PneuSeries: 3D Shape Forming with Modularized Serial-Connected Inflatables

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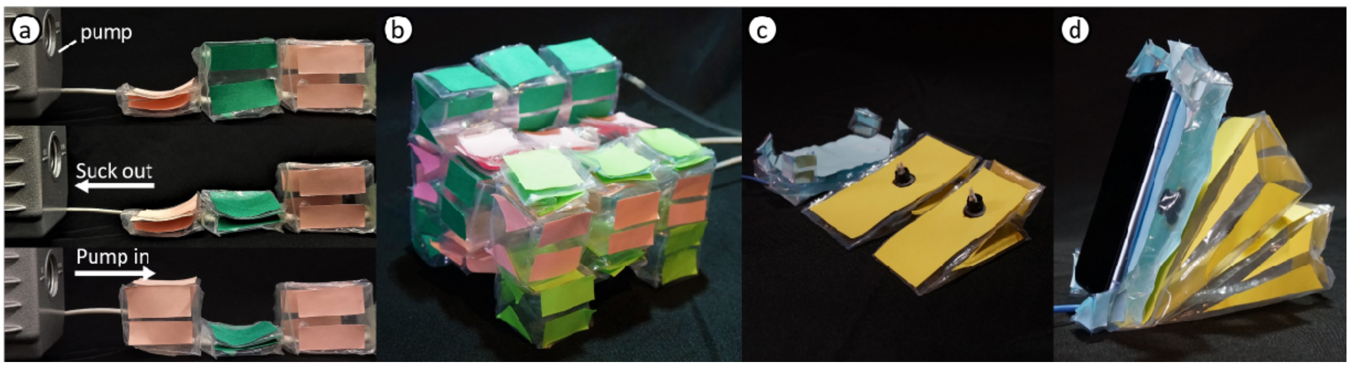

Figure 1: (a) PneuSeries are multiple inflatables connected in series that are controlled by a sequence of pumping in/out the air to form various shapes by propagating inflation/deflation in between. (b) A $3 \times 3 \times 3$ PneuSeries that are programmed to form a chair. (c) PneuSeries inflatables are modularized in primitive shapes (a cuboid in blue and prisms in yellow) and can be quickly connected through the fast assembly connectors. (d) A smartphone holder made of PneuSeries where the tilt angle can be programmed.

ABSTRACT

We present PneuSeries, a series of modularized inflatables where their inflation and deflation are propagated in-between stage by stage to form various shapes. The key component of PneuSeries is the bidirectional check valve that passively regulates the air flowing in/out from/to adjacent inflatables, allowing each of the inflatables to be inflated/deflated one by one through serial propagation. The form of the inflatable series thus is programmed by the sequential operations of a pump that push/pull the air in/out. In this paper, we explored the design of PneuSeries and implemented working prototypes as a proof of concept. In particular, we built PneuSeries with (1) modularized cubical, cuboidal, tetrahedral, prismatic, and custom inflatables to examine their shape forming, (2) fast assembly connectors to allow quick reconfiguration of the series, and (3) folding mechanism to reduce irregularity of the shrunken inflatables. We also evaluated the inflating and deflating time and the flow rate of the valve for simulating the inflating and deflating process and display the steps and time required to transform in our software. Finally, we demonstrate example objects that show the capability of PneuSeries and its potential applications.

*Both authors contributed equally to this research.

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CCS CONCEPTS

• **Hardware** → **Emerging technologies**.

KEYWORDS

Shape-changing interface, pneumatic devices, multi-inflatable systems

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1 INTRODUCTION

Shape-changing interfaces enable computers to physically interact with users and have long been a research interest. Prior surveys have examined the design space [15, 19] and identified the grand challenges [1] of the shape-changing interfaces. Among all the approaches, pneumatic shape-changing interfaces have a great potential for miniaturizing device form factors because they are lightweight and able to change the volume freely to form various shapes. Many researches have explored pneumatic shape-changing interfaces using multiple customized inflatables [23, 26] and inflatable matrices [20, 24]. The former fits more for particular uses, while the latter is more generic in representing shapes.

However, in these multi-inflatable systems, each inflatable requires a tube and an active valve that connects to the pneumatic actuation system for pumping in/out the air independently. This constrains the layout of inflatables to avoid the tubes and limits the scalability of the system by the number of active valves.

In this paper, we contribute a novel multi-inflatable shape-changing interface that alleviates the layout constraints. Inspired by a sequential motion control of a soft robot [13], we achieve more flexible 3D shape forming systems and their fabrication by controlling each inflatable in *series* instead of in parallel. We propose PneuSeries, modularized inflatables that allow the airflow to be propagated in-between stage by stage. As shown in Fig. 1a, 3 inflatables are connected in series with a pump connected with the leftmost inflatable deflated. As the pump draws out the air, the middle is deflated while the rightmost maintain inflated. The pump again pushes the air in, and only the leftmost is inflated, finishing the forming. The key component of PneuSeries is the bidirectional check valve connector that passively regulates the airflow between adjacent inflatables. The air flows only when the differential pressure between two adjacent inflatables is larger than a cracking threshold.

PneuSeries largely reduces the overheads required to control the same number of inflatables, enabling new types of 3D forming. Fig. 1b shows an example of PneuSeries using 27 inflatables and 3 control tubes to form a chair with a cavity at the bottom and inner structure. In addition, PneuSeries is scalable with self-folding modularized primitives and fast assembly connectors as shown in Fig. 1c. For example, the smartphone holder in Fig. 1d is made of 1 cuboidal and 2 prismatic inflatables. The tilt angle of the smartphone holder is programmed by a sequence of inflating and deflating operations.

