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Sticky Actuator: Free-Form Planar Actuators for Animated Objects

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Figure 1. The tape actuator and an active box (left). The sticker actuator and an actuated origami crane (right)

ABSTRACT

We propose soft planar actuators enhanced by free-form fabrication that are suitable for making everyday objects move. The actuator consists of one or more inflatable pouches with an adhesive back. We have developed a machine for the fabrication of free-form pouches; squares, circles and ribbons are all possible. The deformation of the pouches can provide linear, rotational, and more complicated motion corresponding to the pouch's geometry. We also provide a both manual and programmable control system. In a user study, we organized a hands-on workshop of actuated origami for children. The results show that the combination of the actuator and classic materials can enhance rapid prototyping of animated objects.

Author Keywords

Tangible Media; Soft Robotics; Soft Actuator; Robot Toy; Origami; Shape-Changing Interface; Pneumatic;

ACM Classification Keywords

H.5.2. Information interfaces and presentation (e.g., HCI): User Interfaces---Haptic I/O.

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INTRODUCTION

Programmable and interactive features of computation can be extended into physical interactions, such as a shape-changing interface [1] that allows users to change physical parameters of the objects. Altering material properties through computation is a potential new frontier in human-computer interaction. In order to go beyond the simple changing of RGB values of pixels and delve into changing the shape, volume, and physical texture of three-dimensional objects, the system requires smart actuators embedded into its materials. There are only a few practical actuation techniques [2][3] due to limitations in technology. As such, shape-changing materials require costly delicate hardware that is not flexible. The goal of this research is to provide accessible smart actuators with a flexible fabrication method.

Another important aspect of the shape-changing user interface is the compatibility with classic materials. The programmable matter approach assumes that the shape-changing objects are made from programmable materials. This approach conflict with classic materials and does not support existing objects. Robotic construction toys and modular robots also have compatibility issues with other pieces of hardware. Classic materials such as paper, fabric, and clay have good flexibility and support tangible interactions. On the other hand, they do not have active motion or programmable features. Thus, we focus on an additive approach: adding free-form actuators on existing materials and objects.

As such, we propose planar soft actuators called “sticky actuators” (Fig.1). The actuator consists of inflatable bladders with an adhesive back. We have developed a fabrication method for making free-form bladders from

inexpensive plastic sheets. We also provide a simple, portable teaching-playback control system for programming actions of multiple actuators. Users can simply attach and detach the actuators by peeling and sticking. Potential applications include adding motion to a specific object to attract attention in a crowded environment, animating static artworks such as paper crafts or picture books, and motorizing everyday products by simply sticking on an actuator. This simple approach is suitable for people who have limited knowledge of robotics, and the proposed system allows users to make robotic system from passive objects.

RELATED WORK

Actuated Construction Toys

One of the most popular actuated construction toys is the LEGO Mindstorms series [4], which contains software and hardware to create customizable, programmable robots. Those robots can be either motor driven or pneumatically driven, and are equipped with various sensors. The form factor is constructed from existing units. Topobo[5] and Kinematics[6] are constructive toys that include both active and passive units. Instead of software interfaces, their movements can be recorded and replayed by manipulating the tangible parts. These toys have limited compatibility with other hardware. Pinoky[7] is the project based on the additive approach that utilizes ring actuators that can be attached to plush toys to turn the toys into soft robots.

Cuttable Electronics

Cuttable electronics have been explored for ad-hoc customization of inkjet printed circuits [8][9]. Different topological layouts of conductive circuitry have been compared to achieve a cuttable capacitive sensing unit. There are also circuit stickers [10] that contain both passive and positive electronic components. These components are manufactured on a flexible substrate, and can be peeled off and attached to other substrates to make a circuit. These cuttable electronics enable fast prototyping and flexible customization of function and form. However, it is hard to apply such techniques to mechanical systems.

Shape-Changing Interface

Shape-changing interfaces with pneumatic actuation have been explored in the HCI field, including PneuUI[2], dynamic changeable buttons[11], inflatable multitouch displays [12] and the inflatable mouse[13]. Compared to other actuation methods, pneumatic actuation provides a large force per weight ratio, softness, and controllability. Beyond HCI, pneumatic actuations have been adapted in the soft robotics field [14][15]. Complex and organic motion can be achieved with pneumatic bladders.

