Designing, Controlling, and Fabricating In-Place Augmented Structures

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ABSTRACT

Emerging 3D printing technology has enabled the rapid development of physical objects. However, 3D-printed objects are rarely interactive and adding interactivity to printed objects is inherently challenging. To boost 3D printing for a wider spectrum of applications, I introduce *in-place augmented structures*, a class of 3D printable parametric structures that can be integrated with physical objects and spaces for augmented behaviors. In my research, I explore how 3D printing can support interaction (*e.g.,* sensing and actuation) by creating novel design techniques and building interactive design tools that enable end-users to design and control desired behaviors. With these techniques and tools, I fabricate the in-place structures with readily available fabrication techniques and demonstrate my approach with a suite of applications across different domains.

Author Keywords

Digital fabrication; 3D printing; everyday objects; space; design techniques; design tool; interaction.

CSS Concepts

• **Human-centered computing~Human computer interaction (HCI)**

INTRODUCTION

3D printing, as an emerging prototyping technology, enables designers to rapidly build physical objects [17, 25], from a rigid Stanford bunny to a simple enclosure for hiding circuits. However, 3D-printed objects are rarely designed and used as custom-made interactive medium due to two challenges. First, 3D-printed objects are traditionally static, which makes it hard to embed interactivity into the outcome shapes. For example, creating a 3D-printed deformable shape for functional movements is difficult [10]. To make 3D-printed kinetic objects, designers need to assemble printed parts using external hardware (*e.g.,* screws, bolts, nuts) and tools (*e.g.,* wrench, screwdriver). Extra actuators such as motors are installed in the 3D-printed objects to control the device movement for interaction. As a result, creating a movable and functional 3D-printed object requires additional manual work or external power. Second, domain knowledge and numerous iterations are required for designing desired behaviors in 3D printable shapes. For example, the user must know how gears work to create a 3D-printable moving pull-back car. To design an interactive device, the form and circuit design must be coordinated through repetitive edits of the digital model, 3D printing, and manual assembly of electronic parts and wires [15].

To address these challenges, I propose a new concept of 3D printable structures—*in-place augmented structures* that are parameterizable mechanisms used for augmented behaviors when integrated with physical objects or real spaces (Figure 1). Throughout my PhD, I aim to address the following research questions:

RQ1: What mechanisms are makers/hobbyists using to create interactive 3D-printable objects?

RQ2: What properties of the mechanism of interest can be utilized for design and control?

RQ3: How to lower the barrier for the end-user to design, control, and fabricate the 3D printable behaviors for interaction?

RQ4: What applications can benefit from on-demand 3D printable structures?

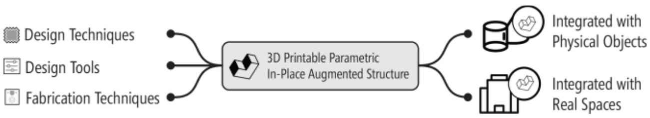

Figure 1. The overview of designing, controlling, and fabricating in-place augmented 3D printable structures for multi-context applications.

To answer these questions, I create *design techniques* to construct the in-place augmented structures for interaction (*e.g.,* sensing and actuation) and investigate their mechanical and material properties for desired behaviors (RQ1&2). I also build *design tools* that allows end-users to create and parameterize 3D printable behaviors using the in-place augmented structures (RQ3). To fabricate these structures with limited assembly, I explore *fabrication techniques* upon readily available machines and approaches (RQ3). The in-place augmented structures can support a wide range of applications (*e.g.,* physical computing,

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wearable computing, assistive devices) through the integration with physical objects to add augmented functionality or the integration with real spaces to support human-environment interaction (RQ4). Figure 1 shows the overview of my research approach.