The rest of the paper is organized as follows. We start with a brief review of past literature in section 2. We describe the design and implementation and elaborate how PneuSeries is programmed by a series of pump operations in section 3. We report our technical evaluation on capabilities of PneuSeries in section 4. We demonstrate PneuSeries with example objects and applications in section 5. Finally, we discuss limitations and potential directions to improve the current prototype in section 6.

2 RELATED WORK

Shape-changing interfaces have been thoroughly reviewed by recent studies [1, 15, 19]. In this section, we briefly touch on most related topics: pneumatic shape-changing interfaces and modular tangibles.

2.1 Pneumatic Shape-Changing Interfaces

Pneumatic shape-changing interfaces have the advantage of freely changing the volume, forming large and complex shapes on demand while shrinking into a sheet for storage. Many researchers thus have proposed the uses of pneumatic interfaces in various scales. Poimo [10] presents a new family of portable and inflatable mobility devices made of a mass-manufacturable material. PuPoP [23] uses one or more inflatables to represent handheld objects in VR. TilePoP [24] builds a 3D array of stacked cubes for human-scale haptic feedback. LiftTile [20] uses a party-horn-liked structure to build a modular system for large-scale prototyping and interaction. Researchers even have explored concatenating inflatables to construct the structure of furniture or building [22].

Beyond representing shapes, researchers also have investigated other functionalities of pneumatic interfaces. AeroMorph [11] explored the shape forming of heat-sealed hinges. BlowFab [25] and PneUI [26] using compositing material to achieve curved shapes or to change texture and stiffness.

2.2 Modular Tangibles

Modular tangibles have the advantage of scalability. Researchers have proposed modular systems for construction kits. StrutModeling [7] constructs 3D shapes by assembling struts and hubs with embedded actuators and sensors. HapTwist [27] uses modules like Rubik's Twist to form shapes as physical proxies. ChainFORM [9] connects servo motors in series which forms linear shapes dynamically. Topobo [14] is a set of modules for building 3D shapes with the ability to record and playback physical motion. Changibles [17] and Cubimorph [16] are shape-changing robots that leverage a modular and reconfigurable design to achieve different geometries. JamSheet [12] layers jamming [2] to control the deformability of the interfaces.

Swarm robots are more advanced modular tangibles that are autonomous. Zooids [6] provide tangible interactions through the collective behavior of small robots. SwarmHaptics [5] explores the design space of using swarm robots to provide haptic feedback. ShapeBots [21] merge the shape-changing functionality to achieve a 2.5D shape display. The number, size, weight, and power of actuators are still the main limits to scale up these systems.

3 PNEUSERIES

Our primary goal is to relax the layout and the scalability constraints by removing the control overheads, i.e., tubes and active valves in multi-inflatable systems. PneuSeries achieves this by (1) bidirectional check valve connectors, (2) self-folding inflatable modules, and (3) sequential control programs.

3.1 Bidirectional Check Valve Connector

The bidirectional check valve is the key component in PneuSeries. It enables control of each inflatable in the multi-inflatable systems in *series* rather than in parallel. It passively regulates the airflow between two adjacent inflatables, allowing inflation and deflation to be propagated between inflatables one by one. This eliminates the need to connect a tube and an active valve to control each inflatable, thus relaxing the layout and the scalability constraints.

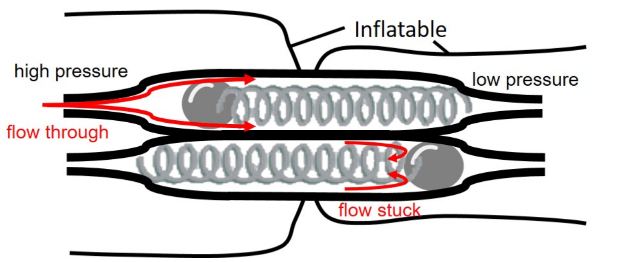

Figure 2: The bidirectional check valve regulates the airflow by the differential pressure between the two adjacent inflatables.

The working principle of the bidirectional check valve is shown in Figure 2. The air flows from the high-pressure side to the low-pressure side only when the differential pressure between two adjacent inflatables is larger than a cracking threshold. In other words, the pressure difference between adjacent inflatables does not exceed the cracking pressure. We used the bidirectional check valve to connect each of two inflatables (Figure 3d) in PneuSeries.

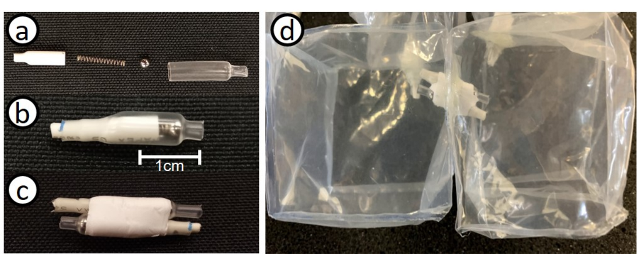

Figure 3: (a) We assembled a steel ball, a spring, and two shrink tubes into (b) a 2-cm ball check valve. (c) We combined two of the ball check valve reversely into our bidirectional check valve. (d) Adjacent inflatables in PneuSeries are connected using the bidirectional check valve.

