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MODELING AND PROTOTYPING OF SELF-FOLDING ORIGAMI STRUCTURE

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ABSTRACT

Inspired by the spring blossoms of tulips and origami engineering, we have designed a monolithic self-deployable structure with the ability to fold (close) and unfold (open). The focus of this paper is the 3D design and prototyping of a self-folding origami structure actuated by shape memory alloys (SMAs). SMA actuators, spring and wires, provide controllable actuation based on the simplicity of their design and the shape memory effect. In mechanical engineering, the art of origami provides a novel approach for compliant mechanisms devices enabling relative movement between the components with reduction of the number of parts. The self-folding origami structures can be used in many applications for volume reduction in packaging and space engineering.

Additive manufacturing technologies enable easy and fast prototyping of the monolithic structure. The geometry of the structure and the integration of smart active materials within the structure enable the design to achieve complete self-folding.

Keywords: self-folding, origami engineering, additive manufacturing, bio-inspired engineering

NOMENCLATURE

l_1, l_2, l_3	Length of the base and the rigid segments
h	Length of the flexures
l	Length of the whole planar structure
F_2, F_3	External actuation forces
G_2, G_3	Gravity forces
F_{in2}, F_{in3}	Inertial forces
α, β	Folding angles

1. INTRODUCTION

Recent research trends are merging smart materials and origami engineering for designing trendy and unique solutions for various applications. Adopting additive manufacturing for the fabrication of the structures, creativity for aesthetic monolithic structures has become almost limitless. Integration of smart materials within the structure results in the design of smart structures able to imitate shape morphing and adaptations inspired by the flowers, such as self-folding. This paper analyzes the potential of a 2D planar structure to transform into 3D structural shape using external stimuli.

Monolithic flexible structures as compliant mechanisms use elastic deformations to transfer motion and force, therefore they are advantageous for production, assembling and performance control. Traditionally, compliant mechanisms are defined as single-piece monolithic structures that deliver the desired motion by undergoing elastic deformation as opposed to the rigid body motion in conventional mechanisms [1]. Origami structures belong to the broad category of compliant mechanisms. Due to the advances in manufacturing technologies and novel materials, the compliant mechanisms have become increasingly important, especially in bio-inspired engineering. Inspired by the biological systems that have adapted and evolved over several billion years into efficient configurations, the self-organization of the form, structure, geometry, material and behavior are combined in order to achieve self-actuating compliant mechanisms [2].

3D printing is an additive manufacturing process technology where the products are built on a layer-by layer basis, through a series of cross-sectional slices [10]. 3D printing offers a potential route to the rapid fabrication of customized components, enabled this technology to be employed across a various range of applications. However, the integration of active materials and structures such as actuators, sensors, and electrical circuits for computation is still in progress of 3D printing techniques [11]. The scientists presented an alternative approach to rapid, customizable fabrication of 3D structures through the origami-inspired folding of 2D sheets [12]. In [3] a programmable method was used to replicate the shape-changing of the mechanisms inspired by the nature in order to achieve artificial bio-inspired composites.

Origami engineering provides solutions for compact configuration through folding. Many foldable product solutions are inspired by origami, known as the art of folding paper [4]. Origami, the traditional paper art, is a folding technique in which elegant and complex three-dimensional objects are produced from planar sheets. The design and kinetics of insect-wing origami is studied in [5], to achieve design of bio-inspired deployable engineering structures. A self-deployable origami structure for jump gliding is analyzed in [6], analyzing the trajectory of movement and the deployment process and applied methodology.

A shape memory alloy (SMA)-based self-folding sheet is considered in [7], using the capabilities of active materials that enable the folding, transforming the non-mechanical energy into the mechanical work. Combining origami principles with smart materials can produce active origami shapes that fold and unfold in response to external stimuli. S. Ahmed et al in [8] are exploring the potential and the possible ways of implementing dielectric elastomers as the enabling material in active origami structures. In [9], a research of the use of dielectric elastomer and magneto active elastomer materials to create multi-field responsive structure that fold and unfold in different ways in response of the materials was analyzed. Origami-inspired self-folding could be useful in a variety of engineering applications such as mechanical component design, metamaterial design, medical devices, folding of printed structures, and the compact storage of structures for space missions and deployment.

