Animated Paper: A Toolkit for Building Moving Toys

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In recent years, there has been a surge in the number of available rapid prototyping tools, making it easier than ever to create functioning prototypes with minimal technical background and at a low cost. However, most of these tools do not have the flexibility to allow for immediate physical modifications once a prototype has been built or programmed, and are often limited in movement by the size or range of the wired system. Accordingly, simple paper remains one of the most pervasive creative platforms in the world due to its low cost, light weight, freedom of physical spatial manipulation, disposability, and low interaction overhead.

In this article we introduce "Animated Paper," a new wireless prototyping platform which combines paper, shape memory alloy (SMA), retro-reflective material, and copper foil. This platform makes it possible to create moving toys out of ordinary print paper with minimal modification to the physical composition of the paper itself, facilitating simple trial-and-error modifications. We also introduce a laser control system which allows for precise, wireless motion control of the SMA-enhanced paper by tracking retro-reflective markers on the paper using a laser and photo sensor. Lastly, we present the results of a preliminary user study to demonstrate the usability of our prototype system and also provide possibilities for how to further develop our wirelessly controlled, moving paper platform.

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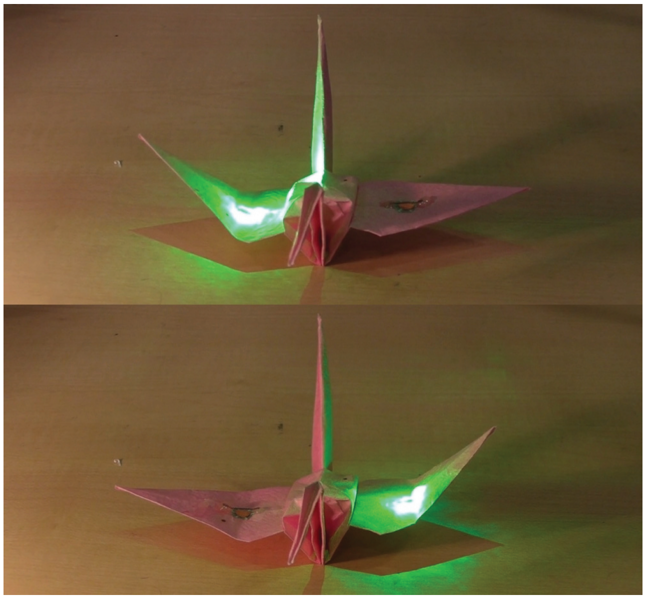

Fig. 1. Animated Paper sample. The origami crane flaps its wings when heated by the green laser point.

1. INTRODUCTION

Paper is an inherent part of our history and our everyday lives. Japanese origami, a paper art form over 300 years old, has continued to be practiced by people throughout the world, However, we are interested in changing origami from what has largely remained the art of creating beautiful but static figures, to the interactive art of experimenting with beautiful moving figures.

The inherent usability of paper has made it one of the most common, cheap, and simple interfaces on the planet—anyone can write, draw, and build things out of it. There are also a wide range of similarly familiar tools to assist in more precise and complex paper creations including printers, cutters, and glue. We introduce an animated paper platform that aims to build this comfortable interface into an intuitive, physical prototyping medium that would empower and encourage all people to experiment tactilely, allowing them to imagine, easily build, bring to life, and then modify their own creations with their own hands. With animated paper, we hope to turn static origami forms into seemingly living creatures, as shown in Figure 1.

1.1 Benefits of Paper

Our Animated Paper system aims to augment the following advantages of paper prototyping and design:

- Freedom in spatial manipulation;
  Paper is much easier to shape and maneuver in a 3D plane than its computer counterpart;

- Ease in face-to-face collaboration;
  In Cook and Bailey's contextual interviews with twelve designers from varying fields, physical tools were found to be extremely important for the early stages of design. Physical copies and prototypes were more likely to solicit feedback and facilitate group discussions because they allowed designers and clients to focus more on social cues typically lost in electronic communication [Cook and Bailey 2005].
- Lower interaction overhead;
  Paper can be placed directly on any physical space and then be directly modified; and
- Disposability/
  In Cook and Bailey's interviews [Cook and Bailey 2005], they also found that cheap paper prototypes and sketches are more conducive to generating new ideas, modifying old ideas, and discarding obsolete ideas because of the low material cost and disposability.