Our bidirectional check valve consists of two ball check vales [3, 4, 8] that are bonded in opposite direction (Figure 3c). We made the ball check valves by ourselves to adjust cracking pressure and form factor easily when prototyping. The ball check valve (Figure 3b) consists of 3 parts: 2 heat shrink tubes, a spring, and a steel ball (Figure 3a). We adjusted the cracking pressure of the ball check valve by putting a spring and a steel ball in the tube and then shrinking both sides of the tube to compress the spring to the desired length. The steel ball then stuck the tube with the desired pressure, preventing the air from flowing in-between. We used 4 mm diameter(transparent) and 3 mm (white) heat shrink tube as the tube and shrunk the tube by the lighter to be 2.5 mm and 2 mm. We used springs with *wire diameter*:0.2 mm, d:2.3 mm, l:13 mm and steel balls with 1/8" diameter.

The bidirectional check valve is then wrapped up in our 3D-printed male screw joint to form a fast and durable assembly connector, pairing with a female screw joint to connect or a cork to stop the airflow (Figure 4a). Additional silicon gaskets are added to prevent leakage. As shown in Figure 4, both the male and female connectors were attached and sealed to the inflatable, allowing the inflatables to quickly connect with each other.

Figure 4: (a) We wrapped the bidirectional check valve with our 3D printed fast assembly connectors: male, female, cork. (b) We attached the fast assembly connectors on the inflatables to (c) quickly connect other inflatables to form PneuSeries.

3.2 Self-folding Inflatable Module

We designed and made a set of primitive inflatable modules at a handheld scale. Inspired by previous works [18, 23, 24], we used 0.08 mm non-elastic PE sheets and a heat-sealer machine(PFS-400) to seal the PE sheet into cubical, cuboidal, tetrahedral, prismatic, and custom shapes to examine their shape forming in PneuSeries. We unwrapped the shapes in 2D as shown in Figure 5, cut PE the sheet accordingly and heat-sealed along the connecting edges.

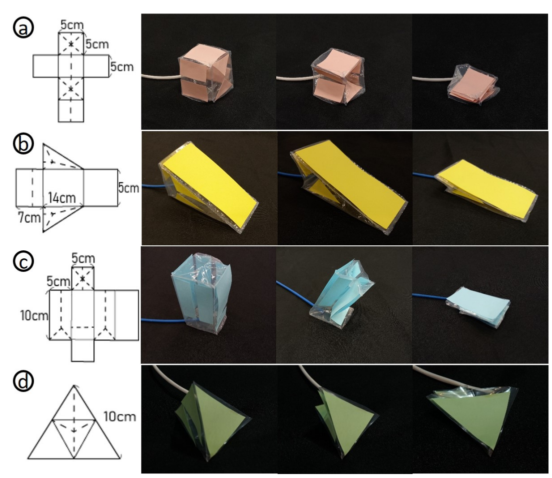

Figure 5: We cut the PE sheet along the drawing and heat-seal them to form cube, triangular prism, cuboid, tetrahedron inflatable. We attached cardboard to the inflatables to fold neatly.

Since the shrunken inflatables are irregular and may affect the forming in series, we devised a folding mechanism on the inflatables. We attached cardboard on the surface of the inflatables leaves gaps along the solid and dashed lines Figure 5. As the inflatable deflates, the cardboard supports the attached surface while the gaps are crushed. Figure 6 shows an example of the cubic inflatable deflates into a flat plane. The dashed lines were empirically found to have the best folding.

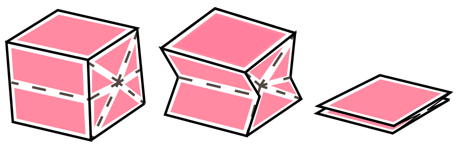

Figure 6: An illustration of our folding mechanism. The cubic inflatable folds along the gaps between the attached cardboard.

Each inflatable in PneuSeries is fully serial and has only two bidirectional check valve connectors attached on two sides of the surfaces. Placing the connectors on different sides results in different configurations. Figure 7 illustrate possible configurations of cube-based PneuSeries. These various configurations then are building blocks to be assembled into complex multi-PneuSeries systems where each inflatable in a PneuSeries is controlled in serial while each PneuSeries is controlled in parallel.

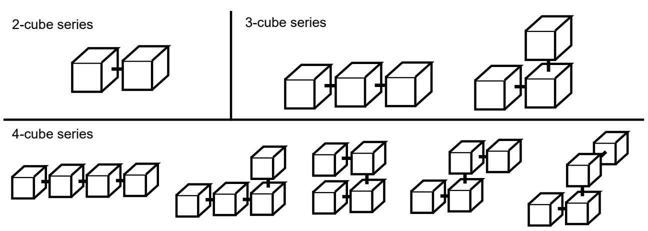

Figure 7: Possible configurations of 2-, 3-, and 4-cube-based PneuSeries.

3.3 Programming PneuSeries

PneuSeries is programmed sequentially as our key idea is to control each inflatable in series in instead of in parallel. That is, only one pump is required to program a PneuSeries. The pump that can vacuum and compress the air is connected to the first inflatables in the series through a check valve to prevent air from flowing back. We then control the forming of the inflatables through sequential operations of pushing/pulling air in/out.

