Hydrogel-based DIY Underwater Morphing Artifacts

A morphing and fabrication technique to democratize the creation of controllable morphing 3D underwater structures with low-cost, easily available hydrogel beads adhered to a substrate.

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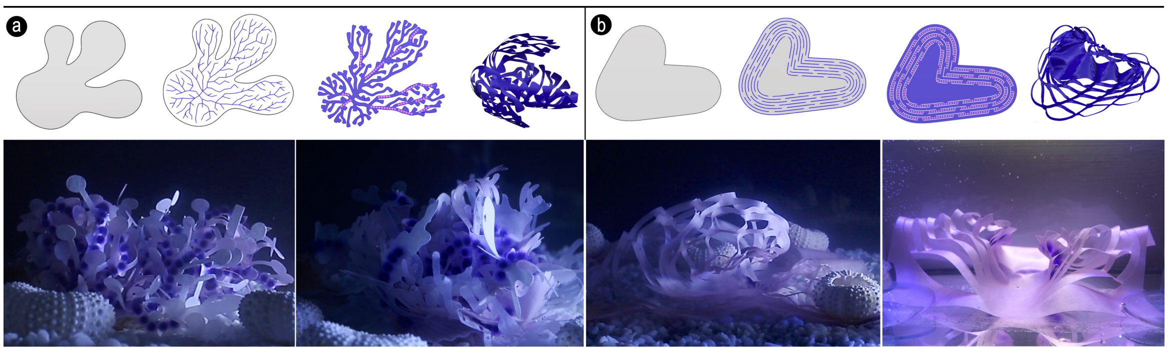

Figure 1: Hydrogel-based (a) branching and (b) kirigami demonstrational morphing artifacts created using our computational tool.

ABSTRACT

Hydrogels are versatile morphing materials that have recently been adopted for creating shape-changing interfaces. However, most shape-changing interfaces require advanced material synthesis, specialized lab settings for fabrication, and technical knowledge is needed to simulate their morphing behavior. To replicate such structures, these factors become a barrier for makers. Therefore, to democratize the creation of hydrogel-based morphing artifacts and to extend their design space in HCI, we propose a water-triggered morphing mechanism that utilizes the distance between adjacent hydrogel beads adhered on a thin substrate to control their bending angle. This paper describes the bending angle quantification experiments for creating a simulator, the process of developing a computational tool along with its user-friendly workflow and demonstrates kirigami and branch-based artifacts built with the tool. Using our method, anyone can easily design and fabricate custom morphing structures.

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CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); Interactive systems and tools; User interface toolkits.

KEYWORDS

Fabrication, Artifact or System, Prototyping/ Implementation, Quantitative Methods

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1 INTRODUCTION

Hydrogels are hydrophilic and polymeric networks capable of absorbing large quantities of water and maintaining a distinct 3D structure. Their swelling performance is based on pH, salinity, and temperature [1]. In the past, their reversible swelling and deswelling behavior has been utilized to engineer nonreversible self-folding [25, 32] and reversible self-actuating applications [26]. They are easy to handle as they can be synthesized into a solution or preforms such as beads and particles. In the field of fabrication research, easy-to-access digital fabrication platforms have been developed for hydrogels [31]. They have also been used for shape-changing interfaces in food [25, 32], wearables [37], and sensing devices

[10]. However, the most common methods of creating morphing structures with hydrogels require very complicated highly complex fabrication processes and material synthesis, specialized materials, and the accuracy of bending angles in the structures is very low. These methods also pose a barrier to makers for replicating.

Taking advantage of the unique properties of hydrogels, we propose a way to create low-cost, easy to fabricate hydrogel-based structures with readily available materials which self-actuate in water. These can be flattened and packed in a compact manner owing to their fabrication technique. Upon deployment, they self-morph due to osmosis using water as a simulant and grow into free-standing 3D structures (Fig 1). The morphing structures retain their 3D geometry underwater due to buoyancy and constant hydration of the hydrogel. To enable a larger audience to fabricate these morphing artifacts and push the limits of democratization, we created a computational tool that allows for the creative exploration of different geometries and visualizes their morphing behavior. To summarize, the paper presents the following contributions:

- Quantification of the distance between hydrogel beads on a substrate to control the bending angle of self-actuating structures.
- A computational platform and simulator for creating generative geometries such as kirigami[1] and branch-based structures and simulating their morphing behavior. Morphing primitives that serve as the building blocks for these are also provided.
- An easy fabrication process for creating tailored morphing artifacts that enables a larger audience to create them.

2 RELATED WORK

Among all hydrogel-based morphing structures, our work uniquely leverages the distance between adjacent hydrogel beads on a thin substrate to achieve a controllable and parametric bending angle. More complex morphing geometries can be achieved by our computational tool, which is uniquely tailored to the beads-on-substrate mechanism and provides a friendly design interface for novice users. We suggest that our work will enrich the existing toolbox of shape-changing mechanisms and interfaces in HCI.

