Animating Paper using Shape Memory Alloys

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ABSTRACT

Our aim is to make shape memory alloys (SMAs) accessible and visible as creative crafting materials by combining them with paper. In this paper, we begin by presenting mechanisms for actuating paper with SMAs along with a set of design guidelines for achieving dramatic movement. We then describe how we tested the usability and educational potential of one of these mechanisms in a workshop where participants, age 9 to 15, made actuated electronic origami cranes. We found that participants were able to successfully build constructions integrating SMAs and paper, that they enjoyed doing so, and were able to learn skills like circuitry design and soldering over the course of the workshop.

Author Keywords

paper craft; paper mechanisms; paper electronics; shape memory alloy; education; origami

ACM Classification Keywords

J.5 [Arts and Humanities]: Arts, fine and performing; B.m [Hardware]: Miscellaneous

General Terms

Design

INTRODUCTION

Paper has long been used as a versatile building material. Soft enough to manipulate by hand yet rigid enough to hold a shape, while also inexpensive and plentiful in diverse forms, paper offers endless creative possibilities. As a result there has been a growing interest in combining the technological and aesthetic promises of paper with the interactive power of electronics. This has inspired novel techniques for fabrication such as embedding circuitry directly into the paper [2] and new technologies like electronically augmented pop-up interfaces [5], and kits for drawing electronic circuits on paper [?]. These examples demonstrate not only the functional aspect of paper electronics, but also its expressive and creative potential.

Recent works also examine how the mechanical nature of paper can be controlled with electronics and thus programmed. To make these mechanisms move electronically, nontraditional actuators that are lighter than traditional actuators–motors and solenoids–must be used to prevent destroying the paper as well as for direct integration with the material. Shape memory alloys (SMAs), which are metals that change shape in response to heat, are a popular solution precisely for their light weight and flexibility. One example is the programmable matter project, in which an array of custom made SMA hinges actuated a sheet to fold autonomously into various forms [3]. Saul et al. used SMA wires to make paper robots that bobbed and bounced [6]. The Animated Paper toolkit uses scanning and targeted lasers to heat the SMA precisely and wirelessly [4].

While research has been done on the use of shape memory alloys and paper, it is still largely an underused material. For beginner users of SMAs, the material is often prohibitively difficult to use and the effects are frequently not as dramatic as desired.

In this paper we introduce simple methods for incorporating SMAs into paper, including a series of reliable mechanisms for getting different movements. We then present a case study of using SMAs in an educational setting. Finally, we examine how effectively the activity works to inspire interest and teach topics in electronics.

SMA MATERIAL PROPERTIES

Shape memory alloys are metals that change shape with respect to temperature. At deactivated temperatures the metal is malleable and when heated to an activation temperature the metal returns to a ”remembered” shape. Since setting SMAs requires specialized equipment, to make our research accessible we focus on a pre-trained form of SMA called muscle wire. This wire is commercially available and comes in the form of wire that contracts approximately ten percent of its original length upon heating. While heat can be applied through various methods including light and body heat [4], we heat the muscle wire by running electric current through so that movement can be controlled electronically and be used in programmable interfaces.

WORKING WITH MUSCLE WIRE ON PAPER

Working with muscle wire is a process of experimenting to find an optimal combination of mechanism, structural force and electrical power. Keeping the wire taut in the mechanism ensures that the full contraction is used to move the structure. Heating the muscle wire for the first time often causes some strain in the wire, so it is important to re-tension the wire after initial heating for maximum movement. The electrical power used to heat the wire must be strong enough to run the desired