By combining additive manufacturing and origami methods, a powerful new approach to design complex structures can be established. In [10], a method combining a direct-write assembly with folding origami technique is shown to create 3D shapes that range from simple polyhedrons to intricate origami forms, which are then transformed to metallic and ceramic structures by thermal annealing.

Nickel Titanium is one of the most attractive and widely used shape memory alloy material because of its unique functional properties including superelastic (SE) behavior and shape memory (SM) effect, biocompability, low stiffness, corrosion behavior and damping characteristics. NiTi materials have superelastic behavior that enable restoring large strains up to 8% theoretically by unloading and heating established from a phase transformation between martensite and austenite [9]. The superelasticity refers to the ability of the material to return to its original shape upon unloading after significant deformation. The flexible property of Nitinol occurs when lower-temperature form (martensite), and resumes to its original shape and stiffness when heated to its higher-temperature form (austenite). The unique material properties make Nitinol a suitable candidate in many functional designs. Using NiTi wires for actuation enables creating smart structures with the ability of creating autonomous movement.

Our research aims to explore self-folding origami inspired design combined with smart materials that may be useful for the design of foldable engineering applications. The 3D printed structure with smart material for actuation achieves self-folding. The process of 3D printing with implemented smart material actuation enables creating a trendy functional design that can be used for variety of design solutions. In this paper, a conceptual model will be developed, followed by CAD model, supported with analytical modeling for variables parameterizing and concluding it all with a functional prototype.

The organization of this paper is as follows: Section 2 presents the design concept, providing a CAD model for 3D printing; Section 3 provides analytical modeling of the self-foldable structure; Section 4 presents the prototype of the structure; and section 5 discusses the conclusions and the proposed future work.

2. DESIGN CONCEPT

A self-folding structure actuated by SMA wires and springs is analyzed in this paper. The initial position is to get from 2D flat sheet to 3D compact shape. The self-folding structure is 3-D printed with implemented NiTi wires to achieve the self-folding, achieving three-dimensional mechanisms from planar structures. In this section, the modeling of the structure is presented, analyzing the trajectory of the individual parts, and their maximum movement, so they won't collide with the surrounding items. Also, the dependence between the time and the folding angle is analyzed. Figure 1 shows the tulip-inspired origami structure.

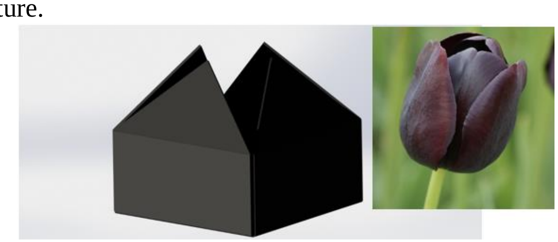


Figure 1. Tulip-inspired origami structure

The structure is designed as a cubicle, consisted of four identical sections that have the capability of folding and unfolding using the smart materials as actuation force. Figure 2 shows the CAD model in three positions, where it can be noticed the transition from planar structure to spacious 3D structure.

The first step in designing origami-inspired robots is to define folds in planar form on a thin sheet of material, which either become fixed or flexural joints in the folded device. To define the folds, the thickness of the structure is analyzed, reducing the thickness in the flexural joints to reduce bending stiffness at the desired fold lines. The inspiration is from origami techniques in developing principles for designing 2-D foldable patterns.