The PneuUI paper provided a guide to replacing classic materials with shape-changing composites. In contrast, this paper focuses on applying new actuation techniques to classic materials. We believe that the additive approach would provide more practical applications than less popular

shape-changing composites. Furthermore, while the PneuUI paper broadly discussed various structures and materials for pneumatic actuation, this paper explores in depth planar actuators with non-elastic materials. We explore new forms such as tape and stickers with a computer-controlled platform for complex pouch fabrication. We also provide quantitative measurement of the physical properties and analysis of the usability through a user study.

FREE-FORM PLANAR SOFT ACTUATOR

Overview

Our free-form actuators are enhanced by a custom-built fabrication machine (Fig.2). Two simple shapes that can be easily fabricated are tape and sticker: the ribbon-shape with a series of pouches and the individual square/circle-shape pouches. These elementary shapes can generate inflation, bending, and contraction. Pouches with more complex shapes can generate a variety of motions and texture which we call corrugation. All types of actuators are based on the same principle of pneumatic inflation/deflation of the pouch.

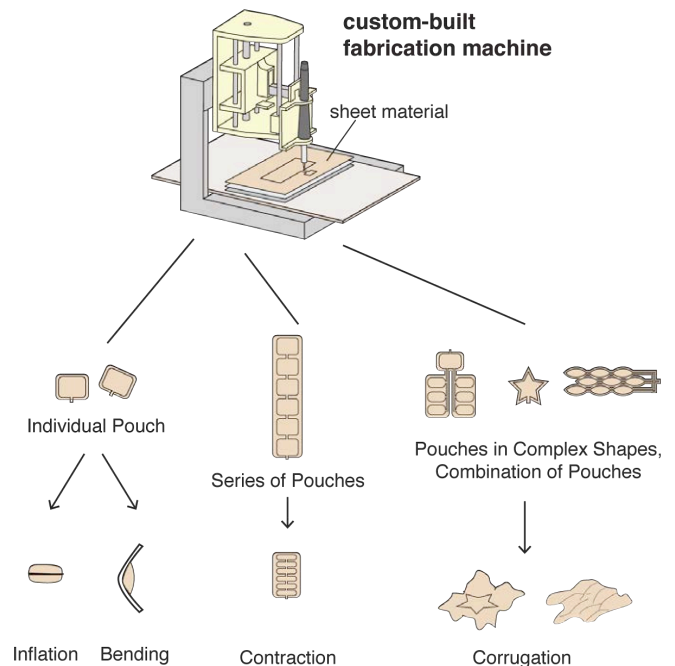


Figure 2. Overview of the sticky actuator family.

Tape Actuator

Like a muscle, the tape actuator provides linear motion. If the tape actuator is adhered to the two wings of a hinge joint, the inflation can result in a rotational motion.

In this prototype model (Fig.3), the tape actuator is 50mm wide, and each pouch unit 24mm long, manufactured from 0.004" (4mil) thick Polyethylene (PE) sheets. To make a tape actuator, a user simply tears off the tape at any desired length, plugs in the connector at one end, and seals the back of the tape actuator with a piece of sticky tape.

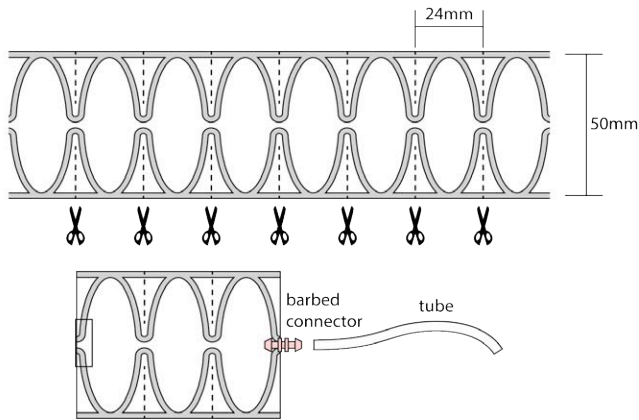


Figure 3. Design of the tape actuator (top), and an sample of three pouches tape actuator with connector (bottom).

