PneuBots: Modular Inflatables for Playful Exploration of Soft Robotics

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Figure 1: The PneuBots kit features (a) 7 inflatable modules, (b) 3 types of pneumatic connectors, and (c) a custom-designed package. Some of the dynamic assemblies possible with PneuBots, in combination with FlowIO Platform, include (d) a rolling robot, (e, f) different artistic designs, (g) a self-assembled ball, (h) a haptic bracelet, and (i) an interactive flower.

ABSTRACT

PneuBots is a modular soft robotics construction kit consisting of seven types of self-foldable segments with high tensile strength, three types of pneumatic connectors and splitters, and a custom-designed box. The kit enables various assemblies to be made with the modu-lar pieces, allowing creators to explore the world of soft robotics in playful ways. When combined with a FlowIO device, PneuBots allows seamless programmability of the different assemblies, en-abling artists, designers, engineers, and makers to create dynamic, shape-changing, and interactive works that can be used for educa-tion, storytelling, dynamic art, or expression of affect and gratitude. In this paper, we present our current progress towards developing a soft robotics starter kit that is affordable, modular, programmable, and adaptable to users' creative visions. Finally, we discuss some of our preliminary results with users who had the opportunity to try using PneuBots.

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CCS CONCEPTS

• **Human Computer Interaction (HCI)**; • **User Interface Toolkits**;

KEYWORDS

Soft Robotics, Construction kit, Pneumatics, Shape changing interfaces, Inflatables, Design, Art, Interactivity, Modularity, Education

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1 INTRODUCTION

Constructive assemblies and modular toolkits [1, 2] provide a low-barrier way for people to be exposed to a new field, learn about advanced concepts through a creative and playful approach, and rapidly start applying their creative skills within a given domain even without any prior exposure to that domain. One example of a constructive assembly is Topobo [3], which was designed to teach children about physics and enable them to make biomorphic forms that can record and replay motion. LEGO Mindstorms[1] is another example that allows people to rapidly start prototyping basic robots and learn advanced concepts about the design, actuation, and motion of robots even without any prior exposure to robotics. Similarly, electronic modules like those from Sparkfun[2] and Adafruit[3] can also be viewed from the perspective of constructive assemblies. They allow makers, even without any prior electronics design background, to quickly build advanced projects just by purchasing pre-made electronic modules and development boards, and then reading a quick tutorial about how to connect and program them. Moreover, while working with such electronic modules, makers gradually begin learning advanced electronics concepts.

Soft robotics is an emerging and rapidly accelerating field with a very high potential for impact, which is also of strong interest to the Human Computer Interaction (HCI) and Haptic communities [4]. Yet the barriers to entry for most researchers and makers are still very high, and those barriers are even greater for people who come from nontechnical backgrounds. Learning about soft robotics fabrication techniques became even more difficult in the wake of the COVID-19 pandemic. That's because most fabrication and prototyping processes necessitate expensive materials that are not readily available in most countries, space for molding and casting, computer aided design (CAD) skills, and access to equipment such as 3D printers. Additionally, the actuation and sensing of soft robots requires advanced skills in pneumatics, engineering, and programming. Websites such as softroboticstoolkit.com, opensoftmachines.com, and softrobotics.io offer a variety of resources related to soft robotics research and prototyping. However, while such online resources offer a great starting point, reading and watching videos alone does not allow for people to actually develop intuition about soft robots and to use the creative learning process of learning through doing and playing.

On the other hand, a constructive assembly kit in combination with carefully curated informational resources could significantly reduce the barrier to entry and allow people to easily get started with soft robotics, prototype basic interactions, develop intuition about the behavior and control of such robots, and be inspired and motivated to go beyond the offering of a kit. Currently, there are only few examples of such kits related to this field, and most of them are only research prototypes, not readily available to people. Chao Zhang et.al. [5] wrote a comprehensive review paper in 2020 on modular soft robots that also lists nearly all known soft robotics construction kits. Two examples of reconfigurable soft robotic kits include InflatiBits [6] and Soft LEGO [7].

