Metamaterial Devices

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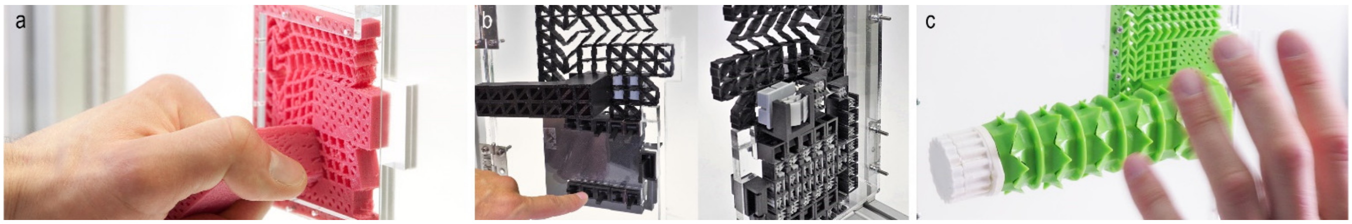

Figure 1: We demonstrate three types of metamaterials: (a) materials that implement mechanisms, (b) employ simple mechanical computation, and (c) interactive metamaterial objects that change their outside to interact with their environment.

ABSTRACT

In our hands-on demonstration, we show several objects, the functionality of which is defined by the objects' internal microstructure. Such metamaterial machines can (1) be mechanisms based on their microstructures, (2) employ simple mechanical computation, or (3) change their outside to interact with their environment. They are 3D printed from one piece and we support their creating by providing interactive software tools.

CCS CONCEPTS

• **Human-centered computing** → **HCI;** Interactive systems and tools • **Hardware** → Emerging technologies

KEYWORDS

Metamaterials, microstructures, fabrication, programmable matter.

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1 INTRODUCTION

Digital fabrication machines such as 3D printers excel at producing arbitrary shapes, such as for decorative objects. Recently, researchers started exploring 3D printing as a means to design the *inside* of objects. Applications include rearranging material on the inside to let arbitrary shapes spin [Bächer et al. 2014].

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Pushing this further, researchers created objects that consist internally of many 3D cells arranged on a regular grid. Since each cell is designed to perform a specific deformation, objects that entirely consist of such cells literally offer thousands of degrees of freedom. Such structures are also known as *metamaterials*. Metamaterials are artificial structures with mechanical properties that are defined by their usually repetitive cell patterns, rather than the material they are made of [Paulose et al. 2015]

Based on this concept, researchers have created objects with unusual behaviors, such as metamaterials that collapse abruptly when compressed, that shrink in two dimensions upon one-dimensional compression [Bertoldi et al. 2017], or objects that vary the elasticity across an object [Schumacher et al. 2015].

2 METAMATERIAL DEVICES

So far, metamaterials have been understood as materials. The main contribution of this work is that we want to think of them as *devices*.

We demonstrate three aspects of such functional metamaterial objects: (1) materials that implement mechanisms based on their microstructures, (2) that employ simple mechanical computation, and (3) interactive metamaterial objects that change their outside to interact with their environment. The main benefit of this approach is that the functionality is solely defined by the object's microstructure, and that no assembly is required.

2.1 Metamaterial Mechanisms

In this work [Ion et al. 2016], we push the concept of metamaterials further by creating objects that allow for *controlled directional movement*. This allows users to create objects that perform mechanical functions. Our objects thereby implement devices that transform input forces and movement into a desired set of output forces and movement—also known as *mechanisms*.

We demonstrate metamaterial objects that perform a mechanical function. Such *metamaterial mechanisms* consist of a single block of material the cells of which play together in a well-defined way in order to achieve macroscopic movement. Figure 1a shows our metamaterial door latch, for example, that transforms the rotary movement of its handle into a linear motion of the latch. Our metamaterial Jansen walker consists of a single block of cells—that can walk. The key element behind our metamaterial mechanisms is a specialized type of cell, the only ability of which is to shear.

