Designing 3D-Printed Deformation Behaviors Using Spring-Based Structures: An Initial Investigation

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ABSTRACT

Recent work in 3D printing has focused on tools and techniques to design deformation behaviors using mechanical structures such as joints and metamaterials. In this poster, we explore how to embed and control mechanical springs to create deformable 3D-printed objects. We propose an initial design space of 3D-printable spring-based structures to support a wide range of expressive behaviors, including *stretch and compress*, *bend*, *twist*, and all possible combinations. The poster concludes with a brief feasibility test and enumerates future work.

Author Keywords

3D printing; fabrication; deformation behaviors; design space; mechanical spring.

ACM Classification Keywords

H.5.2. Information interfaces and presentation (e.g., HCI): User Interfaces.

INTRODUCTION

Additive manufacturing, or 3D printing, has moved beyond simply fabricating the shape of a 3D geometry. Researchers have explored imbuing 3D-printed models with mechanical properties and functions [3, 7, 8]. *Coded Skeleton* [5], for example, uses repetitive slit patterns to enable planar objects to stretch, bend and twist. *Metamaterial Mechanisms* [4] employs a block of shear cells printed with flexible material to achieve controlled directional movements. Finally, *MechProfessor* [2] applies joint structures to creates one-off articulated models with consumer-grade 3D printers. To our knowledge, however, spring-based structures, which are one of the most widely used mechanical mechanisms, have not received commensurate attention by the 3D printing community.

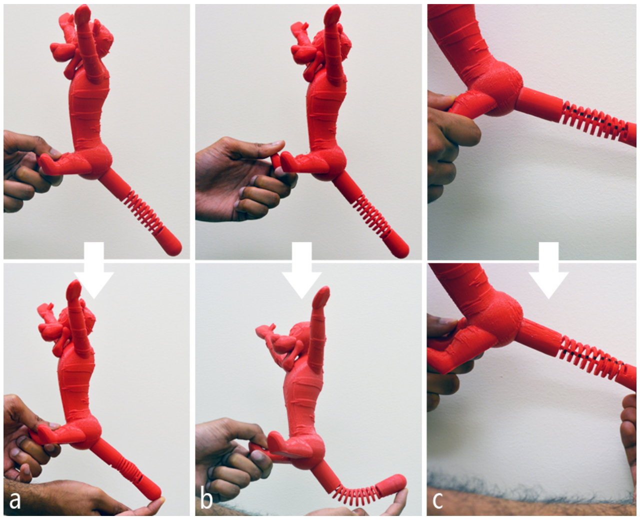

Figure 1. Tigger example with three types of deformable tails: (a) sketch and compress only; (b) bend only; and (c) twist only (black marked dots show the rotation).

In our research, we are designing and investigating tools and techniques to embed mechanical springs with controllable deformations into 3D-printed objects. We focus primarily on *helical* springs because the helix structure encapsulates *linear deflection* (stretch and compress) and *planar deflection* (bend and twist). Thus, we believe that springs have the potential to achieve different types of expressive deformation behaviors compared to other mechanical structures (*e.g.,* joints and metamaterials). However, manually designing embedded spring structures is not intuitive because deflections are mixed in the coil structure. To design and print specified functions, the spring deformation behaviors need to be decoupled.

In this poster paper, we contribute an initial design space of possible spring-based structures that constrain different types of printable deformation behaviors. We decouple spring behaviors into three individual categories: *stretch and/or compress*, *bend*, and *twist*. Each of the single-deformation springs are printed with a standard helical spring structure and an integrated constraint structure at the center. The resulting 3D-printed object can achieve *stretch/compress-only*, *bend-only* and *twist-only* deformations. The decoupled spring structures can be further combined for more complex behaviors such as *compress+twist* deformations.

DESIGN SPACE

Informed by prior work [4, 5] and mechanical spring theory [1], we designed three basic single-deformation structures—*stretch and compress*, *bend*, and *twist*—and all possible combinations (Figure 2). The constraint structure for each deformation differs. For *linear deformations*, we designed a prismatic joint to limit the spring's bending and