Here we present a novel soft robotics construction starter kit, called PneuBots, made from durable, low-cost inflatable materials. The PneuBots project is an expression of gratitude for the privileges and opportunities we have to pursue research in an exciting emerging field and collaborate with people from diverse backgrounds. Through this low-cost project, we are providing similar opportunities to more people, including those who may not have such privileges or access to advanced resources. PneuBots includes a variety of building blocks with different actuation behaviors and comes with a FlowIO Platform [8] that allows even novice users without any programming or electronics background to create soft robots with dynamic interactions and bring their creations to life. Moreover, this physical prototyping toolkit even allows users to express and share their own gratitude through applications such as a hugging robot, an affective device like AuxeticBreath [10] that metaphorically expresses emotion through a rhythmic pattern, interactive flowers that can serve as gifts for loved ones, or ghostly presence interfaces for those who are far away or are isolated in quarantine. Additionally, PneuBots starter kit can also be used for numerous educational, storytelling, or artistic purposes.

[1]www.lego.com/en-us/themes/mindstorms
[2]www.sparkfun.com
[3]www.adafruit.com

2 DESIGN PROCESS

2.1 Design Research

In our design process we used a mixed method comprising interviews and existing product reviews. We started by concentrating on creators interested in working on soft robotics projects. In particular, our initial target user group consisted of graduate students new to this field. In the future, we will also include undergraduate and k-12 students. Over the course of developing this project, we informally interacted with 20 graduate students who provided feedback about the behaviors and interactions they want to achieve with soft robotic design concepts, and who also shared some of the barriers and obstacles that prevent them from realizing their goals. The primary challenges reported by the students included lack of equipment, complexity of developing a suitable control system, and difficult in implementing control algorithms. We depict these design research findings in Figure 2 where we group them into three categories: desired compound behaviors, desired primitive actions, and barriers & challenges faced.

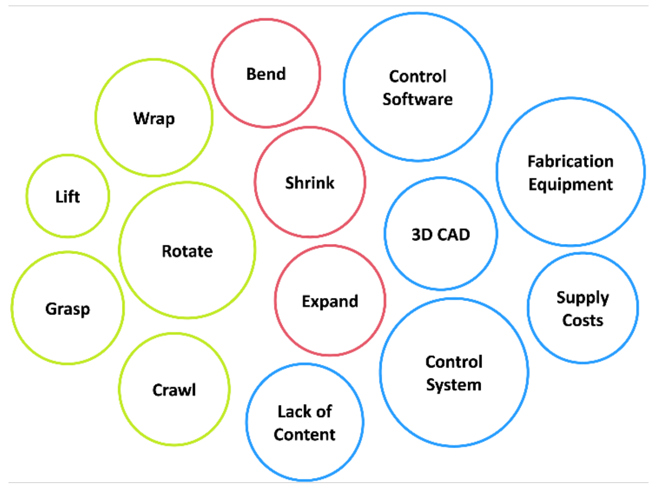

Figure 2: The green and red bubbles show the behaviors and primitive actions that graduate students were interested in achieving with soft robots, while the blue bubbles show the challenges and barriers preventing them from achieving those goals.