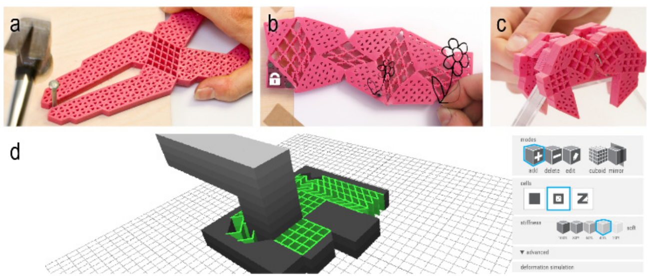

Figure 2: We demonstrate several metamaterial mechanisms: (a) pliers, (b) a drawing replicating pantograph, and a (c) Jansen walker, which are made (d) with our editor.

Metamaterial mechanisms are simple. While a traditional door latch mechanism consists of several parts, including an axle, bearings, springs, etc., the metamaterial door latch in Figure 1a consists of a single block of material, as it is groups of cells inside the object that perform the mechanical function.

To allow users to create metamaterial mechanisms efficiently we implemented a specialized 3D editor (Figure 2d). It allows users to place different types of cells, thereby allowing users to add mechanical functionality to their objects. To help users verify their designs during editing, our editor allows users to apply forces and simulates how the object deforms in response.

Such *analog* machines, however, are limited in terms of complexity. As forces are passed on from one cell to the next, they are damped, and the activation energy dissipates, causing the mechanical "signal" to decay exponentially. This limits the number of mechanisms that can be concatenated and therefore the complexity of the machine.

2.2 Digital Metamaterials

To eliminate the energy dissipation of analog machines, we extend this concept towards *digital* mechanisms [Ion et al. 2017]. Combining metamaterial mechanisms with concepts from mechanical computing and signal propagation [Raney et al. 2016], we introduce a new type of cell that propagates a digital mechanical signal using an embedded bistable spring. When triggered, the spring discharges and the resulting impulse triggers one or more neighboring cells, resulting in signal propagation, as shown in Figure 3. It counteracts signal decay, thus allows signals to pass through an *arbitrary* number of cells. We extend this basic mechanism to implement simple logic functions.

To illustrate this concept, Figure 1b shows a combination lock implemented using digital metamaterials. The device offers 10 digit buttons on the front. Users tap these buttons to enter their code, then press the 'open' button to unlock the door.

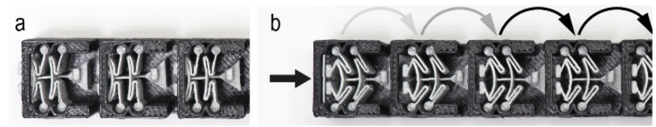

Figure 3: Our cells (a) store energy. When one discharges, (b) it triggers its neighbor cells to propagate signals.

2.3 Metamaterial Textures

While the analog and digital metamaterial mechanisms explore adding functionality to 3D printed objects by employing microstructures on the inside, here we apply the main idea behind metamaterials, i.e., subdivision into many cells and customization on a per-cell basis, to the *outsides* of 3D printed objects. The resulting *metamaterial textures* [Ion et al. 2018] allow designers to shape how the object interacts with the environment and with the tactile sense of the user.

Metamaterial textures offer full control over the transformation, such as in between states and sequence of actuation. This allows for integrating multiple textures that enable functional objects such as, e.g., a transformable door handle shown in Figure 1c, which integrates tactile feedback for visually impaired users, or a shoe sole that transforms from flat to treaded to adapt to weather conditions.

3 CONCLUSIONS

We extend the research field of metamaterials by contributing general-purpose approaches to creating devices from metamaterials. Devices are a new genre of metamaterial structures that is of higher complexity and that exploits more degrees of freedom than previous work in this field, and that allow metamaterials to tackle problems they have traditionally not been able to address. The resulting devices are solely defined by their microstructures, consist of a single piece and thus require no assembly.

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