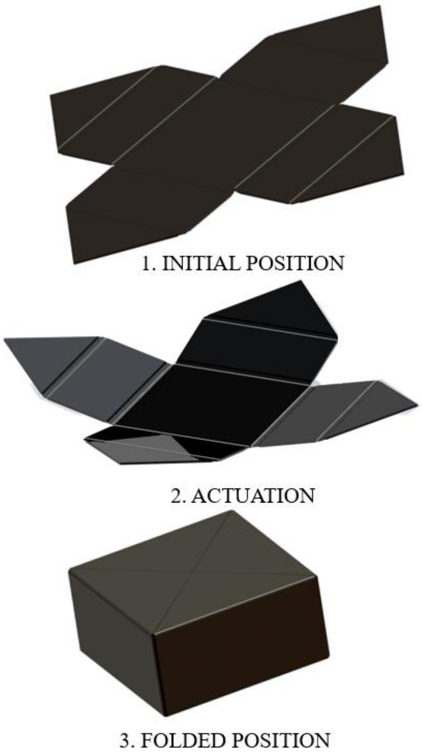
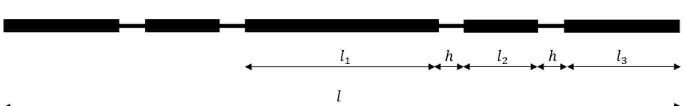


Figure 2. CAD model in three positions

Additive manufacturing uses CAD software and additive manufacturing-based technologies to print objects enabling the rapid and inexpensive manufacturing of functional structures. Two primary design challenges associated with this approach were determined: the identification of foldable 3D mechanisms to achieve a desired task and specifying the associated 2-D fold patterns [13]. A 3D printer was used to print the cubicle structure. The structure is print from flexible filament that offers great mechanical properties such as high strength and elongation. By implementing smart materials such as NiTi springs and wires, the planar structure can fold into 3-D cube.

The cubicle structure is 300 mm long when in its initial position, and 100 mm long when in its folded position. The dimensions of the structure in its initial and folded position are shown on Figure 3. The thickness of the rigid segments is 5 mm, while the flexure is 1mm.



	DIMENSIONS [mm]
l_1	100
l_2	40
l_3	50
h	5
l	300

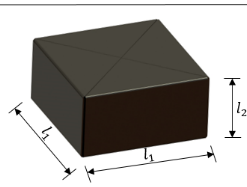


Figure 3. Dimensions of the cubicle structure

The conceptual case can also be modified if different material and manufacturing technique is used. The dimensions of the origami structure can be bigger and smaller, based on the application, taking in consideration the smart material actuation.

The same structure if actuated one way can be used as a folded cubicle and if actuated the opposite direction it can carry its self and the side sections can be used as legs for locomotion (Figure 4).

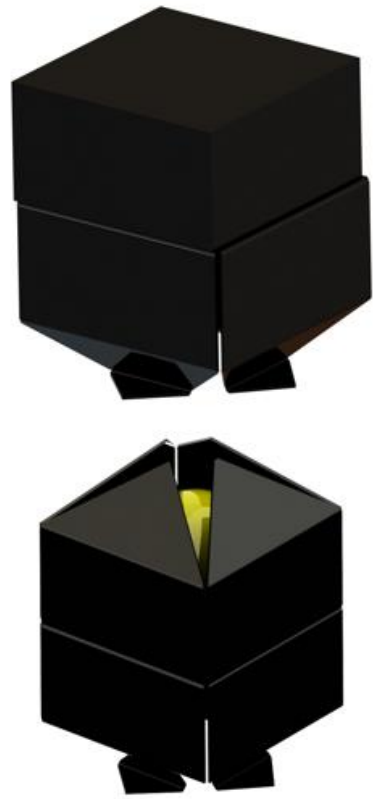


Figure 4. Modular concept

The idea of carrying load in the folded box on the same structure actuated in the other way as a support. This model approach allows multi-functional behavior of the same structure actuated in different manners.

3. ANALYTICAL MODELING

The SMA materials are stimulated using the voltage as input unit. They are set in predetermined stage and when, they reach certain temperature, they are changing their current position achieving folding or unfolding, depending of the situation.