2.1 Morphing Hydrogels

In the field of HCI and material science, morphing materials such as 3D printed hydrogels that display unique swelling behaviors have been utilized for the design of shape-changing interfaces [18]. Gel-like materials that are pH-responsive [10], change opacity, and give haptic feedback [12] have been widely explored as an integration of sensing and actuation interfaces. Techniques such as photolithography [33] and local light irradiation [16] are used for controlled swelling of one or more shape-responsive hydrogels with different properties. Most hydrogel-based morphing structures start with a hydrogel solution via direct-ink writing [32] or film casting [10]. Acknowledging the rich explorations of morphing hydrogel actuators, our tool builds upon this rich lineage and uses the adjacent bead distance to control the bending angle to create complex generative artifacts. The hydrogel beads used in our structures are made of Super Absorbent Polymers such as NaPA (similar to HARICOT [27]) and are readily available off-the-shelf. These are very cost-effective (~0.01 cents/each); thus, our overall fabrication cost is very low.

2.2 Soft and Shape-Changing Interfaces

Flexible and airtight materials such as plastic and fabric composites have been utilized to design inflatable bladders or stiffness changing structures such as AccordionFab [35], Printflatables [22], jamSheets [14], aeroMorph [13] and Hydrogel-Textile Composites [21]. Beyond pneumatic structures, tendon or cable-driven actuators [2, 8] often leverage soft materials as substrates. However, we have chosen an analogous material approach in which the morphing stimulus comes from the water itself, eliminating the need for any motors or electromagnetic systems. Bi-layer structures and inflatable bladders are common morphing approaches that leverage hydrogels. Hydrogel beads on substrate require very minimum material processing and synthesis compared to bi-layer structures. In Transformative Appetite [32] liquid gels are melted and cast into bilayers, while photolithography [33] requires a controlled environment and complex fabrication process. Fabricating hydrogel beads on a substrate using our method is easy, making it suitable for craft/creative practices as compared to fabrication processes of inflatable bladders that require molding-casting [36], printing [21, 37], and customized metal molds and CNC bounding machine [13]. However, hydrogel beads on a substrate are relatively weak actuators and are hard to apply to contexts requiring active manipulation.

2.3 Computational Design for Morphing Structures

Many computational tools that enable the creation of morphing structures require highly specific knowledge, such as differential geometry. For example, origami geometries [3] and non-developable surfaces such as domes and saddles [6, 30] based on bending bi-layers or shrinkage actuators were designed with inverse algorithms; materials that expand with heat were used to fabricate size and shape-changing artifacts in ExpandFab [9]; Kirchhoff-plateau surfaces were simulated and fabricated with pre-tensioned stretchy fabric [17]; A-line transformed a straight line into a 3D linear structure [29]; and bi-layer strips were used to design bending-based active food [32] and garments [37]. While most morphing design tools focus on forward or inverse design workflows, very few focus on generative design. In addition, most simulation tools that analyze the shape-changing process of 4D printed structures concern the strain field and not the behavior of the material [6] or interactions between different parts of the structure [3, 28–30]. Our target users, i.e. makers, may be proficient in creating complex 2D and 3D geometries but aren't necessarily knowledgeable in creating shapes with numerical or computational techniques [19], which limits them to develop more customized shape-changing structures [4, 11]. Apart from having a high learning curve and being difficult to replicate, the high precision offered by such complicated workflows isn't always required in the field of design; rather, a more intuitive and interactive visualization of the shape-changing process would be more meaningful and helpful. Our work is inspired mainly by design tools built for bilayer actuators [20, 24] and we have developed a tailored design tool that accommodates hydrogel

[1] kirigami: is a variation of origami that includes cutting of the paper, rather than solely folding the paper and typically does not use an adhesive.

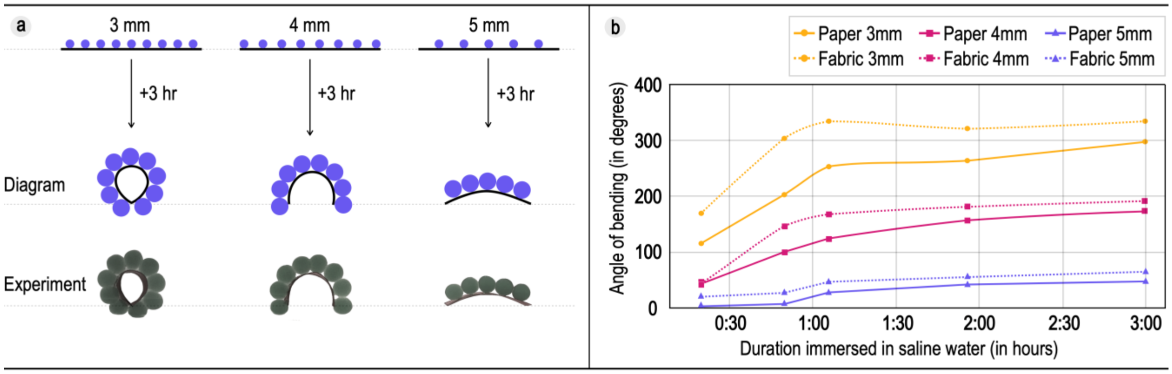


Figure 2: Study of optimal hydrogel placement for uniform linear morphing of non-swelling constrain layer

beads' swelling behavior. We have simulated the beads' expansion and their interaction with the substrate and integrated a generative algorithm in the computational tool to help users design shapes parametrically. Based on the outlines specified by the users, various infill bead patterns can be suggested automatically by the tool. Using our tool, anyone without experience of CAD modeling would still be able to get started easily and create morphing structures very fast.

3 METHOD AND MATERIAL

In this section, we describe bending angle quantification experiments for building the simulator, the simulation model, morphing primitives that serve as a geometric reference for building complex structures and generative geometries for kirigami and branch-based systems. The materials used in the fabrication are readily available off-the-shelf, the structures are easy to fabricate, the bending angle is controllable, a high degree of shape complexity can be reached in the fabrication pipeline, and the fabricated structures display unique aesthetics.