Sticker Actuator

The sticker actuator provides rotational motion when adhered to a hinge joint or equivalent flexible substrate. Users can also utilize a “push” effect through inflation.

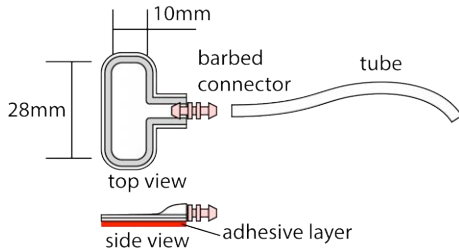


Figure 4. Design of the square-shape sticker actuator.

The prototype sticker actuator (Fig.4) contains a 28mm by 10mm rectangular pouch, made with 0.002” (2mil) thick Nylon sheets. A user simply peels off a sticker actuator from the film liner and attaches it onto the object to be actuated.

FABRICATION

Heat Bonding

Inflatable bladders/pouches are fabricated from plastic sheets through a heat bonding process. The heat seal outlines the shape of the pouches, and then an adhesive layer is applied on the back. This sealing method is commonly seen on heat sealers that seal plastic bags. The tape actuator is a series of pouches that can be cut by tearing. For sticker actuators, each pouch has a barbed tube fitting, which allows pouches to be connected to tubes during operation.

We developed a computer-controlled heat bonding machine that consists of a three-axis CNC gantry holding a heat pencil (Fig.5). The machine can draw sealing lines on thermo plastic sheets mounted on the workspace. We use a layer of high-temperature fiberglass film that covers the target PE film layers. Once the design of the actuator (a two dimensional line drawing) is made on the computer, CAM

software generates G-codes from the design and sends commands to the CNC gantry. The machine then interprets the G-codes line by line and moves the heat pencil to draw the pattern.

After thermally printing pouches for the tape actuators, perforated cuts were made with knives between units in order to make pouches easily separated by tearing.

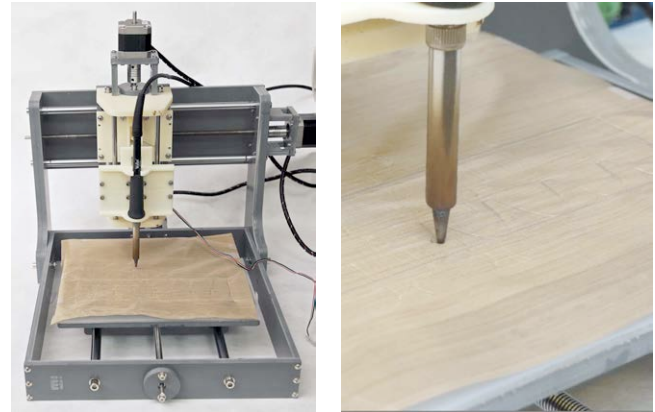


Figure 5. The CNC heat bonding machine: overview (left), and close-up of the heat pencil (right).

After printing sticker actuators, pouches were cut into individual components so that tube fittings could be connected. For each pouch, a barbed PE tube fitting was placed in between two films.

The simplicity of the fabrication process allows sticky actuators to be easily mass manufactured. In fact, the manufacturing process of plastic packaging can be applied directly to make the actuators. It can allow people to use inexpensive actuators.

Material

In order to utilize thermal bonding, the film material must be thermoplastic. In addition, film materials need to be less stretchable but flexible. For this reason, the film materials we selected are nylon films and polyethylene films with a thickness of about 0.002”–0.004” (0.051mm–0.102mm). The actuators can be applied to variety of materials such as paper, plastic, wood, and metal, depending on the performance of the adhesive layer.

CONTROL

Manual Control

We use syringes connected to the actuators by tubes for manual control. As the syringe plunger is pushed and pulled within the cylinder, the airflow inflates or deflates the actuator. The simple principle of cylinder-piston mechanism provides users intuitive interaction with the actuators and their corresponding animated objects.

