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SMA Variables

Directing Kinesis

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Abstract This paper examines the variables inherent in the shape-changing phenomenon and suggests a new method of experimenting with shape memory alloys (SMA) to direct kinesis. This method widens the range of potential interactive applications beyond the traditional "on-off" state. The resulting flexibility permits personalization throughout the course of the transformation, enhancing the use of the material as infrastructure or for interface for pervasive computer systems or mechanical devices.

Keywords Shape Memory Alloy (SMA) · directed kinesis · localized heating · transitive material · ubiquitous interaction · personalization · transformation

1 Introduction

Since the early 1930's researchers have observed an unusual temperature activated shape-changing phenomenon in various alloys. While the effect seemed hopeful to provide physical movement for machinery, the metals themselves proved problematic for mass application. Early alloys were either too expensive or too toxic. Modern researchers continue to test alloys in regards to their efficacy and unique transformation characteristics. Our particular interest is not in the metallurgy, but rather, the variables inherent in the shape-changing phenomenon that allow for variations in the transformation trajectory of the material and enhance the designer's palette.

Indeed, the ubiquitous nature of electronic computing suggests an interconnectivity that is both flexible and personal, having evolved from a central mainframe where users had to go to it, through the onset of personal desk computers, to pervasive technologies. Building upon the metaphor of ubiquitous interactivity, as expressed through materiality, we regard a shape memory alloy (SMA) as a transitive material, an adequate tool to reflect current technologies. We will therefore review the material used in our research, test the variables, suggest new exploration which enhances personalization and integration, and offer concluding remarks.

2 Related Work

Many artists and scientists have experimented with shape memory alloys and claimed fascination by their potential to merge the sensual, architectural and corporal worlds.

Etienne Krähenbühl's 'Onibaba', a field of waving reeds fabricated of shape memory alloys, and the 'Christmas dream', which is arms powered by a shape memory mechanism that periodically deploy and stretch a ribbon heavenward, exemplify the use of SMA's as actuators and levers [1]. As part of a component, the shape memory wire is stressed to simulate muscular movement. Comparable to these are the use of SMAs in contemporary projects, such as the nickel-titanium alloy (NiTinol) spring skeleton that heats the liquid crystalline elastomer (LCE) in Simon Biggs's prototypes [2].

On the other hand, Jean-Marc Philippe's "Hermaphrodite", "The Totem of the Future" and "L'Arbre de la Nouvelle Alliance" seem to be the first art concepts that pay attention to the full transformational process of the alloys installing SMA as the feature, as opposed to the actuator of the piece [3]. That is also evident in the function of the kinetic flower on the "Kukkia" garment or the kinetic hemline in the "Vilkas" dress developed by the Extra-Soft lab [4]. Nevertheless, they still depend on uniform heating to achieve the desired transformation.

Indeed, while much scientific research has been conducted on the overall effects of generally heated and fully actuated SMA's, instances of experimentation on locally heated applications for the enhancement of the trajectory geometry has been sparse. R. S. Dennis developed a laser to locally heat

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a NiTi SMA wire to compositionally change areas of the wire to vary transition temperature along the length, allowing for regions of SMA effects or no SMA effects [5]. However, his work focuses on the elastic qualities of the phenomenon as does much of the locally heated experimentation. Also, “localized heating and cooling of a Shape Memory material can provide a very effective means of damping vibrational energy” as found by Kloucek, Reynolds and Seidman in their research on NiTi Shape Memory wires [6]. There remains a dearth of selectively heated trajectory exploration.

The method of experimentation that we employ adds specificity to the heat application. In doing so, each shape of SMA is activated sequentially resulting in a speed and trajectory that can be ‘coded’, as you will, to predetermined personalized patterns. This evolution of the phenomenon is analogous to the departure from analog computing to integrated variations of data. The following experimentation considers SMA’s as transitive materials, capable of reflecting the multifarious character of ubiquitous computing.

3 Materials

Shape memory alloys are materials whose microstructure changes with an input of thermal energy. Although the phenomenological result may suggest that shape memory materials are energy-exchanging, they are actually phase-changing [7]. Heat enables an alteration of the material’s microstructure through a crystalline phase change.

The material we used for our experimentation is NiTi (Nickel and Titanium alloy). NiTi can be temperature-activated by direct heat or through resistance to electrical current [8]. For our experimentation, two different shape memory alloy forms were used. They are bar shape and NiTinol wire of circular cross section. Their specifications are as follows:

a. Bar Shape #SMA-5A, 0.023” x 0.074” x 5”, by Johnson Mathey Company.

b. HS-6 Nitinol Memory Wire, 0.0297” diameter, by Educational Innovations Inc.