Figure 9 illustrates the entire state diagram of the 3-inflatables series (with the number of total states being $8 = 2^3$). We start with the series of 3 deflated inflatables. When the pump compresses the air, the air would be pushed to inflate the first inflatable. The second inflatable keeps the original state until the pressure of the first inflatable reaches the cracking pressure. The second inflatable would start to inflate if the air continuously pushed in, and then

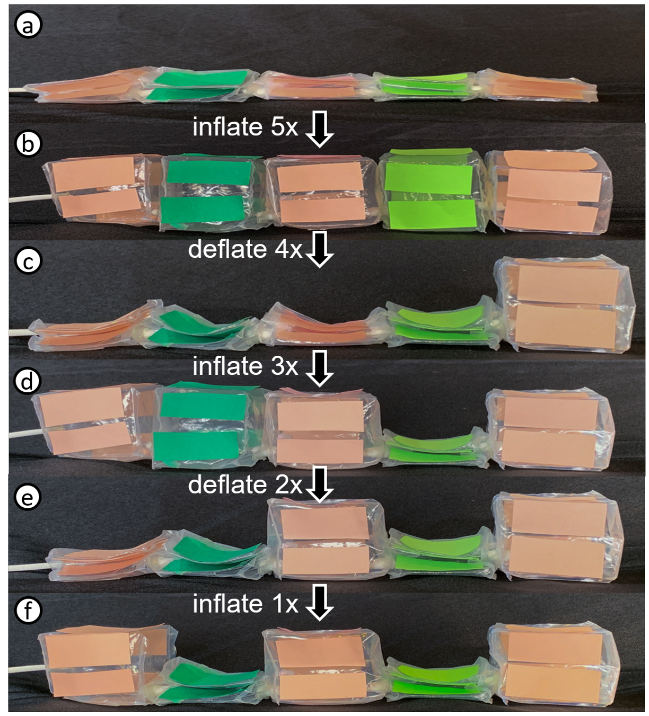

Figure 8: To reach (f) the expected state from (a) the original state. We control the pump to inflate 5 inflatables to form (b), and deflate 4 inflatables to form (c), and then inflate 3 inflatables to form (d), and then deflate 2 inflatables to form (e), and then inflate 1 inflatable to form (f)the expected state

the third inflatable. Similarly, when the pump vacuums the air, the first inflatable starts deflating, then the second, and then the third inflatable. As a result, the series inflatables inflate/deflate in a sequential order instead of inflating/deflating simultaneously.

For a series of inflatables, to reach an expected inflated/deflated state from an original state, we inflate and deflate the series in a specific order. Figure 8 shows an example of a series consists of 5 inflatables. The original state is all of the inflatables are deflated (Figure 8a), and the expected state is only the first, third, and fifth inflatables been inflated (Figure 8f). To reach the expected state, we divide and conquer the unexpected state of the tail in the series. If the state of the tail inflatable is not at the expected state, we push/pull the air in/out of the series until the tail reaches the expected state. We then repeat this process with the next unexpected tail until all the inflatables reach the expected state.

4 EVALUATION

To evaluate the system of PneuSeries and build a simulation software, we conducted several experiments to measure the properties of our system, including the flow rate of the check valve, the time of inflating and deflating. We then built a mathematical model of PneuSeries based on the result of experiments to simulate the inflating and deflating process.

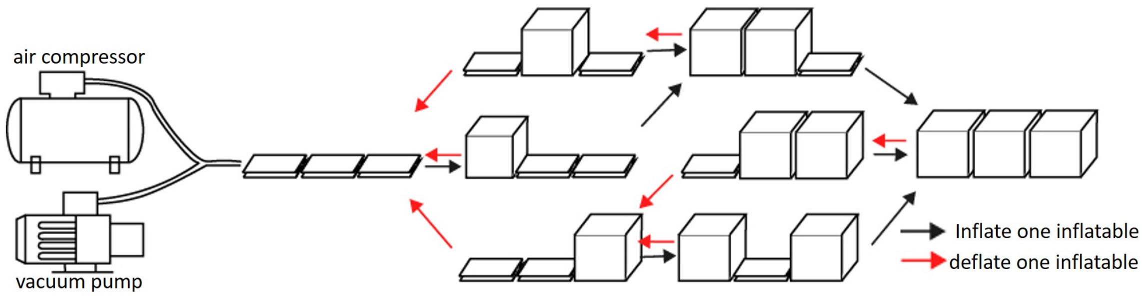

Figure 9: All state transitions of the 3-inflatable series controlled by the sequential operations of a pump

4.1 Flow Rate of The Valve

To predict the time take to inflate or to deflate PneuSeries, we measured the flow rate of the check valve under different pressure differences on both sides of the valve.

We measured the flow rate using the water displacement method with the equipment as shown in Figure 10. We maintained the pressure in the inflatable by putting a constant weight on the piston rod. The pressure of inlet side of the check valve was measured by the barometer and the pressure of outlet side was equal to the atmospheric pressure. Due to the pressure difference, the air exhaust from the outlet to the graduated cylinder through the tube so that we recorded the water level in the graduated cylinder and the timer to calculate the flow rate of the check valve under specific pressure difference.

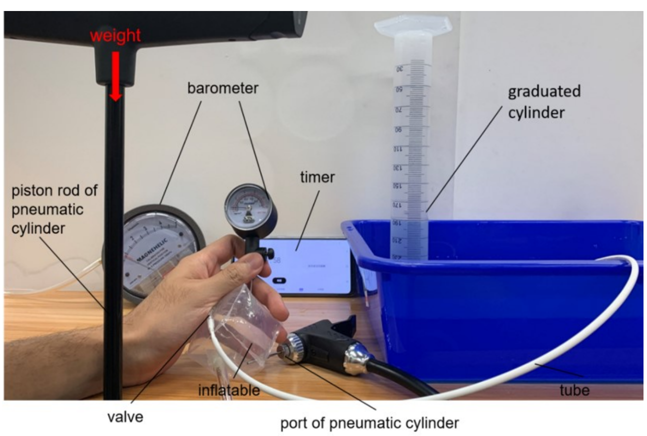

Figure 10: We set up the flow rate experiment and apply the water displacement method.