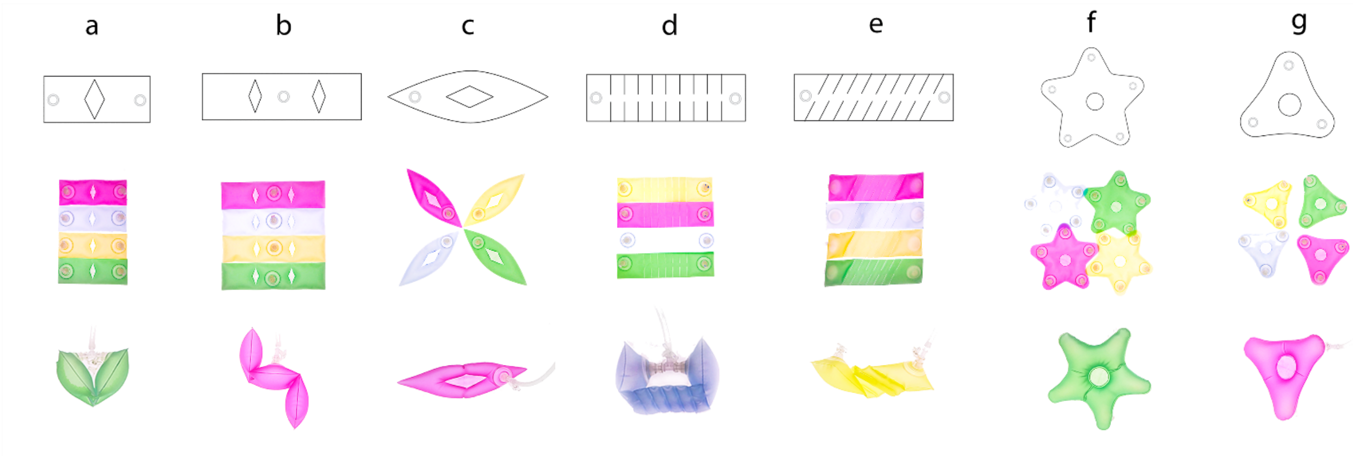

Figure 3: PneuBots includes modules for (a) 1-axis bending, (b) 2-axis bending, (c) half bending, (d) axial contraction,(e) twisting, and (f, g) two modules with radial expansion serving as base connectors for the other modules

Based on the aforementioned design research, we designed a set of origami-inspired modular primitives for the PneuBots kits that achieve the desired primitive actions. Figure 3 shows the set of seven modules developed to date. Additional modules may be added later. The modules can be combined together seamlessly to allow makers to quickly assemble different kinds of structures that can then achieve complex dynamic behaviors. A FlowIO device [8] is also included in the kit to allow users to seamlessly actuate and program the behavior of their soft robot assemblies without having to learn advanced engineering or programming skills.

2.2 Self-Folding Design

The PneuBots kit contains modular self-folding blocks that actuate when air is pumped in, which are shown on Figure 3. We used a design and fabrication process very similar to the one described in [9] for creating structures fabricated out of sheet materials with heat-sealed hinges that fold when inflated. Four hinge types (inner patterns) were used to achieve different bending behaviors: linear, diagonal, diamond, and wide diamond (Figure 4). A module with a linear pattern has a 5mm gap in the middle of each straight line, which causes axial contraction during actuation. As the volume of the inflatable increases, the length of the linear pattern gap decreases and the height increases (Figure 3). The diamond shape-hinge serves as the bending angle control. The seam will continue to curve, and the hinge continue to bend, until the volume in the inflat-able is maximized. Lastly, the diagonal pattern with a 5mm gap serves as the curling control, which is useful for changing the orientation of connected modules. Seven PneuBots modules with different actuation behaviors - including shrinking, curling and bending - were designed. Two of those modules, the star-shaped and triangle-shaped, don't have any hinges and thus have no folding action under actuation.

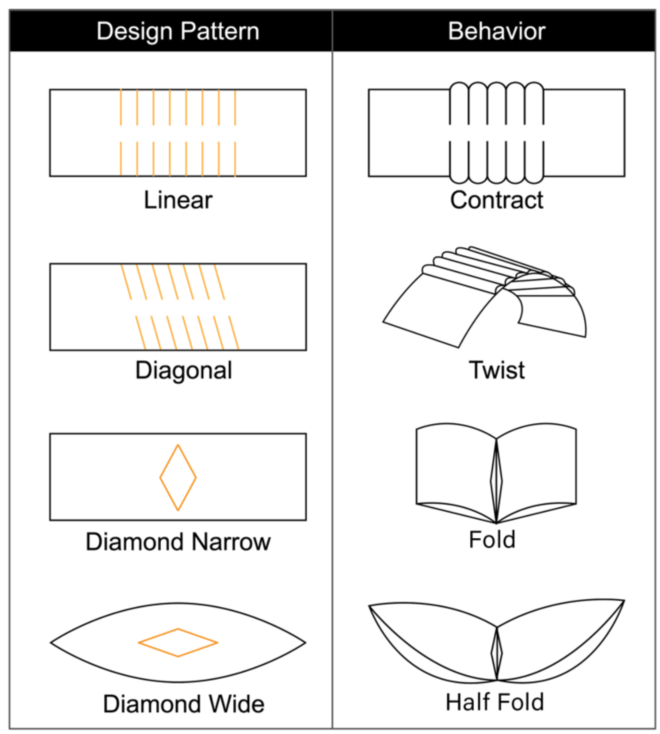

Figure 4: Four inner design patterns corresponding to four different types of actuation behaviors.