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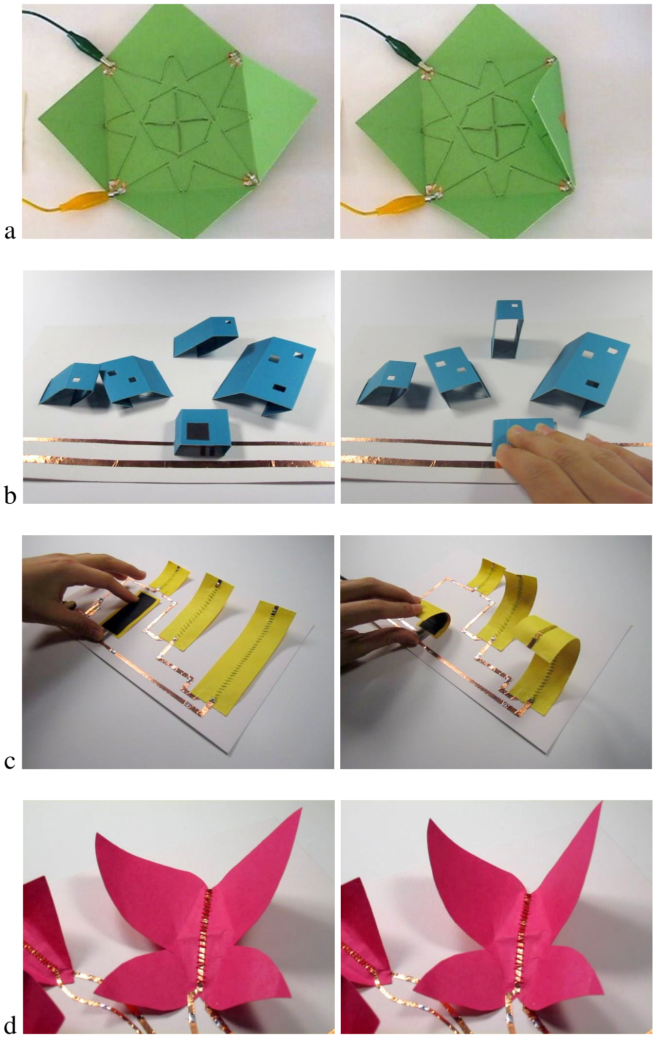

Figure 1. SMA paper mechanisms: folding flap (a), parallelogram (b), curling flap (c) and clam shell (d)

amount of current through, without overheating and straining the wire.

Paper as a medium is easy to manipulate through cutting, folding, drawing, sewing and so forth. Using a basic set of mechanisms, an endless variety of creative works can be made. A flap that curls up and down can be transformed into petals on a flower, the tongue of a snake, or even a skirt blowing in the wind. Paper is particularly appropriate for working with shape memory metals due to its high temperature tolerance as well as light, and pliable nature.

The first step in working with muscle wire is connecting the wire to the circuit. Since it has an oxidized coating, it cannot be easily soldered. One solution is to fold wire tip into a ”u” and insert into a crimp bead [1]. Folding prevents the wire from slipping out of the crimp bead while the bead provides a large surface area for soldering. We have found that cylindrical jewelry crimp beads, in silver or copper, work well for this purpose.

Next it is crucial to anchor the wire firmly to the structure and maintain tension in the wire, so that when the wire contracts, it pulls the structure along. We have found that adhesive on copper tape is strong enough to anchor the copper to the paper. Finally, the crimped muscle wire can be soldered directly to the copper tape, which also functions as a circuit element to deliver current to the wire. Since the wire tends to lengthen slightly after the its initial contraction, we found it helpful to retention the wire after this initial activation.

MECHANISMS

The following are several simple muscle wire mechanisms that we designed to have reliably dramatic effects. We used papers that have medium weight, from printer paper to card stock, which provides sufficient structural strength to hold the mechanism together while remaining pliable enough for the wire to overcome. In all of the following mechanisms, we use the natural springiness of paper to act as the restoring force for returning the structure to its deactivated form.

Folding Flap

In this mechanism the muscle wire pulls a flap along a crease, causing the flap to fold (see figure 1.a). The folding flap is built by anchoring two ends of the muscle wire to the base and attaching the middle of the muscle wire to the flap, so that the wire is taught when the flap is flattened. The simplest way for attaching the wire to the flap is to thread the wire through the paper itself. In this configuration, the flap acts as a lever and the muscle wire is the pulling actuator. The closer the wire is attached to the crease, the greater the degree of folding. Using longer wire will result in more dramatic folding only when the straight path of the wire elongates.