We experimented with two ball check valves: one had the cracking pressure at 0.15 psi and the other at 0.73 psi. The result of the experiments is shown in Figure 11. The blue line in Figure 11 is the 0.15-psi valve. The orange line in Figure 11 is the 0.73-psi valve. The flow rate of the two valves was roughly proportional to the pressure difference when the pressure was larger than the cracking pressure. There were some oscillations in the flow rate experiment when the pressure difference rises. The reason could be that the shrinking tube of the check valve causes the counter direction flow inside, which interfere with the airflow.

We also found that the minimum cracking pressure of the check valve for the minimum pressure that the inflatable can fully expand from fully deflated was 0.13-psi. It allows one of the adjacent inflatables to be inflated and the other to be deflated if the cracking pressure of the check valve were larger than 0.13-psi.

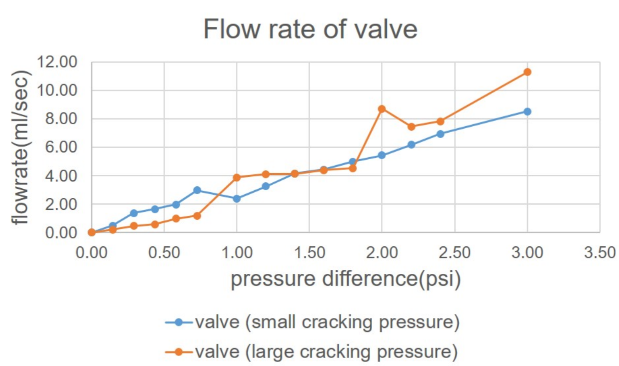

Figure 11: The flow rates of two different valves under different pressure differences. The blue line is the check valve with small crack pressure at 0.15 psi, and the orange line is the check valve with the large cracking pressure at 0.73 psi.

4.2 Modeling Inflating-Deflating Time

During an early experiment, we founded that the inflating time increased significantly after concatenating 5 inflatables in series. To determine the time of changing the inflated/deflated state of an inflatables series from one to another, we built a mathematical model which simulates the inflating and deflating process. From the previous experiment, the flow rate is determined by pressure difference, and the pressure and volume of the inflatable are both functions of the mole number of air. Therefore, We take the mole number of air in each inflatable as state variable, and describe the change as a differential equation.

$$\frac{dn_i}{dt} = flow_v(P(n_{i-1}) - P(n_i)) + flow_v(P(n_{i+1}) - P(n_i))$$

Where n_i is the mole number of air in the ith inflatable, n_i changes with time only due to the air flows in/out adjacent inflatable. $flow$ is the flow rate between adjacent inflatables determined by the bidirectional check valve and the pressure difference between adjacent inflatables using the experiment results of flow rate in Figure 11. The sign of $flow$, that is, the flow direction, is decided by the sign of pressure difference.

We simplify the relationship between pressure, volume, and the mole number of air of the inflatables. We treat air as an ideal gas, where 1 mole of air is 24.58 liters at 1 atm, and the volume of inflatables is limited from 0 to 140 ml, which is the volume of the cubic inflatable when fully expanded. The pressure is -5.0 psi when the mole number of air is zero, which match the pressure of our vacuum pump, and the pressure changes linearly with the mole number of air and reach 0 psi (atmospheric pressure) when the mole number is 0.0057 moles, where the volume of the inflatable is 140 ml. In addition, when the mole number of air is larger than 0.0057 moles, the pressure is equal to the mole number of air divided by the volume of the inflatable (140ml).

We built the model of nine inflatables, which described as a set of differential equations, to simulate the inflating and deflating process.

$$\begin{bmatrix} \frac{dn_1}{dt} \\ \frac{dn_2}{dt} \\ \vdots \\ \frac{dn_8}{dt} \\ \frac{dn_9}{dt} \end{bmatrix} = \begin{bmatrix} flow_v(inletPressure - P(n_1)) + flow_v(P(n_2) - P(n_1)) \\ flow_v(P(n_3) - P(n_2)) + flow_v(P(n_3) - P(n_2)) \\ \vdots \\ flow_v(P(n_7) - P(n_8)) + flow_v(P(n_9) - P(n_8)) \\ flow_v(P(n_8) - P(n_9)) \end{bmatrix}$$

We used the Runge-Kutta method to numerically solve the equation. The orange line in figure 12a is the result of inflating simulation with constant 2.7 psi pressure input, and the orange line in Figure 12b is the result of deflating simulation with constant -5.0 psi pressure input. All inflatables were using the valves with 0.73 psi cracking pressure. The simulation result shows that the time of inflating and deflating rises quickly after connecting more than five inflatables. The pressure of each inflatable during the inflating/deflating simulation is shown in Figure 12c/d. We noticed that the pressure difference between inflatables decrease because the air propagates through the check valve. In the inflating process (Figure 12c), the pressure difference between the 8th and 9th inflatables was about 0.4 psi at 800 seconds, while it was 1.7 psi between 2nd and 3rd inflatables when the pressure of the 3rd inflatable start rising. Consequently, we set the bidirectional check valves cracking pressure lower than 0.4 psi (Figure 11 blue line) and simulated the series of nine inflatables using the valve with small cracking pressure at last five inflatables and the original valve at first four inflatables.

