Dynablock: Dynamic 3D Printing for Instant and Reconstructable Shape Formation

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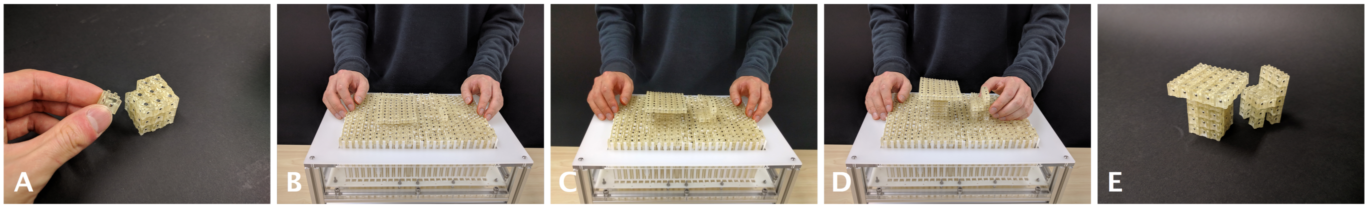

Figure 1. Dynablock is a rapid and reconstructable shape formation system, comprised of a large number of small physical elements. A) Dynablock's shape consists of 9 mm blocks which can be connected with omni-directional magnets. B-D) Dynablock leverages the 24 x 16 pin-based shape display as a parallel assembler of blocks, Dynablock is able to construct three-dimensional shapes in seconds. E) The example shows the output of a miniature model of table and a chair. The constructed shape is graspable and reconstructable.

ABSTRACT

This paper introduces Dynamic 3D Printing, a fast and reconstructable shape formation system. Dynamic 3D Printing assembles an arbitrary three-dimensional shape from a large number of small physical elements. It can also disassemble the shape back to elements and reconstruct a new shape. Dynamic 3D Printing combines the capabilities of 3D printers and shape displays: Like conventional 3D printing, it can generate arbitrary and graspable three-dimensional shapes, while allowing shapes to be rapidly formed and reformed as in a shape display. To demonstrate the idea, we describe the design and implementation of Dynablock, a working prototype of a dynamic 3D printer. Dynablock can form a three-dimensional shape in seconds by assembling 3,000 9 mm blocks, leveraging a 24 x 16 pin-based shape display as a parallel assembler. Dynamic 3D printing is a step toward achieving our long term vision in which 3D printing becomes an interactive medium, rather than the means for fabrication that it is today. In this paper we explore possibilities for this vision by illustrating application scenarios that are difficult to achieve with conventional 3D printing or shape display systems.

CCS Concepts

•**Human-centered computing → Interaction devices;**

Author Keywords

dynamic 3d printing; shape displays; digital materials

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INTRODUCTION

What if 3D printers could form a physical object in seconds? What if the object, once it is no longer needed, could quickly and easily be disassembled and reconstructed as a new object? Today's 3D printers take hours to print objects, and output a single static object. However, we envision a future in which 3D printing could instantly create objects from reusable and reconstructable materials.

With these capabilities, a 3D printer would become an interactive medium, rather than merely a fabrication device. For example, such a 3D printer could be used in a Virtual Reality or Augmented Reality application to dynamically form a tangible object or controller to provide haptic feedback and engage users physically. For children, it could dynamically form a physical educational manipulative, such as a molecular or architectural model, to learn and explore topics, for example in a science museum. Designers could use it to render a physical product to present to clients and interactively change the product's design through direct manipulation. In this vision, Dynamic 3D printing is an environment in which the user thinks, designs, explores, and communicates through dynamic and interactive physical representation.

