Reprogrammable Digital Metamaterials for Interactive Devices

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Figure 1: In this paper, we show (a) reprogrammable digital metamaterials that enable computation loops and decision-making within the material. We demonstrate that by reconfiguring material properties, this material can be used to build interactive devices, for example (b) a display that reveals a hidden message set by the host when a visitor walks by, or (c) a large-scale haptic floor with dynamically reprogrammable local stiffness.

ABSTRACT

We present digital mechanical metamaterials that enable multiple computation loops and reprogrammable logic functions, making a significant step towards passive yet interactive devices. Our materials consist of many cells that transmit signals using an embedded bistable spring. When triggered, the bistable spring displaces and triggers the next cell. We integrate a recharging mechanism to recharge the bistable springs, enabling multiple computation rounds. Between the iterations, we enable reprogramming the logic functions after fabrication. We demonstrate that such materials can trigger a simple controlled actuation anywhere in the material to change the local shape, texture, stiffness, and display. This enables large-scale interactive and functional materials with no or a small number of external actuators. We showcase the capabilities of our system with various examples: a haptic floor with tunable stiffness for different VR scenarios, a display with easy-to-reconfigure messages after fabrication, or a tactile notification integrated into users' desktops.

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**.

KEYWORDS

Metamaterials, Fabrication, Programmable Matter

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1 INTRODUCTION

Digital fabrication machines, such as 3D printers, enable making custom objects with arbitrary geometry. With such flexibility, there is rising interest in digitally fabricating interactive and functional devices. Initially, 3D printed objects were often used to hold external parts, which provided the interactivity. Such external parts include sensors [40, 41], displays [44], motors and other actuators [24], or entire mobile devices [19]. Beyond encasing parts, fabrication machines assist in creating custom objects with mechanical functions such as springs [10], linkages [20], directional bending [22], or shape-changing interfaces [46]. Like traditional devices, these interactive devices rely on external digital processors and actuators.

With the flexibility of 3D printers, researchers have also created objects consisting internally of a large number of cells, with each cell designed to perform a specific deformation [23]. Such structures are known as mechanical metamaterials [3], whose "mechanical properties are defined by their usually repetitive cell patterns, rather than the materials they are made of" [28]. Metamaterials of varying scales have been demonstrated [2, 43, 49] with engineered internal structures enabling unique mechanical properties, such as spatially varying stiffness in an object [27, 34], auxetic materials that change volume [1], or materials that embed functional mechanisms [11].

The ability to engineer such complex metamaterials recently sparked interest in integrating mechanical computation, or decision-making capabilities, into the material's geometry. This effectively enables future materials where 'information processing can be viewed as a material property' [47]. The key benefit of such systems is that they can be additively manufactured as embedded parts of metamaterials to interact mechanically with their surrounding environment while processing digital information internally [35].

While previous work focused on partial aspects of such passive digital devices, i.e., developing cell-based logic gates [13, 35, 42, 49], or external configuration of stable memory [6], or electromagnetic resetting of cells [21], we are interested in exploring the applicability of full-loop reprogrammable computational materials. With our exploration, we do not aim to replace traditional computers and CPUs with computational metamaterials but to equip passive devices with simple, functional processing capabilities to support versatile physical user interactions.

1.1 Reprogrammable Digital Metamaterials

We contribute to the research on integrating decision-making into passive materials and build on prior work by developing new geometry that enables loops and is reprogrammable. We explore complex end-to-end applications to understand the utility that such digital mechanical metamaterials might have in the future. We create a design space for our reprogrammable digital metamaterials that assists users in creating *interactive, passive, and functional devices.*

Specifically, we build on previous works on mechanical computation and make the following key contributions. We develop signal transmitting cells that (1) include an integrated recharging mechanism to enable *multiple computation rounds* for true interactivity. The recharging mechanism allows users to reset multiple cells at once with only one manual action at an external location and with reduced force. This enables the digital metamaterial cells to be flexibly stacked and layered in 3D, or embedded into other structures. Additionally, we present simple mechanisms that allows users to (2) reprogram the material's logic *after fabrication*. A part of our reprogrammable processing cells also allows users (3) to embed *multiple programs* into the material and activate the desired program later without the need to change the object. The resulting reprogrammable metamaterial enables us to explore the (4) *applicability* of such materials in the future. We use the small displacements produced in the structure during the computation as simple actuators for output within the material. We show example mechanisms that leverage these small displacements to change appearance, access, or material properties.

To demonstrate their utility, we developed 3 such interactive and functional end-to-end application examples based on reprogrammable metamaterials that cover a broad space: manual and computer-controlled, medium scale (e.g., a desktop) to room-scale (e.g., an interactive floor holding a human), and that change different properties (e.g., stiffness or texture). Our application examples include a haptic floor with controllable stiffness for virtual reality environments, an interactive shape-changing desktop, or a reprogrammable message display that supports implicit user interactions. The wide variety of outputs and applications are all achieved through building blocks from one single system and can be further extended by the users for different scenarios.

1.2 Contributions

The main contribution of this work is to create a system for passive interactive metamaterial machines. Compared to traditional sensor, processor, and actuator-based interactive machines, the passively interactive metamaterials can sense, compute, and actuate internally within the material upon a small external trigger. This allows us to build interactive machines that can be integrated into built environments and require no or only a small number of actuators with minimum energy consumption. Such machines can dynamically reconfigure material properties based on changing inputs to serve different functions. We present a set of cells to form a design space to enable making such passive interactive materials. To achieve this, we make the following specific contributions.

(1) *Recharging cells:* We develop a novel digital cell that in addition to transmitting signals, employs a recharging mechanism to support multiple computation loops.
(2) *Simple reconfiguration of logic functions:* We present how users can re-program their cells to execute different programs after the material has been installed.
(3) *Set of input and output cells:* We demonstrate input and output mechanisms that support different input interactions and enable complex shape-changing effects.
(4) *Showcase interactive metamaterial devices:* We demonstrate the applicability of such reprogrammable materials in building functional and interactive devices with several end-to-end interactive systems.
(5) *Design tool:* We provide an editor that helps users design reprogrammable digital metamaterials and simulate the shape-changing outputs.
(6) *Technical evaluation:* We present a technical evaluation of our cells' performance to facilitate replication and building on our initial designs.

	Functionality	Manual actuation	Logic computation	Signal transmission	Reprogrammable	Integrated recharging	Supports resetting in 3D
[42]	logic gates	✔	✔	✖	✖	✖	✖
[35, 49]	logic gates	✔	✔	✖	✖	✖	✖
[6]	mechanical memory	✖	✖	✖	✔	✖	✖
[21]	logic gates	✖	✔	✔	✔	✖	✔
[13]	simple programmable machines	✔	✔	✔	✖	✖	✖
this work	interactive reprogrammable machines with complex outputs	✔	✔	✔	✔	✔	✔

Figure 2: Comparison between this work and previous works on (re)programmable metamaterials.

2 RELATED WORK

We build on previous work in fabricating material properties, embedding functionalities into digitally fabricated devices, and reprogrammable mechanical metamaterials.

2.1 Fabricating Material Properties

Aided by digital fabrication approaches, personal fabrication machines such as 3D printers enable users to design and fabricate customized objects. Other than fabricating objects of different shapes with uniformly filled materials for aesthetic or functional purposes, there's a growing interest in fabricating custom material properties. The flexibility enables the fabrication of unique material properties that can't be found in conventional materials or spatially varying material properties in one single object.

Auxetic materials with a negative Poisson's ratio, which expand in the lateral direction when stretched longitudinally, are an emerging class of materials and have been widely adopted in aerospace engineering [1, 18]. Researchers have enabled custom control of spatially varying stiffness of printed objects by tiling varying microstructures [27, 34] or by injecting filaments into silicone during fabrication [48]. Deformation of materials have also been pre-programmed so that the deformed object achieves pre-defined functions [4, 7].