3.1 Hydrogel beads on a substrate

The basic structure is composed of a flexible substrate— paper or natural woven fabric on which hydrogel beads are attached at a measured distance from each other. We conducted quantitative tests to evaluate the relation between the bead distance and the maximum bending angle on copy paper and woven cotton cloth strips which were 1 cm x 3 cm in dimension. The beads were placed 3 mm, 4 mm, and 5 mm apart respectively (Fig 2a). We could control the maximum bending angle of the substrate by varying the gap distance between beads, which to our knowledge, has not been studied previously. The bending angle quantification led to the creation of our simulation tool (Fig 2b). Referring to Fig 4, the measured bending curvature between the simulation and experiment results are aligned to a great extent.

To attach the hydrogel beads to the flexible substrate, we tested multiple off-the-shelf adhesives such as a silicone sealant (Clear Silicone sealant and adhesive, J-B Weld), fabric glue (Fabri-Tac permanent adhesive, Beacon), and cyanoacrylate glue (Super Glue, Loctite). The beads got attached firmly with the silicone adhesive and fabric glue, but when immersed in saline water for more than 12 hours, they lost their adhesion and came off. Here we chose saline water instead of neutral pH water for ease and accuracy of measurement of our experimental results, as saline water slows down the bead swelling time and thus helps to control the bending. Cyanoacrylate glue showed very promising results and the beads did not come off despite being immersed in water for multiple days. Since cyanoacrylate glue bonds with a surface in the presence of moisture, it is the most appropriate for our underwater deployment use case. It is widely adopted as a bio-adhesive and has been used for marine conditions [7]. However, we plan to explore alternative options to cyanoacrylate glue in the future since there are concerns about its toxicity when exposed to it for long durations [5].

3.2 Simulation Model

As hydrogel beads expand when immersed in water, they eventually collide with each other. The expansion of the beads causes the substrate to bend. The maximum bending angle is determined by the distance (D) between adjacent beads and the radius (r) of each bead, as illustrated in Fig 3a. Since the radius is a controllable parameter, any bead size can be used for building the structures (our dehydrated bead radius is 1.5mm). The simulation is validated to be accurate by testing the real model with the simulated computational tool output.

To accommodate diverse substrate patterns in our simulation model while keeping the underlying simulation model simple and fast, we divide a given structure into three basic geometrical elements: bead, line, and substrate (Fig 3b). A line with beads resides on top of a substrate and can be drawn and defined by users in our computational design tool interface. We first simulate the bending of the line based on the distribution of beads. A 'circle packing method' [23] is employed to define the moment of bead expansion and collision. The final simulation of the substrate is then achieved by mapping the original positions of points on the line to the final positions (Fig 3b-d). We further verified this bending-angle control mechanism with a numerical simulation model as shown in Fig 4. It shows that the experimental results match relatively well with our simulation. The percentage of mismatch between the simulation and experimental results is between 7.99 - 21.3 % for the maximum bending angle. The most complex double-sided geometry was reported to have the largest mismatch.

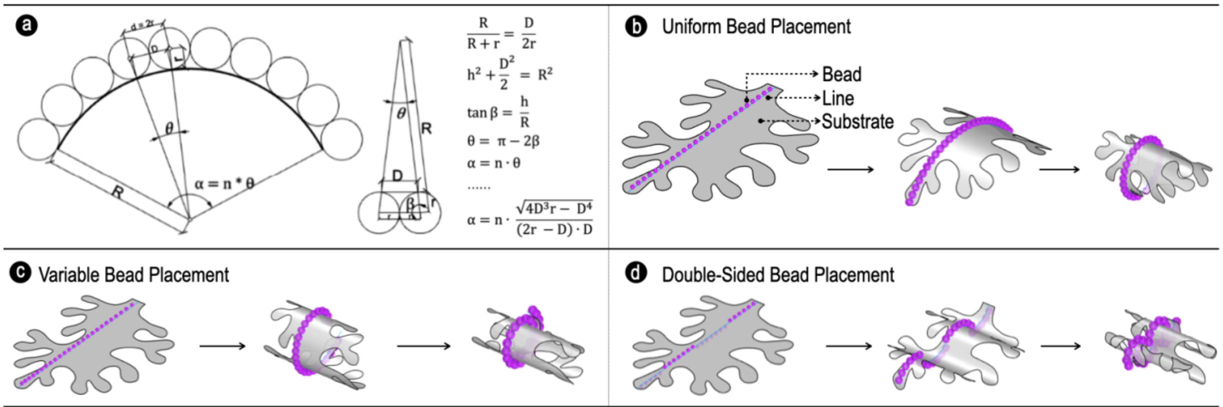


Figure 3: (a) In the structure of hydrogel beads on substrates, the distance (D) between adjacent beads and the radius (r) of each bead determine the maximum bending curvature of the substrate. (b) The simulation process involves mapping a 2D substrate to an actuating line defined by the user for uniform bead placement. (c) Variable bead placement to achieve a gradient curvature. (d) Double-sided bead placement for a sinuous curvature.

