CoilFORM: the impact of the winding on the flat spiral shape memory alloy coils

Ahmed Amine Chafik
FEMTO-ST/DISC/OMNI UMR CNRS 6174, Univ. Bourgogne Franche-Comté, UTBM
Belfort, France
ahmed.chafik@utbm.fr

Jaafar Gaber
FEMTO-ST/DISC/OMNI UMR CNRS 6174, Univ. Bourgogne Franche-Comté, UTBM
Belfort, France
jaafar.gaber@utbm.fr

Souad Tayane
Laboratory of complex cyber-physical systems LCCPS ENSAM, Hassan II University of Casablanca
Casablanca, Morocco
souadtayane2013@gmail.com

Mohamed Ennaji
Laboratory of complex cyber-physical systems LCCPS ENSAM, Hassan II University of Casablanca
Casablanca, Morocco
ennaji.moh@gmail.com

***Abstract*—CoilFORM is a shape changing interface that relies on the programmable deformation of its patterned actuating coils, to deform a malleable covering surface. The actuating coils inherit their geometric characteristics and their controllable shape changing behavior, from twisting shape memory alloy wires in a flat spiral trajectory. Thus, CoilFORM is significantly compact and can pack more actuators, unlike the existing devices. In this article, we feature the various configurations of the actuating coils, their quirks, and their impact on the performance and the rendering of CoilFORM. More precisely, we examine the geometric characteristics and the thermomechanical behavior of each coil inside and out of CoilFORM through numerical simulation.**

Keywords—Programmable Matter, Smart materials, Smart actuators, Shape Memory Alloy.

I. Introduction

Programmable matter represents matter, agents, and interfaces that can alter their shape or formation on command. It is expressed in the literature through several approaches, namely the collection of modular robots, kinetic interfaces and programmable materials. Such a technology targets prototyping and augmented interfaces as it bridges the digital environment to its physical twin.

Current kinetic shape changing interfaces rely on the movement of motorized mechanisms, arranged in a given pattern, to deform a covering malleable surface. The most commonly used mechanism is leadscrew, it provides precise displacements and favors the integration of interaction sensors [1]. Nevertheless, it requires spacing as the form factor of the motor constrains its positioning. Crank shaft mechanism resolves this issue, but packs fewer actuators to prevent from mechanical interference (e.g., blockage, restricted movement). Other devices [2] incorporate smart actuators made out of programmable materials that embed controlled behaviors when subjected to an external stimulus. One example is shape memory alloy. It can be trained to remember one or two memorized shapes, and then can be activated with heat energy to attain one of the memorized shapes (e.g., flat in cold temperature, and folded in hot temperature).

Shape memory alloy can be framed in an expandable or deployable architecture to deliver important displacement and to adapt to multiple configuration (orientation and arrangement pattern). Henceforth, it excludes the need for any adaptation mechanisms when used, resulting in a relatively compact interface. Still, devices using shape memory integrate guiding mechanisms to preserve the direction of the deformation, and counter springs to reset the actuators to their initial shape [3]. Such use raises questions on the possibility of increasing the compactness of shape changing interfaces using shape memory alloy while providing decent functionality.

One possible approach would be to wind shape memory alloy wire in a flat spiral trajectory (e.g., Fermat's spiral) keeping both ends on the same side. This way we can grant the stability of the deformation, increase the length of actuator and enhance their arrangement while conserving a compact form factor. Furthermore, by changing the winding trajectory, we can develop more flat actuators which increase the possibilities of customization in our shape changing interface labeled as CoilFORM.

Another question to address is the influence of the winding trajectory on the performance of the different coils and on the usefulness of CoilFORM. More exactly, what shape can react quickly, occupy less surface, dissipate less thermal energy, and in which configuration?

This paper illustrates the impact of the winding trajectory on the performance of CoilFORM actuators. It first presents the paving features of each twisted coil, such as the fill ratio and the disposition pattern, then examines their thermomechanical behavior inside and out of CoilFORM, and finally addresses improvement from the observed results.