Other than pre-programming the material properties of the objects to be printed, researchers have also explored *post-print modifications* that would allow users to reconfigure the objects for the intended functions. Such reconfiguration through physical manipulation gives users more flexibility, is cost-effective as it needs no reprint, and simplifies the digital design process. Ko et al. [15] proposed thermoformable cells-based 3D printed objects whose surface and form factor can be modified upon heating. Similarly, ShrinCage [36] proposed a 4D printing system that easily created shrinkable adaptations to fit existing objects thereby simplifying digital designing. Ion et al. [12] presented 3D printed surface geometries that can perform controlled transitions between multiple textures.

These past works demonstrate that an object or device's mechanical function can be changed by reconfiguring its material property. However, most However, as shape-changing analog materials without digital processing capabilities, the complexity of these reconfigurations and the mechanical functions of the fabricated object are limited. Due to this lack of processing power, a coupling between the devices' input and output in terms of their position, form, and scale is created. We aim to break this coupling by supplementing a digital processing layer to the reconfigurable analog materials which treats the user action as an input signal that can be transmitted and computed and can interact with the analog material layer. This allows the materials to exhibit more complex output behavior and enables the fabrication of flexible and highly functional mechanical devices.

2.2 Embedding Functionality Into Digitally Fabricated Devices

There is rising interest in digitally fabricating interactive and functional devices by either embedding external parts or engineering the material's internal structures. The realization of the functions is achieved through the device processing the input which then triggers the pre-programmed output, reconfiguring some properties of the device including form factor, appearance, texture, digital signals, etc. One line of research embedded external parts into the devices during the fabrication. Past studies have proposed systems to embed tubes [30], optical fibers [44], conductive ink [31–33], sensors [40, 41], or even mobile devices [19] into 3D printed objects for interactivity. To trigger physical change, actuators including heating elements [9], or motors [24] have been embedded for interactive and shape-changing physical objects.

Such actuated objects have have also been demonstrated in larger scales by combining ready-made objects with powerful external actuators (e.g., linear actuators [16, 17], pneumatic actuation [38], robots [37]) that can move loads such as furniture or hold humans.

Digital tools and algorithmic techniques have also enabled the direct engineering of printed objects' mechanical properties such as fabricating custom linkages [20], haptic aesthetics [39], and directional bending behaviors [22]. With digital fabrication methods, this line of research enables quick, relatively low-cost, and simple fabrication of interactive, custom, and highly functional objects.

Metamaterial mechanisms [11], on the other hand, are based on passive materials with engineered internal structures that undergo cell-level deformation to achieve pre-programmed macroscopic movements and thus pre-defined mechanical functions. Past studies have developed *metamaterials* into shape-changing structures [26], an un-feelability cloak that elastically hides objects [5], and objects with controlled directional movement [11]. Compared to embedding parts into a fabricated object, a metamaterial device consists of a single part/material thus is easy to fabricate, requires no assembly, and has less friction [11].

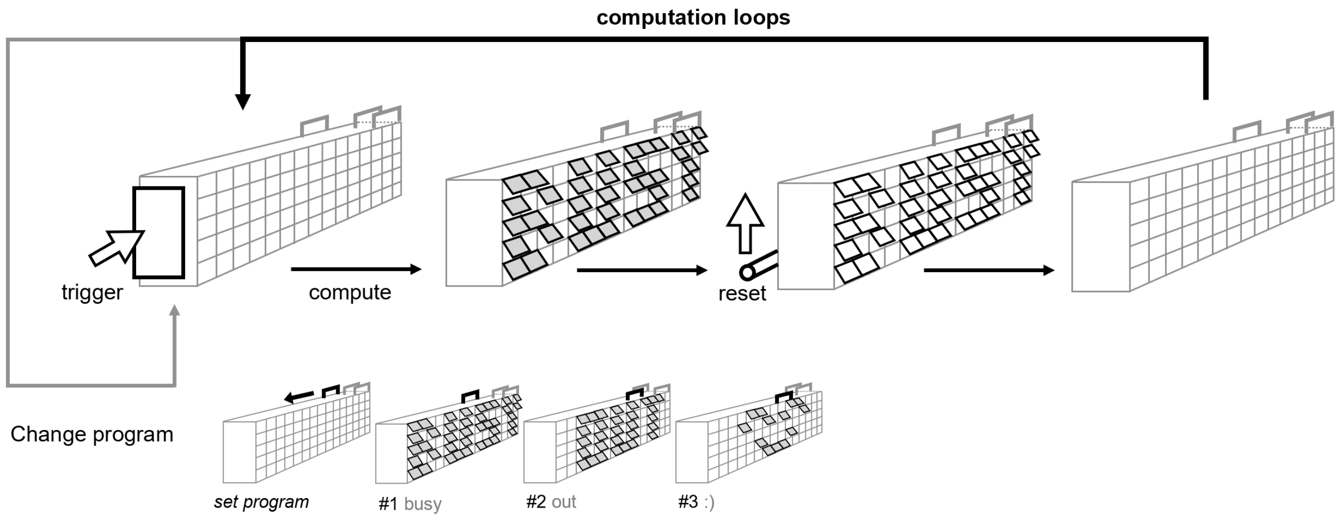

Figure 3: Our passive message display example shows how our reprogrammable metamaterials support computation loops to switch the display on and off; it also allows embedding multiple programs (messages), which the users can easily change between and replace after fabrication.

These works demonstrate the rising desire to add interactivity into custom objects. Typically, interactivity is achieved with external sensors, processors and actuators, that need to be wired, assembled, and powered. We propose leveraging integrated processing within metamaterials and augmenting their interactivity to balance capabilities and assembly effort.

Coupled with a reprogrammable digital layer with simple decision-making capability, we demonstrate metamaterial devices that are capable of delivering mechanical functions of different types and at different places. We hope this flexibility and encourages users to create their own metamaterial devices with self-defined functionalities and triggered mechanisms with digital fabrication methods.

2.3 Programmable Mechanical Metamaterials

Novel computing approaches which leverage mechanical computing for information processing have been introduced [47], enabling information processing to be viewed as an integrated material property. This can typically be achieved through embedding programmable structures within a mechanical device whose output/functionality is recomputed based on the new input.

Researchers have proposed approaches to propagate mechanical signals in soft materials [29], to integrate mechanical logic functions [13, 21, 35, 42, 49] into the devices, and to develop mechanical memory [6, 21] that can be read and written to support programmability. Song et al. [35], Zhang et al. [49], and Waheed et al. [42] similarly utilized multi-stable micro-flexures which would buckle under mechanical forces and displacement to perform Boolean computations. Mei et al. [21] proposed a reprogrammable mechanological metamaterial in which computation is achieved through imposing sequential electromagnetic excitation. Chen et al. [6] designed a tileable mechanical metamaterial with stable memory at the unit-cell level. Magnetic actuation enables state changes of each bistable cell with varying elasticity in each state. Ion et al. [13] developed a system that employed mechanical signal transmission and implemented gate cells based on rod logic, which only unblocks a mechanical signal upon the right input, for logic computation.

Only a few of these works support recharging, which is necessary for performing multiple computation rounds [6, 13, 21] and crucial for fast and easy user interactions. The systems that do offer recharging mechanisms do not integrate them fully into the material such that cells can be recharged independent of their assembly and orientation, e.g., Ion et al. [13]. Other systems require external electromechanical parts for recharging [6, 21]. Among these works with a recharging strategy, even fewer are reprogrammable, or can run different functions.

To augment passive metamaterials' interactivity, we thus push towards reprogrammable metamaterials by proposing an integrated recharging mechanism which only requires one recharging action for each reconfiguration for a device and a small force input relative to the device's scale. We summarize the space of prior work on (re)programmable metamaterials in Figure 2 and compare them to our work's contributions.

3 REPROGRAMMABLE PROCESSING

We provide an overview of our reprogrammable processing in Figure 3, using a message display as an example. The ability to run a different function is supported by an integrated recharging mechanism which allows easy and quick transition between computation rounds, e.g., switching the display message on-and-off flexibly. Switching between multiple embedded programs (i.e., the three different messages) or replacing the embedded programs after fabrication reprograms the device. These together allow users to flexibly run different programs in computation rounds. The achieved reprogrammable processing forms the base of the proposed passive, interactive, and multi-functional metamaterial devices.