1.2 Basic Features of Animated Paper

Our platform utilizes a helix-type shape memory alloy (SMA), called Bio-Metal (Toki Corporation), a fiber form actuator made from an extremely light and flexible metal that can be easily bound and removed from paper, allowing for quick and cost-effective prototyping. When heated to between 70 to 80 degrees Celsius, the SMA immediately shrinks, causing the SMA-mounted paper to bend. After heating, the SMA quickly returns to its original length, and, accordingly, the paper returns to its original shape. We propose this combination as a type of thin and resilient transformable bimaterial with SMA as the heat activated material that induces motion and paper as a low-cost elastic base material.

It is possible to change the movement of the paper figure by varying where the SMA is mounted, how it is heated, how the paper is held, the type of paper used, as well as the length of the SMA, creating a wide range of possible applications. In our current system, we were able to achieve four major movement types, which will be discussed later in this article.

2. RELATED WORKS

2.1 Prototyping

Due to paper's prototyping benefits, there have been many developments to enhance and build on this intuitive interface.

In this section we summarize other paper prototyping interfaces and SMA-embedded materials, as well as the control systems for them.

Many of the current applications for SMA in building materials involve embedding the SMA directly into the fibers of the parent material. For example, the Pulp Computing project at MIT Media Labs has created a new type of paper embedded with sensors, actuators, and circuit boards that add a range of new capabilities for almost any type of paper [Coelho et al. 2009]. In Electronic Popables [Qi and Buechley 2010], Jie Qi utilizes this paper augmentation process to build an interactive pop-up book that allows users to control electronic components in the book simply by touching various points on the paper. However, the range of motions and interactions are limited to the sensors and actuators embedded in the paper during the actual paper-making process. Accordingly, it becomes difficult to make changes once the paper has dried with the embedded sensors.

On the other hand, there have also been prototyping projects using SMA that involve more surface changes to the parent material and have placed a greater focus on the control mechanism of the material's movements. Surflex [Coelho et al. 2008], a material developed by MIT's Fluid Media Group that combines SMA, foam, and printed circuit boards (PCB), is a malleable material that can assume and revert back from a variety of shapes. The surface is constructed by piercing a 1" foam substrate by four assemblies of two PCBs connected by eight SMA coils on an x,y plane, creating a motion grid. Because the SMA coils are not embedded inside the foam, it is easier to modify the motion grid if a designer wants to change the range of potential movements. However, due to the rigidity of the PCBs and the topological configuration, this system is limited to single solid surfaces, making it difficult to build and move more complicated shapes. Counter movement to the SMA's actuation is also highly reliant on the foam's ability to return naturally to its original shape.

The Sleepy Box paper robot developed by Saul utilizes paper, SMA, and an Arduino [2005] that allows the figure to react to sound [Saul et al. 2010]. Their system is actuated through a gold leaf circuit that has been created by spraying adhesive through a laser cut stencil and then applying a gold leaf. To this circuit additional components were attached using conductive glue, and brass clips were used to connect the circuit with the external power supply. These thin circuits add little weight, providing greater flexibility and mobility to the paper. However, this system relies on an electronic microcontroller enclosed at the base, making it difficult to mobilize the entire figure. Also, the current prototyped version has only flex-neck and hinge mechanisms, limiting the range of movements for the paper.

Our animated paper system is wireless and because the combination of SMA, copper foil, and retro-reflective materials are affixed on the surface rather than inherently modifying the composition of the paper itself, it can be easily utilized on any type of paper and just as easily modified. Our animated paper system essentially allows users to physically and intuitively mark points directly on the surface of the paper, just as they would if taking notes or sketching reference points.

2.2 New Types of Thin Materials

A growing interest in Green Technology has resulted in significant research for new types of eco-friendly, smart paper alternatives. Sung-Ryul Yun reported a flexible paper transistor made from regenerated cellulose that has been covalently bonded to multiwalled carbon nanotubes [Yun et al. 2009]. Renewed interest in cellulose as a functional material, namely in electro-active paper (EAPap), is largely the result of the material's biocompatibility and low energy consumption, opening the possibilities for new eco-friendly industrial applications [Kim 2006]. While EAPap may provide greater durability and biodegradability compared to current commonly available copy paper, the actuation performance of EAPap is highly contingent on humidity levels. Furthermore, actuation is currently achieved by sending an electrical current from a function generator directly to the EAPap, but in the current prototypes, the movements cannot be controlled.