This paper develops this vision by proposing Dynamic 3D Printing, a class of systems for rapid and reconstructable shape formation. We define "reconstructibility" as the ability to disassemble a shape back to individual material elements and reuse them to construct a new shape from scratch. Dynamic 3D Printing assembles digital material elements to form reconstructable physical objects. Each element can be connected with and disconnected from neighboring elements, and elements can be formed into an arbitrary three-dimensional physical object. Dynamic 3D printing differs from existing 3D printing in speed and reconstructability: Dynamic 3D printing forms shapes in seconds, rather than minutes. In addition, because individual elements can be disconnected, the shape can be easily disassembled into its basic building blocks once the object is no longer needed.

The idea of dynamic three-dimensional shape formation is not new. Shape formation by assembling discrete elements has been investigated through several approaches, such as modular self-assembly robots [55] and robotic construction [42, 56]. However, existing approaches have three key limitations. 1) Limited cost scalability: Realistic rendering of 3D objects with modular self-assembly would require thousands of tiny modules, but due to the cost and complexity of individual modules, each of which employs motors and sensors, most current proof-of-concept systems are limited to no more than 100 modules. 2) Limited time scalability: In terms of assembly time, rendering at higher resolutions takes significantly longer. For example, building a 10 x 10 x 30 cm^3 cube using 1 cm^3 elements requires 3,000 elements. With linear assembly methods [13, 26, 43], even at an assembly speed of 1 second per element, the total time would be close to an hour, far from being able to support interactive applications. 3) Limited resolution: The size of individual elements in most existing systems are at centimeter-scale. To achieve higher resolution by reducing both the individual elements and the assembler to millimeter scale requires overcoming significant engineering challenges [2]. Thus, due to these design and engineering challenges, fast and high resolution dynamic shape formation still remains an unrealized goal.

To address these problems, we propose a design for Dynamic 3D Printing by introducing two key design components: 1) a parallel assembler and 2) a rapid connection and disconnection mechanism. Drawing inspiration from recent Digital Light Projector (DLP) 3D printing, we explore an assembly method to form entire layers in parallel, instead of assembling each individual element in sequence, which significantly reduces the per-layer construction time. In addition, a fast (i.e., 0.1 sec) connection and disconnection mechanism allows layers to be quickly stacked into a stable shape. Combining these two design components enables fast shape formation independent of vertical and horizontal resolution.

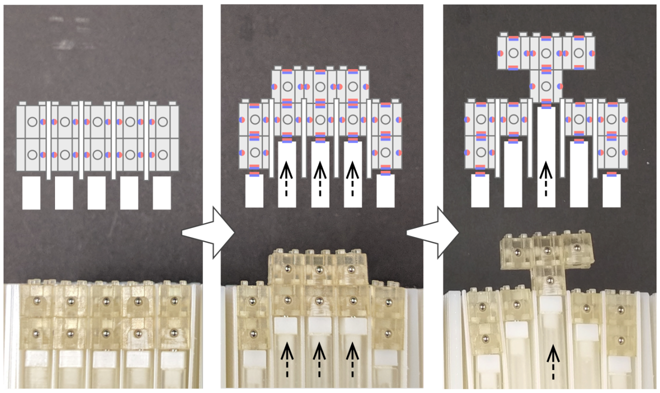

Figure 2. Side view of Dynablock: The parallel assembler creates a shape with an overhang from magnetically connected blocks.

To demonstrate this design, we introduce Dynablock, a hardware and software prototype of dynamic 3D printing. Shapes made with Dynablock consist of 9 mm blocks, which connect to neighboring blocks with embedded permanent magnets. Dynablock's hardware employs a 24 x 16 pin-based shape display as a parallel assembler. 3,072 (= 24 x 16 x 8 layers) blocks are stacked atop the shape display, and each motorized pin pushes up blocks to assemble the object layer by layer. Figure 2 depicts the assembly process. When blocks are inside the assembler, separators keep their horizontal magnets disconnected. As the blocks are pushed upwards and out of the assembler, they connect with their neighbors magnetically to form an object. Due to weaker vertical magnetic connections, blocks can disconnect vertically during this process to form overhangs. Therefore, Dynablock can assemble arbitrary and graspable 3D shapes with overhangs, rather than the 2.5D shapes of existing shape displays [6]. Given a shape of 3,000 elements, Dynablock drastically reduces the assembly time to seconds, which enables interactive applications that conventional 3D printing techniques do not support. Moreover, the generated objects can be disassembled into individual elements for our system to reuse to assemble the next shape.