3.1 Basics of Our Signal Transmission

Our bit cell features a bistable spring and a signal spring which re-routes the bistable spring's vertical displacement to a lateral direction. Figure 4a shows that the bit cell has two input ports. Displacement at the signal spring can be produced by actuation at both the bistable spring and the signal spring. This structure thus enables the decoupling of input and output direction which gives more flexibility in routing the signals.

Concatenating the bit cells together enable signal transmission as shown in Figure 4c-d. The small displacement produced by the signal spring carries out the signal propagation.

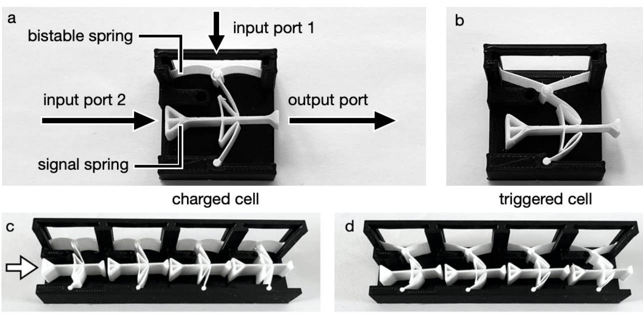

Figure 4: (a) Force input from both port 1 and port 2 triggers the cell and (b) results in a force/displacement at the output port. (c-d) Output displacement is propagated through the cells to realize signal transmission.

Figure 5 shows re-directing signals within a plane (a-b) and across planes (c-d). Redirecting is achieved in two neighboring cells by actuating the receiving cell through its input port 1 (at the bistable spring). Redirecting to a specific direction, for example, turning right or left, can be controlled by flipping the signal spring of the receiving cell.

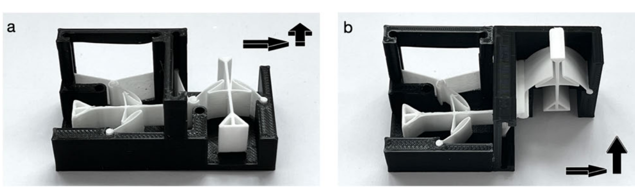

Figure 5: Re-directing the mechanical signal (a) within a plane and (b) across planes.

3.2 Integrated Recharging Mechanism

We build a recharging mechanism which (1) is *integrated* into the bit cell and therefore doesn't require extra space, (2) reduces the force needed to recharge one cell, and (3) transmits and connects the recharging of multiple cells so that they can be recharged together from any place.

This allows us to get the bistable springs back into their charged position and ready for the next computation. This mechanism extends the capabilities of our digital metamaterials toward multiple computation loops. Figure 6 shows how we integrate a lever to reset the top spring, which effectively recharges the cell without interfering with the signal transmitting springs. The lever is printed separately and assembled. With its pivot positioned below the bistable spring, the recharge lever rotates to push the spring up and rotates back to its original position when the cell is recharged. The lever is designed for a 2:1 mechanical advantage to decrease the force needed for recharging the bit cells.

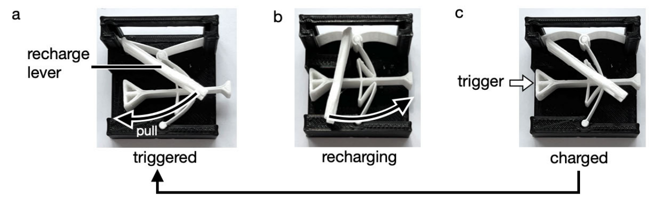

Figure 6: (a) A triggered bit cell is (b) recharged by rotating the recharge lever to reset the top spring. (c) After recharging, the lever is pulled back so the charged cell is ready to be triggered again.

Figure 7 demonstrates how the recharge levers in multiple cells of different directions are connected such that all the cells can be recharged together with one pulling action. The levers in cells of the same direction can be conveniently connected by rigid links. To redirect the pulling force to recharge cells of different directions, we routed inelastic strings (e.g. fishing lines) around corner columns to connect the recharge levers. We tie the lever in the last cell to be recharged to a corner column with an elastic rubber band which is extended during recharging and would pull all the levers back to their original position after the cells are charged. This adds a small force of 0.8N when pulling to reset multiple cells. With our integrated recharging mechanism, the recharge levers in the entire system can be connected to reset the system by only one pulling action or by one actuator.

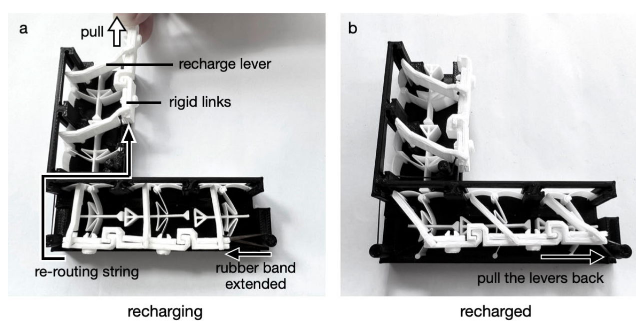

Figure 7: Recharging multiple re-routed cells.

Mechanical logic computations demonstrated in previous works [13] can be implemented with our cells and with the additional recharging capabilities. Here we demonstrate one such example - a NAND gate implemented with our recharging integrated bit cells (Figure 8). The gate can be reset for the next computation loop with only two manual actions - one to recharge all the signal evaluation cells and one to recharge the user input cells.

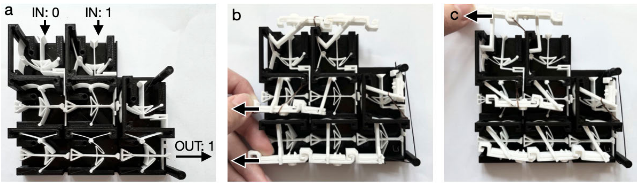

Figure 8: (a) A NAND gate built with our bit cells. The gate is reset by recharging the (b) signal evaluation cells and (c) the input cells.

3.3 User-configurable Logic

In many prior works on programmable materials, the executable logic functions are oftentimes dependent on specific cell arrangements or the shape of the printed material [35, 49]. As a result, it is often hard or impossible to change the logic functions after fabrication. We extend on Ion et al. [13]'s gate cells based on rod logic, which block or unblock the signal transmission in one neighboring cell with a rod connected to a bistable signal spring. But we decouple the rod from other printed structures so that re-printing and replacing only the rod achieves reconfiguration of the logic functions, making the material reprogrammable. We also extend the dimension of this blocking mechanism to an array of cells as well as two-dimensional layouts of cells. We call this the *logic filter*. The key benefits of the logic filter are that (1) it produces an output pattern, or controlled actuation at multiple cells instead of at one single bit cell for each round of computation, and (2) it can be replaced after the fabrication, allowing users to reconfigure the logic functions realized by the fabricated cells easily. This enriches the output capabilities of metamaterial machines and enables the reconfiguration of machine functionalities by changing the logic functions *after* fabrication.

Figure 9 shows a one-dimensional logic filter in which one user input determines multiple neighboring cells' outputs. One logic filter can host multiple blockers. The position of each blocker determines the output of one bit cell; the position of the logic filter thus determines the output pattern of multiple bit cells. (a) When the input cell is not triggered, only the middle output cell is unblocked. (b) Triggering the input cell moves all the blockers towards the left, unblocking the left and right output cells and blocking the middle output cell. Different output patterns are thus produced depending on the user input. (c) Users can easily reconfigure the logic functions of the fabricated cells by simply replacing the logic filter.

The granularity of the logic filters, or the number of blockers that one filter hosts, is flexible and can be adjusted with the scale of the application in mind. Our system is modular and can provide 1D or 2D logic filters which can then be connected to form 1D, 2D, or 3D logic functions. In our applications (Section 5), we use logic filters of varying granularity for different applications such that it's easy and quick for users to print, rearrange, and exchange the filters.

