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# Self-folding and Self-actuating Robots: a Pneumatic Approach

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*Abstract*— **Self-assembling robots can be transported and deployed inexpensively and autonomously in remote and dangerous environments. In this paper, we introduce a novel self-assembling method with a planar pneumatic system. Inflation of pouches translate into shape changes, turning a sheet of composite material into a complex robotic structure. This new method enables a flat origami-based robotic structure to self-fold to desired angles with pressure control. It allows a static joint to become dynamic, self-actuate to reconfigure itself after initial folding. Finally, the folded robot can unfold itself at the end of a robotic application. We believe this new pneumatic approach provides an important toolkit to build more powerful and capable self-assembling robots.**

## I. INTRODUCTION

Fabrication by folding is a promising method for building structures and machines because it is capable producing of lightweight, inexpensive, and complex geometries without tedious assembly processes. Flat sheets and composites are relatively fast and easy to build, and yet these flat sheets can be folded into a wide variety of shapes, including any polyhedron [1]. Researchers have developed computational tools which can automate the design of fold patterns based on the desired shape [2]. Folding has been used to produce functional electromechanical machines [3].

Self-folding refers to any method that enables these planar materials to fold themselves. This enables the rapid assembly of folded structures in parallel, without human involvement. It can be used to construct devices that are too small for humans to easily manipulate or in environments where external manipulators cannot reach [4]. A variety of self-folding methods have been developed which rely on pre-stressed layers [5] [6], magnetic fields [7] [8], or differential expansion [9]. Most of these techniques, however, have one or more limitations which make them ill-suited for building functional machines. Many of them rely on particular stimuli which limit their environment, such as an aqueous medium [9]. Others are limited to length scales of less than 1 mm due to the maximum torque that these self-folding hinges can produce. Others are functional, but rely on discrete actuated shape memory alloy foils [10]. The fabrication and installation of these hinges mitigates the speed and ease of assembly that self-folding is meant to enable.

One successful self-folding method utilizes shape memory composites that combine layers of shape memory polymer (SMP) with stiffer substrates [11] [12]. The SMP is induced to contract via heat, and during this process pulls on the substrate, causing the composite to fold. The fabrication process of the composite is relatively fast and inexpensive because it relies on laminates. This technique has been used to build a variety of structures and machines at scales from 5 to 150 mm [13] [14] [15] [16], including a fully autonomous crawling machine [17]. However, this technique has its own limitations. The heat required to activate folding releases a significant amount of energy. This technique so far has not been particularly robust, and the folding process is irreversible.

We propose a new self-folding technique that relies on pneumatic "pouch" motors to actuate folding [18]. Unlike other pneumatic actuators, pouch motors are made with a 2D fabrication process. The substrate is laser-machined, and the pouches are formed from a single sheet by a CNC machine wielding a soldering iron. This technique enables new patterns to be quickly machined without building new tools such as molds or stamps. These pneumatic hinges are reversible, repeatable, and have behave predictably for robust folding. In addition, similar pneumatic pouches can be used to actuate the dynamic mechanisms in a machine, so that a single pump can be used for both the folding and operation of a device.

In this paper, we first introduce the construction and self-folding method on a single pneumatic hinge. We provide an analytical model to describe its behavior. Then we made two self-folding applications to show its advantages. One is a dodecahedron that uses a one-valve to keep the fold. Unplugging the valve unfolds the structure. The other is a gripper that uses a self-locking mechanism to keep the fold, and use pouches to not only fold but also to achieve precise bending angles. Finally, we compare this new pneumatic folding approach with existing self-folding mechanisms.

## II. PNEUMATIC SELF-FOLDING AND ACTUATION

### A. Construction

The planar and compact nature of pouch motors make them suitable for origami structures to "self-fold." Linear type multi-unit pouch motors are used in all the applications presented in this paper. The shrink in length of the pouch during inflation pulls two ends of the hinge to fold. Compare to a single pouch in hinge bending, a such multi-unit linear pouch can generate greater folding angles and is less likely to detach from the structural layer.

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A layer of polyester film is adhered to the joint beneath the pouch motor layer. This layer acts like a torsion spring that not only mechanically connects the structural components but also provides a spring back force when folded. This force is desirable during unfolding process to squeeze out air. However, stiffer springs require greater pressure to overcome their bending moment and can limit the maximum bending angle. Therefore, if unfolding is more important for a particular hinge, the a thicker polyester film (10 mils) is used. If achieving a greater folding angle is more important, a thinner polyester films (2 mils) is used.