Programmable Control: Teaching-Playback

We have also created a control system that the user can use to record a sequence of inflating and deflating actions. The

system consists of an Arduino board, a motor driver, miniature pumps, solenoid valves, a battery, and buttons. The controller shown in Fig.6 has two large buttons with LEDs so that user can control the two channels of pneumatic inflation/deflation.

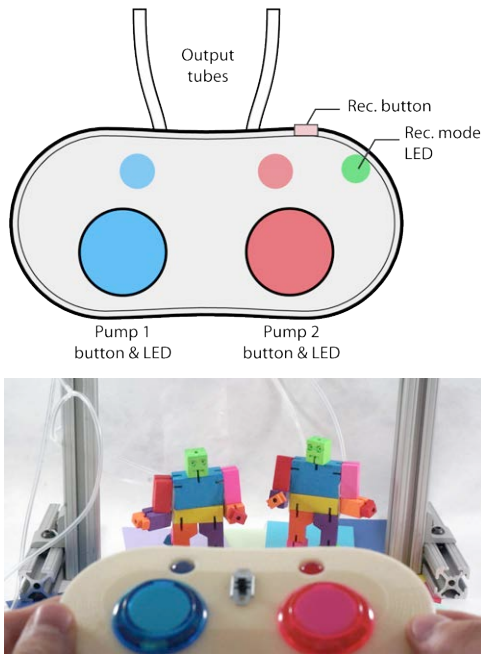


Figure 6. Design of the teaching-playback controller.

The pump vacuums air out of the pouch as the program initiates. Then, as the user pushes big pump buttons, the corresponding pump starts pumping and the LED indicators light up.

If the recording button is pushed, the green LED lights up showing the system is entering record mode. While still holding the record button down, the system records how long the user pushes each pump button, and in what sequence. Once the record button is released, the green LED goes off, and the system plays back the pump sequence that was recorded. If the recording button is pressed and released quickly again, the program will erase the recorded sequence. The control system thus allows users to choreograph the animated objects with tape/sticker actuators without complicated programming.

PERFORMANCE OF THE ACTUATOR

We performed a tension test to examine the basic properties of the tape actuator using a single-axis tension testing machine with a force sensor and a linear potentiometer. Fig.7 shows force-length relationships of the tape actuator. The sample used was a tape actuator with four pouches, which were pressure controlled at 5kPa, 10kPa, and 20kPa.

The result of the tension test shows that the tape actuator can generate tension force up to 10N at 20kPa. The observed maximum contraction ratio is 15% at 20kPa, and generated less contraction ratio at lower pressures. In the

fully contracted state, the tension force goes to a minimum because the pouches are fully inflated.

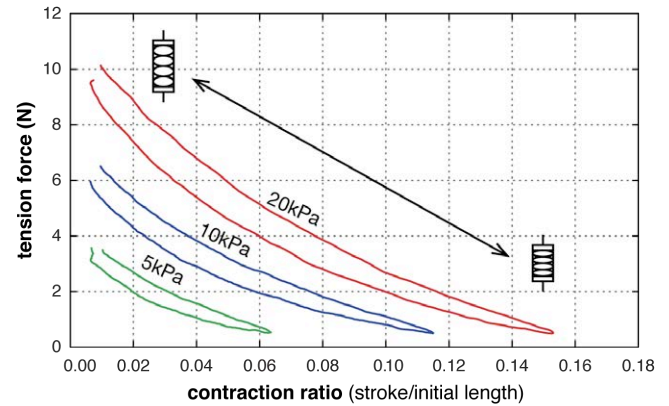


Figure 7. The measured data of the force-length relationships of the four pouches tape actuator.

APPLICATION EXAMPLES

Tape Actuator Examples

The tape actuator can easily drive the joints of objects like muscles. We put two tape actuators onto a box in order to actuate its opening. One end of each tape actuator is adhered above a folding line of the opening and the other end below, onto the side of the box (Fig.8). Once they are inflated, they contract in length and pull the covering boards outward (Fig.9).