2.3 Modularity

The different design patterns heat-sealed on the modular blocks constrain their deformation to yield a specific shape change under inflation. Each of the modules can be connected to one or more identical or different modules, thus enabling a diverse range of configurations, structures, and applications to be explored seamlessly and playfully. Each modular design features small, standardized units that can be independently combined in various configurations to create different forms and provide multiple functions. Our goals for designing modules were to identify what modules will be part of the planned system and what their functions will be; identify how different modules will connect to each other; and explore the performance of the modules in various arrangements.

2.4 Fabrication Process

The modules of PneuBots were developed by a heat-pressing fabrication process, where two layers of PVC (Polyvinyl Chloride) film were sandwiched together and then sealed along specific origami-inspired patterns. The process of making PneuBots is seamless to learn, requires no 3D modeling, and uses inexpensive materials.

The typical heat pressing fabrication method is to first laser cut geometric pattern on a paper, then manually stamp it on a semi-flexible film using a heat press. This isn't convenient because the method creates undesired wrinkles, holes, and irregular linear shapes during the manual heat pressing. Therefore, in our mold design, we used 1/2-inch-thick bronze block etched using a CNC-mill to depth of 1/8 inch to create metallic molds. Then, PVC film was pressed for 5 seconds at 260°C onto the bronze mold (Figure 5).

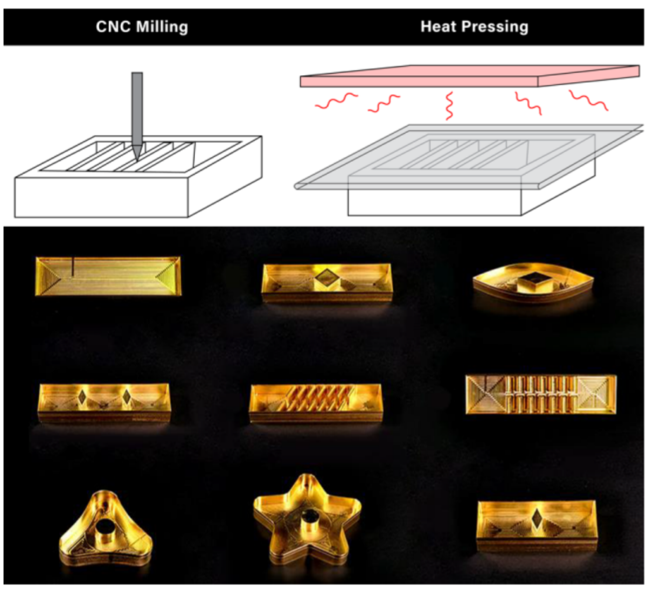

Figure 5: (top). two steps fabrication process: CNC milling of desired pattern on a block of bronze and heat pressing of a PVC film on the bronze mold (bottom) nine CNC-milled bronze molds.

The CNC-milling plus heat pressing fabrication method achieves an accurate and smooth geometric pattern without wrinkles. In addition, the bronze molds allow consistent patterns useful for mass-production. The versatility of PVC film and the smooth finishing of the seam make the modules resistant to bursting from over-inflation.

2.5 Connectors

Each PneuBots module has between one and five pneumatic ports with oral-inflation-valves that are commonly used on beach balls and swimming tubes as shown on Figure 6. Some of the modules have more than one port, allowing air to flow in or out from multiple holes, and the users can choose which holes are open and which they wish to close with the plugs. Modules can be connected to each other using three types of pneumatic connectors: Straight-shaped, T-shaped, and Cross-shaped (Figure 7). (A) **Straight connectos** allow multiple modules to be daisy-chained. (B) The **T-shaped connector** allows for more complicated assemblies. It also allows a single module with multiple inflation valves to connect to another one of its valves, which can be useful for achieving certain aesthetic outcomes. (C) The **Cross-shaped connector** allows up to four modular blocks to be connected to each other.