The structure is consisted of four identical sections on each side of the base. Figure 5 shows one part of the structure that is consisted of 3 rigid segments and 2 flexures. By using SMA materials, the folding and unfolding of the structure could be established.

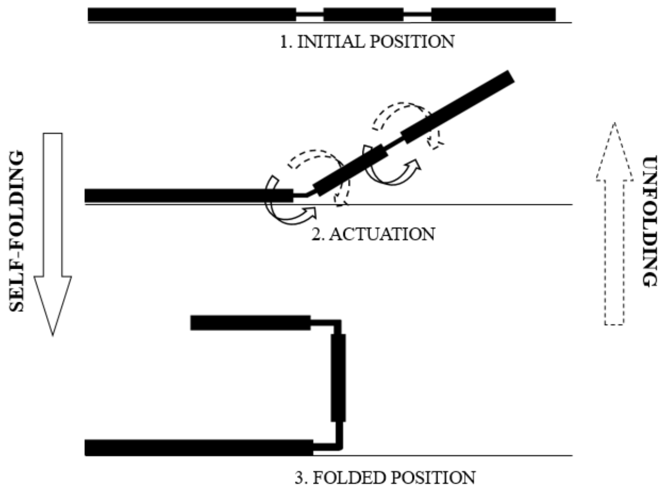


Figure 5. Process of folding of one section

When folding the part of the structure, the applied forces from the NiTi springs enable the movements. Figure 6 shows the actuation forces and the additional reaction forces from each of the segments.

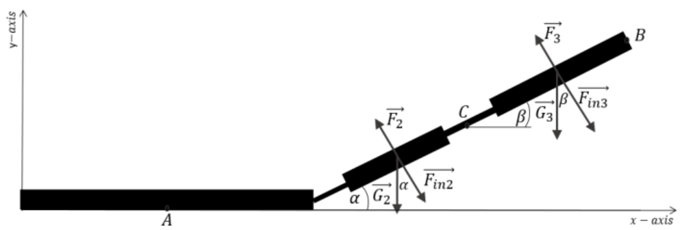


Figure 6. Reaction forces on one section

To accomplish folding, meaning the end position B gets parallel with A, the following equations should be set:

$$\sum F_x = -F_2 sin\alpha + F_{in2} sin\alpha - F_3 sin\beta + F_{in3} sin\beta = 0 \quad (1)$$

(1)

$$\sum F_y = F_2 cos\alpha - F_{in2} cos\alpha - G_2 + F_3 cos\beta - F_{in3} cos\beta - G_3 = 0 \ (2)$$

$$\sum M_A = (F_2 cos\alpha - F_{in2} cos\alpha - G_2) \cdot \left(\frac{l_1}{2} + hcos\alpha + \frac{l_2}{2} cos\alpha\right) + (F_3 cos\beta - F_{in3} cos\beta - G_3) \cdot \left(\frac{l_1}{2} + \frac{3}{2} hcos\alpha + l_2 cos\alpha + \frac{1}{2} hcos\beta + \frac{l_3}{2} cos\beta\right) + (F_2 sin\alpha - F_{in2} sin\alpha)(hsin\alpha + \frac{l_2}{2} sin\alpha) + (F_3 sin\beta - F_{m3} sin\beta) \cdot \left(\frac{3}{2} hsin\alpha + l_2 sin\alpha + \frac{h}{2} sin\beta + \frac{l_3}{2} sin\beta\right) = 0 \quad (3)$$

Figure 6 shows the reaction forces and the equations above show the relationship between the forces and the geometry. The equations show the reaction forces from the model. In addition to achieve the folding, meaning position B gets parallel with position A, the external forces F_2 and F_3 from the actuation have to be bigger than the reaction forces. In that way, to gain the proper actuation, the springs and wires stiffness have to be defined in relation to the reaction forces. For different geometry and dimensions, different actuation forces are attained.

