3D Printing Shape-Changing Devices with Inductive Sensing

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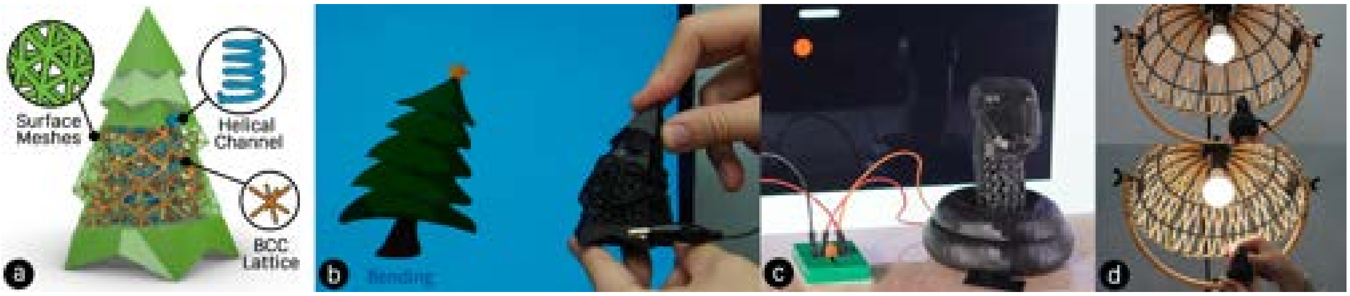

Figure 1: 3D printable shape-changing devices are created with (a) integrated helix-and-lattice structures, such as (b) a deformable Christmas tree application, (c) a joystick snake game controller, and (d) a snowman-like light control.

ABSTRACT

We present a novel technique that converts arbitrary 3D models into 3D printable shape-changing devices with sensing capability through the integrated helix-and-lattice structure. The structure comprises a central hollow helical channel, surrounded by lattice padding and a surface mesh, which allows the device to become elastic and deformable. By inserting a conductive steel wire into the hollow helical channel, inductive signals are generated when a current runs through the wire. When the device undergoes deformations, these inductive signals vary distinctively, reflecting the specific changes in the device's shape. These signals, specific to each type of deformation, are interpreted as interactive user input using a trained machine-learning classifier. We also showcase three example applications, including a deformable Christmas tree, a Snake game joystick controller, and a snowman-like light control.

CCS CONCEPTS

• **Human-centered computing → User interface toolkits**.

KEYWORDS

3D printing, Shape-changing, Inductive sensing, Helix, Lattice.

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1 INTRODUCTION

The development of 3D printing has enabled the creation of custom devices with more affordable properties, such as colors and materials. However, adding interactivity, such as sensing capability, to 3D-printed devices has been a long-standing challenge. Researchers have explored embedding capacitive sensors [He et al. 2022; Savage et al. 2013] and combining conductive materials with controllable mechanisms[Alalawi et al. 2023; Gong et al. 2021; Sakura et al. 2023] to convert 3D-printed objects into sensors for interactivity. Due to the specialized electronics, materials, and mechanisms integrated into 3D-printed devices, existing techniques only explore capacitive sensing and often sacrifice the aesthetic of the devices. In our work, we propose a novel technique that converts a 3D model into a shape-changing device by embedding a helix-and-lattice structure to enable sensing capability for 3D-printed objects (Figure 1). The device is 3D printable in one piece with a readily available Stereolithography (SLA) 3D printer and elastic resin. A conductive steel wire can be manually inserted into the helical channel in the post-printing process. When a current travels through the wire coils, the helix becomes an inductor and builds up a magnetic field flux, which results in changes in inductance measurement when the device is deformed. The variation in inductance caused by the deformation can be interpreted as interactive user input with a trained machine-learning classifier. The classifier can detect four types of deformation: compression, extension, bending, and twisting.

