Coded Skeleton: Shape Changing User Interface with Mechanical Metamaterial

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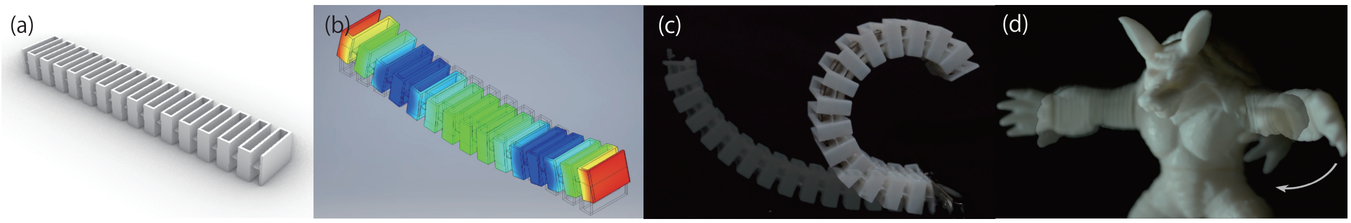

Figure 1: Overview of Coded Skeleton. (a) Predefined structure, (b) Result of eigenvalue analysis, (c) Manipulated Coded Skeleton, (d) Deformable figure as an application of Coded Skeleton.

ABSTRACT

We propose a design method for fabricating a novel shape-changing user interface, called “Coded Skeleton”, by computationally integrating actuators and sensors using a mechanical metamaterial. This design method realizes the deformation of various curves using simple expansion and contraction actuators, leveraging the fact that the Coded Skeleton is flexible in one deformation mode but stiff in other. We describe the design method and structural analysis of the mechanical metamaterial that can uniquely define deformation along with outlining the creation and control method of the Coded Skeleton using this structure. Finally, we propose three applications of the Coded Skeleton.

CCS CONCEPTS

• **Human-centered computing** → *User interface design*;

KEYWORDS

Shape-changing user interfaces, Mechanical metamaterials, Digital fabrication

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1 INTRODUCTION

In recent years, shape-changing user interfaces have been actively studied in the field of human-computer interaction (HCI) as they present computer information in a 3D space and are noted for their affordance and usability, which cannot be reproduced by a 2D display interface. There are eight types of deformations for shape-changing user interfaces: orientation, form, volume, texture, viscosity, spatiality, adding/subtracting, and permeability [Rasmussen et al. 2012]. Our proposed method focuses on changes in orientation, emphasizing on curved deformation, assuming a wide range of applications. The curved deformation shape-changing interface has been proposed within and beyond the field of HCI [Marchese et al. 2014; Nakagaki et al. 2015; Ou et al. 2013; Park et al. 2014; Yao et al. 2013]. We summarize this information in the table shown in Figure 2. From the perspective of both the actuation methods and characteristics of the actuated material, our method combines shape memory alloy (SMA) and anisotropic material. Actuation by SMA is silent and has high mobility. However, since it has only one degree of freedom of deformation, in order to drive the isotropic material

		Actuation Methods		
		Motor	Pneumatic Actuator	Shape Memory Alloy
Actuated Materials	Isotropic	LineFORM [Nakagaki et al. 2015]	jamSheets [Ou et al. 2014] Soft robot arms [Marchese et al. 2014]	Wriggl0 [Park et la. 2014]
	Anisotropic	—	Pne UI [Yao et al. 2013]	Our Method

Figure 2: Overview of the curved deformation shape-changing interface, which has been proposed within and beyond HCI field.

to the desired deformation, it was necessary to devise the arrangement of the SMA. Thus, there was a limitation of deformable shapes. Therefore, we proposed a framework which introduces anisotropic materials based on a mechanical metamaterial as a user interface. In the field of material science, Filipov et al. proposed a mechanical metamaterial that is flexible yet consists of stiff materials [Filipov et al. 2015]. This mechanical metamaterial has the property of one deformation mode with a simple external force.

We defined this concept as "isolated deformation". Applying this concept to our study, we showed a novel shape-changing user interface called the "Coded Skeleton" [Iwafune et al. 2016]. The various deformation of mechanical metamaterial can be actuated by SMA which expands or contracts and we showed the possibility of actuation and sensing with the SMA. However, the noise generated from the SMA during sensing, due to heat generated during actuation, makes it difficult to accurately control the deformation. Contrary to previous works, we can successfully control the deformation state using a flex sensor.