Figure 7 shows the folding results for the given geometry and parameters, modeled in Matlab. The positions A, B and C are analyzed. To attain complete folding, the movement of the positions C and B are shown. The equations 4 and 5 show the transition of the position B from initial to final position:

$$x = \frac{l_1}{2} + l_2 cos\alpha + l_3 cos\beta \quad (4)$$

$$y = l_2 sin\alpha + l_3 sin\beta \quad (5)$$

Some of the possible movements when folding is achieved are shown on Figure 7. When the section is in its initial position, the angle α is 0° and β is 0°. In the final position, angle α is 90° and angle β is 180°. Between the two positions, there can be achieved several positions, and only two of them are shown (position n+1: $\alpha_{n+1} = 30°$ and $\beta_{n+1} = 70°$; position n+2: $\alpha_{n+1} = 60°$ and $\beta_{n+1} = 110°$).

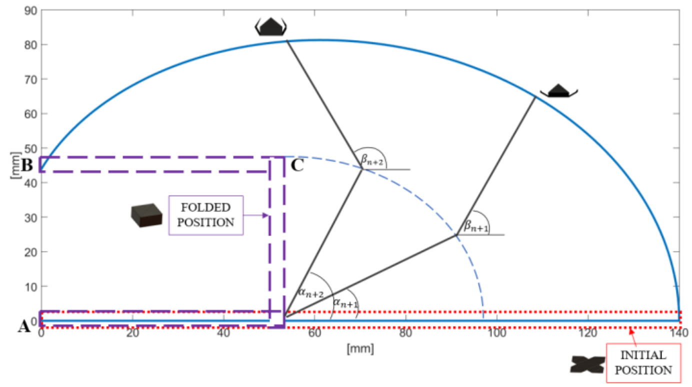


Figure 7. Folding results in Matlab

The folding angle α gets to its final position when achieving $90° = \frac{\pi}{2}$. If the voltage (V) is constant, the time and the folding angle are correlated. The folding angle benefits from the material properties and the length of the rigid segments.

$$\alpha = V \cdot t \quad (6)$$

$$\alpha = f(V, t)$$

By varying the material use for 3-D printing and the geometry, multiple shapes could be created resulting in parametric designs for variety of engineering applications.

4. PROTOTYPING

The use of origami engineering in designing 3D shapes has the potential to revolutionize active material structures and compliant mechanisms. The SMA materials exhibit some unique performances, such as sensing, large-stroke actuation, high damping, adaptive responses, shape memory and super elasticity capability, which can be utilized in various engineering approaches in origami-inspired smart applications. At this stage, we are developing the prototype manually in the lab using affordable SMA springs and wires and low-budget 3D printer (Ender).

The prototype is a monolithic structure printed from flexible filament (Felxifill 92A from Fillamentum) using additive manufacturing process. After designing the structure and observing the rules for design for additive manufacturing, the prototype was printed. Flexure design has been analyzed in [14], and here we have introduced polynomial shape change to achieve local large deformation. The 3D printer has enabled the flexure design performing advantageous compared to other fabrication techniques. In order to produce autonomous structure, NiTi wires and springs were connected to the structure. The structure manages to self-fold by providing an actuation input signal by a DC current with 9V voltage.

To establish unfolding of the structure, SMA wires are used. NiTi springs have the ability to contract, shorting their length, when current is running through them. On the other hand, when current is running through the NiTi wires, they tend to straighten themselves. When the structure is folded, by actuating the wires, the structure unfolds. To sum up, the stimulation of the NiTi wires and springs does not occur simultaneously. For example, when we actuate the NiTi springs, the NiTi wires change their shape, due to the force of the springs and the folding of the structure. Table 1 shows the properties of the NiTi wires and springs.

