocking Patterns. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 517, 17 pages. https://doi.org/10.1145/3613904.3642848

[18] Larry L. Howell. 2004. *Compliant Mechanisms.* John Wiley and Sons.

[19] Alexandra Ion, Johannes Frohnhofen, Ludwig Wall, Robert Kovacs, Mirela Alistar, Jack Lindsay, Pedro Lopes, Hsiang Ting Chen, and Patrick Baudisch. 2016. Metamaterial mechanisms. *UIST 2016 - Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (2016), 529–539. https://doi.org/10.1145/2984511.2984540

[20] Alexandra Ion, David Lindlbauer, Philipp Herholz, Marc Alexa, and Patrick Baudisch. 2019. Understanding Metamaterial Mechanisms. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3290605.3300877

[21] Alexandra Ion, Ludwig Wall, Robert Kovacs, and Patrick Baudisch. 2017. Digital Mechanical Metamaterials. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 977–988. https://doi.org/10.1145/3025453.3025624

[22] Hiroo Iwata, Hiroaki Yano, Fumitaka Nakaizumi, and Ryo Kawamura. 2001. Project FEELEX: Adding Haptic Surface to Graphics. In *Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '01)*. Association for Computing Machinery, New York, NY, USA, 469–476. https://doi.org/10.1145/383259.383314

[23] Yu Jiang, Shobhit Aggarwal, Zhipeng Li, Yuanchun Shi, and Alexandra Ion. 2023. Reprogrammable Digital Metamaterials for Interactive Devices. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (<conf-loc>, <city>San Francisco</city>, <state>CA</state>, <country>USA</country>, </conf-loc>) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 56, 15 pages. https://doi.org/10.1145/3586183.3606752

[24] Yu Jiang, Alice C Haynes, Narjes Pourjafarian, Jan Borchers, and Jürgen Steimle. 2024. Embrogami: Shape-Changing Textiles with Machine Embroidery. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology* (Pittsburgh, PA, USA) *(UIST '24)*. Association for Computing Machinery, New

[1] GitHub repository: https://github.com/aotaran/MetamaterialDesignAndSimulation

York, NY, USA, Article 63, 15 pages. https://doi.org/10.1145/3654777.3676431

[25] Ozgun Kilic Afsar, Ali Shtarbanov, Hila Mor, Ken Nakagaki, Jack Forman, Karen Modrei, Seung Hee Jeong, Klas Hjort, Kristina Höök, and Hiroshi Ishii. 2021. OmniFiber: Integrated Fluidic Fiber Actuators for Weaving Movement based Interactions into the 'Fabric of Everyday Life'. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 1010–1026. https://doi.org/10.1145/3472749.3474802

[26] Hyunyoung Kim, Aluna Everitt, Carlos Tejada, Mengyu Zhong, and Daniel Ashbrook. 2021. MorpheesPlug: A Toolkit for Prototyping Shape-Changing Interfaces. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 101, 13 pages. https://doi.org/10.1145/3411764.3445786

[27] Mirko Kovač. 2014. The Bioinspiration Design Paradigm: A Perspective for Soft Robotics. *Soft Robotics* 1, 1 (2014), 28–37. https://doi.org/10.1089/soro.2013.0004 arXiv:https://doi.org/10.1089/soro.2013.0004

[28] Suhas Raghavendra Kulkarni, Bernardo Noronha, Domenico Campolo, and Dino Accoto. 2021. Modelling and optimisation of a mechanism-based metamaterial for a wrist flexion-extension assistive device. *Proceedings - IEEE International Conference on Robotics and Automation* 2021-May (2021), 7020–7026. Issue Icra. https://doi.org/10.1109/ICRA48506.2021.9562099

[29] Roderic Lakes. 1987. Foam Structures with a Negative Poisson's Ratio. *Science* 235, 4792 (1987), 1038–1040. http://www.jstor.org/stable/1698767

[30] Vittorio Megaro, Jonas Zehnder, Moritz Bächer, Stelian Coros, Markus Gross, and Bernhard Thomaszewski. 2017. A Computational Design Tool for Compliant Mechanisms. *ACM Trans. Graph.* 36, 4, Article 82 (jul 2017), 12 pages. https://doi.org/10.1145/3072959.3073636

[31] Ken Nakagaki, Artem Dementyev, Sean Follmer, Joseph A. Paradiso, and Hiroshi Ishii. 2016. ChainFORM: A Linear Integrated Modular Hardware System for Shape Changing Interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 87–96. https://doi.org/10.1145/2984511.2984587

[32] Ken Nakagaki, Sean Follmer, and Hiroshi Ishii. 2015. LineFORM: Actuated Curve Interfaces for Display, Interaction, and Constraint. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (Charlotte, NC, USA) *(UIST '15)*. Association for Computing Machinery, New York, NY, USA, 333–339. https://doi.org/10.1145/2807442.2807452

[33] Madalina Nicolae, Claire Lefez, Anne Roudaut, Samuel Huron, Jürgen Steimle, and Marc Teyssier. 2024. SoftBioMorph: Fabricating Sustainable Shape-changing Interfaces using Soft Biopolymers. In *Proceedings of the 2024 ACM Designing Interactive Systems Conference* (Copenhagen, Denmark) *(DIS '24)*. Association for Computing Machinery, New York, NY, USA, 496–508. https://doi.org/10.1145/3643834.3661610