2 HELIX-AND-LATTICE STRUCTURE

To enable deformation, the helix-and-lattice structure is embedded and it consists of three components (Figure 1a): the helix (inner), the body-centered cubic (BCC) lattice structures (middle), and the surface meshes (outer). The *helix* situated in the center is created with a hollow channel that guides the insertion of the conductive material in the post-printing process. The stiffness of the helical channel can be controlled by parameterizing the helix diameter (d), number of turns (N), and coil pitch (P). Around the helical channel,

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the 3D body is padded with the *BCC lattice structures*. The beam thickness in the lattice can be altered for various solidities of the padding (currently adjustable between 0-20%) and the body's overall rigidity. Thicker beams result in a higher lattice solidity, making the body more rigid and more difficult to deform, and vice versa. To approximate the device's appearance, *surface meshes* composed of beams closely conform to the polygonal wireframe of the 3D body.

We take the following steps in *Rhino3D*, a commonly used computer aided design (CAD) software, to embed a helix-and-lattice structure into a body. First, a helix channel is generated along the model's medial skeleton, manually drawn in the 3D scene, with inputted turns and coil pitch using commands *Helix* and *Pipe*. The lattice padding is created using *Crystallon*, an open-source *Grasshopper3D* add-on, with desired lattice beam thickness. Finally, using commands *QuadRemesh* and *ExtractWireframe*, the wireframe surface mesh is generated with a beam thickness of 0.6mm.

3 INDUCTIVE SENSING FOR DEFORMATION

To detect the device's deformation behaviors, a conductive material, *i.e.,* a steel wire, is inserted into the embedded helical channel. When the current goes through the inserted wire, the device becomes a coil-based inductor. The yielded inductance signal can be varied with different helical channel parameters (Figure 2a). When the device body deforms, the magnetic field flux built up by the coil-based inductor also alters by its form, yielding unique inductive signals that can be detected and received by the *Texas Instruments LDC1614 Evaluation board*, which is an inductance measurement tool (Figure 2b). The raw inductive signals are received and fed into a pre-trained machine-learning classifier using the Random Forest model to recognize four distinct deformation behaviors: bending, twisting, compression, and extension. To train the classifier, we collected five data trials for each individual deformation by performing the corresponding deformation behaviors. This data was collected by the authors for training. We also collected random touches on the 3D-printed objects and labeled them as noises. The trained classifier can reach an accuracy of 92% for recognizing the four distinct deformation behaviors.

Figure 2: Our approach uses (a) a helical inductor and (b) an external evaluation board for inductive sensing.

4 FABRICATION

The proposed structure can be printed with a commercialized SLA 3D printer (*i.e., ELEGOO Mars 3 Pro 4K*) using elastic *Resione F80* resin. We chose this resin because it provides elasticity with a Shore Hardness of 50-60A, and it has ideal resilience for the deformed device to rapidly regain its original shape. After the device is printed, the helical channel needs to be cleaned before inserting the steel wire and curing the model. We first dredge the channel with a 22-gauge, easily bendable wire and then wash out the remaining uncured resin in the channel using a needle and a syringe with isopropyl alcohol. Based on the empirical experiment, the 22-gauge wire was the most appropriate for this process with the best rigidity. Inserting the steel wire post-cleaning but before the resin's curing phase is recommended due to the lubricating properties of the residual cleaning liquid in the channel. Additionally, extra resin can be pushed out from the channel. The leftover resin is then cured to secure the inserted wire inside the helix.

5 APPLICATIONS

Below, we demonstrate our approach through three examples: a deformable physical character, a game controller, and a light control.

Deformable Tree: We converted a Christmas tree into a deformable model by embedding the helix-and-lattice structure in the tree trunk for multiple deformation behaviors (*e.g.,* bending and twisting), which converts the 3D-printed tree into an interactive prop for animating a digital character in storytelling (Figure 1b).

Snake Game Controller: We showcased a snake model with its neck converted into a helix-and-lattice structure, which allows players to control the snake's movements in the game. Players can bend the controller in one of the desired four directions (*i.e.,* forward, backward, left, and right) to command the snake(Figure 1c).

Light Control: We also created a snowman-shaped light control that enables custom control of a lamp through various manipulations, including compressing to toggle the light, twisting to adjust the light brightness, and bending to switch light colors (Figure 1d).

6 FUTURE WORK AND CONCLUSION

In this poster, we presented a technique that converts 3D models into 3D printable deformable sensors using the helix-and-lattice structure embedded. In the future, we plan to conduct mechanical fatigue tests to evaluate the robustness of our approach and develop a tool for end-users to create controllable and parametric designs.

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