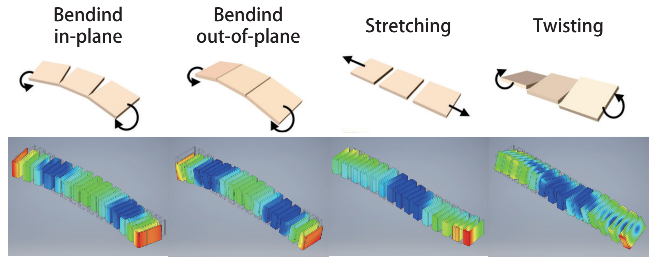

Figure 3: Deformation modes of LET.

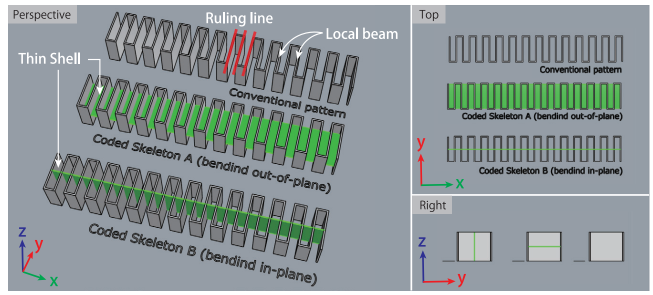

Figure 4: Conventional pattern (LET) and the structure of Coded Skeleton A and Coded Skeleton B.

2 ISOLATED STRUCTURE

2.1 Principle of Isolated Deformation

In this study, we use the lamina emergent torsion (LET) structure to realize a curved shape-changing user interface. The LET structure is renowned as a compliant mechanism that produces out-of-plane deformations by performing torsional deformation on the local beam [Jacobsen et al. 2009]. We consider the deformation modes of LET structure to be roughly divided into four types; bending in-plane, bending out-of-plane, stretching and twisting (Figure 3). Of these deformations, a structure that is isolated only in one deformation is considered the body of the Coded Skeleton. To realize this deformation characteristic, we insert a thin shell structure into the neutral plane of the LET structure. Using this method, it is possible to isolate two deformations, bending out-of-plane and bending in-plane, by changing the direction in which the thin shell is inserted. As shown in Figure 4, a thin shell is inserted in the x-y and x-z planes. The structure isolated in bending out-of-plane is called "Coded Skeleton A", whereas the structure isolated in bending in-plane is called "Coded Skeleton B". Moreover, torsional deformation can be realized by changing the angle of the ruling line in this structure as shown in Figure 4. The parameters of the Coded Skeleton are shown in Figure 6 (a) and are described as follows: a - the thickness of the local beam, l - the length of the local beam, g - the distance between the local beams, b - the thickness of the structure, d - the thickness of the shell and n - the number of local beams.

2.2 Evaluation Method of Isolated Deformation

The structure of Coded Skeleton is isolated, which means the body is flexible in one deformation mode but stiff in the other modes. To evaluate this characteristic, we use the eigenvalue analysis method proposed by previous study [Filipov et al. 2015]. In this method, each eigenmode corresponds to the deformation mode of the structure. Since the eigenvalue is proportional to the stiffness of the structure, it is easier to deform it into corresponding deformation modes at lower eigenvalues; whereas, higher eigenvalues make deformation more difficult. Also, the analysis is done without considering boundary conditions. In this case, since the six eigenmodes from the beginning represent rigid body motion in a 3D space (movement and rotation in the axial direction of each of the x, y, and z axes), the eigenvalues are zero. For this reason, we omit the first six eigenmodes. Moreover, in this study, we define that isolation is sufficiently isolated when the eigenvalue of the deformation to be induced is more than twice the eigenvalue (the smallest one) of the other transformations as the criterion of isolation of deformation.

2.3 Result

Figure 5 shows the result of the eigenvalue analysis of each structure shown in Figure 4. The conventional LET structure has relatively low eigenvalues for four deformation modes. In particular, the difference between eigenvalues of bending in-plane and bending out-of-plane is less than two times, therefore, the structure is not isolated. On the other hand, with Coded Skeleton A, it can be said that the eigenvalue of the deformation of bending out-of-plane is isolated and sufficiently lower than the eigenvalues of the other three deformations. Similarly, it was shown that Coded Skeleton B is also isolated in bending in-plane.

3 CODED SKELETON

As shown in Figure 6 (b), the Coded Skeleton is created by embedding actuators and sensors inside an isolated structure. In the following subsection, we describe details of the actuators and sensors, and the principle and results of manipulation. In addition, the isolated structure is printed by SLA printer.