Both are Nickel-Titanium Alloys with a transition temperature between 30°C and 50°C.

3.1 Variables

In our bibliographical research and experimentation with the shape memory alloy, we identified different variables that influence the phenomenological effects of ‘memory’ and ‘movement’. In our analysis, we define memory as the ability to return to the austenitic phase. Movement is expressed by the path of trajectory.

The following functions summarize the interconnectedness of the variables, as learned through bibliographical research and initial experimentation (see Table 1).

More specifically:

a. Temperature enables the shape transformation.

b. Temperature influences the velocity of the transformation (it is a non- linear function).

c. The wire diameter is inversely proportional to the minimum bend radius and the force released [9].

d. The duration of heat application affects reaction speed and fatigue.

e. Re-set ability is dependant on an external or counterbalanced force.

We selected to focus on speed and trajectory for our examination. In doing so, we introduced *selective zone heating* as a method of analysis and experimentation.

Table 1 Primary functions

Shape = f (T)
Velocity = f (T) and Velocity = f (Hd)
Bend Radius = f (Wd)
Fatigue = f (Hd)
Force = f (Wd)

T: temperature, Hd: Heat application duration, Wd: Wire diameter

4 Selective zone heating

Many manufacturers of shape memory wires propose activating the material with general heating, either by submersion in hot liquid or buffeting with hot air. They direct that the wire should be uniformly heated for maximum effect. The experiments presented in this paper inform us that by heating particular zones of the wire, different effects are exhibited. These allow further design flexibility.

4.1 Observation

Velocity is highly influenced by the point of heat application. We noticed that when a looped NiTi wire was heated close to the deformation, it immediately returned to the straight position. When heat was applied farther from the bend, it took much longer to return to the austenite state (see Fig. 1).

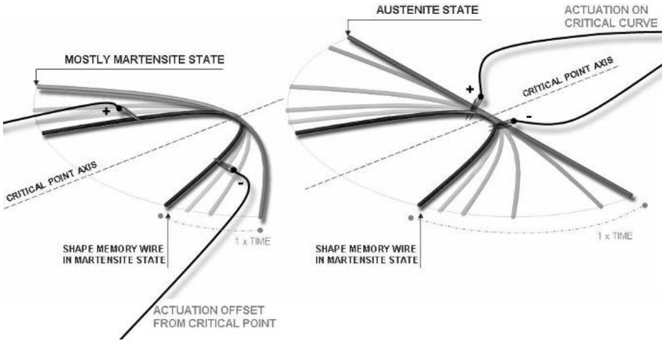


Fig. 1 Velocity as a function of local resistive heat application.

We surmise that the lengthened period is related to the time needed for the “critical curve” to fully reach the temperature required for activation. NiTi is a relatively poor conductive material. In regards to resistive heating, the current (which changes with the length and cross-section of the Nitinol wire) controls the temperature required to fully attain the Af state. Rather than consider this a material deficiency, we chose to highlight its design potential. This was the catalyst for defining the "critical curves" of shape memory wires and proceeding to experimentation to explore the trajectory of a wire as it progresses from shape 'A' to shape 'B' while selectively heated.

4.2 Definition

We define a "critical curve" as the area of the material where more stress is exerted. Usually this occurs at the deformed curve in a straight shape memory wire, or the straight part of a wire that is "set" to be bent in the austenite state. We define a "critical point" as the peak of a "critical curve".

4.3 Postulations

We assumed that:

a. In a NiTi wire of consistent density and cross-section, directly applied heat at the axis of the critical point causes the greatest transformational velocity. In a similar SMA wire, with resistive heating, the proximity of the contacts to the axis of the critical point is relational to the velocity of the transformation.

b. Local heat application will not enable the shape memory wire to fully reach the austenite state, unless it consists of a single "critical curve".

c. The sequence of local heat application for the full recovery of a shape memory wire with multiple "critical curves" defines the trajectory of its transition from the martensite to the austenite state.

d. The variance from the temperature needed to achieve Af affects the duration of the total transformation.

Experiments were conducted to support these claims. In order to reliably chart the extent of transformation in the wire, we added a fixed point as a new variable to isolate the resultant movement.