RELATED WORK

Researchers have explored converting static 3D-printed artifacts into dynamic objects with embedded mechanical structures [2, 10, 12, 16] and conductive elements [4, 19, 20] for interaction, including 3D printable joints [1, 3], linkages [17], hinges [13, 22], metamaterials [10, 11], telescoping structures [26], and leaf springs [12]. These works suggest a common fabrication approach to enable 3D-printed objects to support interaction—using an embedded 3D printable mechanical structure as a method of actuation or conductive structure for sensing of user input. For example, Calì *et al.* [2] converts static 3D models into articulated sculptures using 3D printed posable joints. *Bend-it* [25] controls the kinematic movements of 3D-printed models using embedded wires. Trilaterate [21] detects a finger hovering, touching, or forcing arbitrary 3D-printed surfaces via capacitive trilateration of actively shielded electrodes embedded inside the 3D body. Tactlets [5] allows the user to design electro-tactile physical controls such as buttons and sliders that sense user input via conductive material applied to tactile 3D-printed objects. In my research, I use a similar approach to explore other mechanical mechanisms that can be used as the elemental structures (*i.e.,* in-place augmented structures) to enable sensing, actuation, and scaffolding in specialized applications. In addition, I also investigate the parametric design of the augmented structures for user control using their mechanical and material properties.

My research also relates to the literature of parametric computer-aided design (CAD) tools for 3D model customization. One common type of these tools allow users to use predefined modular structures to create deformable artifacts from scratch [2, 11, 12, 18]. The editor in *Metamaterial Mechanisms* [10], for example, allows the user to replace 3D shapes with predefined shear cells. Another common approach for 3D model customization is to directly edit an existing model [27]. For example, the design tool in [26] allows a user to directly work on the skeleton of a 3D model to customize telescoping structures. PipeDream [23] enables the user to create internal channels directly in 3D models for interactive functionalities such as sensing and illuminated display by allowing the user to specify the pipe geometry and position. In my work, I build interactive design tools that allows novices to parameterize their desired behaviors such as motion and deformation and preview the resulting performance enabled by the in-place augmented structure.

3D PRINTABLE IN-PLACE AUGMENTED STRUCTURES

The in-place augmented structure is a class of 3D printable elements that can be parameterized for desired interactive behaviors without engineering background and fabricated without heavy manual work. While these structures are created for applications on demand and vary their designs across contexts, they share three common characteristics: (i) they are 3D printable mechanical elements; (ii) they provide user-controllable parametric designs for *sensing*, *actuation*, or *scaffolding* behaviors; and (iii) they are created for two application contexts: *integration into/with physical objects* and *integration with real spaces* (Figure 2).

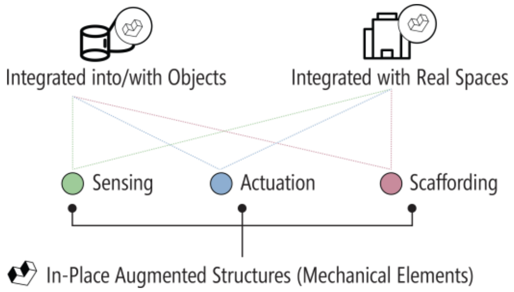


Figure 2. Application contexts and functionalities supported by the in-place augmented structure.

Object Integration. The in-place augmented structure can be integrated into/with physical objects to augment the object functionality and interactivity. I explore how to use in-place augmented structures as sensors for recognizing user input, as actuators for preforming kinetic behaviors such as translating, and as scaffolding forms for accelerating making activities and the custom-made interactive devices.

Space Integration. 3D-printed devices with in-place augmented structures embedded can be deployed in physical spaces to facilitate human-space interaction. In my research projects, I deploy the in-place augmented structures in physical environment to meet the target user needs and provide aid with the user to execute actions or interact with the environment.

My vision for the in-place augmented structure is to allow end-users to design, control, and fabricate augmented behaviors with imbued computational and mechanical capabilities. Below, I describe my research projects to provide a roadmap towards this vision.