3.4 Integrating multiple programs

Other than simple replacing of the logic functions to enable reprogrammability, we also support integrating multiple programs

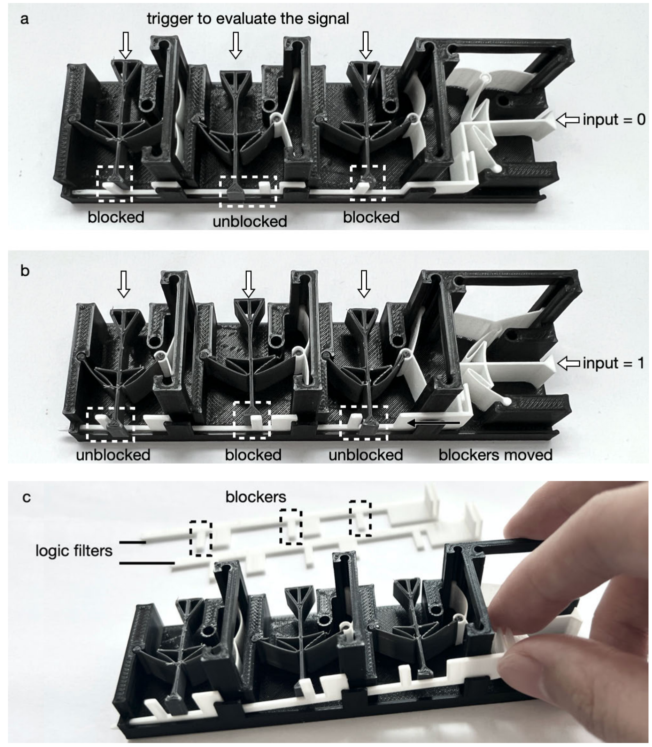

Figure 9: (a-b) In our one-dimensional logic functions, changing user input produces different actuation patterns. (c) The embedded logic function can be reconfigured after fabrication by changing the 1D logic filter, which is analogous to changing the 'punchcards'.

into one metamaterial device. This allows users to easily switch between frequently used functions on a multi-functional metamaterial device. Integrating multiple programs is achieved by layering the logic filters. We demonstrate this on two-dimensional logic filters. The one-dimensional logic filter described in Section 3.3 can be arranged in multiple columns to form a 2D layout of cells in which each cell outputs a controlled actuation. For this layout, we use 2D logic filters that block or unblock the signal transmission at the unit cell level. Figure 10 demonstrates how we extend 1D logic filters to 2D.

(a) Multiple user-configurable logic filters can be layered, with each layer defining one logic function. The signal springs have the same number of blockers, one for each logic layer. Here we show an example with 3 logic layers. Each layer of 2D logic filters can be activated by (b) sliding one layer of the filters towards the right such that the "teeth" on the filters align with the signal springs. The aligned filters then block selected cells and allow other cells to be triggered, producing a specific 2D actuation pattern. With multiple embedded programs, one can simply reprogram the output by deactivating one layer of logic filters and activating another layer. (c) We integrated a planar joint at each 1D logic filter such that users can flexibly assemble and change their 2D logic filters. The connected logic filters are inserted into the slot. We also assist in triggering and recharging multiple cells with one action. We show

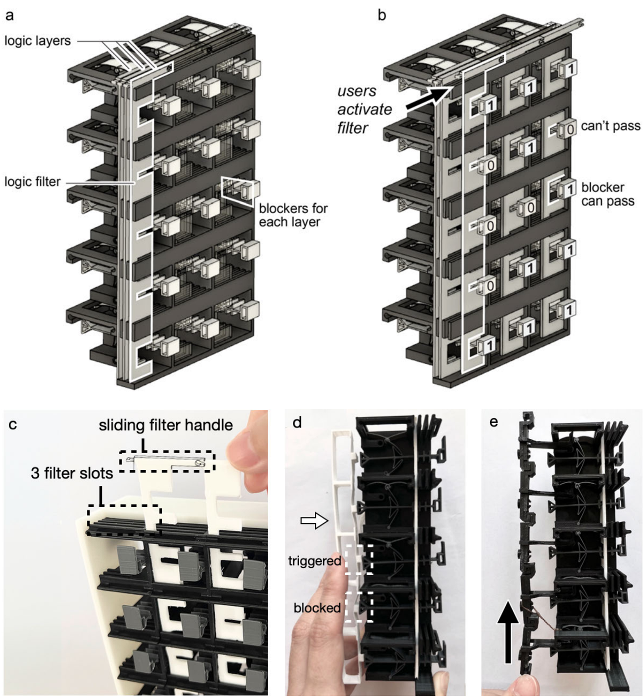

Figure 10: (a) Multiple programs are embedded as layers of logic filers. (b) Activated filters selectively block cells to change the 2D output pattern. (c) The filters are assembled and inserted into a filter slot. All the cells in each 1D logic function can be together triggered by (d) a compliant triggering pusher and recharged by (e) recharge levers connected by rigid links.

a compliant button-like structure in (d) that allows users to input force into all cells of a filter-activated 1D logic filter by pressing the structure once. The thin walls trigger unblocked cells, where the signal should pass, but deform at blocked cells. All cells in a 1D logic filter can then be recharged together by connecting the recharge levers with vertical rigid links, as shown in (e).

4 INPUT AND OUTPUT

To investigate how this reprogrammable material can build functional and interactive devices, here we demonstrate different input mechanisms the material uses to 'sense' user interactions and different output mechanisms and functionalities that the material can produce.

4.1 Input

The input to the digital metamaterial system is a small displacement to trigger the unit cell, initiating an impulse. The unit cell can be triggered from either the bistable or the signal spring. Depending on how users interact with the digital metamaterial machines, the input into the system can be manual, actuated, or built-in (Figure 11). The bit cells can then be concatenated to transmit the small input displacement to a designated destination or to trigger fine-grained shape change from anywhere within the material.

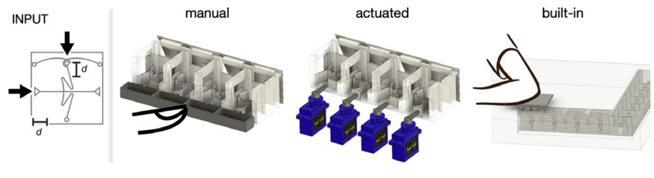

Figure 11: Input mechanisms.

With 4 bit cells as an example, the cells can be triggered manually by the user pushing a compliant triggering pusher (Figure 10d). The cells can also be triggered by external motors that provide the same displacement. One motor that drives the compliant pusher or 4 motors with one for each bit cell can be used depending on the scenario. This enables computerized control of digital metamaterial devices. With the motors, users can also add traditional parts, such as sensors, to expand the range of input to non-mechanical properties, e.g., temperature, humidity, light, etc. Alternatively, by integrating metamaterial cells into the built environment, we can leverage users' unintentional, implicit actions as input into the system. This supports natural interaction with the passive metamaterials without requiring explicit user actions for input. For instance, cells can be triggered by the user resting his/her elbow on the table.

4.2 Output

By construction, a digital metamaterial cell outputs a small displacement. We use this simple displacement as an interface that can connect to other materials and end-effectors. This allows us to extend to other complex outputs, which make these metamaterial devices *functional*. Figure 12 shows that with different end-effectors, the simple linear output can be transformed into rotational or blocking mechanisms. These mechanisms can then lead to macroscopic changes in different material properties, as illustrated in Figure 12.

We can achieve rotational mechanisms by attaching rotational hinges to the cell. By tiling the bit cells and controlling the actuation cell-wise with logic filters, we can achieve macroscopic reconfiguration of the material's surface appearance, or a simple bit display. Alternatively, applying rotational outputs to a series of concatenated signal-transmitting cells allows the output to be transmitted along with the mechanical signal. This enables us to create global texture patterns that can be switched on and off.

When coupled with other shape-changing systems, the output displacement can also realize a blocking mechanism. By moving a blocker in-place or out-of-place, we can change the system's range of motion and macroscopically its property. For instance, blocking can be used to change access and stiffness.

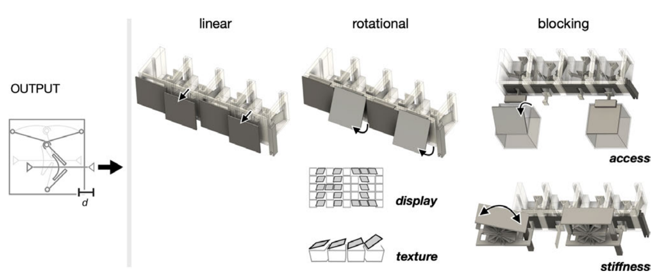

Figure 12: Output mechanisms and the supported shape-changing outputs.