3.1 Actuation

The main idea for actuation is to change geometric distance. The length of developable strip, whose thickness can be ignored, is

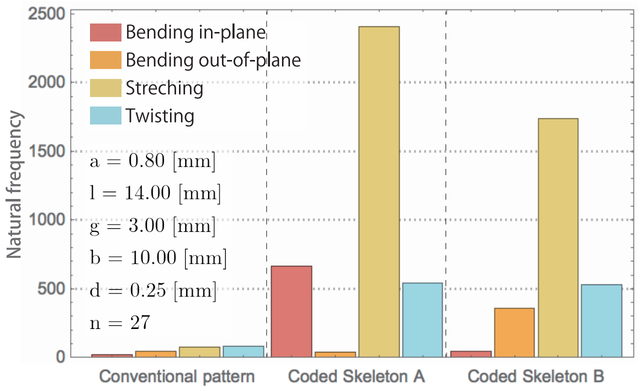

Figure 5: Result of eigenvalue analysis.

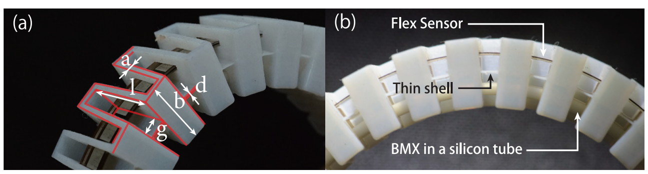

Figure 6: (a) Parameters, (b) Construction.

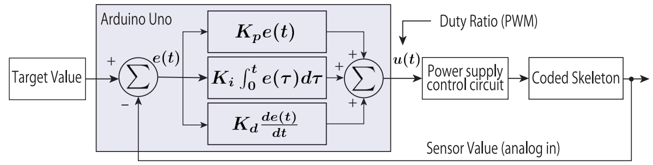

Figure 7: Brock diagram of PID control.

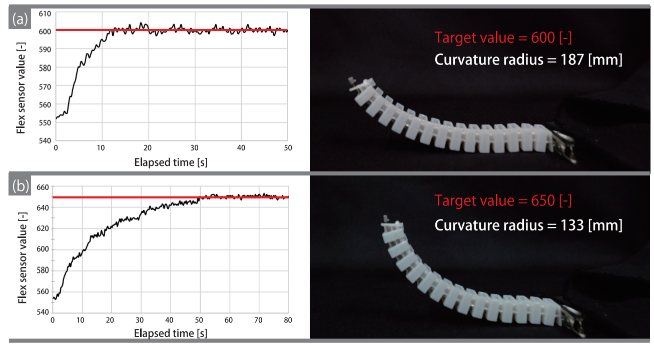

Figure 8: Result of PID control. (a) Target value = 600 [-], (b) Target value = 650 [-].

preserved deformation. However, in the case of the Coded Skeleton, the thickness of deveropable strip can not be ignored, the length geometrically varies according to the deformation and distance from the neutral plane. We used this property to transform the strip with the SMA. We specifically used BioMetal Helix 150 (BMX)[1], which is a specialized stretchy SMA.

3.2 Sensing

Sensing the deformed shape is done using a flex sensor. The flexibility of the flex sensor has multiple degrees of freedom. However, since the deformation is uniquely predefined in the structure of Coded Skeleton, the sensed value of the flex sensor and the deformation of the Coded Skeleton have a one-to-one association. We used the Flex Sensor 4.5"[2] for our proposed method and cut it as necessary to use it (Figure 6 (b)).

3.3 Manipulation Method and System Pipeline

As a method of manipulation, we apply proportional-integral-differential (PID) control, which is a popular method in feedback control. PID control can be expressed as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}$$

where K_p is a factor of proportionality, K_i is the integration constant, and K_d is the differential constant. Also, $u(t)$ is the duty ratio of PWM, and $e(t)$ indicates the difference between the target value and the present value of the flex sensor. Figure 7 shows the pipeline of PID control. This system is data processed by an arduino uno. The coefficients used for PID control in Figure 8 (a), (b) are $K_p = 1, K_i = 15$, and $K_d = 4$.

[1]https://www.toki.co.jp/biometal/english/contents.php (October 22th, 2018)
[2]https://www.sparkfun.com/products/8606 (October 22th, 2018)

3.4 Manipulation Result

Figure 8 (a), (b) shows the result of PID control. In this paper, PID control was performed based on the value of the flex sensor. However, it is necessary that we measure this in advance because the relationship between the sensor value and the curvature radius differs depending on the length of the Coded Skeleton used. As displayed in Figure 8 (a), (b), the Coded Skeleton oscillates around the target value. This is due to two system setup factors: feedback delay and BMX actuation accuracy. Future studies will aim to solve this problem.

4 APPLICATION

We built three prototypes to explore the potential of the shape-changing user interface using the Coded Skeleton.

4.1 Deformable Figure (Figure 1 (d))

Typically, character figures that are 3D printed with hard materials were static objects. By incorporating the Coded Skeleton into the part you want to move the character figure, it is possible to create a moving figure that causes the desired deformation while maintaining the external shape. The design guideline of the deformable figure is shown in Figure 9 (a).