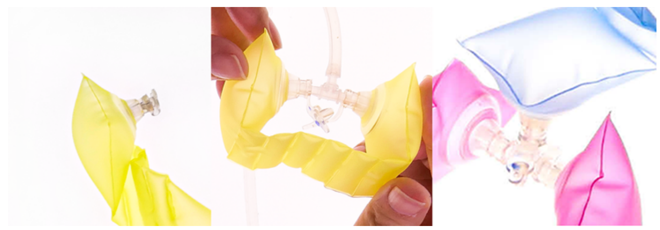

Figure 6: (a) Oral inflation valves with plug, (b) T-shaped connector joining two ends of the same module, (c) three modules connected with a cross-shaped connector.

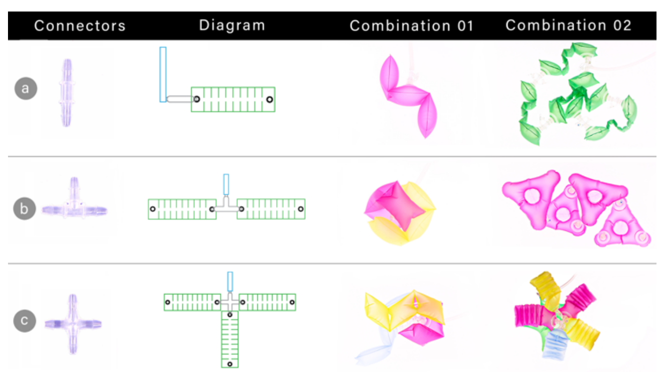

Figure 6: Three types of connectors - (a) straight, (b) t-shaped, (c) cross-shaped - and example uses of each.

The PneuBots modules can be assembled together as easily as LEGOs, and as soon as they are slotted into place they share the same air channel. We observed that users of PneuBots used the straight connector much more often than the other connectors when assembling their own structures. However, the other connectors were also used when users chose to make more complicated structures.

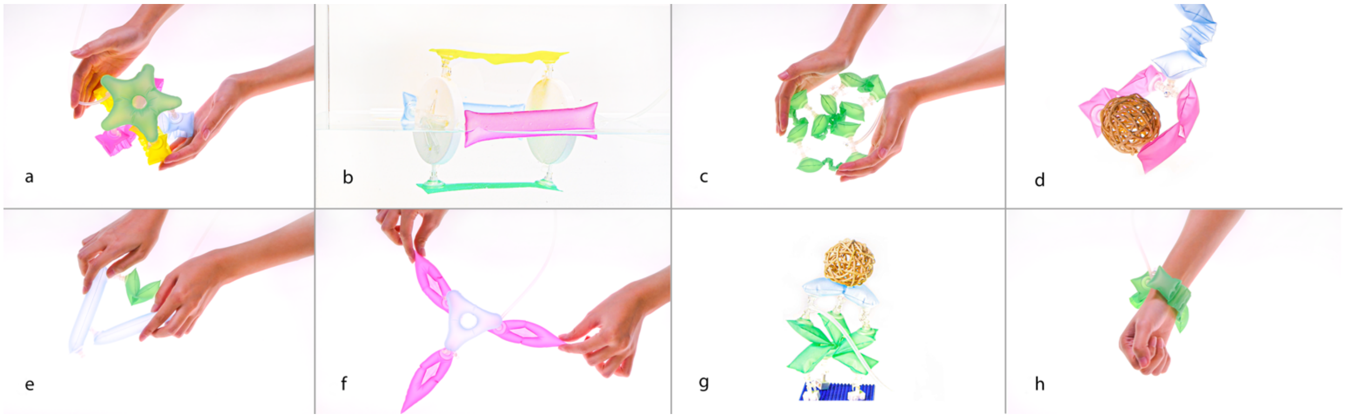

Figure 8: Various applications developed using materials included in PneuBots a) an artistic work, b) an underwater rolling robot, c) garden, d) a gripper, e) a hugging toy, f) an interactive flower, g) a lifting robot, and h) a haptic bracelet.