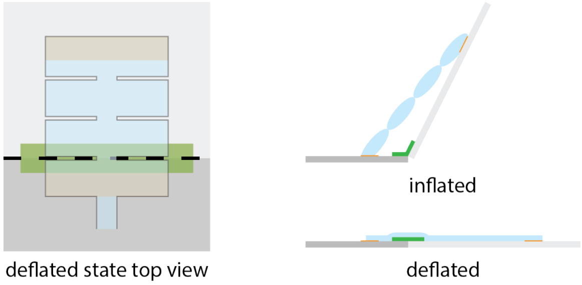

Fig. 1. A simple pneumatic self-folding joint with a four-unit linear type pouch motor

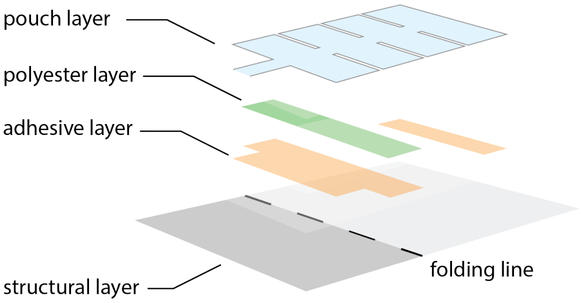

Fig. 2. Layered construction of the joint

One strength of pneumatic self-folding is that everything starts from a flat structure. This nature streamlines the design and fabrication process. A maker can sketch up the robot in a vector drawing or 2D CAD program and generates numerical control (NC) codes with a CAM program for automated fabrication. The NC codes for the pouch layer is sent to a custom-made CNC operated thermal bonding machine to make the pouch, and the NC codes from the other layers are sent to a laser cutter to cut out the profile [19].

## B. Making a fold

After folding, a joint needs to be locked to the folded state to provide mechanical stability. There are two different methods. The first one is to connect a one-way valve in the tubing line before the air enters the pouch. The second one is to make two folds mechanically lock to each other to stand in place.

Although the first method is easier to implement, it cannot be unfolded without manual intervention. In comparison, the second method is complicated but autonomous. As long as the pouch motors used are connected to a two-ways valve, a lock can be opened and the structure can be unfolded automatically.

In this paper, we demonstrate the use of one-way valve in the dodecahedron application and the self-locking mechanism in the gripper application.

## C. Analytical model of a pneumatic fold

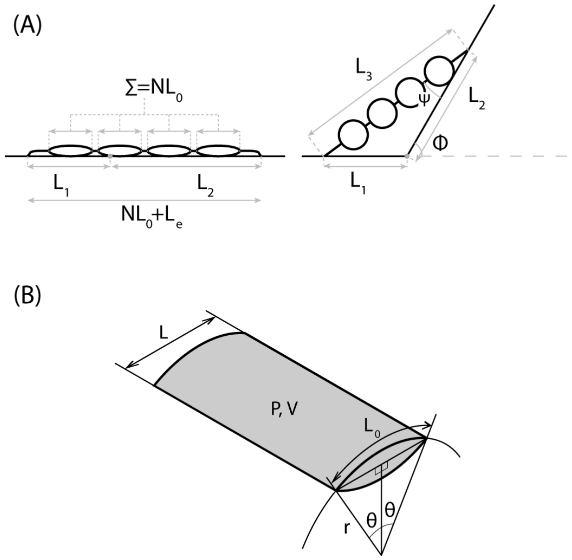

Fig. 3. Dimensions used in the model (A) dimensions used on a joint (B) dimensions used on a single pouch [18]

We developed an analytical model to predict hinge behavior. Unfortunately, solving for an output hinge angle $\phi$ as an explicit function of pressure $P$ is a difficult problem. We instead solve for $P_{pouch}$ as a function of $\phi$. Based on $\phi$ we can solve for the length of the actuator.