We implement these outputs in our applications (Section 5) to demonstrate interactive and functional metamaterial devices. One should also note that though this list covers some common reconfigurable material properties or shape changes, it is not exhaustive. If users want to reconfigure other material properties or work with different form factors for the same properties exemplified above, they can adopt ideas from our end-effectors to design other shape changes.

5 EXAMPLES OF INTERACTIVE METAMATERIAL DEVICES

With the reprogrammable processing (Section 3) and the deliverable shape-changing outputs (Section 4), we demonstrate interactive metamaterial devices that (1) support natural or implicit user interactions, (2) can be repeatedly used in an easy and timely fashion, (3) can be conveniently reprogrammed to change the output after fabrication, (4) produce meaningful and versatile outputs, and (5) are entirely passive or computer-controlled with a small number of motors. The interactive systems we presented wouldn't be possible with existing computational metamaterials as they don't or very poorly support multiple loops or reprogrammability.

With the range of applications we implemented, we demonstrate the flexibility of the reprogrammable bit cells - they can be scaled, stacked in different dimensions to create 3D metamaterials, and embedded into other objects. Moreover, we show that our modular cells can be used as building blocks to create a diverse set of interactive systems which otherwise each require an individual design of its mechanisms, electromechanical parts, integration (e.g., into desktop, floor, etc.), interaction, etc. Our modular approach helps simplify the design and implementation process for users.

5.1 Tactile Desktop Reminder

We implemented a tactile desktop reminder with a passive daily to-do list and a calendar-triggered long-term reminder. We show an overview in Figure 13.

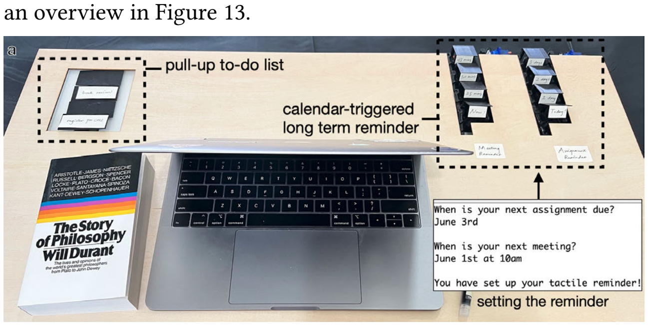

Figure 13: Tactile desktop reminder with a pull-up to-do list and a calendar-triggered texture reminder.

The pull-up to-do list can be controlled at the unit cell level, and each cell's bistable spring outputs a vertical linear displacement. The top cap attached to a bistable spring can thus be pulled up (recharging) and pushed down (triggering), as we show in Figure 14. The user can thus set a to-do task by manually pulling up the top cap attached to a top spring and attaching written stickers. The to-do task can be resolved by pushing down (triggering) the top cap when the task is completed.

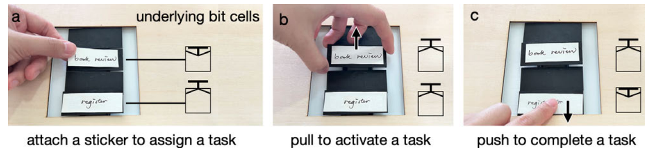

Figure 14: Set up a to-do item by (a) assigning a task and (b) pulling up to activate the task; Resolve an item by (c) pushing down the bistable spring.

Figure 15 shows a long-term tactile reminder which triggers bumpy textures gradually based on digitally set calendar events. We implemented an Arduino script (Figure 13) to allow users to setup calendar reminders for a meeting and an assignment deadline. (a) The texture cells pop out one by one; they get closer in distance and larger in tilting angles as the set event approaches. This is to visually and tangibly remind the user that an event is approaching and becoming increasingly urgent. The user is reminded every 15 minutes for the meeting and every day for the assignment. (b) The cells are triggered at their bistable springs with a sliding input mechanism by a motor that pulls the slider. (c) When an event is completed, the user can manually push to reset a tactile reminder such that the desktop is reconfigured to a flat surface.

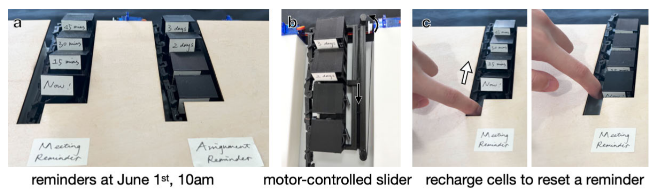

Figure 15: (a) Cells pop up as an event approaches at given intervals, triggered by (b) a sliding input. (c) Push to reset the reminder when the event is completed.

Through this, we show that the users can flexibly combine and arrange the modular output cells with varying shape changes to create customized, interactive, and functional objects.

5.2 Walk-to-trigger Reprogrammable Message Display

Figure 16: The display placed next to the office (a-b) reveals a host-set message when a visitor approaches. (c) As the visitor walks away to enter the office, the message is hidden again.

Based on our reprogrammable metamaterial cells, we demonstrate an interactive message display (Figure 16) that is (1) integrated into the built environment, (2) triggered and reset without explicit actions by the users, and (3) entirely passive.

The display is placed on the wall next to a person's office and can inform the visitors about the host's status. (a) The message remains hidden by default to avoid publicly disclosing the information. (b) As a visitor walks towards the office and passes by the display, the hidden message shows up, which in this case indicates that the host is not busy and "OK" with meeting the visitor. (c) Having seen the message, the visitor then goes ahead to enter the office. The message is hidden again as the visitor walks away from the display.

The message display is realized by a 4 by 8 pixel display consisting of 2D logic filters (Section 3.4) and a spring-embedded tile integrated into the floor (Figure 17a). Each column in this display has a triggering slider and a recharging stick that triggers and recharges the 4 cells. The logic filter controls the output pattern of the column. The triggering sliders of all columns are then connected together so that triggering all cells in the display can be done by pulling one white string; similarly, all recharging sticks are connected together so that recharging all cells is done by pushing the black stick.

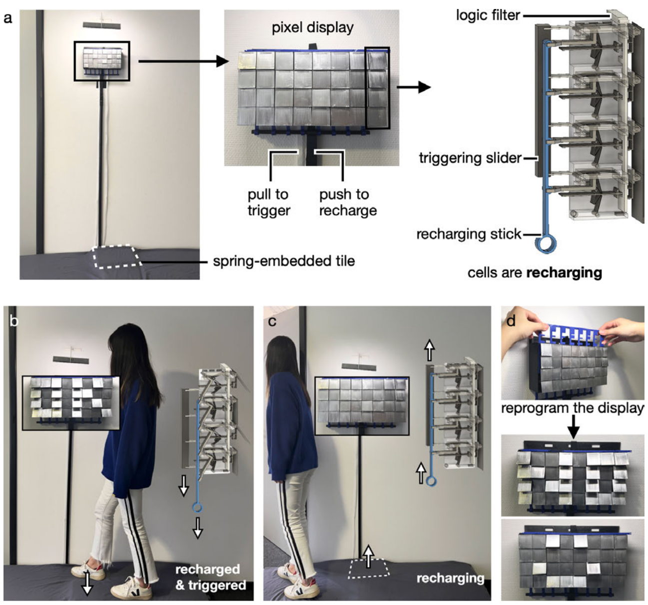

Figure 17: (a) The display consists of 2D logic filters that are controlled by a spring-embedded tile below the display. The message is (b) triggered by the visitor stepping on the tile and (c) recharged when the tile springs back. The host reprograms the display by (d) changing the logic filters.

During user interactions, the cells are recharging by default as the spring holds the recharging sticks in their recharging positions (a). As the visitor walks by and steps onto the hidden tile, the recharging sticks fall down and leave the cells recharged (b). Then the triggering sliders are pulled to trigger all cells and reveal the message. When the visitor's foot leaves the tile and continues walking, the tile springs back, pushing the recharging sticks up to their recharging positions (c). This recharges all the cells and hides the message. To update the status, the host can easily change the embedded message by changing the 2d logic filters (d). We also provide an editor (Section 6) that generates the logic filters based on user-defined output patterns to help users reprogram the display.