Thin materials can also communicate through Two-Dimensional Signal Transmission (2DST) [Shinoda et al. 2007]. These sheets utilize microwave propagation confined to the surface to enable wireless communication between multiple sensor nodes on the sheet as well as to provide electric power to the nodes. The sheet creates an inexpensive and lightweight channel for high-speed signal transmission with minimal power. These large area 2DST sheets can be produced with a range of low-cost materials. By creating a direct channel between our animated paper and the 2DST, it becomes possible to simultaneously control the movements of multiple paper prototypes in any environment while allowing them to wirelessly communicate with each other.

2.3 Laser Tracking System

Most current applications of laser tracking systems are found in robotics and virtual reality, with many requiring the use of high-speed cameras or industrial-sized lasers that cannot be easily incorporated into everyday settings such as offices or classrooms. However, there have been a few recent developments in more intuitive and flexible tracking systems.

Smart Laser Scanner for Human-Computer Interface [Cassinelli et al. 2005] is an effective high-speed tracking system that utilizes a laser and photodetector which, instead of continuously scanning an entire field of view, narrows the scanning window based on the real-time analysis of backscattered signal generated during a rapid circular laser “saccade”. While this system allows for fast-tracking several moving points and was even tested safely on bare skin, it currently does not include an automatic energy output response to the individually tracked points that is necessary to heat the SMA and mobilize the paper.

2.4 Origami

There has also been research on the development of origami shape-building methods that made it more possible to automate the folding process. Jun Mitani and Suzuki proposed a method for producing the unfolded papercraft patterns of rounded origami animal figures using triangulated meshes by means of strip-based approximation [Mitani and Suzuki 2004]. While more recently, Hawkes et al. proposed a self-folding origami sheet called “Programmable Matter,” which is an augmented material that combines SMA and a flat sheet composed of interconnected triangular sections [Hawkes et al. 2010]. This Programmable Matter can be programmed to achieve specific shapes or rigidity upon command. In the current system, they have been able to transform a flat plane into a basic boat and airplane. However, a key difference between our system and the Programmable Matter system is that ours is remotely controlled while theirs utilizes a wired system.

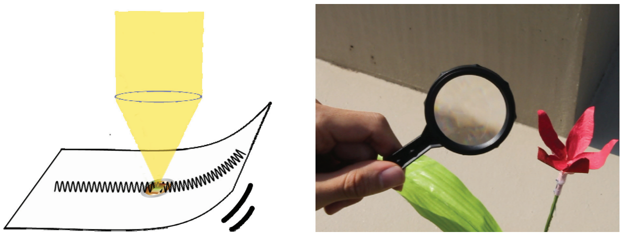

Fig. 2. (left) Blooming Movement From Sunlight Application (right) blooming: By concentrating sunlight energy onto the SMA located at the foot of the flower using a magnifying glass, the SMA helix will constrict and pull open the connected petals.

3. ANIMATED PAPER : APPLICATIONS & SYSTEM HARDWARE

We have tested our Animated Paper with three different energy sources: sunlight, heater, and laser.

3.1 Application with Sunlight

The movement mechanism of the SMA helix works by using any type of heat. To demonstrate the ease-of-use and versatility of this system, we have used only a magnifying lens to harness sunlight energy to mobilize the paper (Figure 2, left). To show the real-world applications of this solar-powered paper, we have developed an animated paper garden, which simulates the blooming effect of a real garden (Figure 2, right). This technique provides a low-cost and eco-friendly platform for us to develop and easily change our own "living" garden.

3.2 Application with Heater

The easiest method to actuate our animated paper is to use a heater. Users only need to put an SMA on their designed paper model and then heat up the material to control the movements. However, this method is not suitable for precise control because a heater emits hot air over a large area and the additional pressure from the air may change the desired shape of the paper.

3.3 Application with Laser

While the sunlight and heater experiments showed the usability of SMA-enhanced paper in different environments, an integral part of our system builds off one of paper's major prototyping advantages: greater control and resolution. To implement a movement control method for our Animated Paper system, we have developed an intuitive laser tracking system.

This laser system provides a number of advantages when compared to other heating methods like a heater or sunlight. Not only does the laser's higher energy provide faster actuation, but by utilizing a laser system we are able to implement an automated scanning method with high spatial resolution, affording greater precision control. As seen in Figure 3, it becomes possible to create animal paper crafts that can achieve specific movements such as walking.