$$NL(\phi) = L_1^2 + L_2^2 - 2L_1L_2\cos(\pi-\phi) - L_e \tag{1}$$

Where $L_1$ and $L_2$ are the lengths between the hinge and the pouch attachment points, $L$ is the length of a single pouch, $N$ is the number of pouches, $L_e$ is the length of the inactive portion of the pouch motor, and $L_3$ is the total length of the motor. To solve for the motor force $F$ we balance the torque exerted by the motor on the hinge $\tau_{pouch}$ and the torque due to the flexural stiffness of the hinge $\tau_{hinge}$. The Young's modulus $E$, width $D$, thickness $t_s$, and length $L_s$ of the flexural material can be combined into the hinge stiffness $k$.

$$k = \frac{EDt_s^3}{12L_s} \tag{2}$$

$$\tau_{hinge} = k\phi \tag{3}$$

$$= \tau_{pouch} = FL_2\sin(\psi) \tag{4}$$

$$\frac{\sin(\psi)}{L_1} = \frac{\sin(\phi)}{L_3} \tag{5}$$

$$F(\phi) = \frac{\phi k\,(NL(\phi)+L_e)}{L_1L_2\sin(\phi)} \tag{6}$$

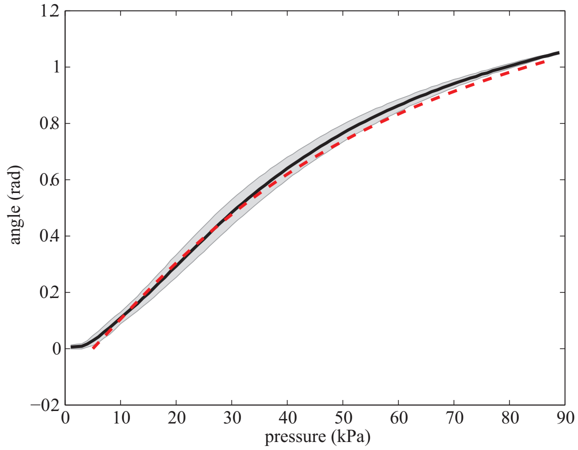

Fig. 4. Plots of the measured fold angle (black line) and the model's predicted angle (dashed red line) as a function of pressure. The shaded region indicates standard deviation, N=6.

$\psi$ indicates the angle between the pouch motor and face 2. Relations between $P_pouch$, $L$, and $F$ are defined by equations in Niiyama et al. found below which rely on an angle $\theta$ which is based on the cross-sectional shape of the pouches. These functions also depend on $D$ and the resting length $L_0$ of the individual pouches.

$$L(\theta) = L_0 \frac{\sin(\theta)}{\theta} \tag{7}$$

$$F(\theta) = L_0 D P_{pouch} \frac{\cos(\theta)}{\theta} \tag{8}$$

To solve for $\theta$ as a function of $L$, we approximate the relation by the second order taylor series. Within the physical limits of $0 \leq \theta \leq \pi/2$, this has a maximum error of 8%.

$$L(\theta) = L_0 \left(1 - \frac{\theta^2}{6}\right) \tag{9}$$

$$\theta(\phi) = \sqrt{6}\sqrt{1 - \frac{L(\phi)}{L_0}} \tag{10}$$

Finally, we can solve for $P_pouch$ as a function of $F$ and $\theta$.

$$P_{pouch}(\phi) = \frac{F(\phi)\,\theta(\phi)}{D\cos(\theta(\phi))} \tag{11}$$

Some behavior of $\phi$ as a function of $P_pouch$ can be deduced from these equations. As $P_pouch \rightarrow \infty$, we can assume that $F$ remains finite because it depends on the flexural stiffness of the hinge. Since the hinge can only fold 180°, the flexural torque and resulting force must be finite. Therefore, $\theta$ must approach zero, resulting in an asymptote for the pouch angle $\theta \rightarrow \pi/2$. This corresponds to a round pouch perimeter and $L = 2L_0/\pi$. Therefore, there is a maximum fold angle defined by the geometry of the hinge and the pouches.

$$\phi = \cos^{-1}\left(\frac{L_1^2 + L_2^2 - \left(\frac{2L_0}{\pi} + L_e\right)^2}{2L_1 L_2}\right) \tag{12}$$

This model results in a singularity at $\phi = 0$, when the force applied by the pouch motor is parallel to the lever arm. In this case, the model is no longer accurate because the inflation of the pouches is pushing them away from the surface of the hinge, increasing the lever arm and allowing them to actuate the hinge. In addition, the effects of air pressure are dominated by the deformation of the pouch material, not the hinge stiffness, which explains the lack of folding at small pressures. To account for this, we include an offset pressure $P_i$ of 5 kPa to our model.

