MilliWare: Parametric Modeling and Simulation of Millifluidic Shape-changing Interface

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ABSTRACT

The innovative millifluidic chamber-based pneumatic interface facilitates the creation of high-frequency, sequentially controlled, and finely detailed deformations—challenging to achieve using traditional pneumatic setups. This advancement finds applications in information visualization, interactive entertainment, and product design. Yet, designing such interfaces demands extensive empirical knowledge, and predicting their deformations remains complex, requiring exhaustive experimentation and design iterations. This study introduces a millifluidic pneumatic interface design tool that employs parametric modeling and simulation. This innovation simplifies structural design and modeling, offering real-time deformation previews. By utilizing this tool, the design process is streamlined, allowing users to prioritize creative exploration, such as inventing new interface forms and envisioning novel applications.

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**.

KEYWORDS

shape-changing interface, computer aided design, pnuematic interface, design tool

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1 INTRODUCTION

As a prominent subdivision of Tangible User Interfaces (TUIs) [3], the filed of Shape-changing Interfaces [1, 15] has garnered substantial attention over the last several decades, resulting in a proliferation of related research. Shape-changing user interfaces aim to seamlessly integrate physical objects with digital information, enabling users to interact with digital content through natural modes like touch, grasp, movement, and assembly. By harnessing emerging technologies like electromechanical actuators and innovative smart materials, shape-changing interfaces not only passively perceive user actions but also manifest digital content in the physical world via morphological transformations, autonomous movements, and changes in material textures [12].

In the early stages of development, pneumatic technology found extensive utilization in the field of soft robot actuation. Internally, soft robots utilize chambers driven by pneumatic or hydraulic systems to achieve deformation. These chambers, with diverse configurations, enable a range of robotic motion postures [11]. Drawing inspiration from this background, previous endeavors like PneUI [18] integrated this technology into the design of shape-changing tangible interfaces. This was achieved by casting and solidifying elastic materials, such as silicone, within customized molds, resulting in inflatable pneumatic shape-changing interfaces capable of altering shape, texture, and volume. Moreover, by incorporating flexible circuits, these interfaces gained sensing and input capabilities. Expanding upon this foundation, other projects like aeroMorph [14] and Printflatable [16] introduced a fabrication approach that involved automated heat-sealing of dual layers of thermoplastic film using CNC machining. This enhanced the customization potential of pneumatic shape-changing interfaces, significantly accelerated prototype production, and reduced fabrication costs. By undergoing morphological changes, pneumatic soft interfaces facilitate information presentation, dynamic functional affordances, and tactile feedback, finding applications in domains such as information visualization, entertainment, productivity enhancement, interior decor, smart agriculture and product design [2, 5, 7–9, 16–18].

When designing shape-changing user interfaces, the conventional workflow entails users initiating with structural design and modeling grounded in their expertise. Subsequent phases involve fabricating prototypes through techniques like 3D printing or CNC machining. These finalized designs then undergo empirical testing to verify their functionality. However, this iterative cycle can be

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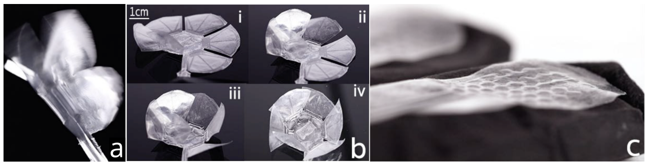


Figure 1: Exemple applications of milliMorph interfaces [6]: (a) a butterfly robot, flapping at 10Hz; (b) 4D fabrication achieved via sequentially deformation; (c) high resolution texture render for finger tip haptic feedback.

time-intensive. To tackle such concern, the HCI field has delved into tailoring computer-aided design and simulation tools [4, 10, 14] to provide a solution. These tools empower users to swiftly assess designs during the modeling stage, effectively diminishing the burden associated with experimentation and iteration. For instance, aeroMorph devised a dedicated design software for pneumatic shape-changing interfaces. This software facilitates the simulation of deformation effects, particularly in interfaces comprising diamond-shaped welded seams.