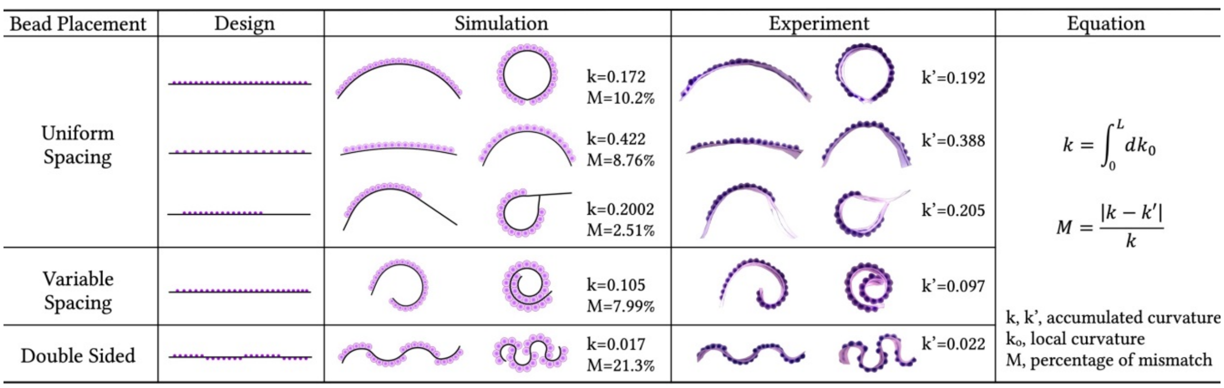


Figure 4: Experiment and Simulation results. Shortening the distance between two adjacent beads enlarges the maximum bending curvature.

Since we only deal with bending behavior that has one degree of freedom, we can simplify our bending model as beads on straight lines. More specifically, a line is represented as a polyline with segments divided by the beads. Each line is set to be free to bend or twist around its axis. One anchor point (i.e., boundary condition) has to be set for each line to run the simulation correctly.

3.3 Morphing Primitives for Hydrogel Beads on a Substrate

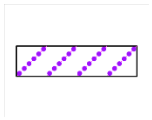
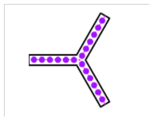
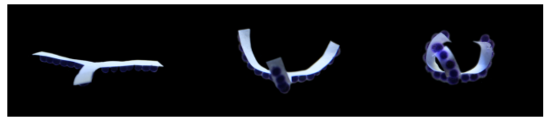
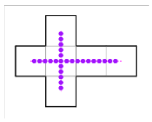
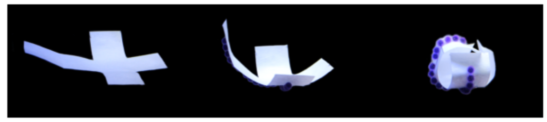
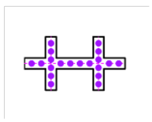
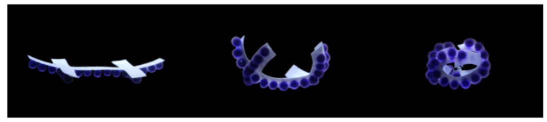
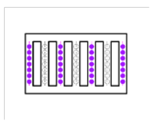
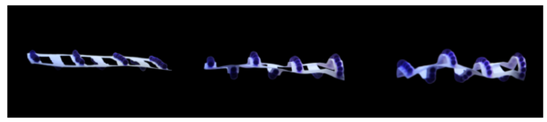
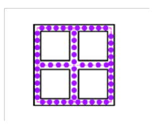
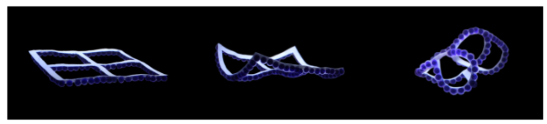
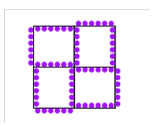
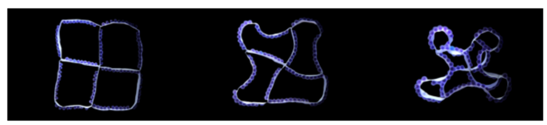
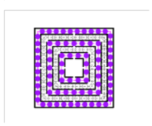
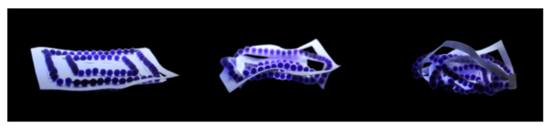
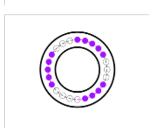
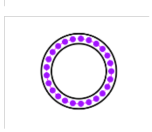
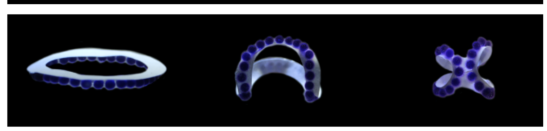
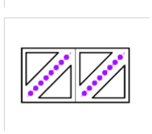
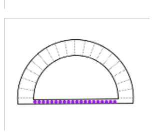
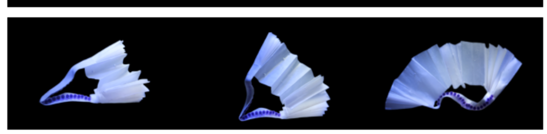
We explored a rich vocabulary of morphing primitives based on the structure and mechanism of hydrogel beads on substrates as shown in Table 1. E.g., by selectively applying beads at defined locations, we created a polyhedron from its net. These primitives helped us investigate the feasibility of different topology, bead placement, and substrate outline combinations for building more complex structures. They can serve as a transformation and geometric reference for the demonstrational artifacts described in the later sections. In the table below, the morphing from a flat sheet to a volumetric structure (from left to right) takes place in ~1 hour in saline water.