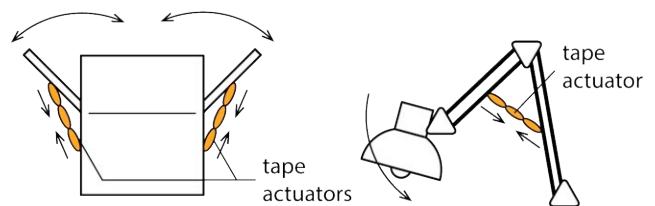


Figure 8. Applied tape actuators on the everyday objects: paper box (left) and desk lamp (right)



Figure 9. The snapshots of the movements: open/close the paper box (top), and swinging the lamp arm (bottom).

We can also use tape actuators to actuate motions on linkages, for example a swing-arm lamp (Fig.8). One end of the tape actuator is adhered to the horizontal arm and the other end to the vertical arm. Once it is inflated, it contracts in length and pulls the light closer to the desk (Fig.9).

Sticker Actuator Examples

Origami allows the transformation of flat sheets of paper into intricate three-dimensional artworks. With sticker actuators, they can be further transformed into “living” creatures. Here we demonstrate how to actuate motion on an origami crane and fish using sticker actuators (Fig.10).

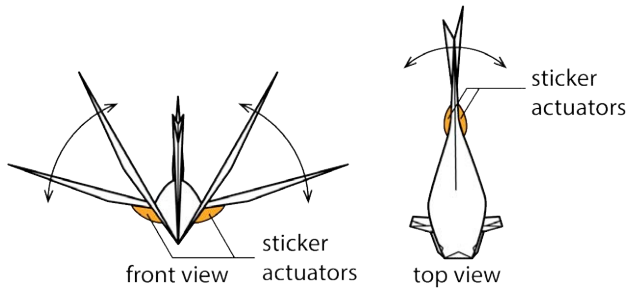


Figure 10. Applied sticker actuators on the origami objects: origami crane (left) and origami fish (right)

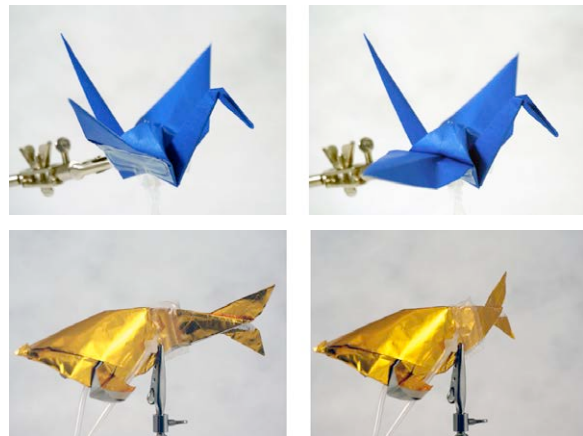


Figure 11. The snapshots of the movements: flapping wings (top), and swinging the tail fin (bottom).

On the origami crane, two sticker actuators are adhered under the joints of the wings. These two sticker actuators are connected to two side parts of a T-shape pneumatic connector. A syringe is connected to the other part. When the syringe is pumped, the two sticker actuators inflate and deflate at the same time, resulting in a wing flapping motion (Fig.11).

On the fish origami, two sticker actuators are adhered to the fish’s tail. Each sticker actuator is connected to a syringe. When the two syringes are pumped alternatively, the tail swing from one side to the other (Fig.11).

Sticker actuators can also be used to provide other types of motion on everyday objects. For example, we attached a

sticker actuator to the hinged mouth of a clay frog (Fig.12). When air is pumped into the pouch with syringe, the inflated pouch pushes the top of the head upwards, causing the mouth to open (Fig.13). When the air is sucked out of the pouch, the mouth closes due to the weight of the head.