Previous research on pneumatic shape-changing interfaces mainly focused on centimeter, meter, or larger-scale gas pipelines and chambers[10, 14, 16–18]. Some researchers also provided design tools of millimeter-level fluidic systems on hydraulic color-changing interfaces[13, 19]. However, with the advent of milliMorph[6], which introduced pneumatic shape-changing interfaces at the millimeter scale, the pneumatic fluidic characteristics at the micro-scale enabled novel forms of outputs such as high frequency actuation, high-resolution deformations and sequentially controlled transformation (Figure 1). Leveraging these new deformation capabilities has enriched the design space for interactive pneumatic shape-changing interfaces. Nevertheless, the conventional design tools developed for large-scale pneumatic shape-changing interfaces or milli-scale fluidic interfaces are no longer entirely suitable. To address this challenge, we proposed a novel design tool that align with the characteristics of milliMorph interfaces. This design tool aid users in efficiently integrating novel deformation modes and interactive forms into the design and fabrication of interfaces.

2 MILLIFLUIDIC SHAPE-CHANGING INTERFACES

MilliMorph is fabricated using two layers of thermoplastic film, each with a thickness of 20 μm. These layers are processed through a specially designed CNC heat-sealing system. The minimum width of its chambers can be as small as 0.5 mm. The closely arranged micro-scale chambers contribute to smoother lines when the interface performs inflation-actuated bending, resulting in high-resolution deformations (Figure 2). To ensure a high-density arrangement of millimeter chambers, milliMorph employs straight-line folding seams rather than using diamond or curved shapes for the seams. This design choice aims to minimize the area occupied by the seams.

Furthermore, by precisely altering the widths of the conduits connecting the sub-millimeter chambers, milliMorph can regulate fluid flow rates. At the millimeter scale, even slight variations in conduit width result in significant differences in conduit resistance. Exploiting this phenomenon, milliMorph achieves flexible control over the filling time of different chambers, thereby enabling control over the sequence of deformations. As depicted in Figure 3, the fluidic channel connecting three sets of chambers consists of pipes with two different widths: 1.5 mm and 0.5 mm. The discrepancy in resistance leads to variations in flow rate, subsequently influencing the filling and deformation rates of different sets of chambers.

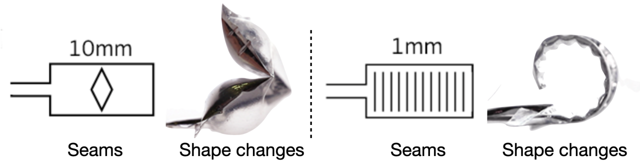


Figure 2: Comparison of shape-changing resolution of (left)1cm- and (right)1mm-width chambers

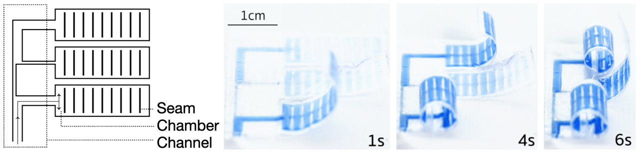


Figure 3: An example of sequence-controlled shape changes

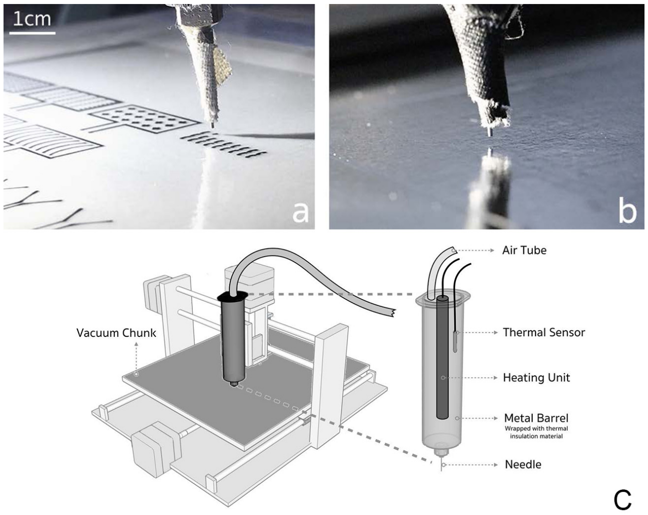


Figure 4: Sealing thin film with NoHAS: (a) Sealing Clear film. (b) Sealing metallized film (c) Hardware platform of the NoHAS System