We describe several application scenarios, such as dynamic physicalizable textbooks, on-demand haptic proxy objects for VR and AR, and direct interactive fabrication. These application scenarios leverage the fast speed and reconstructability of Dynamic 3D Printing and illustrate new opportunities for using printers as interactive media and design exploration tools.

Finally, this paper contributes:

1. A concept of Dynamic 3D Printing for fast and reconstructable shape formation and its design with a parallel assembler and rapidly switchable connection mechanism;
2. An implementation of Dynablock, a prototype system of Dynamic 3D Printing comprised of 3,000 9 mm blocks that can be assembled with a 24 x 16 pin-based actuator; and
3. Three application scenarios that illustrate the potential use of dynamic 3D printers as an interactive medium.

RELATED WORK

Programmable Matter

In 1965, Ivan Sutherland envisioned the "Ultimate Display", a computer that could control the existence of matter [46]. Sutherland's radical concept of computationally controlled matter has driven recent Human-Computer Interaction (HCI) research, which explores computer interfaces with dynamic physical materials [9, 14]. Toward this vision, researchers have investigated various approaches to dynamic shape changing, including shape-displays [6] and shape-changing interfaces [38, 2], self-reconfigurable modular robots [55], robotic construction [42, 56], and digital 3D printing [12, 36].

Shape Displays

Shape displays are user interfaces that can dynamically render a physical shape on a table-top surface [6, 15, 23, 37, 44]. One advantage of shape displays over other shape-changing interfaces is their ability to render an arbitrary shape. By leveraging this ability, Project FEELEX [15] and Lumen [37] introduced a shape-changing surface for tangible interaction and haptic feedback to enhance visual information. Recent work also began exploring techniques for interacting with shape displays. For example, inFORM [6] investigates how shape displays can provide physical affordances by leveraging shape or object manipulation. shapeShift [44] explores spatial interactions and haptic feedback for VR with a shape display. However, existing shape displays are limited to rendering 2.5D shapes, which makes it impossible to grasp the generated shapes, as the pins that drive the shape must remain attached to the table-top surface.

To overcome this limitation, recent work explores using shape displays to assemble stand-alone objects. For example, Kinetic Blocks [42] investigates constructive assembly by actuating passive objects with the inFORM system. However, for robust assembly, the size of each block must be four times bigger than the size of each pin. Thus, it is difficult to achieve finer resolutions with smaller blocks, because miniaturization of the pins poses significant engineering challenges. In addition, as the number of blocks increases, the space required for assembly also increases. Therefore, the construction of arbitrary geometries still remains an unrealized goal. Our goal is to explore an alternative approach that enables a construction mechanism that can achieve a higher and thus more realistic resolution. To achieve this, we use a shape display as a parallel actuator to assemble the form layer by layer, inspired by recent 3D printing mechanisms. This enables fast construction with 9 mm blocks; and we show this can be scaled down to 3 mm blocks without changing the design.

Self-reconfigurable Modular Robots

One approach to achieving reconfigurable three-dimensional shapes is self-reconfigurable modular robots [8, 29, 39, 55]. These robots typically consist of a number of identical unit modules that can arrange themselves into different forms to reconfigure the shape. For example, M-Blocks [39] are self-reconfigurable robots that use an internal flywheel to move themselves and magnetic force to connect with neighboring robots.