The gray line in figure 12a & b is the inflate/deflate simulation result of the modified series of inflatables, which reduce the time of inflating/deflating all inflatable by 40 percentages/33 percentages. Finally, we made a series of inflatables using the valves based on the modified model and validated the inflating time in a real experiment. The blue line in figure 12a is the actual inflating time, which matches the simulation result. The blue line in figure 12b is the actual deflating time, which has an error compared to the simulation result due to the inaccurate model of the relationship between the mole number of air and pressure at low pressure.

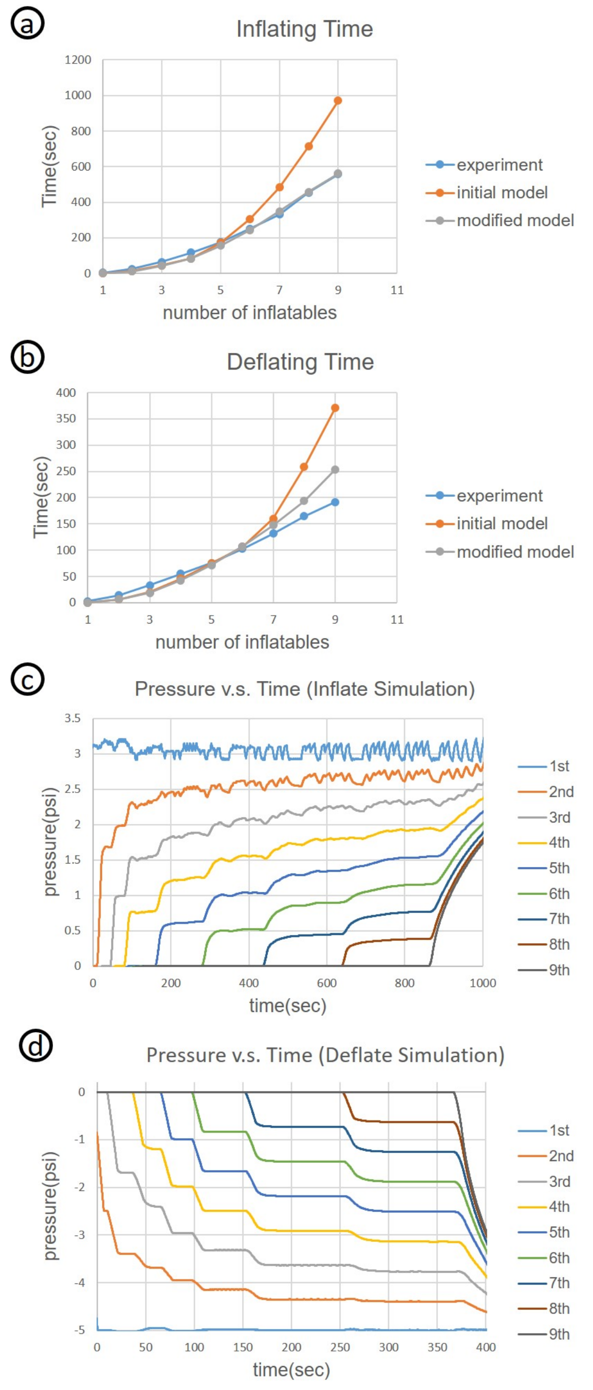

Figure 12: (a) Inflating time per inflatable. (b) Deflating time per inflatable. (c) Pressure per inflatable in the inflating process. (d) Pressure per inflatable in the deflating process

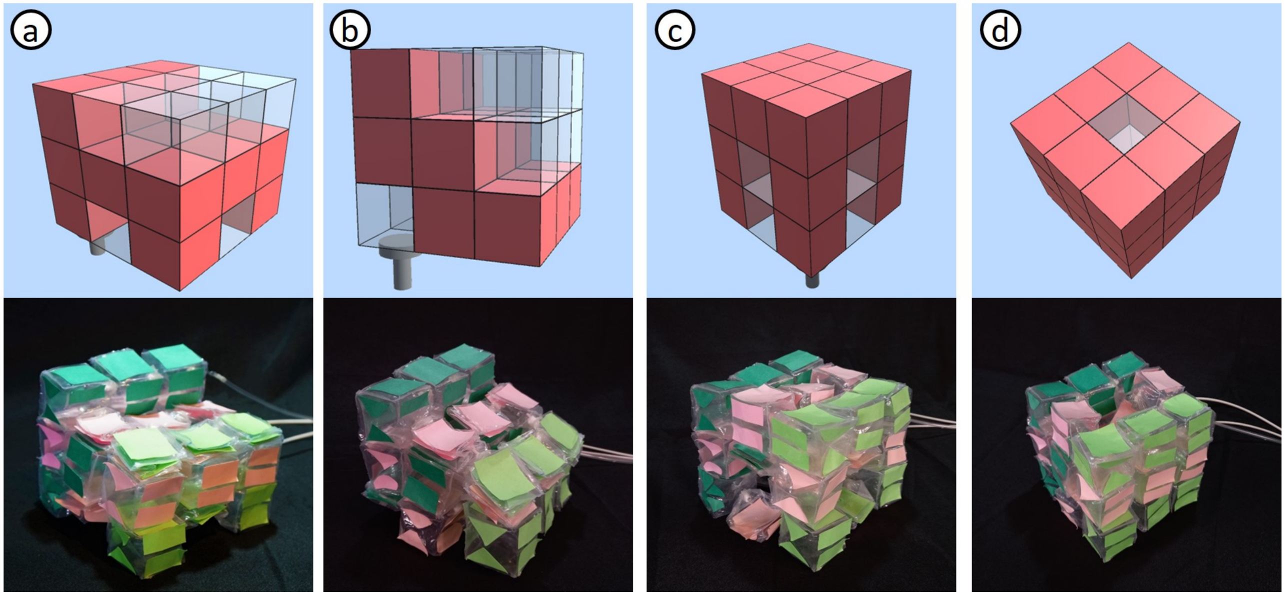

Figure 13: We built a $3 \times 3 \times 3$ PneuSeries by 27 inflatables that are programmed to form (a)a chair (b)a staircase (c) a table (d) a well.