Integrated into/with Physical Objects

To support interactive input with physical objects, I developed *SqueezaPulse* [6], a technique for embedding interactivity into fabricated objects using soft, passive, low-cost bellow-like structures (*i.e.,* in-place augmented structures). When a soft cavity is squeezed, air pulses travel along a flexible pipe and into a uniquely designed corrugated tube that shapes the airflow into predictable sound signatures. A microphone captures and identifies these air pulses with a trained machine-learning classifier enabling interactivity (Figure 3). To demonstrate and evaluate the potential of *SqueezaPulse*, we present four prototype applications, including a game controller, an

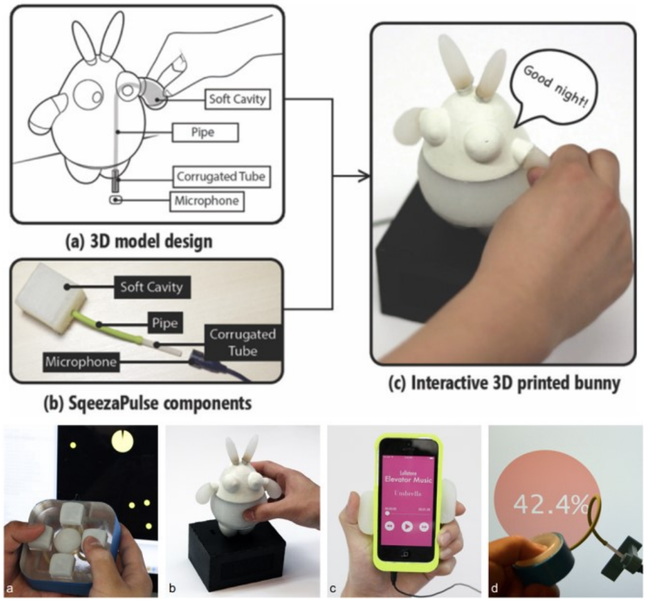


Figure 3. ***SqueezaPulse*** **uses a soft cavity, a pipe, a corrugated 3D-printed tube, and a microphone to convert air pulses into interactive input. It supports a range of applications: a game controller, an interactive toy, a squeezable phone case, and a force sensor.**

interactive storytelling toy, a squeezable phone case, and a force sensor, and a small, lab-based user study (N=9).

Besides sense of user input, I explored how to create 3D printable deformation behaviors in 3D-printed objects in project *Ondulé* [7] (Figure 4). In this project, I developed an interactive design tool that allows novices to create parameterizable deformation behaviors in 3D-printable models using embedded helical springs and joints (*i.e.,* in-place augmented structures). Informed by spring theory and our empirical mechanical experiments, I introduced spring and joint-based design techniques that support a range of parameterizable deformation behaviors, including compress, extend, twist, bend, and various combinations. In the design tool, users can convert selected geometries into springs, customize spring stiffness, and parameterize their design with mechanical constraints for desired behaviors. To demonstrate the feasibility of our approach and the breadth of new designs that *Ondulé* enables, I showcased a set of example 3D-printed applications from launching rocket toys to tangible storytelling props.

Ongoing Research #1: Since I have explored how to add deformation behaviors to 3D-printed objects, I extend this by investigating a suite of mechanical elements (*i.e.,* in-place augmented structures) that allows end-users to design and control 3D printable motion without engineering background. Again, I use spring as the energy source and a series of transmission machines to support a variety of self-propelled motion. To support custom design, I also develop an interactive design tool for editing and previewing the embedded motion in 3D models. A set of practical applications are built to validate the feasibility of our design tool and approach.