While modular self-reconfigurable robots are mostly explored in applications such as space explorations [41] and rescue operations [54], recent works in HCI have started exploring using these robots for tangible interaction and haptic feedback. For example, Zhao et al. [56] investigates the self- and robotic-assembly of small robots (e.g., Zooids [21]) to generate on-demand haptic proxy objects for VR. However, reconfigurability comes at a higher cost, larger size, and heavier weight for individual modules because each requires independent actuation, sensing, power, and communication. Moreover, it is challenging to generate shapes quickly enough for interactive applications because the construction time increases linearly with the number of blocks. Instead, we explore an approach to using an external assembler to construct an object, by leveraging low-cost, light-weight, and easy-to-fabricate elements as a passive physical element. While this approach cannot achieve the reconfigurability (directly transforming one shape into another), a fast refresh rate of reconstruction (disassemble a shape and construct a new shape from its elements) can achieve similar benefits to modular self-assembly. We show that this approach can quickly and repeatedly construct and reconstruct different structures with nearly real-time user interaction.

Digital 3D Printing

Digital materials and digital printers [12, 36] are an alternative paradigm for 3D printing in which physical objects are made of discrete elements like LEGO blocks. The materials are considered "digital" in contrast to today's 3D printing processes in which objects are produced using a continuous material such as plastic. Digital materials have advantages over continuous materials, notably that shapes can be disassembled [4] and that shape information can be replicated or transferred without loss. Researchers have proposed different methods of connecting the discrete elements of digital materials such as press fitting or bonding, and various means to assemble and disassemble the elements have been investigated, such as pick-and-place [43].

The most similar approach is VoxLayer system proposed by Hiller [11]. In contrast to pick-and-place methods, a parallel assembling approach like VoxLayer scales linearly with the number of components used for making objects. Since VoxLayer uses water solvable bonding, the printed object can be also disassembled. However, its chemical connection mechanism requires melting and drying of bonding material, which takes 90 minutes to complete a 10-layer build [11]. In contrast, the rapid connection mechanism of Dynablock enables faster assembling and disassembling, taking less than a minute to complete a 10-layer build. Moreover, users can easily intervene during the printing process or reconfigure assembled objects with their hands. These novel properties enable interesting interactive applications that have not been possible with existing systems.

DYNAMIC 3D PRINTING

Definition of Dynamic 3D Printing

We define Dynamic 3D Printing as a class of systems that have the following properties:

- **Immediate**: The system can form a physical shape in seconds.
- **Reconstructable**: Rendered shapes can be disassembled and reconstructed by hand or with the system, and the blocks are reusable.
- **Arbitrary Shapes**: It can create arbitrary three dimensional shapes.
- **Graspable**: The output shapes and structure are graspable and solid.

Challenges

To meet the requirements of Dynamic 3D Printing, several challenges in design and engineering must be overcome:

Resolution

To render physical objects realistically, Dynamic 3D Printing must support relatively high resolution. For example, for objects that can be held in the hand, each physical element must be millimeter scale, and ideally one order of magnitude smaller.

Scalability

Resolution also dictates the number of elements that are used to form the object. For example, if an element is 1 mm in size, then on the order of one million (= 100 x 100 x 100) elements are needed to build a 10 cm^3 structure. Therefore each element must be inexpensive and easy to manufacture.

Speed

Rendering objects with thousands or tens of thousands of elements places stringent constraints on speed. If the time needed to render an object scales linearly with the number of elements then it will be difficult to support uninterrupted and seamless interaction.

Stability

Objects produced by the Dynamic 3D Printer must be sufficiently stable and robust for users to grasp them. Thus, the connection between the elements should be strong.

Designing a System for Dynamic 3D Printing

In this section, we outline a design for a hardware system to enable Dynamic 3D Printing. We describe the two key components to achieve the requirements: 1) A parallel assembling method and 2) a fast connection and disconnection mechanism. We outline the design considerations and possible methods for both features.