II. CoilFORM's actuators

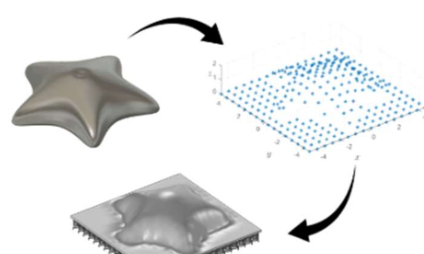

Fig. 1. CoilFORM renders physical shapes by downscaling the corresponding 3D model to a point cloud, which is used then to determine the right amount of electric current to attain the targeted heights.

CoilFORM is a compact shape changing interface that converts heat energy to a physical deformation thanks to the properties of shape memory alloy. It consists of flat coils arranged in a rectangular or triangular pattern, mounted on a rigid PCB, and covered by a malleable silicone surface. Each actuator expands at a certain height, when the required current is injected at its ends, to deform the surface, and by combining the local deformations we obtain a global shape (Fig. 1).

A. The geometric characteristics

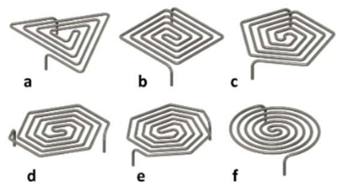

Fig. 2. Flat coils vary in configuration depending on the winding trajectory of shape memory alloy wires. a. Triangular, b. Square, c. Pentagonal, d. Hexagonal, e. Heptagonal, f. Circular.

CoilFORM's actuators are framed by winding both ends of a two-way shape memory wire in opposite directions, following a spiral trajectory around the center of the wire (Fig. 2). Consequently, the obtained coils are compact and occupy more space comparing to regular springs. Moreover, they expand conically, which limits any thermal exchange or the risk of tangling with the neighboring coils. One major drawback is interchangeability with a bigger coil unless it has relatively a narrower pitch, as it should match with the same mounting mechanism.

In Fact, the coil's shape depends on the winding trajectory, thus we can frame various models by changing the spiral form from circular to angular and so on. The advantage of having multiple shapes is to allow room for more customization by tiling the same or different actuators on the holding base.

B. The paving pattern

Actual shape changing interfaces do not offer the possibility to rearrange the position of their actuators when using a parallel leverage system. Hence, the precision of the physical model is adjustable only by rebuilding the interface, or by connecting multiple devices if they support modularity [4].

Henceforth, with these actuators, we can increase the usefulness of the shape changing interfaces either by rearranging their position, by changing their size and shape, or by increasing their number (Fig. 3).

TABLE I. THE IMPACT OF THE WINDING TRAJECTORY AND THE PAVING PATTERN ON THE NUMBER OF ACTUATORS AND THE FILL RATIO OF COILFORM (BASE: 100MM×100MM. WIRE: LENGTH: 219MM, DIAMETER: 0.7MM. WINDING PITCH: 1.75 MM).

Shape	Surface (mm²)	Paving pattern	N. of coils	Fill ratio
Triangle	356,85	Rectangular	16	57,10%
		Triangular	16	57,10%
Square	331,24	Rectangular	25	82,81%
Pentagon	343,21	Rectangular	16	54,91%
		Triangular	18	61,78%
Hexagon	339,53	Rectangular	20	67,91%
		Triangular	18	61,11%
Heptagon	340,24	Rectangular	16	54,44%
		Triangular	20	68,05%
Octagon	335,72	Rectangular	20	67,14%
		Triangular	20	67,14%
Circle	334,86	Rectangular	16	53,58%
		Triangular	20	66,97%

Table I demonstrates that winding the same shape memory alloy wire differently affects the configuration of CoilFORM in term of the number of actuators and the fill rate. The Square shape maximizes both features (25 coils with 82.81% fill rate) thanks to its small surface, although it is limited to one paving pattern. Also, the circular shape increased the number of actuators and occupied less space when arranged in a triangular pattern. The triangular actuator represented the weakest feature combination due to its larger surface. A possible reason, is that the pitch is not maintained in rough angles (Fig. 2. a).