Parallelogram

The parallelogram mechanism lifts a plane out and parallel to the base when activated (see figure 1.b). This mechanism uses the same muscle wire attachment as the folding mechanism. However, here the flap to be actuated is one leg of the parallelogram. Lifting the parallelogram is achieved easily with the muscle wire but getting the parallelogram to lay back flat often requires reinforcing the legs of the parallelogram to be flat against the background. Here it is important to avoid strongly pre-creasing the legs of the parallelogram, or the restoring force will not be strong enough to return the structure to its flattened state.

Curling Flap

In the curling flap mechanism, the flap lays flat against the base when deactivated and curls out from the page upon activation (see figure 1.c). This mechanism is constructed by sewing the muscle wire to the paper or by even threading the muscle wire through small slits in the paper itself. It works by holding the muscle wire against the paper as it contracts, forcing the paper to curl to accommodate the shorter length of wire. For this mechanism it is important to use medium weight paper that the does not simply wrinkle when the wire contracts.

Figure 2. Wall hanging constructed using chained curling mechanisms

Clam shell

In this mechanism, two flaps rise upward symmetrically like two shells of a clam(see figure 1.d). This mechanism is constructed based on the curling mechanism with the addition that each side along the curl is now folded with arced creases. The result is that as the central paper curls down, the side flaps fold upward. This mechanism multiplies the effect of the curling mechanism by links two folding elements, so one actuation point results in three movements result.

DESIGNING FOR MAXIMAL EFFECT

In addition to achieving desired motion, various properties of muscle wire can be exploited to get the most magical effect out of this medium.

With the muscle wire mechanisms presented, it is possible to keep the wires flush with the surface of the paper, which integrates the material nicely into the structure. This also prevents tangling of the wires and thus keeps the circuitry organized and more robust. This can be done easily by sewing the wire directly through the paper structure.

Even though individual movements may be limited, for more startling effects large motions can be made by cascading multiple moving elements. For example, a chain of curling elements can be used to make large snaking motions (see figure 2). Here, the curling and contraction of each unit lifts the following unit, so that the motion adds linearly with each additional unit and the entire chain moves much more dramatically as a whole. Using multiple moving elements in close proximity with contrasting or opposing motions also heightens the effect of the movement.

Finally, the actuation of the wire is silent compared to traditional actuators such as motors or solenoids which produce a whirring or clicking noise. This gives space for emphasizing the sound of motion such as the creaking of materials sliding against one another, the crackling of paper or the collision of one material against another.

EVALUATION

Once several basic mechanisms for muscle wire were determined, we decided to design a simple example project as a case study for testing these techniques and materials in an educational setting. We aimed to teach paper actuation and electronics building an accessible manner that both teaches electronics concepts and draws on participants' arts and crafts background. Through our study, we wanted to see whether participants were capable of using the materials to build functioning, moving circuits and whether the experience inspires interest in pursing these activities further.

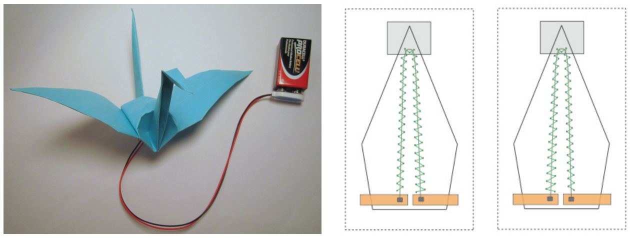

Figure 3. Electronic origami crane (left) and SMA wing template (right)

Electronic Origami Crane

Our goal for the example project and companion activity was to create a project that is simple to make, reliably functions electronically and teaches basic electronics theory and techniques.

We decided to augment the traditional origami crane with wings that curl and created a step by step tutorial for the project [1]. We chose the crane because is a popular model to fold and flapping wings is natural movement that matches both the concept of model and the capabilities of the muscle wire. Pockets in the wings of a traditional origami crane also provides a convenient location for curling wing inserts, so that the electronics portion of the activity is decoupled from the folding portion.