3.3.1 Generative Geometries. In the computational design platform, we provide two predefined generative shape libraries for users i.e., branching system and kirigami system. Both of them can automatically suggest layout paths for beads in their output.

3.3.2 Branching System. We adopted the Diffusion-Limited Aggregation (DLA) method [34] to develop rule-based branching generative structures. While these skeleton lines serve as potential bead layout paths, a non-uniform parametric thickening post-process results in an organic boundary curve with various radius values at different hierarchies of the branch structure. We have added additional randomness in the geometry to mimic naturally occurring forms. (Fig 5a).

3.3.3 Kirigami system. Taking the substrate outline as the basic input geometry, a variety of cutting patterns can be generated by varying different parameters such as the number of concentric cutting cycles, the number of cuts on each cycle, and the size of the gap between cuts (Fig 5b).

Table 1: Morphing primitives based on the structural composition of hydrogel beads on substrates

Primitive Type	2D view	Morphing
Branches		
		
		
		
		
Grid		
		
Kirigami		
		
Curved Folding		
		
Sharp Folding		

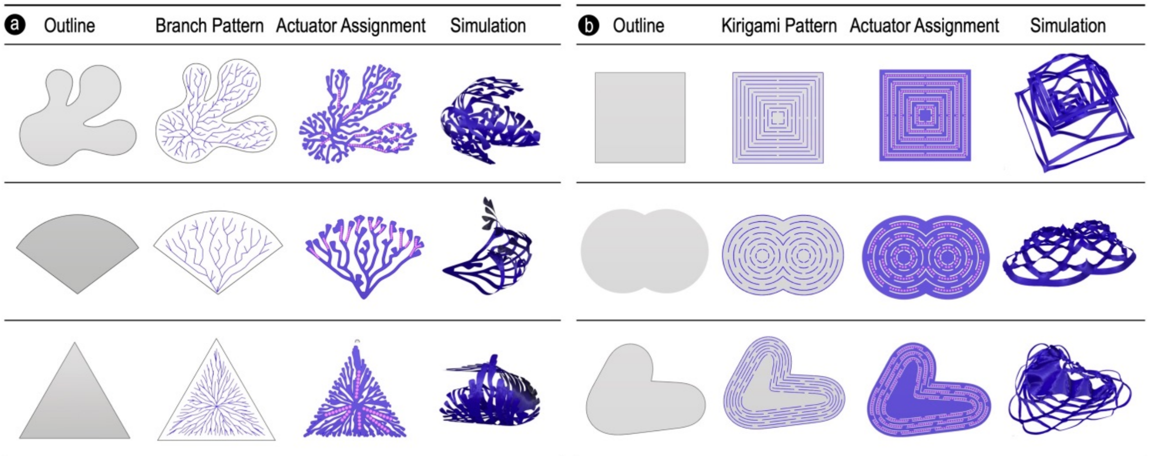


Figure 5: Examples of (a) branch and (b) kirigami patterns generated and simulated by the computational tool.

4 COMPUTATIONAL DESIGN AND FABRICATION WORKFLOW

We present our maker-friendly computational tool. Using this, anyone without prior knowledge of numerical and computational techniques to create morphing structures would easily be able to get started and become familiar with the environment. For both kirigami and branch-based structures, the workflow is similar, which includes generative design and simulation. For branching patterns, we allow more flexibility for defining the types of branches and local curvature, while in kirigami, the pattern is mainly based on the user-defined density of cuts. The user design and fabrication flow for the computational design platform (Fig 8) is composed of the following steps (Fig 6, Fig 7, Fig 9, Fig 10):

Step 1: Specify an outline of the substrate. Users can select a basic outline from the library or draw a closed outline from scratch (Fig 6a).

Step 2: Generate branches that will fill the outline automatically (Fig 6b). Many geometrical features of the branches can be adjusted (Fig 6c - f), such as branch density, branch width, and branch end roundness.

Step 3: Specify the layout of the beads by drawing polylines to indicate which branches to actuate. Beads are generated along those actuation lines (Fig 6g). Users can then adjust the distance between each adjacent bead, which will affect the maximum bending curvature of the corresponding line (Fig 6h). Users can also select the side of the substrate on which the selected beads will reside (defined by a Boolean value – Fig 7c).

Step 4: Simulate the transformation i.e., the morphing behavior (Fig 6i). It can be iterated to reach the desired shape and transformation.

Step 5: Export the outline of the substrate designed in the computational tool for laser cutting and export a .pdf file as a reference for bead placement and adherence to the substrate. Using the digital files generated through the computational tool, cut the designed pattern on a gateway paper and mark the bead locations with a CNC plotter (Curio, Silhouette America) in two sequential steps (Fig 9a).

Step 6: Apply a very small quantity of cyanoacrylate glue to the paper or cloth substrate using a glue dispenser tip, just enough to hold a hydrogel ball. Place the hydrogel balls with tweezers for precision. (Fig 9b). Applying a very small quantity of cyano-acrylate glue discretely at each contact spot is critical for maintaining the flexibility of the substrate. If the glue is applied in a continuous line, the substrate becomes hard and stiff, acting as an additional constraint and reducing the bending behavior's efficacy.