[34] Jifei Ou, Zhao Ma, Jannik Peters, Sen Dai, Nikolaos Vlavianos, and Hiroshi Ishii. 2018. KinetiX - designing auxetic-inspired deformable material structures. *Computers and Graphics (Pergamon)* 75 (2018), 72–81. https://doi.org/10.1016/j.cag.2018.06.003

[35] Jifei Ou, Mélina Skouras, Nikolaos Vlavianos, Felix Heibeck, Chin-Yi Cheng, Jannik Peters, and Hiroshi Ishii. 2016. aeroMorph - Heat-sealing Inflatable Shape-change Materials for Interaction Design. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 121–132. https://doi.org/10.1145/2984511.2984520

[36] Dinesh K. Pai. 2002. STRANDS: Interactive Simulation of Thin Solids using Cosserat Models. *Computer Graphics Forum* 21, 3 (2002), 347–352. https://doi.org/10.1111/1467-8659.00594 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/1467-8659.00594

[37] J. Panetta, M. Konaković-Luković, F. Isvoranu, E. Bouleau, and M. Pauly. 2019. X-Shells: A New Class of Deployable Beam Structures. *ACM Trans. Graph.* 38, 4, Article 83 (jul 2019).

[38] Julian Panetta, Qingnan Zhou, Luigi Malomo, Nico Pietroni, Paolo Cignoni, and Denis Zorin. 2015. Elastic Textures for Additive Fabrication. *ACM Trans. Graph.* 34, 4, Article 135 (jul 2015), 12 pages. https://doi.org/10.1145/2766937

[39] Jesús Pérez, Miguel A. Otaduy, and Bernhard Thomaszewski. 2017. Computational Design and Automated Fabrication of Kirchhoff-Plateau Surfaces. *ACM Trans. Graph.* 36, 4, Article 62 (jul 2017), 12 pages. https://doi.org/10.1145/3072959.3073695

[40] Isabel P. S. Qamar, Rainer Groh, David Holman, and Anne Roudaut. 2018. HCI meets Material Science: A Literature Review of Morphing Materials for the Design of Shape-Changing Interfaces. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (<conf-loc>, <city>Montreal QC</city>, <country>Canada</country>, </conf-loc>) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–23. https://doi.org/10.1145/3173574.3173948

[41] Isabel P. S. Qamar, Katarzyna Stawarz, Simon Robinson, Alix Goguey, Céline Coutrix, and Anne Roudaut. 2020. Morphino: A Nature-Inspired Tool for the Design of Shape-Changing Interfaces. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (<conf-loc>, <city>Eindhoven</city>, <country>Netherlands</country>, </conf-loc>) *(DIS '20)*. Association for Computing Machinery, New York, NY, USA, 1943–1958. https://doi.org/10.1145/3357236.3395453

[42] Anne Roudaut, Abhijit Karnik, Markus Löchtefeld, and Sriram Subramanian. 2013. Morphees: Toward High "Shape Resolution" in Self-Actuated Flexible Mobile Devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Paris, France) *(CHI '13)*. Association for Computing Machinery, New York, NY, USA, 593–602. https://doi.org/10.1145/2470654.2470738

[43] Alexa F. Siu, Eric J. Gonzalez, Shenli Yuan, Jason B. Ginsberg, and Sean Follmer. 2018. ShapeShift: 2D Spatial Manipulation and Self-Actuation of Tabletop Shape Displays for Tangible and Haptic Interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3173865

[44] J. Spillmann and M. Teschner. 2007. CORDE: Cosserat Rod Elements for the Dynamic Simulation of One-Dimensional Elastic Objects. In *Eurographics/SIGGRAPH Symposium on Computer Animation*, Dimitris Metaxas and Jovan Popovic (Eds.). The Eurographics Association. https://doi.org/10.2312/SCA/SCA07/063-072

[45] U. Waheed, Connor Myant, and Sean Dobson. 2020. Boolean AND/OR mechanical logic using multi-plane mechanical metamaterials. *Extreme Mechanics Letters* 40 (2020), 100865.

[46] Hongyi Xu, Espen Knoop, Stelian Coros, and Moritz Bächer. 2018. Bend-It: Design and Fabrication of Kinetic Wire Characters. *ACM Trans. Graph.* 37, 6, Article 239 (dec 2018), 15 pages. https://doi.org/10.1145/3272127.3275089

[47] Vasco Xu and Ken Nakagaki. 2023. Xs: Interactive Scissor Mechanisms as Portable and Customizable Shape-Changing Interfaces. In *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction* (Warsaw, Poland) *(TEI '23)*. Association for Computing Machinery, New York, NY, USA, Article 6, 10 pages. https://doi.org/10.1145/3569009.3572737

[48] Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. 2013. PneUI: pneumatically actuated soft composite materials for shape changing interfaces. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology* (St. Andrews, Scotland, United Kingdom) *(UIST '13)*. Association for Computing Machinery, New York, NY, USA, 13–22. https://doi.org/10.1145/2501988.2502037

[49] X Zhang, FK Chan, T Parthasarathy, and M Gazzola. 2019. Modeling and simulation of complex dynamic musculoskeletal architectures. *Nature Communications* 10, 1 (2019), 1–12. https://doi.org/10.1038/s41467-019-12759-5