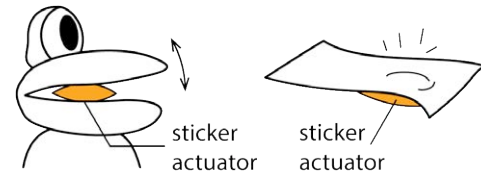


Figure 12. Applied sticker actuators on play dough objects (left) and sticky note (right)

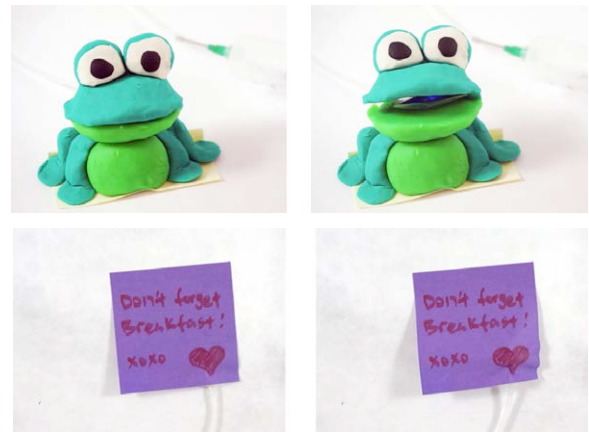


Figure 13. The snapshots of the movements: singing clay frog (top), and beating sticky note (bottom).

We also attached a sticker actuator to the back of a sticky note (Fig.12). When inflating the pouch, bending is induced on the paper’s surface. Deflation returns the paper to its original flat state. By alternating inflation and deflation, a sticky note can attract more attention from viewers (Fig.13).

Mixed Examples

Tape and sticker actuators can be used together. In this demonstration, we adhere one end of a tape actuator to the top bar of a metal frame, and the bottom to the head of the left robot. We also put sticker actuators beneath both of the robots’ arms (Fig.14).

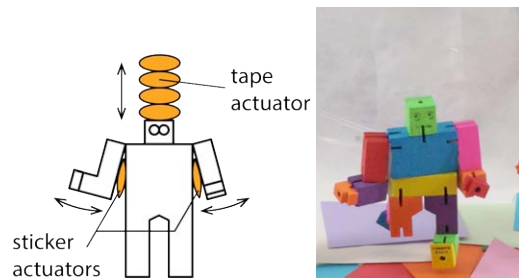


Figure 14. The example that use multiple sticky actuators: actuator arrangement (left), initial state (right)

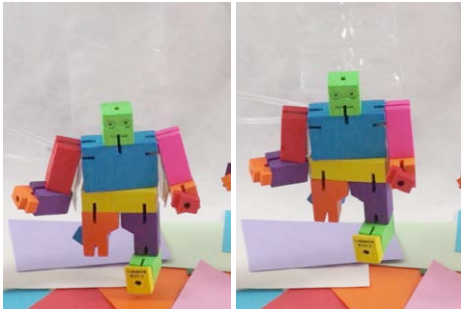


Figure 15. The actuators is used for dancing and jumping motion: arm swing with sticker actuators (left), and jumping with tape actuator (right).

When the tape actuator is inflated, it pulls the left robot up, replicating a jumping motion. When the sticker actuators are inflated, both robots wave their arms (Fig.15).

USER STUDY

Basic Setup and Participants

Two 90-minutes animated origami workshops were held in a museum to study how children interact with sticky actuators (Fig.16). There were twenty participants at each workshop, all accompanied by their parents. The instructor demonstrated how to fold origami models and the use of sticky actuators. Then the participants were asked to make their own creations. Finally, participants presented their creations and answered a short questionnaire. Origami papers, sticky tape, syringes with tubes for manual control, and square-shape sticky actuators of variable sizes were provided to each group.

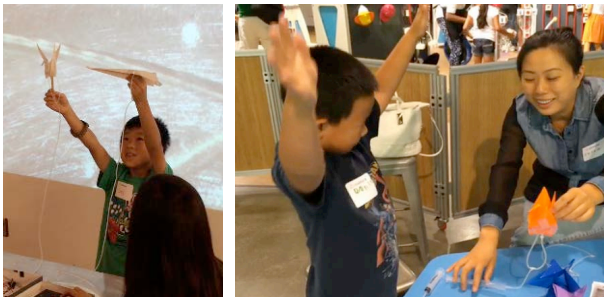


Figure 16. The animated origami workshop.

Questionnaire Results

We received twelve effective questionnaire respondents. We analyzed the answers of the following questions from the responses: 1) “What did you make today?” 2) “How did you use the pouch motor?” 3) “Please let us know if you have any other questions, comments, or requests.” The distribution of subject ages is shown in Fig.17.