$$P(\phi) = P_{pouch}(\phi) + P_i \tag{13}$$

TABLE I

VALUES USED IN ANALYTICAL MODEL OF HINGE ANGLE

| | | |
|---|---|---|
| Resting Actuator Length | $L_0$ | 31 mm |
| Attachment length 1 | $L_1$ | 11.6 mm |
| Attachment length 2 | $L_2$ | 25.7 mm |
| Spring length | $L_s$ | 0.3 mm |
| Spring thickness | $t_s$ | 0.25 mm |
| Hinge Young's modulus | $E_s$ | 3 GPa |
| Hinge width | $D$ | 23.5 mm |
| Offset pressure | $P_i$ | 5 kPa |

## III. SELF-FOLDING AND UNFOLDING ON A DODECAHEDRON

A dodecahedron was made to demonstrate the basic pneumatic self-folding and unfolding. The center piece pentagon is cut from of a 1/16 inch thick acrylic sheet and the surrounding pentagons are cut from a 20 mil cardboard with a laser cutter. The center piece is heavier and helps the structure to stay still in place during folding. The lighter weight cardboard lower the torque requirement on folding.

To make the fold, 90 kPa pressurized air was streamed into pouches through a one-way valve. It takes about 33 seconds for the pressure in the pouches to saturate, and folds up the dodecahedron.

Because the control of this pneumatic fold is simply a one-way valve, the dodecahedron cannot unfold by itself. To unfold, one needs to remove the valve, and the dodecahedron will collapse to about 80% flat in 2 seconds. The self-unfolding can be easily achieved by replacing with an electronically controlled bi-directional valve.

Although there was no noticeable leaks at the connections, we observed that the folded shape unfolded after about 4 hours. We suspect the tubing connection at the pouch to be the major leaking point. It can easily detach as the pouch surface curves at inflation.

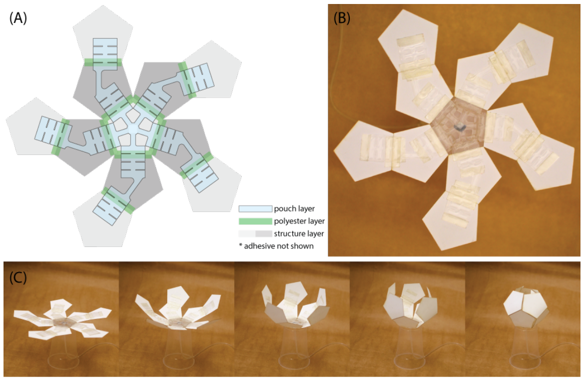

Fig. 5. A self-fold dodecahedron. (A) 2D design (B) automatically fabricated dodecahedron (C) dodecahedron self-folding process

## IV. SEQUENTIAL SELF-FOLDING AND SELF-LOCKING ON A GRIPPER

As pouch motors were introduced to actuate motions, a folded joint with pouch motor can become dynamic. By carefully adjusting the pressure, one can control the angle of the fold. To demonstrate these advanced features, we designed a gripper that folds up itself and grips objects with fingers.

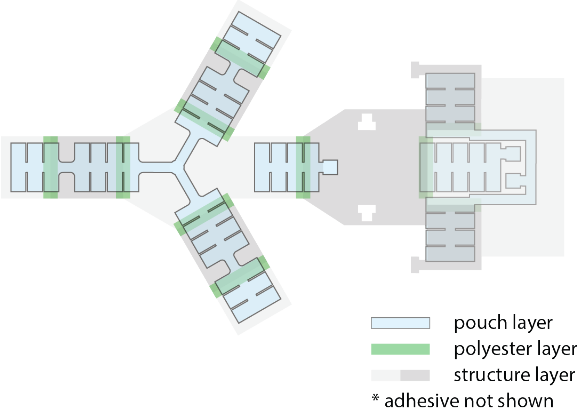

Fig. 6. Self-folding Gripper 2D design

The "hand" portion is made with 20 mil cardboard and the "base" portion is made with 1/16 inch thick acrylic sheet. The reason of materials' selection is the same as the dodecahedron: use light weight material on parts that are going to be folded up. There are two pouch layers on the gripper: one is under of the hand for the gripping motion, and the other is on the top of the base for elbow self-locking.