3 USER TESTS

The PneuBots kit was preliminarily distributed to graduate students from backgrounds in architecture, engineering, and education, who were then tasked with experimenting and brainstorming possible uses for the modular blocks (Figure 8). For most users, this was their first exposure to soft robotics, and in the process, they learned about pneumatic control, actuation patterns, and heat-sealing fabrication. Our preliminary evaluation with the students showed that PneuBots enabled them to playfully create projects including a rolling robot, a wearable device, a gripper with two arms, and several artistic creations.

Grasping arms were composed by connecting a minimum of two modular blocks. The rolling robot was designed using four simple linear shape modules. Two cylindrical molds were separately 3D printed to connect the modular parts on the top and bottom sides. Using the five pneumatic I/O ports from FlowIO, students controlled individual modules to generate various motion patterns. The PneuBots kit also provided aesthetic as well as functional opportunities for designers and artists. The translucency of PVC film creates eye-catching objects, and artists and designers created artwork such as flowers and accessories, as well as internally illuminated objects.

Inspired by this fabrication method, some graduate design students developed inflatable structures with more complicated inner patterns, which include rectangles, circles, irregular shapes, and combination of different shapes (Figure 9). PneuBots has been very useful in helping students understand not only soft robotics and actuation mechanisms, but also the fabrication process of heating thin PVC film, sealing methods, and connections between silicone tubes and modular units.

After providing the modular inflatables to graduate students, we received several questions and helpful feedback (Figure 10). A question about ways to obtain the toolkit inspired us to develop a website for PneuBots (https://www.pneubot.org) which will enable our toolkit to be available for anyone interested in soft robotics. Sustainable packaging was also designed to helpfully organize the modular parts, connectors, and instructions about their use and function. The box is designed to keep all parts readily accessible and well-organized (Figure 11).

Figure 9: Students inspired by Pneubots making their own inflatable designs a) cutting a PVC film b) using a heat press to join two layers of PVC films.

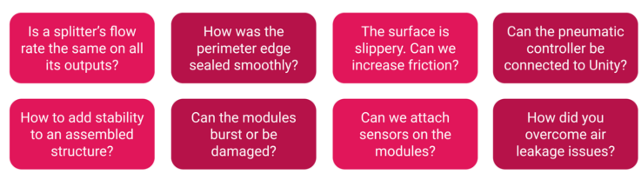

Figure 10: Frequently asked questions about PneuBots from users.

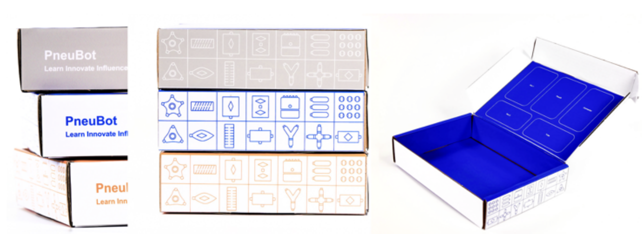

Figure 11: A sustainable packaging that keeps all the constituents in a well-organized way.

4 VISION FOR PNEUBOTS

Some other feedback from users mentioned the smooth surface of PVC film. Since the inflated modular blocks are slippery, the smooth texture may not be ideal for an interaction with other objects. Therefore, to extend PneuBots' functionality, we are planning to create a layer of cloth such as an auxetic structure to generate friction between modules for more stable mobility. We will also eventually broaden the scope of our work to include more diversity in modular block design, and we are currently gathering data to determine the appropriate number of modular blocks to include in our basic package.

For creative thinkers, designers, and engineers with the problem of accessing, understanding, and implementing emerging technologies such as soft robotics, we develop and produce user-friendly interfaces, connecting the dots between academic disciplines and more applied solutions in engineering, design, and other hands-on fields. Our aim is to support designers, artists, and developers in their exploration by providing them with soft robotics kits that are affordable, modular, programmable, and suitable to their creative visions. We want to inspire those unfamiliar with soft robotics to engage with a new way of thinking about structure and architecture and provide them with a straightforward learning and prototyping toolkit.

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