Step 7: Deploy the created shape into a tank with tap water at room temperature (Fig 9c). The full transformation happens in ~12 minutes. The transformation duration in tap water/ normal pH water is faster than saline water.

5 APPLICATIONS

5.1 Demonstrational Artefacts

We fabricated four topologically complex demonstrational artifacts of dimensions 30 cm x 30 cm x 30 cm in which the morphing stimulus comes from the water itself. These are advanced designs based on the morphing primitives. We generated these complex forms using our computational tool following the process described in Section 4. We used a gateway paper sheet as a substrate for building these since it has longer durability in water than copy paper. The branch-based structures are called Florence Bloom and Jeweled Salacia, and the kirigami-based structures are called Euphoria Blossom and Midnight Glory respectively. In the kirigami-based prototypes, only one line of beads can transform the whole structure, while the branch-based ones require a lot more beads, making the kirigami-based prototypes more material-efficient. However, both approaches render unique aesthetics to the prototypes. In the short term, these can serve as self-deployable water tank art pieces and as museum displays for engaging the public. Their unique properties are described in brief.

5.1.1 *Branching Artifacts.*

Branch patterns are inspired by underwater plants, and they are biomimetic and organic. Florence Bloom and Jeweled Salacia (inspired by sea grapes) demonstrate computationally designed structures based on the branch primitives. They

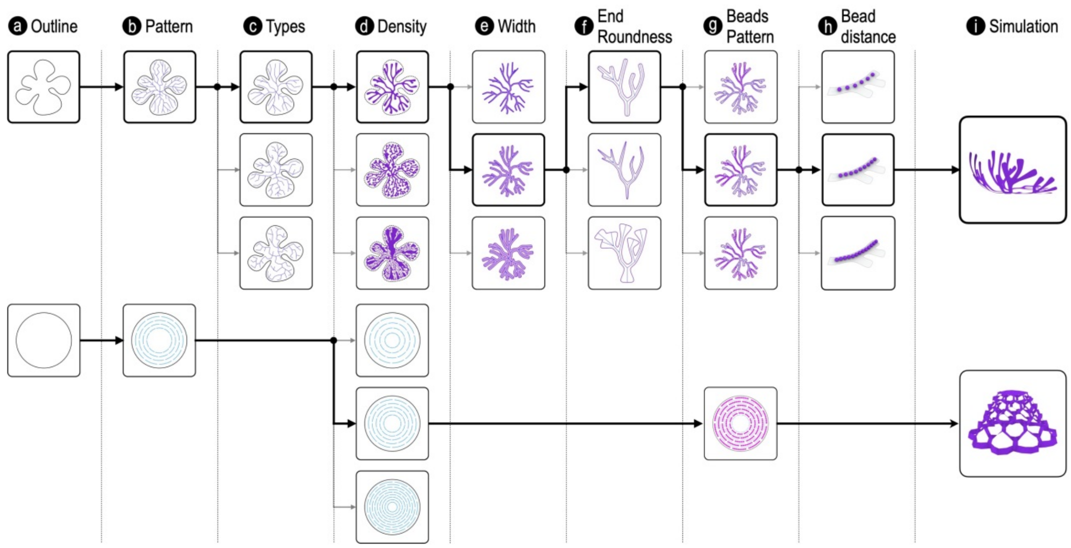


Figure 6: (a) Set outline; (b) generate branch pattern; (c) adjust the branch pattern by choosing different types of branches; (d) specify branch density; (e) specify width of the branch; (f) set end roundness of branch; (g) define actuator region and assign actuators; (h) adjust maximum bending angle through distances between adjacent beads; (i) simulate morphing effect.

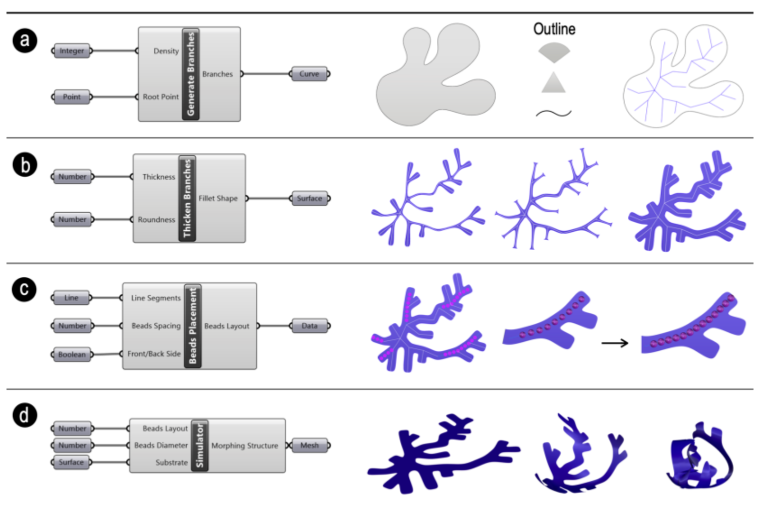


Figure 7: Different input parameters in the computational tool. (a) Define branch density from randomly scattered points that start from the root point; (b) Specify branch thickness and roundness to thicken the central skeleton lines; (c) Pick line segments, define bead spacing, and pick substrate side for bead attachment to determine bead placement; (d) Simulate the structure's actuation by increasing the bead diameter

are constructed by multiple substrate layers (Fig 11) with careful placement of beads which allow the layers to bend inwards. The difference between the two is that the layers of Jeweled Salacia are linear, while those of Florence Bloom have disc-like substrate units.