4.2 Deformable Skeleton (Figure 9 (c))

We propose the application of a deformation skeleton, which has the combined skeletal structure of a robot and plush toy. The structure of the Coded Skeleton has stiffness and predefined flexibility so that it works both as bone and muscle. This makes it possible to print skeletal structures of arbitrary 3D objects at once.

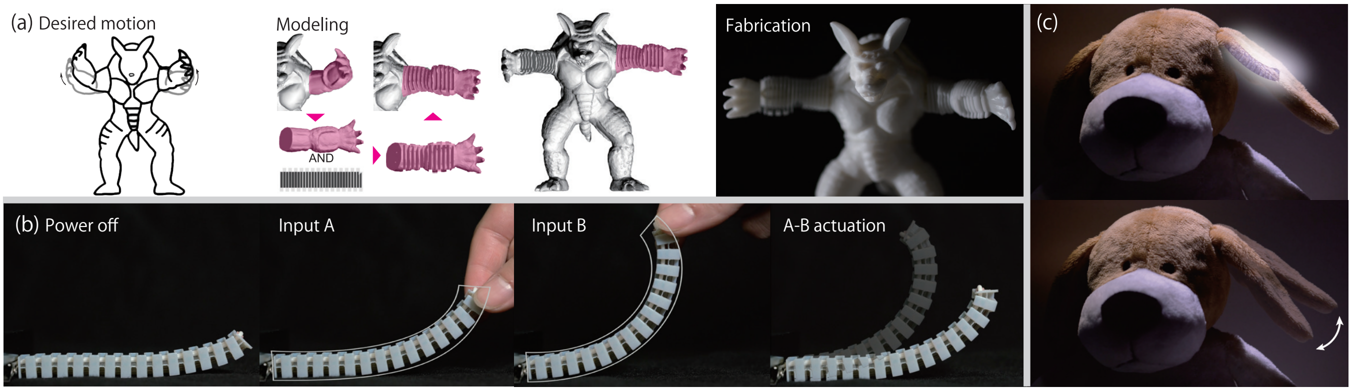

Figure 9: Application. (a) Deformable charactor figure, (b) Shape memory function, (c) Plush toy's robot.

4.3 Shape Memory (Figure 9 (b))

We propose an application to memorize shapes using the Coded Skeleton. Since the deformation of the Coded Skeleton is isolated, deformation and sensing values correspond one-to-one. Therefore, by setting the sensing value when the user inputs a certain deformation to the target value, and performing PID control, it becomes possible to hold the deformation set by the user.

5 DISCUSSION

5.1 Treatment of Generated Heat

The SMA generates heat during actuation that causes the 3D printed structure to melt; hence, destroying it when continuing to actuate the Coded Skeleton for a long time. To solve this problem, we improved the heat dissipation by inserting the SMA through a silicon tube and inserting it inside the 3D printed structure (Figure 6 (b)). However, this method is also limited, and eventually, the structure is deformed or destroyed if the Coded Skeleton is used for a long time. Therefore, considering a more efficient heat dissipation method at the time of actuation is vital in the future.

5.2 3D Printing Materials and Methods

When constructing the Coded Skeleton, isolation of deformation was performed by inserting a thin shell structure inside the conventional LET structure. Initially, we created this structure using a Form 2 photopolymer resin[3]. However, this thin shell structure empirically changed the elastic modulus of the material several weeks after printing and destruction occurred during actuation. This is believed to have happened because the photopolymer resin is further cured by ambient light after printing, and once the material has deteriorated. On the other hand, we observed an improvement in vulnerability when we print the same structure using photopolymer resin of Stratasys Objet260 Connex3[4]. Hence, the vulnerability of the thin shell depends on the materials and method used for 3D printing. Therefore, further study of the printing materials and methods used for the Coded Skeleton could be undertaken.

[3]https://formlabs.com/3d-printers/form-2/ (October 22th, 2018)
[4]http://www.stratasys.com/3d-printers/objet260-connex3 (October 22th, 2018)

6 CONCLUSION

We propose a novel shape-changing user interface called "Coded Skeleton" which include actuators and sensors. The Coded Skeleton introduces a mechanical metamaterial having the properties of flexibility and stiffness. These properties helped the Coded Skeleton realize a soft shape-changing user interface that could be controlled using simple electronic components with multiple degrees of freedom, such as shape memory alloys and flex sensors. We evaluated the mechanical properties of this mechanical metamaterial through an eigenvalue analysis that showed that it was isolated to arbitrary deformation as compared with the conventional structure. Finally, we displayed three applications and described the availability of the Coded Skeleton as a shape-changing user interface.

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