With the message display, we also showcase a potential interaction scenario of reprogrammable metamaterials in which two users collaboratively and asynchronously use one device (i.e., the host sets up the message content, and the visitor triggers the message).

5.3 Haptic Floor with Tunable Stiffness

We implement an interactive floor with tunable local stiffness for Virtual Reality applications, as shown in Figure 18. Different from previous tabletop pin-array shape displays with tunable stiffness [25], we demonstrate how our reprogrammable digital metamaterials can support *load-bearing* and *large-scale* applications, such as supporting users' weight. Any tile of our floor can be switched between soft and rigid and therefore produce *output* to the user. This example also demonstrates how our conceptually passive metamaterials can be *computer-controlled* by adding small servo motors to trigger the cells' signal transmission to reconfigure the output tiles' stiffness according to the current VR scenario. Our approach does not require actuators directly underneath each target location as in, for example, pin-array-based shape displays [14, 38, 45]; it also reconfigures the stiffness of a load-bearing floor, which to our knowledge, has not been presented in prior works.

Figure 18: We can (a) reconfigure our interactive floor's stiffness dynamically, (b) activate pre-programmed patterns (e.g., stepping stone), or (c) make the entire floor rigid or soft.

5.3.1 *Output: Variable Stiffness Cell.*

To achieve tunable stiffness throughout the floor we use a compliant mechanism that allows for rotation [8]. We build a mechanism that can block the compliant output tiles' rotation selectively such that we can switch between soft and rigid states. We show in Figure 19 how we augment the compliant output tile by adding fixed blockers on both sides and sliding blockers underneath. An underlying logic layer consisting of bit cells controls the position of the sliding blocker and, thus, the stiffness of the structure. Figure 19 shows how moving the sliding blocker allows or prevents the compliant structure to rotate.

Each cell can thus alternate between 90°torsional motion or a 1 cm compression. The floor tile is 15 cm wide. We scaled the bit cells up to 6.5 cm to provide the required stroke length of 1.5 cm.

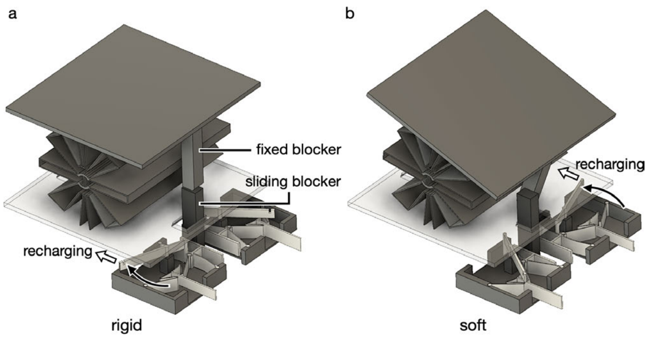

Figure 19: The stiffness of the compliant floor tile is (a-b) controlled by the position of the sliding blocker which is controlled by two opposing bit cells in the underlying logic layer.

We illustrate how the mechanism controls a tile's stiffness in Figure 20. The sliding blocker is moved by two opposing bit cells. (a) To change the output from initially soft to rigid, the lower signal transmission is charged. The displacement in the bit cell pushes the sliding blocker to align with the fixed blocker of the output tile to prevent its rotation, making the tile rigid. Then, the signal is triggered to reset the bit cells for the next action, i.e., the bistable springs are moved out of the way to allow the opposing bit cells to move the blocker if commanded. Note that this resetting step doesn't change the output tile's configuration, it remains in its rigid state. (b) To switch from soft to rigid, the opposing bit cells are charged to slide the blockers out and allow the tile to rotate. Similarly, triggering the signal transmission resets the bit cells and prepares for the next computation.

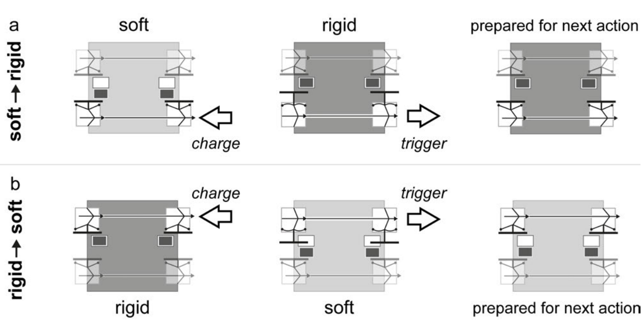

Figure 20: To switch a floor tile's stiffness from (a) soft to rigid, the bottom signal line is charged to align the sliding and the fixed blockers. Triggering the signal moves the springs back to prepare for the next command. Switching from (b) rigid to soft is achieved by charging the top signal line.

5.3.2 Pre-programmed Patterns. We aim to control the stiffness change of multiple output tiles with two opposing signal lines. To control specific and possibly non-uniform stiffness patterns along a signal transmission path, we use bistable springs with different pushing plates, as we show in Figure 21. These push plates determine whether the bistable spring's output displacement affects the sliding blocker or not. In Figure 21 when the bottom signal line is charged, only the middle cells' sliding blockers are affected and we have a soft-rigid-rigid-soft stiffness pattern.

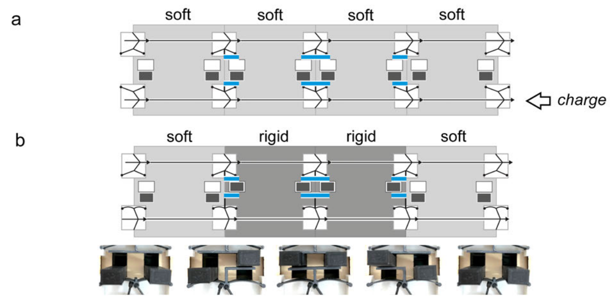

Figure 21: The push plate configurations for changing the tiles' stiffness from (a) to (b) are illustrated. (b) When the underlying bit cells are recharged, the push plates push the blockers forward and make the two middle tiles rigid.

We show how this concept of pre-programmed stiffness patterns can be extended into our 6 × 6 floor example in Figure 22. The blue push plates in (a) are custom designed to switch selected floor tiles to rigid to implement the stepping stone pattern shown in (c). A missing push plate means that the bit cell only transmits the signal but doesn't affect the floor tile's stiffness. (b) Charging the black bit cells globally turns the floor to all-soft. This can simulate an unsteady shaking floor sensation, for example walking in on a muddy swamp. The arrows denote that the signal transmission from left to right in each row. All blue signal lines can be actuated with 1 recharging action. All black signal lines can be actuated together as well, meaning that the pre-programmed pattern can be switched with a minimum of 2 actuation (manual or using motors).

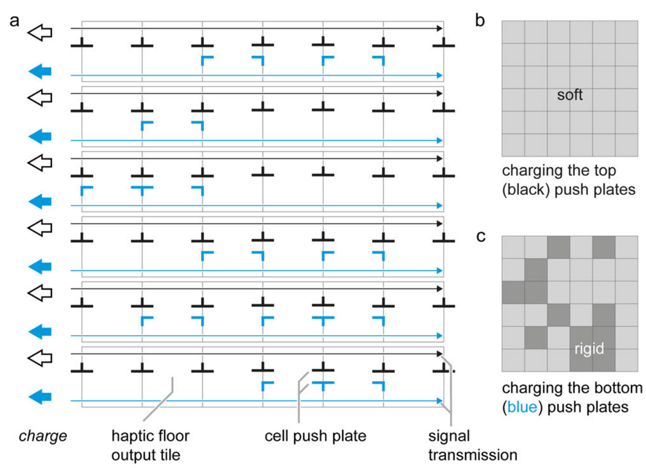

Figure 22: (a) The layout of the floor cells, push plate configuration in each bit cell, and signal transmission are illustrated. The bistable and the signal springs are omitted for visual clarity. By recharging different rows, we can achieve (b) an entirely soft floor or (c) a pre-programmed stepping done pattern in which selected cells are rigid.