5.1.2 Kirigami Artifacts. Euphoria Blossom and Midnight Glory are kirigami-based structures. The benefit of the kirigami approach is that they can morph from a single flat shape to a fully opened blooming state (Fig 12), which further pushes the limit of flat-pack and space-saving deployment. In Euphoria Blossom, the line of hydrogel beads transforms and bends the structure upwards, and the patterned cuts on the paper give it a unique shape (Fig 12a). Whereas in Midnight Glory, the substrate strip with beads is placed face down, and its actuation makes it bend outwards with the hinge unit, pulling the structure up (Fig 12b).

5.2 DIY Toolkit

To enable anyone to design and fabricate morphing structures easily, we created a DIY toolkit (Fig 13) which has the following: substrate

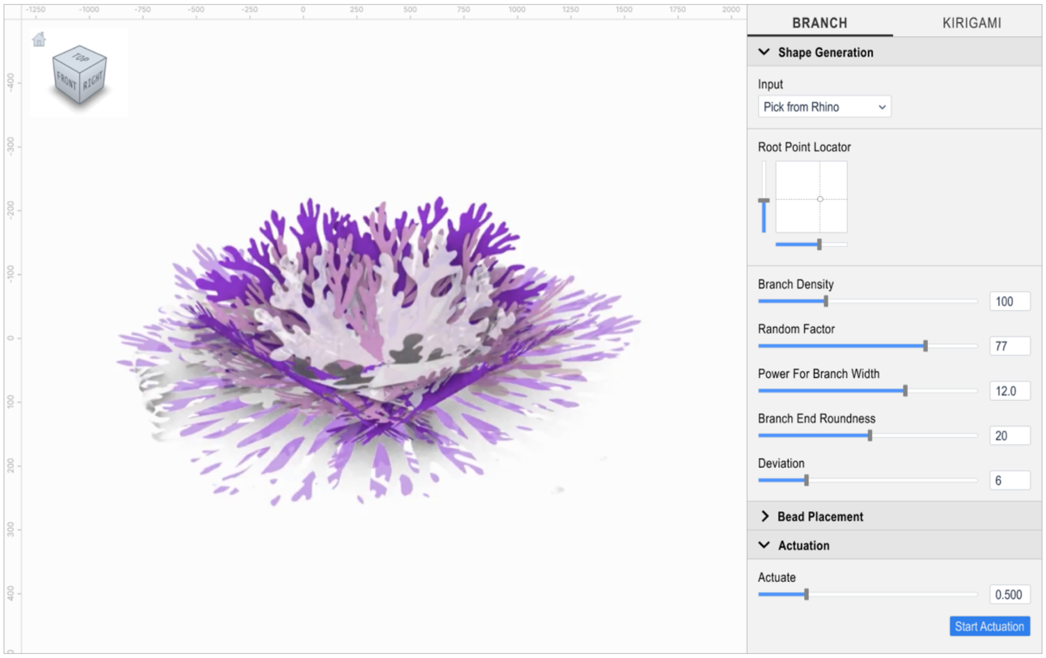


Figure 8: User operation pipeline for the computational design platform

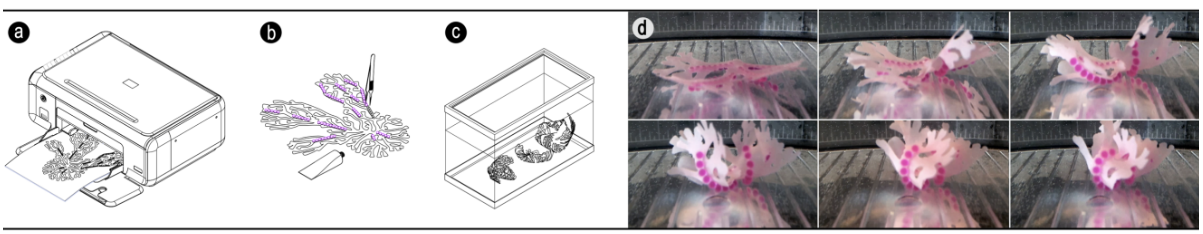


Figure 9: Fabrication and triggering process (a) Cutting a pattern and marking bead location with CNC plotter; (b) Application of beads with cyanoacrylate glue using tweezers; (c) Deployment of structure in a water tank; (d) Triggering and sequential transformation process of a primitive branch structure.

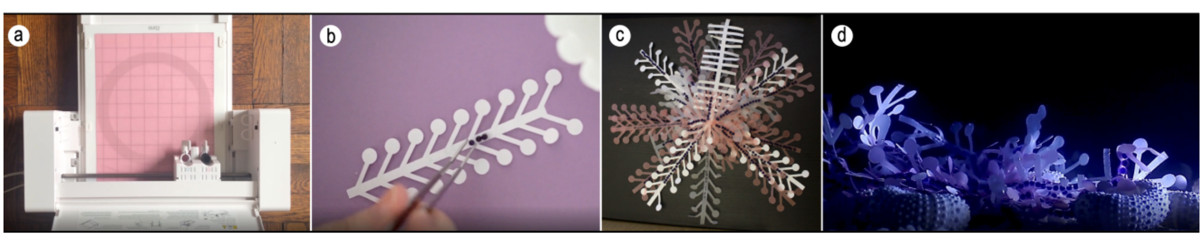


Figure 10: Various stages of production for creating a physical morphing artifact.

outlines printed on gateway sheets, hydrogel beads, a pair of tweezers, a placement tool, and cyanoacrylate glue. Users can cut the substrate outline and follow the process described in 4 to create their structures. They can pick which patterns they want in their toolkit from a library and create novel artistic explorations. We have received great interest from K-12 classroom teachers to make their students try our DIY toolkit. In the short term, we will run workshop studies, observe how students are using the toolkit, and use the learnings to improve it. In the long term, we plan to build on this research to create more robust artifacts for potential coral conservation efforts.