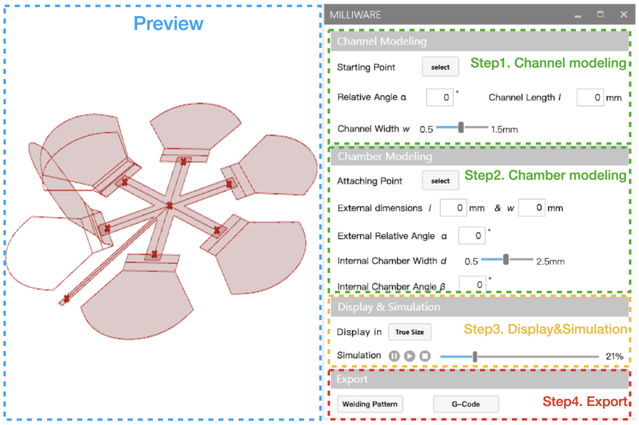
The fabrication process of milliMorph composites can be divided into the following steps. The designer creates a digital drawing of the composite structure, then fabricates this structure using a Non-contact Hot Air Sealing (NoHAS) platform, and finally connects the tube or injects a different liquid medium before closing the seal. Figure 4 illustrates the fabrication step of hot seaing and the hardware platform.

Utilizing these novel features, milliMorph finds applications in 4D rapid manufacturing, ultra-thin tactile feedback layers, intelligent wearable devices, etc [6]. The introduction of these new deformation capabilities and a diverse range of application scenarios also contributes to the increased complexity of design and testing iterations for milliMorph interfaces. To address this challenge, we have designed and developed the corresponding computer-aided design tool called milliWare. With the assistance of milliWare, the design iteration process of millimeter pneumatic shape-changing interfaces is significantly simplified. This enables researchers and designers to focus more on creative aspects of interface morphology and application scenario design, rather than repeatedly adjusting dimensions, modifying models, and fabricating prototype interfaces for testing.

3 COMPUTER AIDED DESIGN AND SIMULATION TOOL

MilliWare offers users a rapid parametric modeling tool, as well as high-resolution deformation and sequential control deformation simulation previews. The holistic interface, depicted in Figure 5, comprises a series of panels, where the *Preview* panel displays the drawn welding patterns and simulation previews through the design procedure. User can go through the design procedure of milliMorph with other panels in the following steps:

- (1-2) Use *Channel/Chamber modeling* panel to edit and model the milliMorph device with a few design parameters.
- (3) Use *Display & Simulation* panel to actuate the real-size display of simulation.
- (4) Use *Export* panel to export vector graph of welding patterns and G-Codes for fabrication.



Starting Point select

Relative Angle α 0 ° Channel Length *l* 0 mm

Channel Width *w* 0.5 1.5mm

Attaching Point select

External dimensions *l* 0 mm & *w* 0 mm

External Relative Angle α 0 °

Internal Chamber Width *d* 0.5 2.5mm

Internal Chamber Angle β 0 °

Display in True Size

Simulation 21%

Figure 5: Overview of milliWare interface

Built upon Rhino 6 and Grasshopper, milliWare leverages the established three-dimensional computer-aided design software Rhino, along with Grasshopper, a visual programming language integrated with Rhino 6. Grasshopper enables the creation of parametric modeling tools for both professional and non-professional users. Through this platform, we on one hand developed customized scripts into Grasshopper components, which cooperate with the platform's existing modules, allowing visual programming to develop customized modeling programs(Figure 6). The tool provides clear and intuitive logical structure, workflow, input data, and output data, which enable users who are professional on Grasshopper to conduct secondary development based on milliWare easily, expanding its modeling capabilities for other types of pneumatic shape-changing interface designs. On the other hand, we also developed a graphical user interface using Grasshopper's built-in plugins. This interface simplifies the process for non-professional users to directly create and modify geometric features by adjusting parameters and simulate deformation effects through intuitive operations (Figure 5).