4.4 Experimentation

Analysis

The Nickel-Titanium alloy bar stock was pre-set in the austenite state to be linear. A 7 ½" length was deformed in the martensitic state to have two opposing radius bends. Direct heat application was used.

We constructed a neutral background and different colored acrylic paints were applied to the SMA wire at each endpoint and to the centerline of each critical curve (see Fig. 2). Heat was directly applied systematically to each zone by a heat gun. We charted the path of the points along the shape to the austenite conclusion.

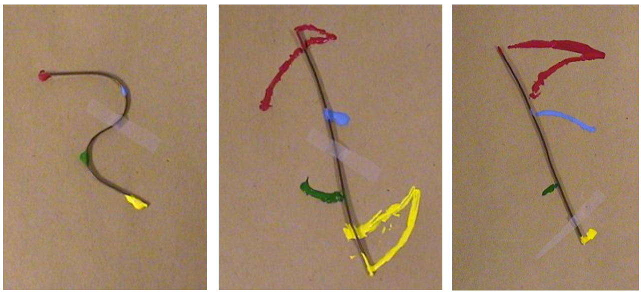
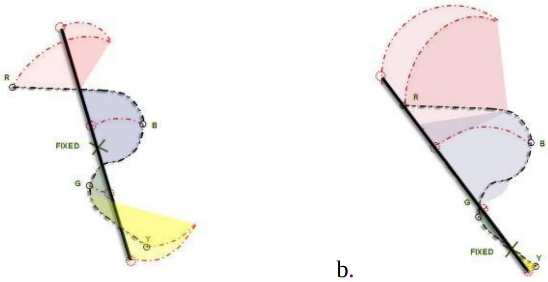


Fig. 2 First Experiment. Shape memory in martensite state and the two trajectories charted to return to the austenite state.

The experiment was repeated twice for two different sequences of heating the "critical curves". For each sequence, the experiment was conducted once with the end-point of the wire fixed to the background and once with the center point fixed.

We noted that selective heating changes the trajectory of points along the shape as well as the culminating shape. The order of heat application determined the distinct route of each point. Also, as a geometrical subsequence, it was noted that heat application near the fixed end of the wire substantially effected the movement at the distant colored unfixed endpoint. The length of path was greater the farther the colored point was from the fixed end. (see Fig. 3)

The zone heating method allows the wire to maintain both martensitic and austenitic states contiguously.



a. b.

Fig. 3 a. Center fixed. b. End fixed. Each actuated in the same sequence of local heating, applied to the axis of each "critical curve". The different trajectories are illustrated fully charted.

Prototypes

We structured our apparatus to investigate the variable of direct heat to various zones of the wire, to experience phenomenon in three dimensions. Our prototypes are not objects, rather, they are armatures to support different applications and their distinct properties.

After reviewing our previous experimentation and research, we compiled a chart to illustrate the variables explored with the prototypes. The following table shows the interplay between fixed parameters and both independent and dependant variables in the new equations that we established for our prototypes (see Table 2).

For our experiments, the temperature transferred to the wires is fixed and produced by a 12 Volt current. The diameter of the nickel-titanium alloy (Nitinol) wires used was chosen to be

0.0297” so as to be thin enough for tight bends. The heat application time is an independent variable which fluctuates upon the user’s discretion. The reset ability is established either by an external force or by a self-deformation generated according to the heat application time (a dependant variable). Finally, selective zone heating is meant to be another independent variable. The zones of heating were pre-selected, but the way of their alteration for the production of the effect was manipulated by the user.

Table 2 The new set of variables, as explored by the prototypes.

Variables	**Decisions**	**Variable Property**
Temperature → Shape, Velocity	12 Volts for high speed	fixed
Wire diameter → Bend radius, Force	0.0297” d Nitinol wire	fixed
Heat application time → Velocity, Fatigue		independent
Reset ability → External, Counterbalanced force	external or self-deformation	dependant
Selective zone heating → Velocity, Trajectory	Alternation of pre-selected zones	independent

In our second level of experimentation, we moved from the single shape memory wire, and the 2D plane of its movement, to a wire gridwork and a three dimensional plane of action. The first prototype considers all the new variables, but is still in a 2D format, while the following two are in 3D. A key difference between our 2D and 3D experimentation is the fact that the 3D tests do not have any fixed points. The wires are free to move in a floating membrane and restraining forces are only employed to counteract the friction or the weight of the system. In contrast, in the 2D experiment each wire of the parallel system of wires has one end fixed.