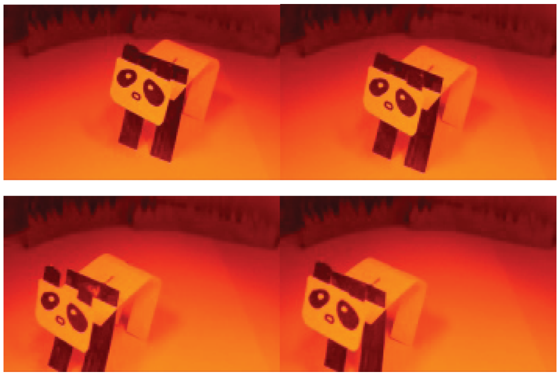

Fig. 3. Walking paper toy: This panda paper craft walks when the SMA located above the forefeet is heated by the laser.

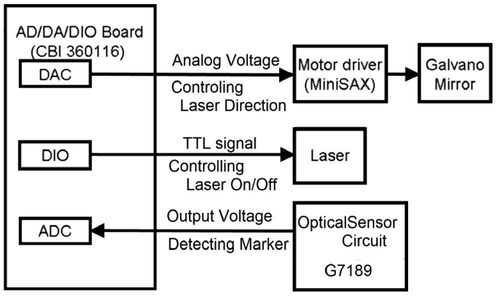

Fig. 4. Block diagram of animated paper's control system. The AD/DA/DIO board controls the motor driver and laser and receives the data from the optical sensor circuit.

3.3.1 *Control System.* This system is mainly composed of a laser, half-mirror, galvanometer mirror, and photo detector (Figure 4).

We use a Diode-pumped solid-state (DPSS) laser (Changchun New Industries (CNI), MGL-III-532). The wavelength is 532[nm] and the power is 50[mW]. The laser passes through a half-mirror (Edmund Optics, 20[mm] X 37[mm], 50R/50T, Plate Beam splitter) and hits the galvanometer mirror (General Scanning Inc.(GSI), VM500) where it is then reflected down to the stage. This galvanometer mirror can rotate between −50 degrees to +50 degrees. The AD/DA/DIO board (Interface Company Ltd, CBI360116) installed into the PC control motor driver (MiniSAX) and control laser position. It can work around a 400[mm] square stage. In addition, this board controls the on/off interface of the laser using the TTL signal from the DIO. The AD port of this board connects to the photo-sensing circuit. This optical sensor (Hamamatsu Photonics K.K., G7189) is placed at the conjugate position as the laser output from the half-mirror, sending the laser light back to the photo sensor reflected by retro-reflective material as a marker (Figure 5). This system can thus detect the position of the marker by checking the output from the photo-sensing circuit. For safety, the laser is contained within a metal box with a laser filter window, and users are able to maneuver it using a remote control system (Figure 6).

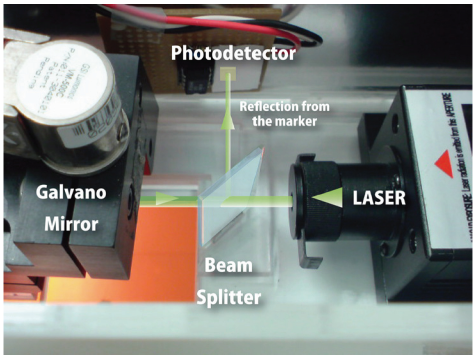

Fig. 5. The position of the Laser, Galvano mirror, Beam splitter, and Photodetector to prevent eye damage from the laser beams. We built a special box covered by aluminum to prevent laser emission. This box has a window made of acrylic which acts as a laser filter, allowing the user to perfectly see the inside without any retinal harm.

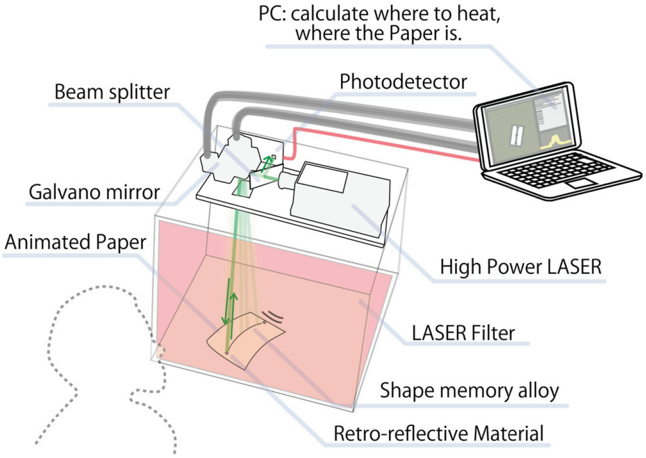

Fig. 6. System overview. The metal box has a laser filter with a protected opening at the top through which the laser passes to control the paper figure in the box.