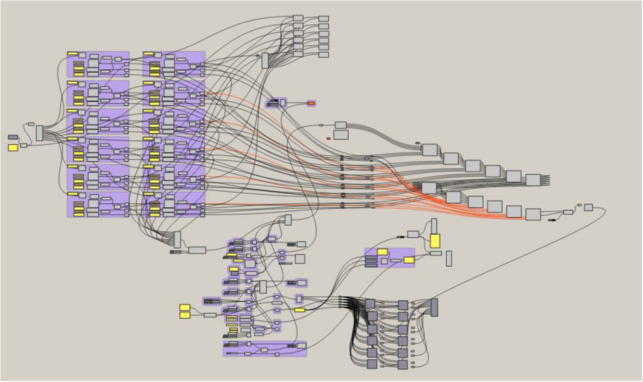


Figure 6: MilliWare is developed based on Rhino Grasshopper

Professionally oriented finite element simulation software for fluid systems typically entails a steep learning curve. Even if users acquire proficiency in software usage, they still need to construct models and analyze boundary conditions for simulations when dealing with customized fluid systems. This can be challenging without relevant expertise. Additionally, these simulations often involve computationally intensive processes, resulting in relatively time-consuming calculations. While Grasshopper does offer some relatively advanced finite element simulation plugins, milliWare's simulation preview functionality is not directly based on finite element simulation. Instead, it employs the following approaches: firstly, for high-resolution deformation simulations, we establish a database of deformation angles under various conditions through experimental testing and simulation calculations. MilliWare employs this database during the simulation process. Secondly, for sequential control deformation simulations, we derive an approximate mathematical model for the interconnected pipe system based on empirical formulas. This allows rapid calculation and comparison of the flow rate within different interconnected pipes. Through these methods, milliWare rapidly furnishes users with relatively accurate simulation results. This facilitates the efficient alteration of the shape-changing interface design, enabling rapid feasibility assessments before prototype fabrication.

3.1 Parametric modeling

As illustrated in Figures 2 and 3, the structure of milliMorph primarily consists of chambers (driven shape-changing effects) and channels (connecting different chambers). Chambers are typically

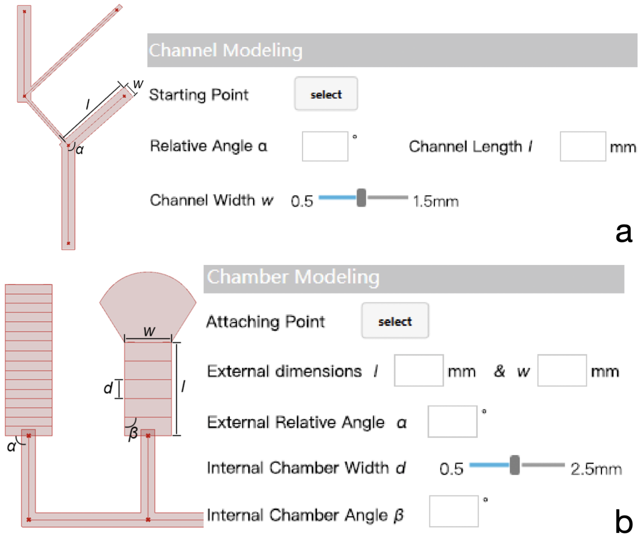


Figure 7: Interface of parametric modeling. (a) Channel modeling panel. (b) Chamber modeling panel.

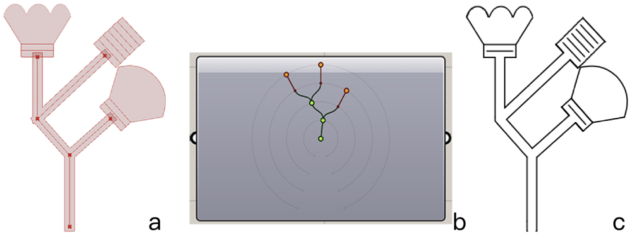


Figure 8: (a) Graphical sketches by user in milliWare. (b) Data tree to store the graphical information by milliWare. (c) Vector graphics of welding patterns generated by the data tree.