First Prototype – The soft sculpture

The Nitinol wires were pre-set in the austenite state to be linear. Six 12” long wires were deformed in the martensitic state to have five alternating 1” d. radius bends each. A wood frame was constructed to support the base of the SMA wires. The wires were fixed to the base in a linear series. A sheer, synthetic yarn material was employed. The fabric’s corners were sewn together to form a shroud and the mass was mounded atop the wire assembly. A 25w., 120v., 60Hz device was used to manually apply direct heat alternately to critical curves in the wires to create a stimulating dichroic effect (see Fig. 4).

As a result of this procedure, we noted that selective heating in random sequences deformed the shape of the fabric in various ways, in different speeds and through a variety of angles. The smooth, visual three-dimensional effect was produced only by transformations of the wires in six XY planes acting as structure to the fabric surface. (see Fig. 5).

We chose a polyester/nylon blend iridescent organza for it’s ability to accentuate the varying planes of geometry through the color change effect and because slight changes in the structure affected the stability of the sheer fabric causing slipping billows of various and often accelerating speeds. We mounted the fabric onto the SMA structure by gravity to avoid bonding stress to the wires that inhibit transformation behavior and to prevent damage to the fabric in the wire heating process through proximity to the direct heat or wire convection.

We selected direct heat application to enhance the fast/ slow transformations by positioning the heat source at varying distances from the critical axis.

There were some limitations to the procedures used. It did not allow for remote heating – an access area in the back was required to actuate the wires, and the heating device was not variable.

Fig. 4 The soft sculpture.

This did prove, however, to be a good experiment in scalability. Large distinctive visual effects were accomplished by small shifts in the structure. Indeed, the largest trajectory transformation was produced by actuating zone 2 {Z2} on the SMA wires (see Fig. 5) in the same effort as applying heat to zone 6 {Z6} (the smallest trajectory).

Future experimentation should focus on ways to set the wires to manipulate dichroic membranes to affect colors based on preset patterns, sequences and speeds. It might be orchestrated to present the array to specific areas in the field, derived from the incidence of light on the membrane plane positioned by the SMA support. Further research should explore ways to actuate a membrane to direct light and control reflection and diffraction.

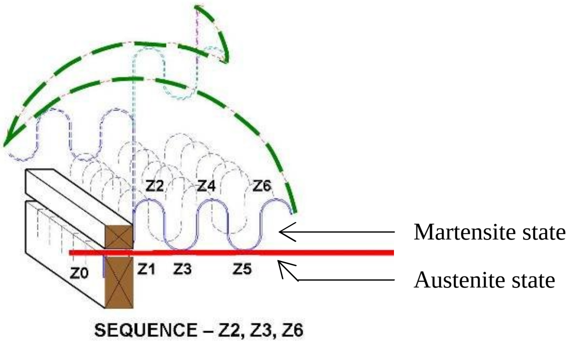


Fig. 5 Analysis of trajectories followed if heated in this sequence. The endpoint is charted.

Second Prototype – The uniform transit

Eight 8” long wires were configured in a grid pattern and adhered to a gauze sheet 9” wide by 9” long. The Nitinol wires were again pre-set in the austenite state to be linear. The gauze was able to move freely in the table and the only force applied to it was from its own weight.

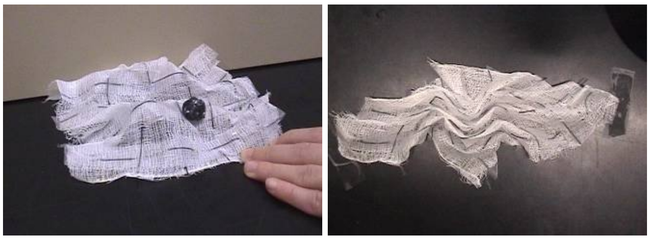


Fig. 6 Symmetrical deformation

Specifically, the shape memory grid (XY), which was attached to the gauze, was bent in the Z axis to create an uneven surface. A hair dryer was then used to bring the system back to its first flat condition. The experiment was repeated ten times with the heating source in different angles. The last three times the sheet was heated in the center. The process was video-recorded as it deformed in a specific pattern (symmetrically) to attest our hypothesis that the way of its restoration can be predicted if the first shape of deformation and the heating process are controlled (see Fig. 6).