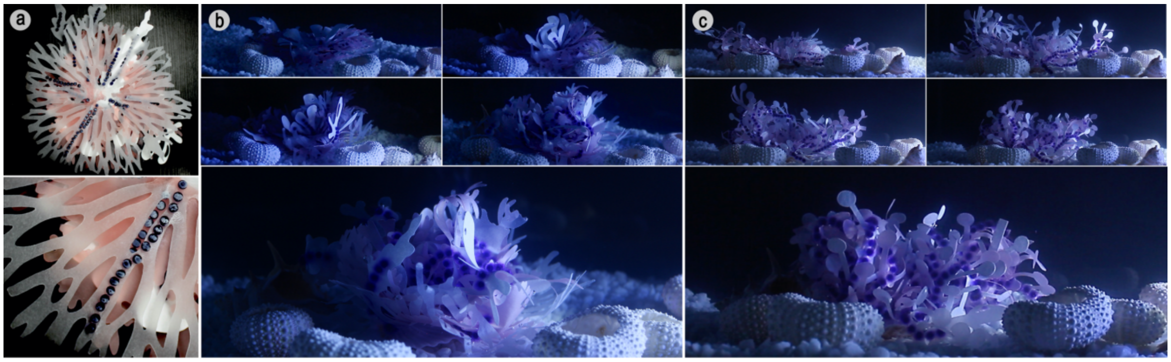


Figure 11: (a) Florence Bloom fabricated with multiple substrate layers, (b) Sequential transformation of the branches of Florence Bloom, (c) Step-by-step morphing of Jeweled Salacia.

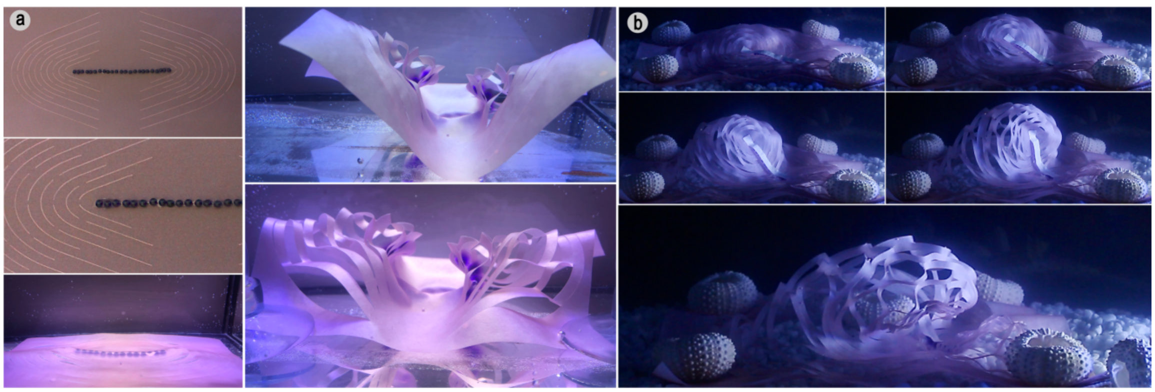


Figure 12: (a) Kirigami pattern with a line of beads and sequential transformation of Euphoria Blossom, (b) Gradual rise and sideward bending of Midnight Glory

Figure 13: DIY Toolkit for makers

6 LIMITATIONS

There are limitations in our fabrication process, scalability, and deployment as discussed below which open up exciting directions for further developing the structures and tool.

6.1 Automated Bead Deposition

Our current individual bead placement method is time-consuming but serves as a proof of concept. While there can be slight errors in bead placement by users, high topological complexity is much more significant than achieving high bead placement precision for our application. However, for the scalability of operations, the bead adherence process can be automated.

6.2 Simulation

The current simulation considers the substrate as a thin sheet without accounting for its thickness. In reality, if beads were adhered to a harder or thicker substrate such as a metal sheet, the bending behavior would be much different than what it is for a flexible substrate such as paper or cloth. Additionally, the bead layout is limited to individual straight lines. In the future, we hope to include more complex actuator patterns such as curved lines [15] or diagonal patterns.

7 CONCLUSION

This paper presents the technical contribution of bending angle quantification experiments to create morphing structures, a novel computational tool and simulator for creating generative geometries and simulating their morphing behavior, along with some morphing primitives. To democratize an easy-to-replicate and hands-on fabrication process of creating generative geometries, we introduced an electricity-free approach that requires very inexpensive off-the-shelf materials (beads, paper, and super glue) and tools (scissors/ precision knife) and water at room temperature as the morphing trigger. This work will enrich the existing toolkit of shape-changing materials and may push the design explorations of morphing materials in more inclusive settings such as K-12 classrooms, STEM workshops, museums, etc. Going forth, we hope to explore interactive design spaces enabled by such morphing composites with participatory workshops by inviting designers, makers, and students of different age groups.

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