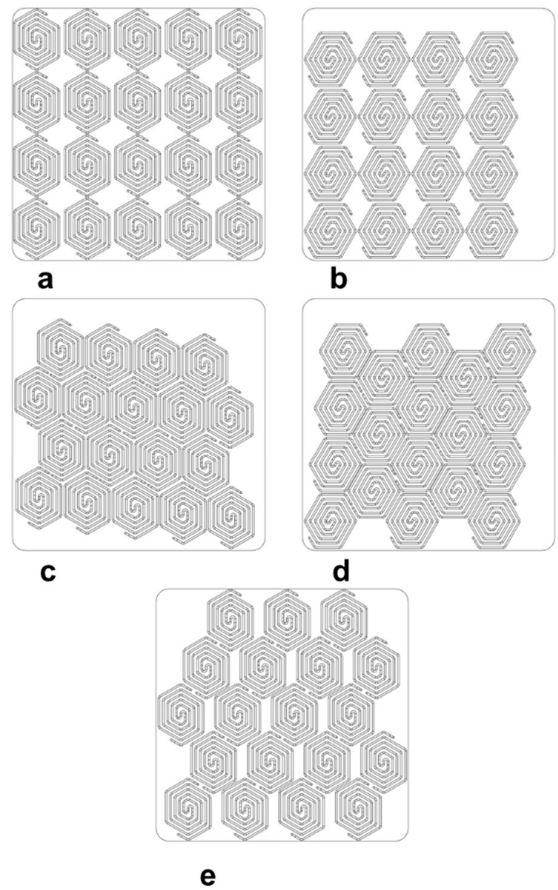

Fig. 3. Paving shaped coils in a certain pattern affects the fill ratio of CoilFORM: a. Rectangular pattern, 20 coils. b. Rectangular pattern, 16 coils. c and d. Triangular pattern, 18 coils. e Triangular spaced pattern, 19 coils.

III. PERFORMANCE

In this section, we measure the performance of CoilFORM and its actuators using numerical simulation. First, we compare the displacement of each coil as well as the global shape using two different arrangements. Then, we examine the thermal behaviors, including heating by joule effect, cooling and heat dissipation. Finally, we study their shape changing behavior. We used the 3D model of the starfish for comparison (Fig. 1).

A. Geometric rendering

CoilFORM requires its actuator to expand freely and to preserve the rendering while being in multiple arrangements. Thus, we monitor the expansion and the resulted stress using **COMSOL Multiphysics®,** and next we compare the physical rendering using **MATLAB** and **CloudCompare.**

1) Stress vs displacement

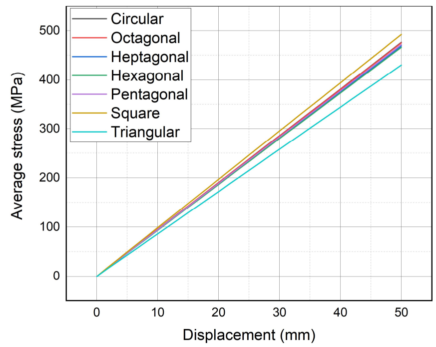

Fig. 4. Evolution of average stress according to the displacement. The number of rough and right angles stresses the coil.

Fig. 4 displays the evolution of the average stress during the expansion of the coil. Circular and shapes that have obtuse winding angles shares approximately equal values. The square shape manifested relatively high stress, considering the right winding angles. Conversely, the triangular is the less stressed since it has the lowest number of angles.

2) Arrangement vs shape

The first step is to downscale the 3D model to a point cloud representation by intersecting the meshed faces with straight lines distributed according to the coil's pattern (Fig. 1). The maximal height is then extracted considering that each intersection gives at least 2 points. Finally, the point cloud is meshed using Delaunay triangulation and exported as. STL file (Fig. 5).