3.3.2 *Control Object.* Our animated paper consists of three key components that are affixed to the paper: (1) SMA, which works as an actuator; (2) retro-reflective material, which works as a marker for the laser tracking system; and (3) copper (Cu) foil, which works as a thermal absorber. The specific heat of Cu is 0.379 [J/g·K], which is very low for similarly priced commodity materials, making it ideal for quick and inexpensive prototyping (Figure 7). It absorbs the laser heat more effectively and accelerates the temperature shifts. Retro-reflective material marker is a regular hexagon with sides of 4.5[mm]. The copper foil has a diameter of 6[mm] and is placed at the center of the marker.

The length of the SMA can be adjusted according to the range of motion desired by the user.

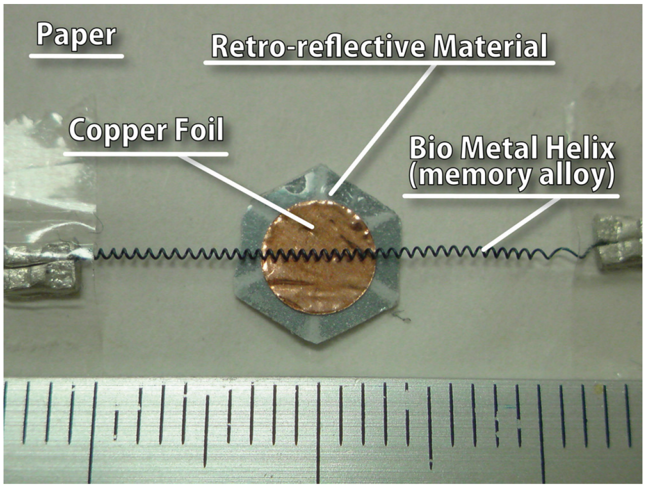

Fig. 7. The marker for the laser system. Our system consists of three key components which are affixed to the paper: SMA(Bio Metal Helix) which serves as an actuator; retro-reflective material which works as a marker; and copper foil which we use as thermal absorber.

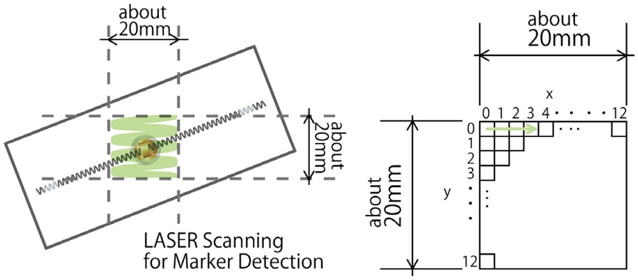

Fig. 8. Tracking area. The laser scans the 20mm × 20 mm square to find the center of the marker by dividing it into 169 areas.

3.3.3 *Control Method.* There is a three-step process to control the Animated Paper: scanning, heating, and tracking.

Scanning. To assess the positions of the markers, this system runs a raster scan and then measures the light reflection from the photo-sensing circuit. The scanning area is 20 millimeters squared, and the system checks the area using 13-by-13 dots. Each scan takes approximately 50ms (Figure 8).

When the laser beam hits the retro-reflective material on the marker, it bounces back in the opposite direction. The system recognizes this reflected light as a marker, with a threshold of 0.5V (Figure 9). After the raster scan, it calculates the central position of the marker.

Heating. After calculating the center, it heats the copper foil at the center of the marker by drawing a 4mm square. This copper foil is especially effective for heating the SMA when the user cannot affix the SMA at the center of the marker. When heated, the copper foil also serves as a thermal absorber to prevent the paper from burning due to the intense laser heat, while also serving