5 APPLICATIONS

We show applications of PneuSeries including our software for designing a multi-PneuSeries system, shape-forming examples through connecting the modular inflatables, and a transformable shape balloon using the customized inflatables.

5.1 PneuSeries Simulation

We designed and implemented a simulation and editing software for users to build prototypes using cube and tetrahedron inflatables as shown in Figure 14. We also used this to explore the potential shape and structure of PneuSeries. Making a PneuSeries in the software has 3 phases: (1) modeling (2) choosing inflatables to inflate/deflate (3) executing.

In the modeling phase (Figure 14a,b), users first select the connecting point on an inflatable in the series. They then choose a cube or a tetrahedron and also select a connecting point and an orientation that they want to connect to the previous inflatable. In the choosing inflatables phase (Figure 14c), users select the inflatables that they want to be inflated or deflated. In the executing phase (Figure 14d), the software generates all the steps to form the expected shape from the original state to the target state.

In Figure 14d, we made a $3 \times 3 \times 3$ cube of 27 cubic inflatables in the editor to explore the shape forming of a multi-PneuSeries system. The $3 \times 3 \times 3$ cube consists of 3 PneuSeries. Each PneuSeries contains 9 cubic-inflatable series that form a flat plane using an S arrangement (like 1-2-3-6-5-4-7-8-9 on a keypad). In the real prototype, these PneuSeries are stacked together with double-sided tape attached to each contacting inflatable surface. These 3 PneuSeries are thus in parallel, controlled by 3 active valves. Each PneuSeries, however, is still controlled in serial.

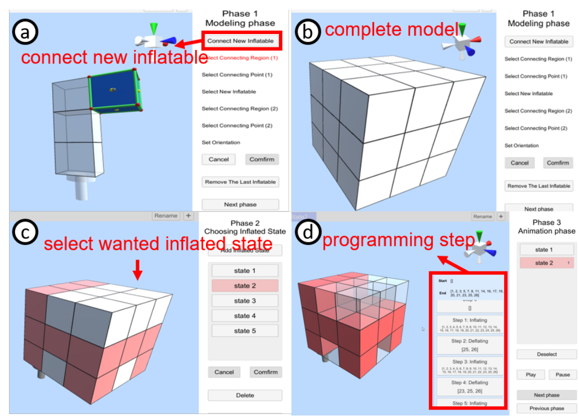

Figure 14: We built a simulation and editing software for PneuSeries. (a) Users can select the connecting point and orientation to connect another inflatable, (b) design layout in the editor by tetrahedron and cube inflatables, (c) choose the inflatables to inflate. (d) In the animation phase, it shows the procedure step by step and indicates the time cost.

In Figure 13, we present 4 shapes including: (a) a chair, (b) a staircase, (c) a table, (d) a well. To provide a detailed look at one of the examples, we point out that the chair is formed by inflating 4 corners at the bottom layer, all inflatables at the middle layer, and 1 edge at the top layer. The bottom layer takes the longest time to arrive at the right state in this case. These examples show the potential of PneuSeries using 27 inflatables to form multiple 3D shapes, including cavities at the bottom.

5.2 Construction Kit

We built a smartphone holder as shown in figure 15. The grabber is made of one cuboid (17 cm × 8.2 cm × 2 cm) and four small triangular prism (base: 3 cm × 3 cm, height: 3 cm) inflatables. The two stands are both triangular prism inflatables (base: 14 cm × 5 cm, height:7 cm). We inflate the grabber and one stand to form the holder in Figure 15b. The tilt angle can be adjusted by changing the number of inflated stands (Figure 15b,c). It takes about 34 seconds to inflate all inflatables in Figure 15.

Figure 15: The smartphone holder made of PneuSeries in which the tilt angle can be programmed.

In Figure 16a,b,c, we built a shelf by a cuboid (23 cm × 23 cm × 5 cm) and 4 cuboid pillars(5 cm × 5 cm × 10 cm).

We introduce a new branch inflatable (1-in-4-out) that allows 4 legs to be inflated in parallel. The 4 legs are inflated/deflated simultaneously after the surface. We inflate the inflatables to form the shape of a one-layer shelf in Figure 16c. In Figure 16d, we connect another shelf with shorter pillar to the original one to form a two-layer shelf. The time to form the two-layer shelf is about 100 seconds, and the shelf can support 600 grams.