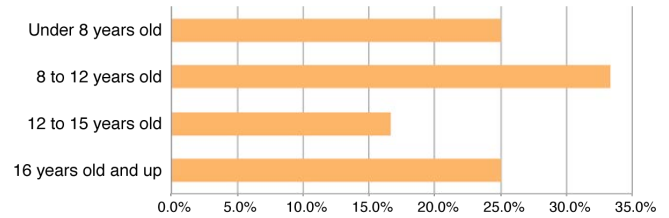


Figure 17. The age of the participants.

Fig. 18 shows the analysis of the motions and mechanisms implemented in the workshop. About 70 percent of the actuation was related to animal locomotion, such as flapping, swimming, and walking. This result shows that the free-form features and softness of the actuator are suitable for nature-inspired objects. The rotational motion (bending) is employed in 95 percent of the creation, and a few objects were controlled by pushing through inflation. This result suggests that children are interested in large straightforward motions rather than more subtle motions such as breathing or beating.

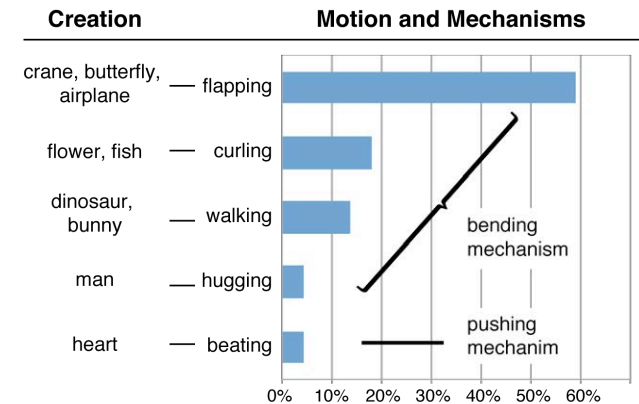


Figure 18. The analysis of motions and mechanisms of the results.

Children who were older and had prior experience with origami found the workshop interesting and were able to make innovative artwork. The difficulty of placing the pouches and actuating origami depends on the type of origami. We found most of flying birds were easy for children to play with; they put pouches either at the tip or bottom of the wings, with both positions producing pleasing results. However, when actuating origami with more complex motion, such as fish, children found it difficult to place the pouches to simulate body movements.

Animated Origami Examples

We observed that the combination of single-motion sticky actuators with a simple origami object could generate diverse behaviors and stories. Fig.19 shows animated origami objects from the workshop. As quoted from one participant, “*The actuator was very interesting, and depending on the origami, there were different challenges*”: the sticky actuator adds more challenges to the already complex art of folding origami. The actuation was even viewed as a new dimension to the origami art, as one participant mentioned: “*I definitely enjoyed it. It added a new dimension to an art I love*”.



Figure 19. The examples from the workshop: a man with heart beat, a blooming flower with a flapping butterfly, a flapping crane, a hugging man, and an airplane with flaps (from upper left to lower right).

LIMITATIONS AND FUTURE WORK

We believe that the sticky actuators can offer practical features by overcoming the following limitations.

One of the limitations of the sticky actuator is the reliability and repeatability of the adhesive. It can be exhausted or may damage the target surface. A disposable feature could solve this issue as well as exploring other attachment methods.

There are many more possibilities in actuator geometries that can create a variety of motions and textures with the sticky actuator. The combination of free-form curves can generate complex motions such as corrugation in contemporary origami.

Advanced sensing and control are also possible directions for the future. Our pneumatic control system is capable of not only binary control but also continuous pressure control of the actuator. However, the current controller design is constrained to the on/off buttons. Direct interaction enhanced by embedding sensors need to be further explored. Printable and deformable electric circuit technologies can also be employed.

CONCLUSION

We proposed planar soft actuators that can be easily applied to passive objects, such as origami/clay animals, puppets, and everyday products. To facilitate mass production, we developed a fast fabrication method with inexpensive materials for the actuators. In addition to the manual control system with syringe, we also provided a programmable control system that can animate objects by using a teaching-playback method. With these beginnings, we envision a future in which soft/ flexible robotic components can quickly and cheaply expand the capability of passive objects and static environments.

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