Unlike dodecahedron which folds up uniformly all at once with a one-way valve, the gripper folds up sequentially and locks its body with a self-locking mechanism.

The pouches on two wings fold up first (as shown on the third step). Then the arm folds up, inserting "keys" on the wings into two "locks." Finally the pouches on the wings deflates, the polyester films attached on the joint uses its spring back mechanism to push the keys sideway further onto the small slots. The arm is now locked vertically in place.

In a steady run, the total time it takes for the gripper to fold up and finger gripped is about 15 seconds. This can be reduced further by finely tunning the control codes. The total time it takes to unfold is about 40 seconds. The unfolding time is largely dependent on how long it takes for a pouch motor to exhaust air. In current design, exhausting air is only enabled from the spring back mechanism of the flexure. To reduce its unfolding time, one need to implement even thicker flexure film while not exceeding pouch power.

## V. CONTROLLED SELF-ACTUATION ON GRIPPER

We designed a pressure control system to control the pressure in the elbow pouch, which in turn, to control the folding angle. While monitoring the pressure in the pouch, an Arduino microcontroller controls the intake and exhaust of a pressurized air source by opening and closing of an air supply valve and an exhaust valve.

Because the geometry of each joint and the effects of gravity both affect the behavior of the joint, the pressure-angle relationship of each joint can vary significantly. The analytical model we provided does a good job in predicting a bare minimum design of a hinge in figure 2, but ignores the effects of gravity, which can be significant when the folding face is not resting parallel to the ground. In the case of predicting the elbow hinge behavior, the weight of the "hand" portion above the elbow hinge makes our earlier analytical model less suitable. Therefore to achieve a more accurate control, we characterize this hinge's pressure and angle relationship with physical experiments first.

With new data obtained, we choose to use a third power polynomial estimation to describe the angle to pressure characteristic. This empirical equation is then feed into the control program to command the elbow to turn to desired angles.

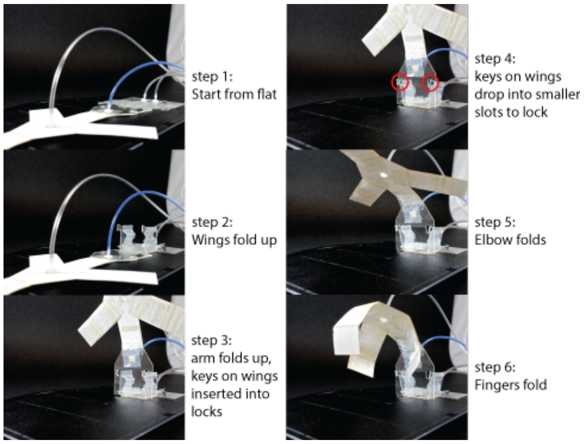

Fig. 7. Gripper sequential folding process. Steps 2-4 illustrate the self-locking mechanism used

Because of the weight of the "hand", even when the pressure is 0 kPa, there appeared a bending angle on the joint. During the control phase, each commanded angle was

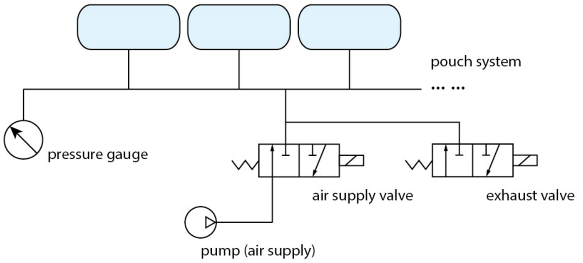

Fig. 8. Pressure control system designed to manipulate folding angle

turned directly after the previous command. We calculated an average error of 0.75 degrees.