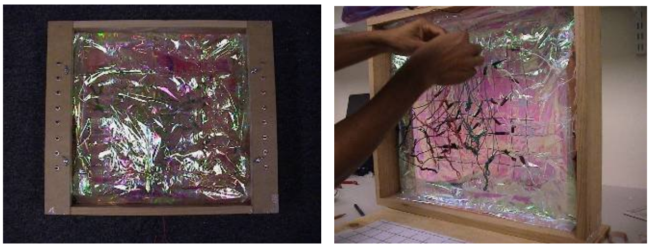


Fig. 7 Directed Kinesis

Final Prototype – Directed Kinesis

For this prototype, Nitinol wires were again pre-set in the austenite state to be linear. Eight 1-foot long wires were configured in a grid pattern and adhered to a dichroic acetate membrane 18” wide by 18” long. The corners of the membrane were attached to a wooden frame with elastic bands. Electrical wiring was installed to provide 16 circuits to the shape memory wire grid (see Fig. 7).

Specifically, the assembly was deformed to provide radiuses in the Z-axis direction. The electric circuit was powered and attached to 16 specific bends of the surface. Switches enabled the control of each point separately. The affected bends were expected to go back to their straight shape, influencing the vicinage, as it had happened in the previous experimental prototype.

In the cases where two or more points were activated at the same time, the voltage was divided between them reducing the power exerted to each one (they were connected in parallel). A series of technical problems was specified as responsible for the partial success of this prototype. Specifically, the membrane was stiff and loosely connected to the wires. Thus, it soon became unable to follow the movement of the wires. The circuit wires, on the other hand, were very heavy and disabled the movement of the shape memory grid to which they were attached. Finally, the shape memory wires themselves should probably have been stronger (have a larger diameter) in order to support the motion of such a wide and heavy area, or be fragmented in multiple short pieces with less “critical curves”. Proper adhesion of the wire to the membrane must be explored to provide enough foundation for the membrane without incurring bonding and debonding stresses as sometimes occurs in NiTi wires embedded in membranes and resistively heated [10] .

Through the experience gained by this prototype, the knowledge for a successful future model lies in specific modifications. These modifications include: a lighter and flexible membrane properly attached to the shape memory grid, a lighter and shorter length circuit system, higher voltage (or a non-parallel circuit), slightly thicker SMA wire for greater electrical force. In regards to the heating system, we surmise that replacing the circuit with conductive thread or with custom flexible heaters would exhibit better motion and higher flexibility. More specifically, the heaters, which use silicone or polyester with multiple circuits that proportion wattage to distribute varying heat levels, would be the following step for a fully directed kinesis.

5 Conclusions and Extensions

Being aware of the numerous interconnected variables inherent in shape memory materials, we understand that our research provides only an introduction to the possibilities of these alloys. Foremost is the knowledge that changing even a small variable can significantly influence the whole behavior of the material. A small alteration can produce a great effect. This can lead to a variety of design applications.

Evaluating this project requires open-minded attention to both process and outcome. We never saw the prototypes as end products. They served only as fields of experimentation to prove our claims with regards to local heating application for the manipulation of kinesis.

We explored a way of controlling shape memory wires and SMA meshes by locally heating them, both directly and remotely (using resistive heating).The potential to control the transformation trajectory and direct kinesis is promising. Establishing the full criteria for such a direction will enable the following advancement - having a desired trajectory (or transformation) as a given, correctly heating a material to achieve it, resetting back to the austenite state and then reheating the same material following a different sequence to achieve another predetermined path. This would enable, for instance, a device, made “universal” by the sequential codes of transformations. Further exploration to direct kinesis might systematically record and analyze the shape memory material transformation in space (in lieu of the 2D plane). Also, more attention should be paid to the concept of critical point. Research to explore heat application offset from the point will add the 4th dimension of Time to the application. Thus, each sequenced trajectory could be manipulated in terms of transformation period – fast/slow reactions.

Finally, it is crucial to take into account, when viewing this material as a reflection of contemporary ubiquitous nature, that each material has unique properties for exploitation and its optimal use is not independent from scale. The high cost, low strength, relatively low thermal conductivity or slow reaction SMA wire may have worked for a long time as impediments in the use of the item in the architectural environment. However, we believe it is up to the designer to study their properties more precisely and use them wisely – by accepting the differences they imply, taking advantage of them and respecting the smaller scale they introduce to the design by their dimensions. These materials should not be used as substitutes to replace conventional materials, but as something novel with great potential to influence an integrated architecture.

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