We chose a simple circuit to made up of a 9V battery, 0.006" high-temperature Flexinol muscle wire [1], connecting wires and two pieces of copper tape to make a switch. Touching copper tapes together closes the circuit connecting the battery to the muscle wire, which activates wire and curls the wings down. Separating the copper tapes opens the circuit, allowing the muscle wire to cool down and the wings to rise up. Since the switch is made of two pieces of copper tape, they can be placed anywhere on the model, which gives individuals freedom to design the form of the switch. In the tutorial, we suggest putting the copper tapes on the tail of the crane, so that when the tail is squeezed, the wings curl down.

Preliminary Electronic Origami Workshop

As part of the Cambridge Science Festival, we held a four-hour workshop on making the electronic origami crane. Our workshop was attended by ten participants– five female and five male– ages nine to fifteen. Each student was accompanied by a parent or guardian. All of our participants had some experience with paper craft but only 50% had previous experience with electronics.

We began the workshop with a survey on the participants' previous experience and expectations for the workshop. The

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[1] `http://hlt.media.mit.edu/?p=1448`

first half hour of the workshop was a lesson on how to fold origami cranes. Next, we helped students build the curling SMA wing inserts. This session included a demonstration of soldering and a short explanation of the circuit. Finally, we had students assemble the crane by embedding their wings into the origami model. We concluded with a show-and-tell and a discussion of how participants felt about the experience. Before leaving, we gave participants a post-workshop survey designed to gauge how much was learned, what the participants enjoyed and what participants found challenging.

Analysis

All participants successfully completed the tasks–folding the crane, sewing the mechanism, and soldering the electrical connections. Everyone completed the pre-workshop survey and 9 out of 10 completed the post-workshop survey. By the end of the workshop, even though not everyone had cranes that successfully flapped, every respondent said that they had made a project they were happy with and 89% of respondents replied they were interested in learning more about electronics.

It is worth mentioning that, despite the template we provided, 67% of participants who responded on the post survey found that the greatest challenge was getting the desired motion from their wings. Participants were prone to keep the wings activated for extended periods of time in hopes of more dramatic curling. However, this had the effect of overheating the muscle wire, which reduced the contracting abilities of the metal. As a result, half of the participants were faced with the challenge of rebuilding their wing inserts. While upsetting, this provided an interesting lesson (for the participants and the authors) in debugging. Most participants were not terribly discouraged and were able to make dramatically flapping cranes the second time around.

Ultimately, we feel that the workshop successfully introduced participants to the idea and process of crafting electronics. Our pre and post workshop surveys show learning and increased self efficacy. At the beginning of the workshop 40% of students said they they were comfortable working with electronics. This percentages jumped to 78% of respondents at the conclusion of the session. Additionally, 89% of participants who responded on our post survey indicated that they were interested in learning more about electronics. Students felt that they learned valuable lessons in the workshop including, how a circuit functions, and how to solder electronics. One participants parent sent us a message after the workshop explaining that her son was so excited by the workshop that they purchased a soldering iron and electronics kit so that he could continue explorations on his own.

Though these results are preliminary, derived from a single session attended by a small number of students, we believe that they indicate that activities like this one, that blend paper crafting with electronics, are promising activities for engaging diverse youth in building electronics. We believe that the novelty and magic of self-moving paper motivated our participants to build and debug a delicate circuit. Our participants demonstrated that SMAs can be used successfully in introductory electronics workshops. In fact, the sensitive nature of the material arguably supports teaching important concepts like debugging. As one participant remarked on the survey, ”you learn from your mistakes.” In sum, introducing technical skills like soldering a circuit around familiar activities like cutting and folding paper effectively engaged participants in tasks that they might otherwise not have been exposed to, or thought they were capable of.

CONCLUSION

We presented techniques and approaches for working with SMAs and paper and demonstrated that starting with simple techniques, a wide range of creative works can be made. We also successfully introduced a group of young students to circuits and paper crafting, hopefully inspiring a deeper interest in electronics. We plan to continue to develop SMA mechanisms and activities to help students use SMAs to animate their paper projects.

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