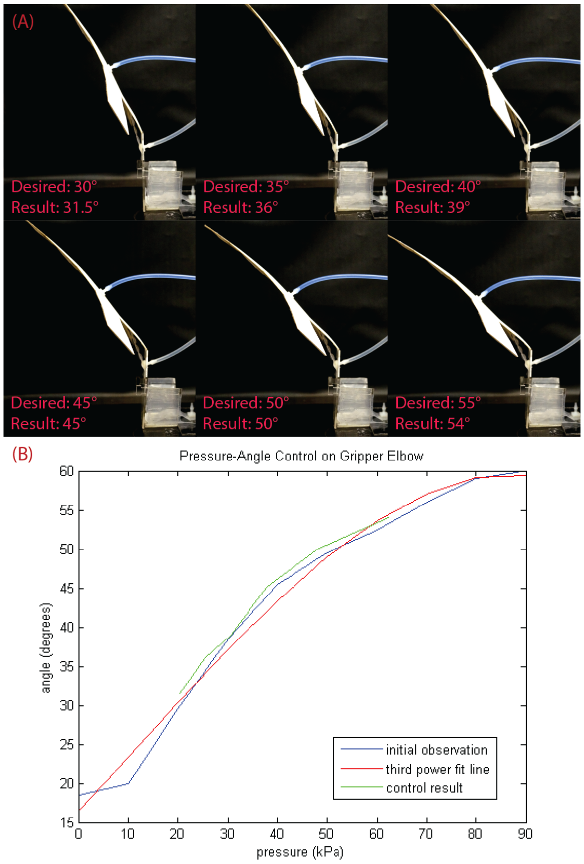

Fig. 9. pressure-angle bending control on elbow (A) commanded bending results (B) a plot of comparison of the observed raw data, a third power fit line, and the commanded bending results

## VI. DISCUSSION

Self-folding with pneumatics provides a functional method of reversibly folding and unfolding structures and machines. Previous work has demonstrated that printable pouch motors are possible for actuating machines, and in this paper we have demonstrated their application in more permanent, structural folds. We have shown that hinges can be locked in place via low-profile valves in order to maintain a constant mass of air in the pouches by constructing a self-folding dodecahedron. This technique would be ideal for structures that transform intermittently, such as solar panels that follow the sun or cleaning robots that operate daily and flatten themselves for storage. We have also demonstrated self-folding machines that use pneumatics for both assembly and operation in the form of a self-folding gripper. This machine locks its structural folds through mechanical features, which enables more permanent folds than valve-locking, but requires additional assembly steps. This technique would be ideal for assembling load-bearing structures such as furniture and robotic arms.

There are currently limitations to this technique that will have to be addressed before its widespread use. Low-profile pumps will have to be developed if we wish to enable folding from a truly flat conformation. Sharper fold angles will also be required to produce complex geometries; our current technique can only fold angles up to 90 degrees. As geometries and mechanisms become more complex, we will also have to address appropriate routing of the multiple pneumatic paths that will be required. Significant work has already been done on actuating multiple pneumatic units with a limited number of valves [20] but will require further work for integration into our printable process.

TABLE II

COMPARISON OF SELF-FOLDING METHODS

| Actuation | Hinge length | Reversible? | Max angle | fold time |
|---|---|---|---|---|
| Pre-Stress [21] [4] | 10 $\mu$m | No | 135° | 100 ms |
| SMA [10] | 1 cm | Yes | 180° | 10 s |
| SMP [22] [17] | 1 cm | No | 135° | 60 s |
| Pneumatics | 1 cm | Yes | 90° | 1 s |

Table 2 presents a variety of self-folding methods used today. Residual stress is suitable primarily for sub-centimeter length scales, and shape memory polymers are irreversible, so pneumatics has obvious applications that these methods are unsuited for. The most similar technique is using shape memory alloy (SMA) hinges. However, in addition to being faster than SMA actuation, these pneumatic pouches are easier to fabricate because they can be assembled from flat sheets. SMA hinges, in contrast, must be fabricated, mechanically programmed, and installed individually, significantly increasing the time and cost required to build the self-folding composite.

## VII. CONCLUSIONS

We exploit the use of pouch motors on self-folding, unfolding, and accurate pressure-controlled folding and actuation. We compared this pneumatic self-folding approach with other mechanisms and find that it exceeds others by being be able to switch between being a static folding joint and a dynamic actuating joint and has a very short fold time. However, the maximum folding angle is constrained by the current pouch pattern, and the lasting time is constrained by the pouch-to-tube connector. Nevertheless, these two shortcomings can be improved through better designs in the future. Thanks to the computer aided fabrication technique, pouch motor actuated self-assemble robots are cheap and fast to make. In the future, people will be able to make programmable unfolded flat robots for convenient transportation, have them assemble themselves remotely, and work autonomously in salvage, security, emergency and other tasks.

## ACKNOWLEDGMENT

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