Table 1. Material properties of NiTi springs and wires

NiTi wires 	Material: NiTi Transition temperature: 40 °C Length: 50/35 mm Wire diameter: 1 mm
NiTi springs 	Material: NiTiCu Length when heated - 20 mm Maximum deformation - 150 mm Transition temperature - 65 °C Outer diameter - 6.5 mm Number of windings - 21 Wire diameter - 0.75 mm

Figure 8 shows the smart material integration in the 3D printed structure. For the analyzed structure, 4 NiTi springs and 12 NiTi wires were used.

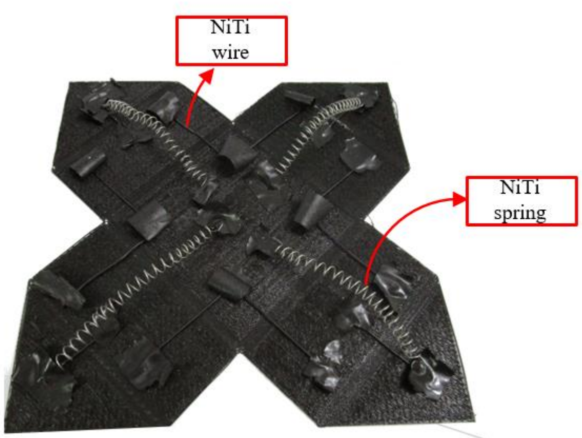


Figure 8. Integrated smart materials in the 3D printed structure

Figure 9. Folded position of the cubicle structure

Figure 9 shows the folded cubicle structure. As described earlier, the folding was enabled by smart material actuation. By analyzing the design of the structure, implementing additive manufacturing in order to get 3D printed structure with desired geometry and material on one side, and implementing smart materials for actuation on the other side, the final result is having a smart structure enabled to do autonomous bio-inspired movement. The used voltage is 9V, so the time needed for the structure to get to its final position will be:

$$t = \frac{\alpha}{V} = \frac{\frac{\pi}{2}}{9} = \frac{\pi}{18}[sec]$$

The design framework showed in Figure 10 can be used for different geometries and different smart actuation. Different smart materials including electroactive polymers, piezo-electric and magnetostrictive materials can potentially be used as an actuation force. Cellular structures could also be designed in this way to exhibit multi-functionality and better performance overall.

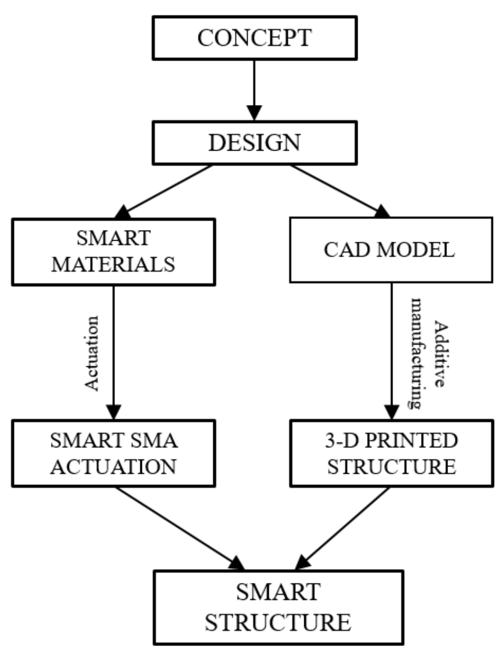


Figure 10. Design framework for parametric modeling and smart material integration

Smart structures are beneficial for many engineering applications, especially in space and unreachable places. Active origami structures can be applied to a broad range of areas such as reconfigurable aircraft and deployable space structures as well as instruments for minimally invasive surgery.

5. CONCLUSIONS

The combinations of advances in technology for smart materials and additive manufacturing allow origami designed concepts to become feasible. In this work we have demonstrated a simple flexible structure designed for additive manufacturing can integrate SMA wires and springs and exhibit self-folding. The combination of the geometrical design with smart materials creates smart structures.

The self-folding origami designs can be beneficial for volume reduction applications and external stimuli self-actuation. The SMA wires and springs have become affordable and accessible for variety of learning experiments and applications.

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