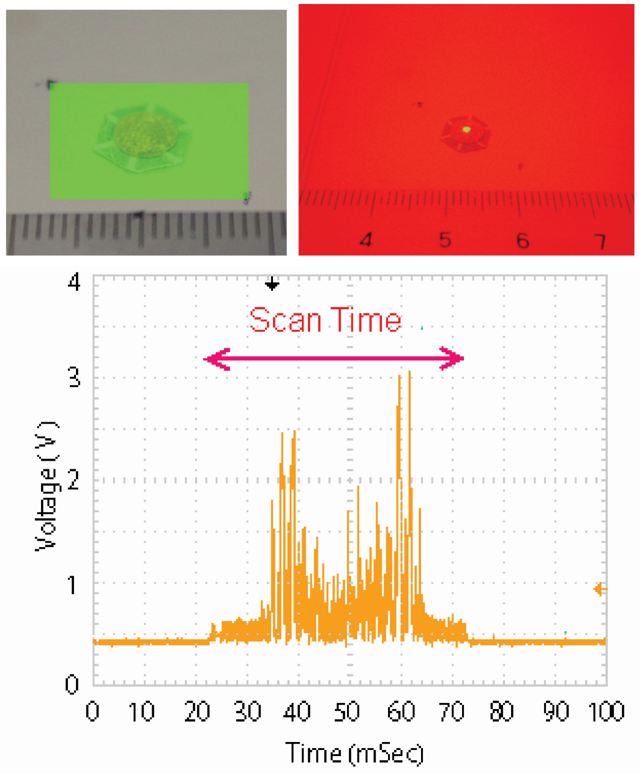

Fig. 9. Marker and tracking area (top left); laser tracking the marker's center point (top right); output waveform of photo-sensing circuit (bottom).

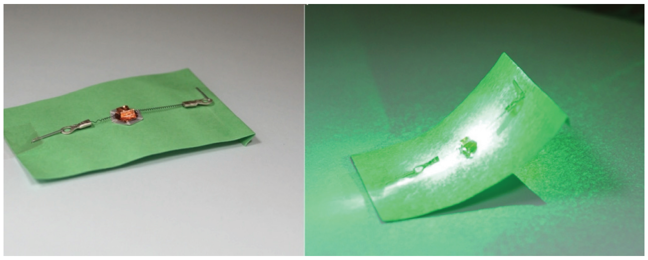

Fig. 10. Animated paper module (left); bending movement (right). The maximum angle of the bending motion is around 60 degrees.

as a heatsink when heating is halted. In other words, this Cu foil function helps the paper to adjust to the rapid temperature changes.

When the SMA is heated to about 70 degree Celsius, it shrinks, bending the paper (Figure 10). These user-dictated motions allow for a user to literally "animate" any type of paper.

Tracking. When the paper has moved, the position of the affixed marker within the scanning area also changes. Accordingly, when the marker moves, the laser light once again hits the retro-reflective material that has been placed

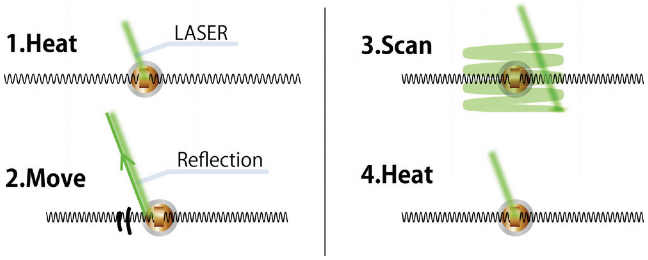

Fig. 11. Tracking sequence: (1) Laser heats the center of the marker where the copper foil is affixed; (2) laser hits the retro-reflective material and the light is reflected back to the photo sensor; (3) sensor detects the movement of the marker and the laser scans again to find the new center; (4) laser heats the copper again.

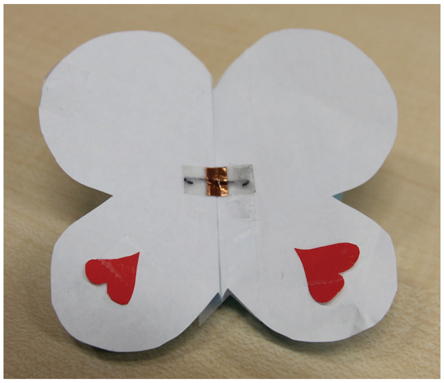

Fig. 12. Animated paper butterly. There is a SMA strip at the center of the butterfly. When the SMA is heated, it shrinks and pulls both wings together, creating a flapping motion.

around the copper foil in a doughnut shape, sending the light back to the photo again, which then triggers a rescan. After the system rescans the area, it tracks the new center position of the copper foil and heats the point accordingly. By repeating this sequence, our tracking system allows for continuous, automated movement of the paper (Figure 11).

Users can make unique, moving prototypes by adding the Animated Paper components to their originals. like Figure 12.

4. MOVEMENT

We have worked with four styles of movement.