5.3.3 Selective Patterns. Going beyond pre-programmed patterns, we showcase a design that allows us to reconfigure the local stiffness flexibly. As shown in Figure 23, multiple logic layers of bit cells can be stacked underneath the haptic floor cell layer to achieve different stiffness patterns. This is enabled by our recharging mechanism, which allows the user to control the logic cells from the outside. Here we demonstrate 2 logic layers we implemented in our floor. The first layer is the aforementioned pre-programmed stepping stone pattern.

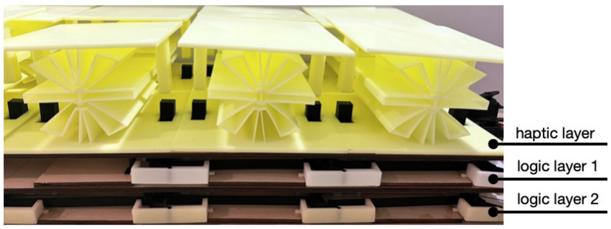

Figure 23: The floor is made up of a top haptic layer and two underlying logic layers that hold the bit cells. The logic functions implemented in layers 1 and 2 are detailed in Figure 22 and Figure 24.

The second logic layer implements a more modular controlling pattern in which local stiffness can be dynamically reconfigured. The logic design allows control over every 2×2 floor cells, which is a reasonable stepping area for the user. Figure 24 illustrates the design for controlling 2 rows of haptic cells. The remaining 4 rows repeat this pattern. (a) The signal transmits from left to right in the blue cell rows and transmits from the left or right side towards the middle through two haptic cells. (b) Recharging the blue cell rows turns all the cells rigid. Then, recharging the black cell rows from either (c) left or (d) right turns the left or right 2×2 area soft, respectively. (e) If the black cell rows are recharged from both sides, only the middle 2 by 2 area would be rigid and the rest are soft. (f) All the cells can be reset to soft using the first logic layer (Figure 22). Every two rows are thus capable of producing 5 different stiffness patterns and the entire floor can produce $5^3 = 125$ **patterns**. By routing the rows with the same actuation pattern together, the black cell rows actuated from the left or right can be controlled by 1 motor and the blue cell rows can be controlled by 1 motor. Therefore the dynamic logic layer can produce **125 different global patterns** with a minimum of only $3 \times 3 = 9$ motors.

5.3.4 Actuation. The reconfiguration of the floor's stiffness can be done manually. Yet to enable synchronous changes with the VR applications, we used motors so that the floor could be controlled electronically by the running VR application. In our implementation, recharging an entire row of 7 bit cells requires approximately 11 N of force which we achieved with off-the-shelf MG996 Micro Servo Motors. Recharging multiple rows together as discussed in both logic layers, however, adds more force due to both the number of bit cells and the friction when re-routing the recharging levers. This can be solved by (1) using motors with larger torque and/or (2) using additional mechanisms to gain a mechanical advantage (e.g., through pulley systems) to reduce the recharging force. Since these factors are not within the scope of this paper, we used more motors

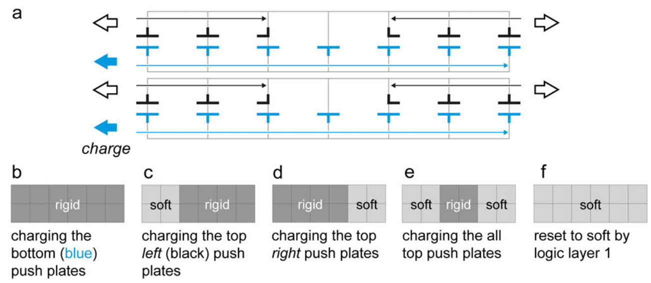

Figure 24: (a) The detailed logic design is illustrated. Recharging different rows can result in 5 (d-f) different stiffness patterns in the two rows.

than the theoretical minimum (9 motors) in our implementation and focused on demonstrating the logic designs that enable the output.

6 DESIGNING DIGITAL METAMATERIALS

To assist in designing and building interactive digital metamaterials, we provide an add-in for Autodesk Fusion 360[1]. Our add-in allows users to generate reprogrammable digital metamaterials with user-specified cell primitives (bit cells, 1D/2D logic functions), type of output (linear or rotational), number of cells in a logic function, and the logic output of the function (Figure 25a). The add-in generates the according cell structure, including the frame, bistable springs, signal springs, recharge levers, and output end-effectors. For example in Figure 25b, a 2D logic function with 3 cells, rotational outputs, and a '101' logic output is generated in the current design. The user then simulates the actuation of the generated structure to verify the designed output (Figure 25c).

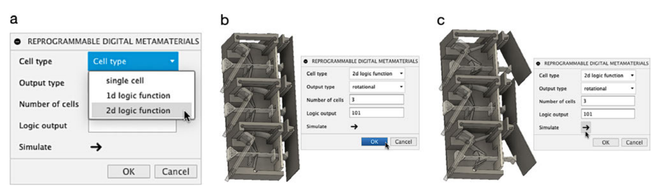

Figure 25: Our editor allows users to (a-b) easily design and generate reprogrammable metamaterial cell structures, and (c) simulate the actuation by visualizing the output.

A larger reprogrammable digital metamaterial, e.g., a pixel display, can be generated by inserting cell primitives multiple times. Here we show an example of a user creating a 3-by-7 pixel display with the message "HI" (Figure 26). The user designs the display by inserting a 3-cell 2d logic function 7 times and specifying the logic output for each one. The output is then simulated with the chosen rotational output, which correctly makes the message 'HI'. Inside Fusion, the user can then conveniently select the generated parts and send them to print (Figure 26c). By quickly specifying and verifying the logic outputs for the logic functions, the user can very easily generate new filters to reprogram the output of the metamaterial device.

[1]https://www.autodesk.com/products/fusion-360

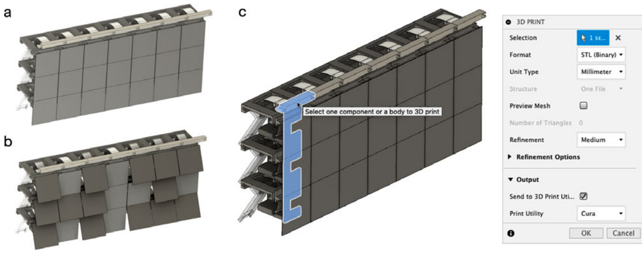

Figure 26: (a-b) Users make and simulate a pixel display that shows HI by inserting multiple 2d logic functions. (c) Our editor allows users to re-design logic outputs easily and send them to print, which reprograms the device.

With the add-in, we provide reprogrammable metamaterials' core input, output, and logic processing structures. Users can utilize Fusion's other powerful functionalities to edit the generated models additively (e.g., couple a cell's linear output with an external structure to achieve blocking) to build personalized interactive devices for their specific use cases.

7 TECHNICAL EVALUATION

To support the replicability of our work, we characterize the performance of our cell. We illustrate the parameters of the cells we used in Figure 27. We printed the cells using ABS filament on an Ultimaker 2+. The cell frames are printed in one piece and the springs and recharge levers are printed separately and later assembled. Since previous work evaluated larger parameter spaces for such bistable springs, we focus on evaluating the effectiveness of our recharging mechanism as one of our key contributions.

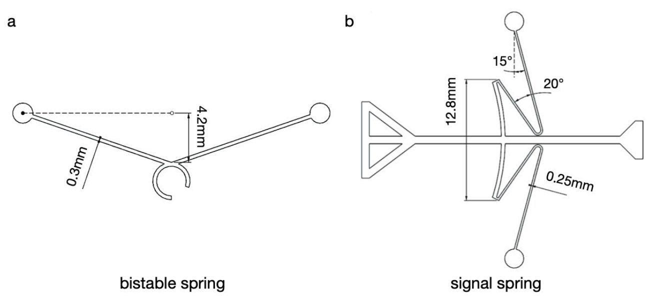

Figure 27: Geometry of the bistable and the signal spring.