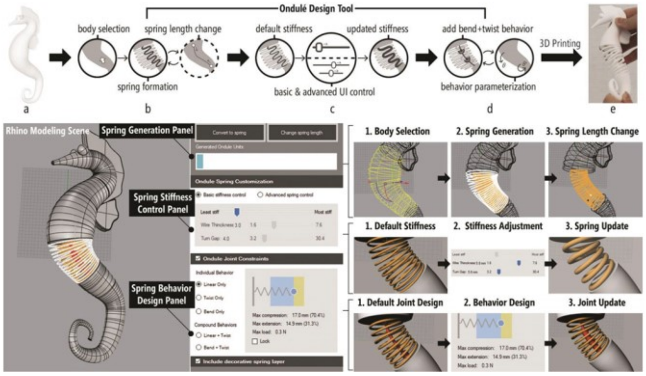


Figure 4. In the workflow provided by *Ondulé*, the user can select and convert a 3D body into a deformable spring. The spring can be customized and controlled for different stiffness and deformation behaviors with internal joints.

Ongoing Research #2: Arranging and wiring electronics in a 3D printable shape for a physical computing system is cumbersome and requires numerous iterations of manual assembly and testing. To coordinate both digital 3D model design and embedded circuit design, I develop an interactive design tool that scaffolds the placement and orientation of electronics in an organic 3D body. The conductive wires can be 3D printed using a multi-material printing printer. With the conductive scaffolding wires (*i.e.,* in-place augmented structures) and electronics before fabrication, I believe that the design and assembly of circuit in 3D-printed organic objects can be accelerated.

Ongoing Research #3: Following the above two ongoing projects, I explore a hybrid fabricate technique to create conductive channels in a sheet of auxetic structures (*i.e.,* in-place augmented structures), which scaffolds electrical connections for circuit design and acts as an elastic cover adapted to arbitrary surfaces. Similar, an interactive design tool is developed to support the custom cover design and the circuit that can be deployed on the cover.

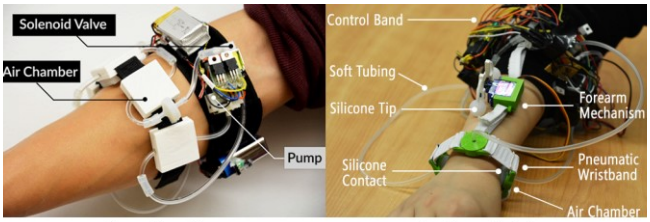
Integrated with Real Spaces

Ongoing Research #4: To attempt to integrate the on-demand structure with physical spaces, I explore creating 3D-printed tactile paving to assist blind and visually impaired (BVI) people to navigate in an indoor environment. In this project, I investigate the salient tactile paver patterns (*i.e.,* in-place augmented structures) that can be printable and perceived by visually impaired users. Then, I build a custom walking 3D printer that creates tactile paving coordinated with a planner design tool. To augment the interaction, we also embed uniquely interactive paving tiles that provide richer navigation information.

CONCLUSION AND FUTURE WORK

My research contributes: (i) a new concept of in-place augmented structures that serve for interaction such as sensing, actuation, and scaffolding; (ii) design techniques that utilize mechanical and material properties for the parameterization of the in-place augmented structure; (iii) design tools that lower the barriers for end-users to design and control 3D printable behaviors offered by the in-place augmented structure; (iv) fabrication techniques that support the fabrication of the in-place augmented structure; and (v) a wide spectrum of applications that thrive in different contexts.

Besides the above ongoing research projects, I have planned three more research projects to exemplify my vision for the in-place augmented structure in both application contexts. In my future career, I believe that combining artificial intelligence with 3D-printed objects can offer more design opportunities for more impactful applications. Further, I think integrating in-place augmented structures with the human body is an open yet exciting field. In two of my past projects—*PneuHaptic* [9] and *PneuFetch* [8], I installed soft silicone-based chambers (*i.e.,* in-place augmented structures) that can inflate and deflate under pneumatic control on the body to provide haptic feedback (Figure 5). The simulated haptic patterns can be used as directional clues for the wearer and serves as an assistive device for visually impaired users. This opens new design and application opportunities and can be further studied as an extension of my current research vision.



a. PneuHaptic b. PneuFetch

Figure 5. Both *PneuHaptic* and *PneuFetch* projects use soft inflatable chambers to provide on-body tactile feedback.

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