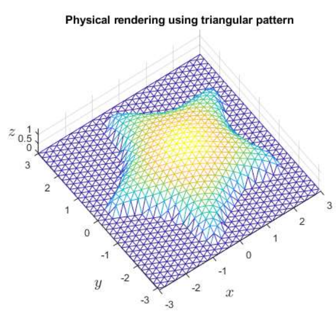

Fig. 5. Representation of the physical rendering of a starfish using 957 springs arranged in a triangular pattern.

Triangular and Rectangular rendering are smoothened in **MeshLab** using Laplacian Mesh Processing [5] and then compared with the 3D model using **CloudCompare**.

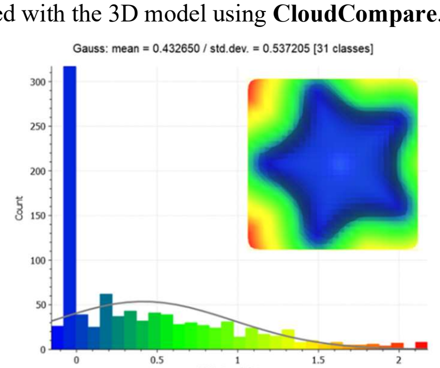

Fig. 6. Classification of the signed distances between the 3D model and the generated surface using a rectangular pattern. 317 points have a marginal height gap ranging from -0.08 mm to 0.005 mm. The remaining points represented the disabled coils.

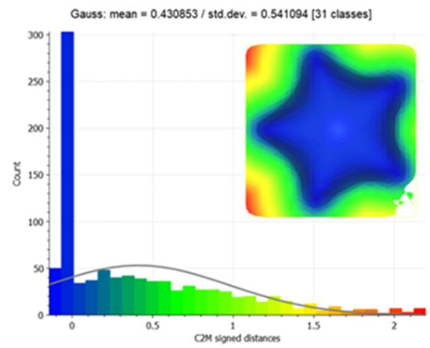

Fig. 7. Classification of the signed distances between the 3D model and the generated surface using a triangular pattern. 303 points have a marginal height gap ranging from -0.07 mm to 0.009 mm. The remaining points represented the disabled coils.

Fig. 6 and Fig. 7 demonstrates that both of the dispositions delivered alike results while using a considerable number of actuators. Some inconsistencies were measured during the process as the downscaling algorithm fills the remaining area with flat surfaces (see Fig. 1 for reference)

B. Thermal behavior

Here, we study the thermal behavior of each coil inside and out of CoilFORM using the Joule effect. More precisely, we induce an electric current of 2A for 10s in the different coils, to monitor the temperature increase, the cooling and the transferred heat to the neighboring coils.

1) Heating "Joule effect"

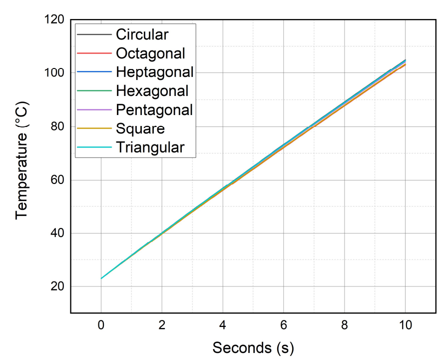

Fig. 8. The coils heat evenly when subjected to 2A for 10s, despite their different winding trajectories. The heating temperature increased from 23°C to 104°C.

Fig. 8 shows that coils heat evenly to attain 104°C after 10s, which demonstrates that heating depends only on geometric and composition characteristics of the wire (length, cross section, material) and not the winding trajectory. Such a phenomenon can be expressed and validated by the following equation (approximation):

$$T_{heat} = \frac{R\Delta t}{\frac{mC}{\Delta t} + hA} I^2 + T_i \quad (1)$$

2) Cooling

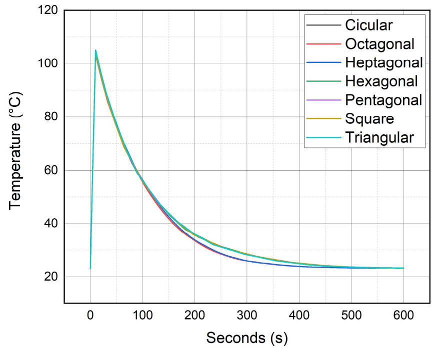

Fig. 9. The cooling phase took approximately 600s for all the coils, with a slight out performance from the octagonal and heptagonal coil.