Figure 9: Welding pattern export and G-code export

composed of an arrangement of small rectangular chambers, forming an overall rectangular shape that can perform bending and folding deformations when inflated. Channels vary in thickness and are employed for fluid transportation. With regard to the characteristics of the chambers and channels, milliWare provides a parametric modeling pipeline for both components.

Channel Modeling: As depicted in Figure 7a, each channel segment requires the user to input three geometric parameters: the starting point (except for the first channel segment, which is mandatory to select; the starting point must be one endpoint of a previously drawn conduit, and the software automatically assigns sequential numbers to all endpoints for user selection), the relative rotational angle (α), the length (l), and the width (w, 0.5-1.5mm). For already drawn channels, users can modify their relevant parameters after selecting them. Alternatively, users can directly alter the length and relative angle by dragging endpoints within the preview area.

Chamber Modeling: As depicted in Figure 7b, users can sketch chambers at open channel endpoints. Initially, users choose an open channel endpoint (Attaching Point). Subsequently, they input the external dimensions of the chamber (l, w), the internal chamber rotation angle (α), the internal chamber width (d, 0.5-2.5mm), and the rotation angle (β). This sequence of inputs completes the chamber modeling process.

Additional Component Modeling: Furthermore, as depicted in Figure 7b and Figure 8a, apart from the channels and chambers, users can leverage the inherent drawing tools within Grasshopper platform to sketch custom components appended to the termini of the chambers. These components do not contain any chambers or channels, and will be treated as undeformed rigid bodies in simulation.

Simultaneously with user modeling, milliWare is capable of automatically generate the abstract database to store the graphical information of user's models. Given that the actual structure of the connecting fluidic channels does not involve closed-loop configurations, the underlying structure inherently resembles a tree-like topology. As illustrated in Figure 8b, milliWare employs data trees to store the graphical structure of the connecting channels: firstly, the topological arrangement of the data tree imitates the topological structure of the connecting channels as drawn by the user; secondly, each node within the data tree contains a series of data, including channel lengths, widths, relative rotation angles, and the number of subsequent channels or the geometric parameters of the chambers connected to the end of this channel. Through the utilization of the data tree, milliWare comprehensively stores the complete information of the graphical fluidic structures drawn by the user.

After modeling, users can preview the effects through simulation. If they are not satisfied, adjustments can be made to the model until satisfaction. It should be noted that, for the convenience of rapid user modeling and model adjustments, when users use the parametric modeling tool to draw patterns, some auxiliary points and lines (such as the central line and endpoints of a pipe) will be retained in the preview area. There may also be intersections and discontinuities between the lines. These conditions do not affect the simulation; however, the drawn patterns cannot be directly used as the final welding patterns. Once users are satisfied with the preview effects, the Welding Pattern export function (Figure 9) can be used to export the welding patterns suitable for thermal sealing processing. MilliWare will automatically segment and merge the lines of each part based on the geometric information stored in the data tree, delete redundant line segments, and generate seam vector graphics for processing (Figure 8c). After exporting the vector graphics, users can still modify the vector graphics using Grasshopper's built-in drawing functions as needed. Once satisfied, the G-Code export function (Figure 9) of milliWare can be utilized to generate the controlling code for CNC sealing fabrication.

3.2 High resolution shape-changing simulation

Compared to larger-scale chambers, millimeter chambers perform minimal volume expansion during inflation. In the case of millimeter pneumatic shape-changing interfaces, the intrinsic volumetric expansion of the chambers is not a primary design consideration. Designers are primarily concerned with the macroscopic shape changes of the entire interface caused by chamber expansion, such as bending. Relative to the macroscopic interface shape changes, the expansion deformations of the chambers can be effectively disregarded. Therefore, in the simulation process, a two-dimensional simplification of the interface is applied, in order to skip the complex simulation of the expansion deformation of each individual chamber. Instead, the simulation focuses directly on simulating the macroscopic shape changes of the interface.