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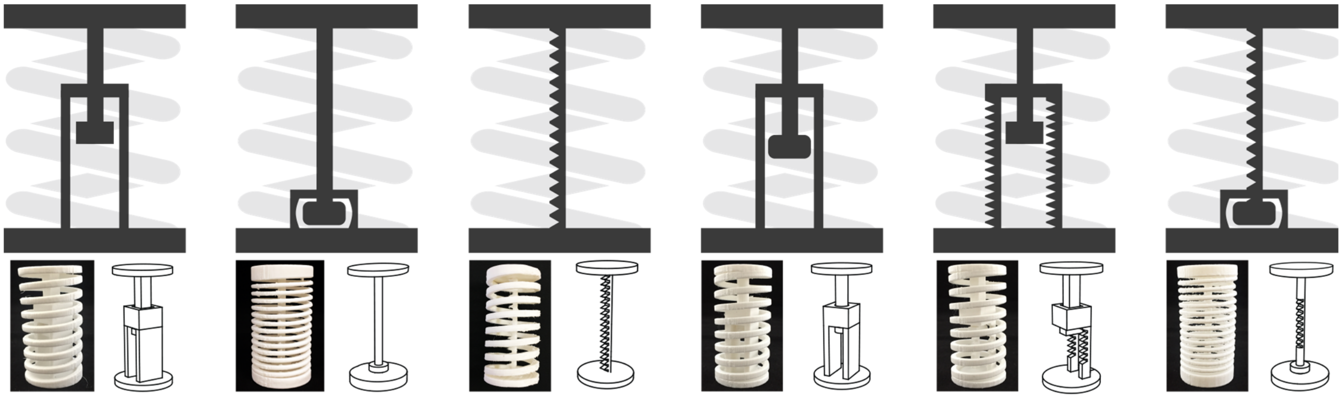

(a) Stretch and compress only with a prismatic joint

(b) Twist only with a ring bearing structure

(c) Bend only with a flexible sawtooth backbone

(d) Linear + twist with a cylindrical joint

(e) Linear + bend with a prismatic joint and a sawtooth beam

(f) Twist + bend with a ring bearing and a toothsaw beam

Figure 2. Proposed design space for making deformable spring-based structures in 3D-printed object: diagram of each design (top) and corresponding 3D-printed output companied with a 3D model of the constraint structure (bottom).

twisting behavior; for *bend deformations*, we connect the ceiling and floor of the spring with a flexible sawtooth backbone to limit its linear motion and twisting behavior; for *twist deformation,* we employed a ring bearing structure so that the spring can rotate along its centerline but has limited bending and linear motion. These basic building blocks can be combined to enable new deformations such as *linear+bend*, *linear+twist*, *twist+bend* (Figure 2d, e, and f). Without any constraint structures, a regular helical spring can achieve all basic and combinatory behaviors (*i.e., linear+bend+twist*).

The flexibility and elasticity of a spring is controlled by spring parameters such as *coil number*, *coil diameter*, *wire diameter*, and *modulus of elasticity* [1]. Although Figure 2 only shows simple cylindrical spring shapes, we envision CAD users being able to select and replace arbitrary parts in their 3D model with spring-based structures. For example, a bunny's ear can be bendable by applying the structure similar to Figure 2c. The embedded spring's shape will mimic the part geometry it replaces.

CREATING SPRING-BASE STRUCTURES

In this poster, all spring-based structures were built manually using Rhino CAD software. A GUI-based interface is under development to support automated spring generation. We envision this tool will (i) allow users to define desired deformation functions for a 3D model; (ii) automate the creation of embedded spring-based structures and allow users to manually adjust the parameters of those added structures in iterative cycles; (iii) provide users with a preview of all possible deformation behaviors by simulating the performance of the spring-based structures using finite element analyses.

PRINTING RESULTS AND APPLICATIONS

To examine the feasibility of our spring designs, we printed out the models in Figure 2 with two consumer-grade 3D printers (a *Printrbot Simple* and *MakerBot Replicator*) using regular PLA filament. All structures were printed as one piece without post assembly. The spring-based CAD models were sliced using standard slicer software with thin-wall infill as the support structure. All models were printed with both horizontal and vertical orientation successfully.

To demonstrate the potential application space, we created a Tigger example (Figure 1) with three tail designs: (i) a *jumping tail*, which can be easily compressed to perform Tigger's proverbial jump; (ii) a *bendable tail*; and (iii) a *twistable tail*. See the complementary video figure.

CONCLUSION AND FUTURE WORK

In this poster, we explored a set of spring-based structures that imbue 3D-printed objects with rich deformation functions using consumer-grade 3D printers. In the future, we plan to (i) develop a GUI-based interface that allows end users to rapidly prototype deformable and interactive objects using spring-based structures; (ii) build impactful applications with the compound structures in our proposed design space to demonstrate our approach's potential; and (iii) investigate the simulation of material properties [6] to open up new opportunities for modeling interactivity.

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