The first is the bending style, which is the easiest to achieve. In this style, the SMA shrinks and bends the paper. When the SMA cools down, it returns to its original shape by the force of the paper.

The second is the counter pulling style, which is comparable to a seesaw shape that allows for basic ambulatory movements. This consists of two crossing papers and two SMAs. When one SMA shrinks, it pulls one of the paper legs forward, but because the SMA is not bending the paper when it shrinks (as with the first movement style) but rather pulling it, there is no resistance from the paper to pull the paper leg back to its original position. By affixing SMAs on opposing intersection points between the two crisscrossed sheets of paper, it is possible to move each paper leg forward or backward through counter SMA force.

The third style is the closing-opening (blooming) type where one edge of SMA is fixed to a paper pulley that is attached to several separate components and the other end of the SMA is free. When the SMA shrinks, it pulls the pulley down, which can extend or retract the components attached to the pulley (see image of blooming flower).

The fourth movement style is the rotation/spinning type. Similar to the closing/opening style, the edge of the SMA is fixed to the paper, while the other end is completely free. Since our SMA is helix-shaped, it shrinks in a circular motion.

5. USER STUDY

This paper is a proof of concept for our wireless, moving paper platform, Animated Paper.

In order to test the usability of the system and to gauge the level of engagement and enjoyment from users, we conducted a small user study with three people ranging between the ages of 16 to 29: a female high school student with minimal technology background, a design student, and an industrial designer.

We first observed their free use of the animated paper and then conducted in-depth interviews to better understand their thought process and interactions with the system.

To illustrate the user interactions we observed, we introduce the case of the industrial designer.

We began the user study by explaining what the system is and how to make the SMA-enhanced Animated Paper. We then provided several paper samples and a range of everyday paper tools (from scissors to markers) to allow for ample experimentation. At first, without any guidance, he made simple paper models like a round alien, and then pasted the SMA on the tail of the alien to animate. However, he soon found that the paper he had used for the tail was too thick and rigid, so it did not readily bend when the SMA was heated.

After this preliminary test, we taught him how to achieve three different types of movements: 1) basic bending style, 2) counter pulling (ambulatory) style, and 3) closing-opening (blooming) style. After this, he made a simple segmented insect with basic bending motion in order to test the system. Upon seeing the actual movement of the paper, he said he became very excited and began to imagine a whole range of other figures he wanted to animate. After tinkering with several designs, he discovered a new spinning movement on his own that took advantage of the SMA's inherent coil structure. By dangling the paper figure from a SMA strip and heating the SMA at the dangling point, the figure would move in a circular motion in tandem with the shrinking SMA helix. This movement was also implemented in a different way by the high school student who participated in our user study (Figure 13). This spinning movement was new for our system.

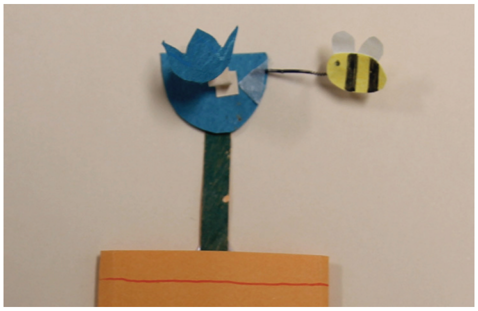

Fig. 13. Spinning movement. The bee is connected to the flower by a short SMA helix. When the laser heats the SMA, the SMA shrinks in a spiral motion, so that the bee spins toward the flower.

While this story is from just one of our preliminary user studies, it shows the animated paper system has a range of experimental potential that changes with each user. Each of our three users spent an average of forty minutes tinkering with their paper designs, and when put in a group setting, spent an average of two hours building models and helping each other think of new ways for achieving the motions they wanted, showing that the system both encourages experimentation and is also conducive to collaboration. We believe our animated paper can be a creative and playful tool that can be used by people of different ages and backgrounds.

6. DISCUSSION

6.1 Benefits of the System

Our system allows for remotely-powered and remotely-controlled everyday thin materials. In our user studies, the industrial designer pointed out the importance of showing the expected movements of a new product through a working physical prototype, and that this system would be useful for quickly showing moving prototypes. While simple Flash animations and other manipulation tools can create the illusion of movement, our goal is to provide the actual ability to control and customize the movement while still retaining the distinct physical and lightweight characteristics of paper.