Fig. 9 indicates that all the coils cool equally but at a slow pace. The cooling temperature can be described and predicted mathematically using the heat equation;

$$T_{cool} = (T_i - T_f)e^{-\frac{hA}{mC}t} + T_f \quad (2)$$

Again, winding does not impact the passive cooling of shape memory coils, as they have the same outer surface. However, negligible difference of 2°C was noticed in the octagonal and heptagonal coils.

3) *Heat dissipation*

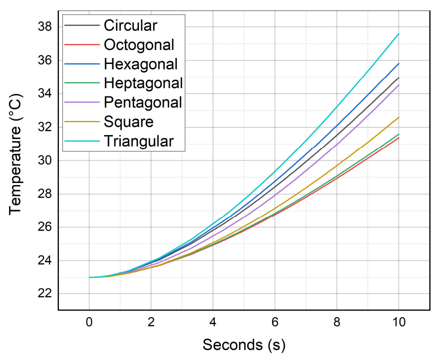

Fig. 10. The maximum temperature measured in the neighboring coils when the central coil is heated by joule effect. The triangular coil favors heat exchange more than the others with an increase of 15°C.

Fig. 10 indicates that the triangular shape favors heat dissipation more that the rest of the shapes. One reason is triangular shapes have the highest number of neighbors comparing to the other shapes. Some shapes have the same number of neighbors, such as square and octagon, but differ in term of heat exchange since octagons cannot pave perfectly.

C. Memory behavior

It is possible to simulate the shape memory effect of the different coils when subjected to heat energy, using **COMSOL Multiphysics®.** The Simulation starts by deforming the spring to its plastic state, then heating until the memory effect is provoked. Results show that the coils carried out similar behavior when using one-way shape memory alloy, apart from the triangular coil (Fig. 11).

Results can be fitted into three phases, where two are stationary and correspond to the initial and final shapes, and a transitionary phase which describes the memory behavior of the coils.

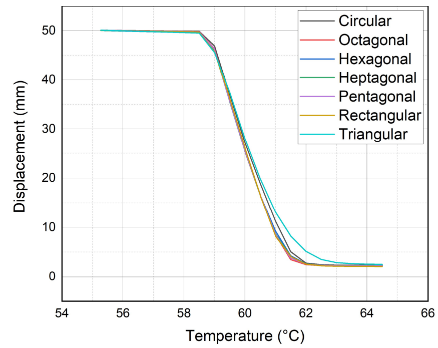

Fig. 11. Representation of the themomechanical behavior of the coils.

IV. Conclusion and Future Work

In this paper, we featured the impact of the winding on the individual performance of the actuating coils and their arrangement in CoilFORM. Having such a shape allowed not only to decrease the thickness of the shape changing interface but also to increase the number of the actuators. This is possible by tiling the actuators in various pattern including rectangular or triangular. These actuators are suitable to develop mainly compact prototyping platforms.

In fact, CoilFORM can pack more actuators when using square, circular or hexagonal winding in a rectangular pattern. Simulation results showed that using the rectangular or the triangular pattern generates similar physical models as long as the number of actuators is high. Coils presented similar behavior when subjected to heat energy, with a slight out performance from the octagonal coils. Moreover, they have a good heat retention, which will ease their control using two-way shape memory alloy, as the shape reacts reversibly with the change of temperature.

Although, CoilFORM requires an active cooling source to increase its responsiveness as the coil regains its original shape passively after 600s. Additionally, the winding could be improved further to pave more actuators. Future work seeks the improvement of the user experience of CoilFORM by embedding interactive features and implementing the solutions highlighted above.

Acknowledgments

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