Based on experimental findings, it is evident that the shape-changing angles of the rectangular chambers employed in milliMorph are primarily influenced by the chamber's width. Through a combination of simulations and extensive experimentation, we have constructed a comprehensive database correlating chamber width with shape-changing angles. During the simulation process within milliWare, the program directly accesses the content of this database, enabling a shape-changing preview rendering. All simulations are conducted under a default pressure of 1.2 bar.

Figure 10a compares the simulation results of the shape-changing process with experimental results. Figure 10b compares the simulation results of shape-changing units with varying chamber widths against their experimental results. It is evident that as the chamber width diminishes, the curvature resolution of the deformation units incrementally improves, transitioning from geometric polylines to smooth curves. The simulation outcomes provided by milliWare align remarkably well with experimental results.

As depicted in Figure 11, in order to provide users with a more intuitive preview of shape-changing resolution, we have incorporated a "True Size" functionality. Upon user activation of the "True Size" button, milliWare will scale the contents of the preview window to render the preview in actual dimensions. The specific scaling ratio will be automatically calculated based on the user's display size and resolution. The "simulation" widget offers options for starting, pausing, and terminating the simulation process. Users can also use a slider to preview the simulated shape-changing process at any stage between the initial state (0% deformation) and the final state (100% deformation).

3.3 Controlled sequence shape-changing simulation

In comparison to the relatively standardized rectangular design of the deformation chambers, the design of connecting channels is notably more flexible and versatile, making it challenging to establish a database through experiments or simulations in advance.

Given the variations in geometric dimensions such as thickness and length of connecting channels, the resistance experienced by air flow differs across different channels. Consequently, certain chambers might fill with air more readily, while others inflate at a relatively slower pace. This variation in inflation rates contributes to a sequential order of shape changes among multiple pneumatic chambers. Within milliWare, our primary focus lies in qualitatively simulating the sequence of such shape changes. This simulation aids designers in controlling the order of the chambers changing their shapes by adjusting the structure of the connecting channels.

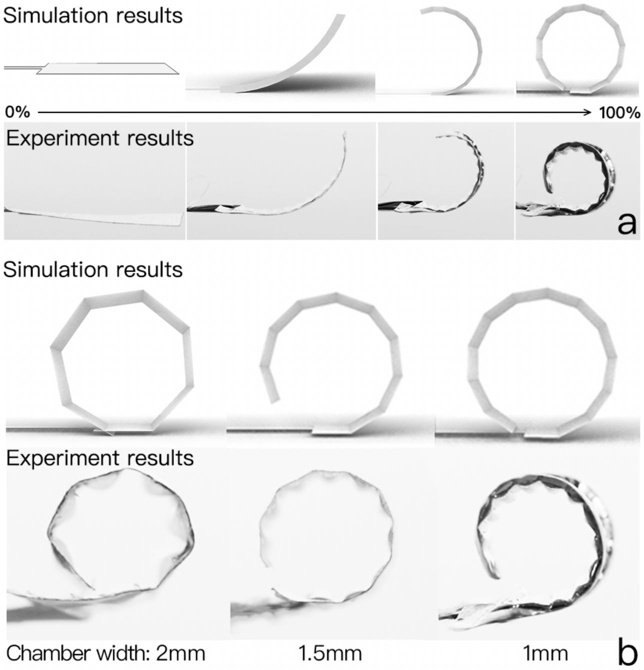


Figure 10: Examples of high resolution shape-changing simulation. (a) Simulation and experiment results of bending primitive's shape-changing process. (b) Simulation and experiment results of bending primitive with varying chamber widths.