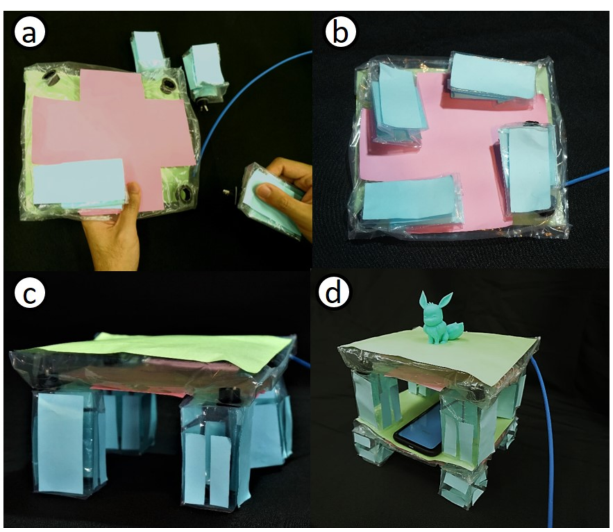

Figure 16: We prototype a shelf with modularized inflatables. (a) We assemble the pillars to the base quickly by fast assembly connectors. (b) Deflated shelf forms a flat surface. (c) We Inflate the shelf. (d) We assemble a modularized shelf to (c) by fast assembly connector forming a two-layer shelf.

5.3 Customized Shaped Balloons

PneuSeries use not only primitive shapes but customized inflatables. We built a shaped balloon consist of 3 inflatables that can transform into a sword and a bow (Figure 17). We make a strip inflatable (width 8cm, length 100cm) and two curved inflatables (diameter:2cm and 4cm, radius of rotation:110cm and 7 cm, central angle: 150 degrees and 330 degrees).

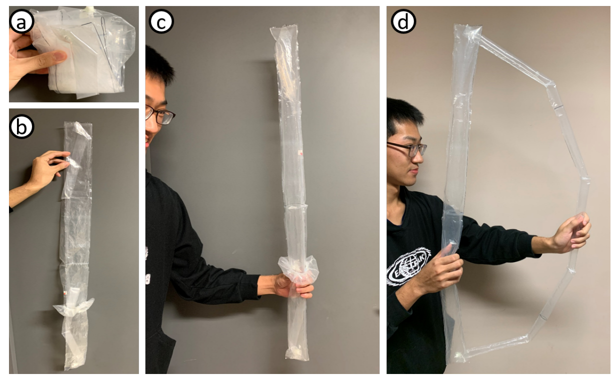

Figure 17: We built shaped balloons using customized inflatables. (a) We fold and deflate inflatables for storage. (b)The shaped balloon is composed of a strip and two curved inflatables. (c) We inflate the strip and smaller curved inflatables to form the sword. (d) We inflate the strip and the larger curved inflatables to form the bow.

We deflate and fold inflatables for storage in Figure 17a. We inflated the strip and smaller curved inflatable to form a sword in Figure 17c. We inflate the strip and the larger curved inflatables to form a bow in Figure 17d. It takes about 22.5 seconds to form the sword/bow respectively. Also, this example shows PneuSeries is able to maintain its shape after disconnecting from the pressure supply.

6 LIMITATION AND FUTURE WORK

We found several issues, including time cost, the number of inflatables, and shape forming, that could be further investigated with current PneuSeries. We discuss these issues and their possible solutions in the following section.

6.1 Preparation Time

As a trade off for less tubes and valves, the inflating/deflating time is long in PneuSeries. There are several factors affecting the inflating/deflating speed in PneuSeries. (1) Maximum pressure that the system can bear: the larger the pressure difference, the faster inflating speed. The inflatables in PneuSeries can bear about 7.8 psi. However, the air may be leakage from the connection point while pressure rising to about 3 psi. (2) Size of bidirectional check valve: the flow rate of the valve is in proportion to the cross-section area. We made the check valve with a minimum 2mm diameter. If we made the valve with a larger cross-section area, the inflating/deflating speed would be faster. However, the weight and shape of the valve would influence the shape forming. (3) Size of inflatables: larger inflatables would take more time to wait for the air pressure to rise.

6.2 Number of Inflatables

In our prototype, we connected up to 9 inflatables in one series. Theoretically, the pressure would drop by the cracking pressure of the valve through the air propagation. Therefore, the maximum number of inflatables that can be connected is equal to the maximum pressure divide by the cracking pressure. The exact number is $3psi/0.15psi = 20$ inflatables in our current implementation.

This limitation brought up the trade-off between connecting inflatables in series to simplify the system and to control the inflatables in parallel to meet the speed requirement and technical capability. The designer should start by composing all our inflatables in series, breaking them into a new layer if the number exceeds the limit, and then binary partitioning the inflatable series into layers until the tubes start to affect the 3D forming.

In the future, we would change the material of inflatables that can afford larger pressure and improve the connection method and inflatables to make the system bear the larger pressure.

6.3 Connecting and Deflating Constraints

There are two problems in shape forming that should be addressed: (1) constraints at connection points, (2) the volume of deflated inflatables. The constraints of connection points limited the position of the deflated inflatables, which makes it unable to present shapes ideally, especially if we stacked many inflatables into a 3D array as Figure 13. The volume of deflated inflatables influences the shape even though we apply the folding mechanism. The deflated inflatables might not turn into a flat plane due to the constraints of connection, and a few air leaks into the inflatables make it look still inflated. In the future, we would explore better folding mechanisms such as using the hook and loop fastener to provide stronger constraints of folded inflatables and the suitable stacking pattern for shape forming.

7 CONCLUSION

We have presented PneuSeries, a multi-inflatable system that has modularized inflatables controlled in a series to alleviate the layout constraints. Through sequential operations of pushing/pulling air in/out, PneuSeries can be programmed to form complex 3D shapes. We implemented working prototypes and demonstrated the capabilities of PneuSeries with series of experiments and example objects. With PneuSeries, users can fabricate customized multi-inflatable systems quickly through the fast assembly connectors without adding a large number of tubes and active valves, achieving a more flexible layout with more inflatables.

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