6.2 Potential for Our Method

While currently we have only shown the usage in a small laser-proof box for proof of concept, our system's remote control system can be scaled accordingly for usage, such as for micro-machine control or remote airplane control from space. Additionally, our system can be used for controlling multiple robots using a single laser projector. On a prototyping level, different permutations of the actuators attached on one object can be tested in order to produce different movements.

6.3 Practicality and Safety

One of our goals is to make this system more accessible to anyone interested in interactive crafts and rapid prototyping. In order to create a more cost-effective version of this system, it is possible to use components from cheaper and more readily available consumer products such as the lasers found in Blu-ray drives or the micro-laser scanners used in projectors in our system, since the wattage in these lasers is adequate for actuation.

Safety is also something we have considered throughout our research. Our method will not cause fires because SMA requires less than 100 degrees Celsius to shrink, while paper burns between 250 to 450 degrees Celsius. Moreover, our laser system heats the copper foil rather than the paper directly, allowing the copper to serve as an absorptive material,

6.4 System Limitation

Currently, the laser is the biggest limitation of our system. Because of the laser's high energy it is currently not possible to use our tracking-heating system outside of the laser-protected box for safety reasons. We will continue researching new actuator materials that may increase the versatility of our system and allow for precise motion control with more widely applicable heat sources [Smela 2003; Wallace et al. 1999]. For example, recent research by Yoshino et al. [2010] on liquid-crystalline polymer fibers containing azobenzene moieties exhibit three-dimensional movement under photo-irradiation, and this movement can be controlled by manipulating the actinic light source. Because these actinic light sources are more accessible and safer than laser light, we will further experiment with these fibers to replace SMA in our Animated Paper system for the future.

Also, while our system can control the bending and retraction of the paper, it cannot control the speed of the bending. Because the speed is dependent on several additional parameters such as ambient temperature, length of the SMA, and the type of paper, it is difficult to create a precise speed control system without applying several system restrictions. In the future we will add a cooling component to the laser-protected box in order to speed up the retraction time to facilitate faster continuous motion.

In the current system, figures made with standard 6" origami paper worked best for actuation, but because the system allows for wireless control, the paper can be scaled up or down to any proportion. Thicker papers, such as construction paper, did not readily move when the SMA was heated with the laser. However, in our preliminary user studies, we also found that the thinner paper was more flexible and more conducive for experimenting.

7. FUTURE WORK

There is a range of interesting directions for the further development of our technology.

At the core of this system is the fundamental simplicity and affordability of paper as a platform for creating and distributing. Paper can be easily copied or scanned, and ideas can be easily shared through the Internet and then printed. We would like to share our animated paper platform and hope to build it into a new rapid prototyping method that can be easily utilized by anyone. There are already so many tools for hardware and software development like

Arduino [2005] or Processing [Reas and Fry 2003] that have encouraged even those without a technology backgrounds to build and experiment. We hope to develop our animated paper into a new empowering prototyping tool.

For this purpose, we will conduct more contextual interviews with a greater range of designers and evaluate which shapes and forms are most relevant for different design fields. We will then develop our system to best enable relevant movements for these shapes and functions. We will also create a design module to make our Animated Paper system easier to use.

By combining our animated paper system with Pepakura [2003], a program that allows designers to transform their 3D models into 2D printable formats, it is possible to create and control even more complicated figures. Recent developments in origami design tools [Mitani and Suzuki, 2004] also make it possible to precisely replicate physical papercraft designs, including more organic rounded shapes, by using physics-based mesh model simulations. Our new approach can enrich this research because our system does not require PCB space on the design.

8. CONCLUSION

In this article, we presented a novel and intuitive prototyping method that allows designers to build and control moving paper prototypes by combining readily available and low-cost paper with SMA.

We have also presented three paper-controlling methods: sunlight, heater, and laser. To facilitate greater precision control, we have described an automated laser tracking system that enables users to automatically control and mobilize their paper prototypes.

However, we hope to develop a more generalized algorithm or control method using more commonly available energy sources to make our system more useful and accessible. We have considered further development of solar-powered paper to create a more eco-friendly system.

We have considered the development of potential new toys using this system, such as (1) new picture books with easily added and modified pop-up pages that change when heated; (2) photo-controlled paper airplanes that can fly autonomously; and (3) Living Paper Zoo, which would allow anyone to create origami animals that can then be controlled remotely and move depending on the movements of the other figures.

We see this work as an opening to the larger issue of how to bring new functionality to everyday materials, particularly flat materials such as paper, cloth, or film that may encourage people to think of their surroundings differently.

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