Figure 11: Display & simulation panel

MilliWare employs the following mathematical models for the connecting channel system: Initially, each channel segment i is assigned a fluid resistance weight r_i. In this context, each channel segment is approximated as a cylindrical channel. According to the calculation formula for flow resistance in microfluidics for cylindrical channels (Equation 1), it is evident that the resistance encountered by flowing gas or liquid is directly proportional to the length L of the channel and inversely proportional to the fourth power of its diameter d. For a given connecting channel system, other parameters in the formula (μ for dynamic viscosity) remain constant or are approximated to be the same. Consequently, the value of $L/(d^4)$ can be regarded as the fluid resistance weight r_i of a channel segment i (Equation 2).

$$R = \frac{128\mu L}{\pi d^4} \tag{1}$$

$$r_i = \frac{L}{d^4} \tag{2}$$

Then, milliWare calculates the cumulative resistance weight R_j for each individual chamber j, which reflects the resistance experienced by the gas or liquid flow from the inlet to chamber j. As expressed in Equation 3, R_j is calculated by firstly identifying each channel segment i within the path l that leads from the inlet to chamber j, and then summing up the resistance weights r_i of these channel segments within the path l to obtain the cumulative resistance weight R_j.

$$R_j = \sum_{i \in l} r_i \tag{3}$$

At last, milliWare designates the chamber j with the maximum R_{jmax} as the one that reaches a fully deformed state when the simulation interface's percentage bar is dragged to 100%. MilliWare then calculates the ratio of the R_j of other chambers to the maximum R_{jmax}, and uses the ratio to determine at which simulation percentage each chamber will attain complete deformation. This mechanism effectively controls the sequential order of deformation for the various chambers within the simulation process.

As depicted in Figure 12, we conducted comparative tests that demonstrate the simulated results with the experimental results for various channel systems. In the given examples, the flower achieves distinct folding patterns through different folding sequences. The simulation outcomes align remarkably well with the observed real-world results, demonstrating a high degree of correspondence between simulated and actual deformation behaviors.

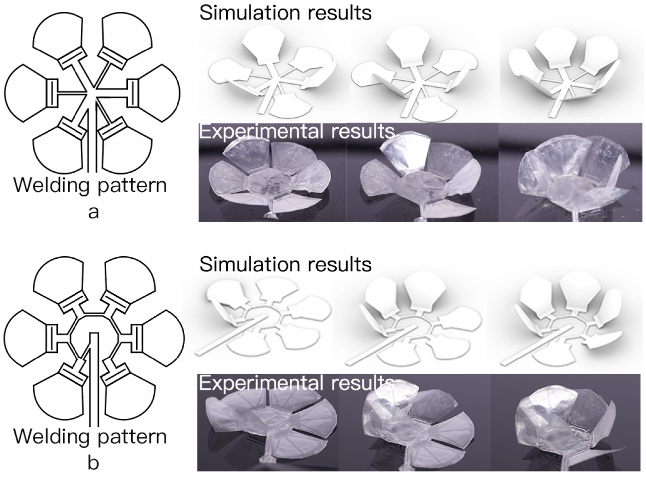


Figure 12: Examples of controlled sequence shape-changing simulation. (a) The petals are divided into two groups and folded sequentially. (b) The petals are folded clockwise sequentially.

4 CONCLUSION

This work has been dedicated to the research and development of a parametric design and simulation tool for millimeter pneumatic shape-changing interfaces. Our efforts have effectively lowered the design barrier, streamlined the iterative design process, and empowered designers to channel their creative energies into shaping the interface aesthetics and application scenarios. Through this research, we have also identified certain aspects that could be further refined. For instance, in the context of sequential shape-changing simulation, the variation in chamber sizes can influence simulation outcomes. In our current design, we advise users to maintain similar or approximate uniform dimensions for all chambers to control the deformation sequence. Furthermore, the present shape-changing simulation only provides qualitative outcomes; in future work, we intend to establish more precise mathematical models with the aim of achieving relatively accurate quantitative results.

In summary, the study of shape-changing tangible interfaces inherently involves interface design, fabrication, and testing. Developing corresponding computer-aided design tools to simplify the iterative design process has become a crucial aspect of such research. While this work primarily focuses on millimeter pneumatic shape-changing interfaces, the principles and forms of the developed design tools can be similarly applicable to various other types of shape-changing tangible interfaces. Moreover, this tool is built on an open-source platform and realized through modular graphical programming, making it conveniently extensible and adaptable for further development and expanded functionalities.

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