First, we characterized a single cell. We measured different forces and present the results as a box plot with the crosses highlighting the means in Figure 28. We performed 5 different tests and measured *trigger* forces on the (1) bistable and (2) signal spring, (3) the force that the signal spring *outputs* after being triggered, and the forces it takes to *recharge* the bistable spring (4) with and (5) without the recharge lever. We tested each dependent variable with 3 copies of 3D printed springs and 3 trials each, yielding 9 data points per variable.

We performed all measurements using a manual push/pull test stand, which we placed horizontally. It consists of digital calipers for distance, a force gauge (Baoshishan ZP-50N with 0.01 N accuracy) for force measurement, and a manual crank, as we show in Figure 28 (bottom).

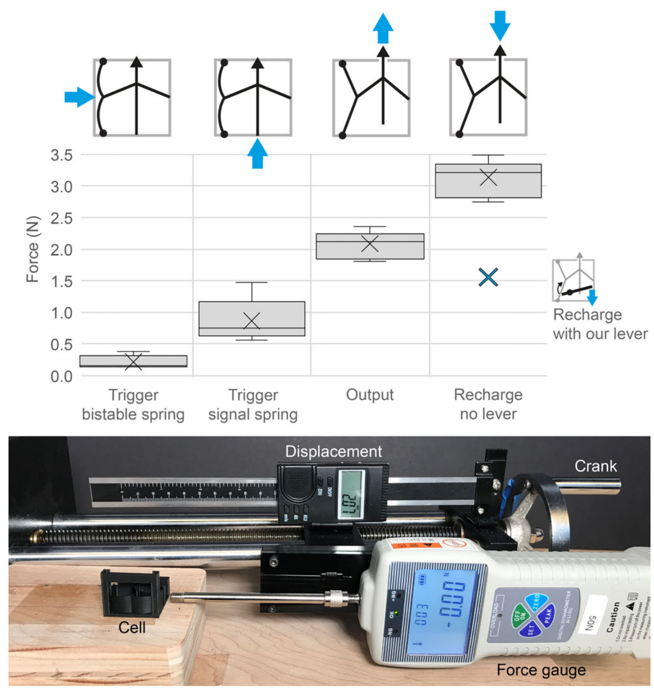

Figure 28: We characterize trigger, output and recharging forces for a single cell. We use a force gauge (accuracy 0.01 N) on a horizontal test stand.

Results. Our results show that the trigger force on the signal spring is approximately $\frac{1}{2}$ of the force that is the output of a cell, 0.87 N, and 2.08 N, respectively. Triggering the bistable spring directly requires even less force at 0.22 N, which confirms stable signal routing. Recall that we re-route signals by 90°by rotating the cell and letting the signal spring trigger the bistable spring directly. Both trigger energies are small enough compared to the output energy to enable stable signal transmission and to allow for signal bifurcation if needed.

The asymmetry of output vs trigger force, which we designed for, in turn makes a large force necessary to recharge the cell. Our results show that recharging the bistable spring without the recharge lever takes 3.14 N, i.e., 3.6× more than the trigger force. With the recharge lever, only 1.62 N is required, confirming the effectiveness of our recharging mechanism.

Recharging multiple cells. We further characterized our recharging mechanism when integrated within multiple cells. We tested straight signal rows with 1, 2, 3, and show our results with a boxplot with highlighted means in Figure 29. Our results confirm that the force required to recharge multiple cells grows approximately linearly with the number of cells in a line. The mean force required to recharge the signal lines is 1.62 N for a single cell, 3.09 N for 2 cells, 4.56 N for 3 cells, and 8.17 N for 6 cells.

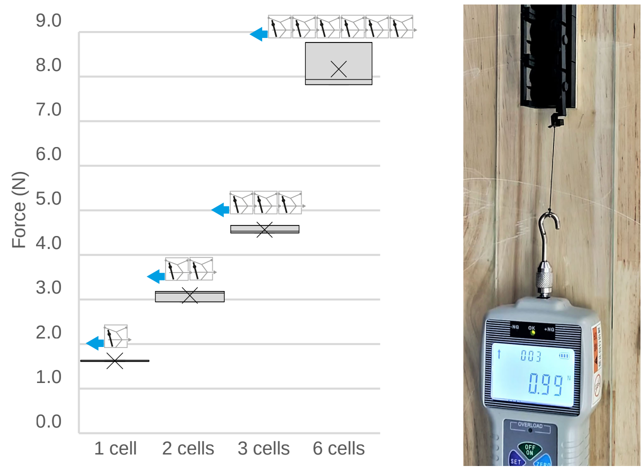

Figure 29: (a) We characterize the growth in required force to recharge multiple cells with the recharge levers. (b) We measure the force using the same force gauge (0.01 N accuracy), which we manually pull linearly within a custom cut acrylic template.

8 DISCUSSION & FUTURE WORK

Entirely v.s. Mostly Passive Metamaterials. The proposed design space enables building interactive metamaterial devices that are *entirely passive*—the materials have small actuation inherently built into each cell and are thus usable in their entirely passive state. All the triggering and recharging of the cells can be done through user action, either manually or as part of the user's interactions and movements. Triggering multiple cells can be achieved through one manual action, enabled by signal transmission between the cells. Similarly, multiple cells can be recharged together. Through this, we minimize the number of manual, intentional actions required by the users to interact with the devices. Entirely passive metamaterials are thus appropriate for devices that are not interacted with frequently, or that are embedded into other structures where installing and wiring external motors is impractical.

However, we also support *mostly passive* interactive metamaterials in which users may choose to add simple, low-force actuators to provide input and recharge at the outside of the material for computer-controlled use. This (1) further reduces the physical effort needed to interact with especially large-scale metamaterial devices, e.g., our haptic floor with controllable stiffness (Section 5.3), and (2) allows processing input other than force and displacement, e.g., digital signal (Section 5.1), temperature, light, etc.

Designing user interactions with passive reprogrammable metamaterials. While mostly passive interactive devices are digitally controlled, interacting with entirely passive devices relies solely on users' manual actions. Designing natural and effortless user interactions is thus crucial for these passive interactive devices. In this paper, we present materials that support interactive uses and give designers tools and examples to enable them to expand on this emerging space. Detailed interaction design differs greatly device-by-device and is thus out of the scope of this paper.

Cell miniaturization. The limiting factor for miniaturization is the thickness of the springs which depends on the resolution of the 3D printer used. With our Ultimaker 2+ and a 0.25 mm nozzle, the smallest cell size we implemented was 3 cm. SLA printers with a resolution finer than 150 microns enable miniaturization to a approx. 1.5 cm cell size. 3D printers with even higher resolution (e.g., Nanoscribe) would allow for further miniaturization. However, maintaining the structure's mechanical properties in a smaller cell needs more experimentation which we leave to future exploration. With our research prototypes, we demonstrated scaling the 3 cm cells up to different sizes to obtain large displacement and/or force for user interactions.

Material and Durability. The durability of our research prototypes is governed by the filament that is available to us. We used ABS for our examples as it provided better durability than PLA. However, we note that ABS is not the ideal material for such bistable elements that undergo large deformations repeatedly. Ideally, we would use materials with similar material properties to spring steel that has a large linear elastic region. In this paper, we focus on the structures that enable makers to create reprogrammable metamaterials. Research into better base materials or fabrication techniques is outside of the scope of this work. Our technical evaluation, therefore, focuses on evaluating the recharging mechanism. The stiffness and repeatability of bistable metamaterial structures of varying materials have been evaluated before [6, 49].

9 CONCLUSION

We presented reprogrammable digital metamaterials with integrated input, computation, and output. The materials are tiled by unit bistable cells that produce displacement upon a force input. We integrated a recharging mechanism into the cells to easily reset the digital metamaterials to enable multiple computation loops. Based on the cells, we presented logic functions that are reconfigurable after fabrication and outputs that would give the materials simple decision-making capabilities and enable complex functionalities. Specifically, we demonstrated how to reconfigure material properties such as stiffness, accessibility, texture, and display with the basic output motion. To showcase the potential of the presented reprogrammable digital metamaterials, we implemented several applications including a haptic floor with tunable stiffness, a tactile desktop reminder, and a personalized message display that supports implicit user interactions. As we push towards passive yet interactive devices, we envision metamaterial machines that sense active human input or passive environment input, process and output information, and interact with users in real-time without electronics.

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