Parallel Assembler

Dynamic 3D printing deploys a large number of small discrete material elements, which are assembled to form arbitrary shaped macro-scale objects. Individual elements are passive, which requires an external actuator to perform the assembly. A straightforward way to assemble these material elements is the pick-and-place [26, 43] method or depositing single elements [13] (e.g., using a 3DOF robot arm), similar to an FDM 3D printer. However, in this method assembly time scales with the cube of the dimensions and assembling many elements would take a long time. Alternatively, we explore a parallel assembly method that can create an entire layer of an object at once. We considered several designs for parallel assembly.

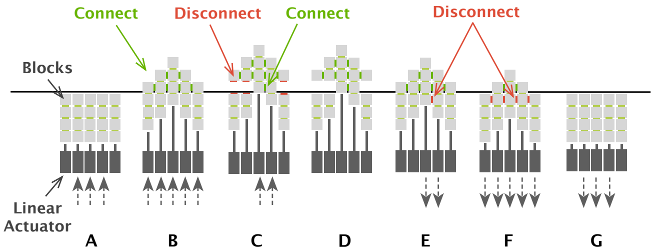

Figure 3. Illustration of parallel assembly using a pin-based display.

The first design uses a pin-based display to push elements into place and then connect them. As illustrated in Figure 3, the assembler consists of an N x N grid of motorized pins and linear actuators. The elements, which are the same size as the pins, are stacked on top of the pins (Figure 3 A). When stacked, the elements are connected in vertical direction, while disconnected with nearby elements in horizontal direction. Similar to existing pin-based shape displays [6], the assembler can incrementally generate 2.5D shapes by individually moving pins to push elements to the surface. Once the elements are pushed onto the surface, each element connects to neighboring elements to form one layer of the shape. As the elements in this layer are now connected horizontally, the next layer can be formed by the same process while the previously formed layer lies on top of the next layer (Figure 3 B). To go from 2.5D to 3D, the elements can be disconnected in the vertical direction (Figure 3 C). Thus, if the pin simply pushes each layer, it can construct an overhang or inner hole structure without needing support structures. By repeating this process, the desired three-dimensional shape can be formed.

It can also disassemble a rendered shape with a similar process. By selectively moving pins down or manually pushing the object from the top, each layer will be buried to its initial position. When clearing the object, the horizontal connector is disconnected so that each element can move down (Figure 3 E-F). Then, the system can reconstruct a new shape from the beginning, or possibly reconfigure an existing shape through partial clearing and reconstruction.

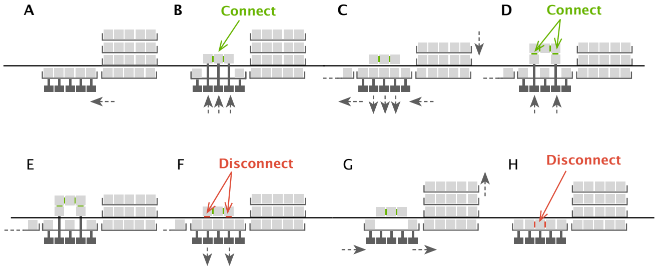

Figure 4. Illustration of parallel assembly using a horizontal feeder.

Another design for a parallel assembler is to use a horizontal feeder. As illustrated in Figure 4, the system is composed of a binary linear actuator in the vertical direction and material feeder in the horizontal direction. The system can actuate individual pins, while each pin can only go back and forth. The system prepares a stack of layers and feeds them to the build platform, then similarly assembles one layer at a time, pushing each layer up with a linear actuator. Similar to the first design, each layer is connected horizontally to prevent from falling apart while feeding the next layer. By sequentially feeding and forming each layer, the system can assemble a 3D object.

Each proposed design has both advantages and disadvantages. The design using a pin-based display enables fast and interactive rendering of 3D shapes, regardless of resolution. The construction time depends only on the speed of the motorized pins and the number of layers, assuming the connection speed is negligible. However, it can only support elements of a single material as there is no way to change the element during production. In addition, miniaturizing shape displays is also an engineering challenge. Compared to the pin-based design, the second design is a simpler in mechanism, thus can be more easily scaled, as it requires only a binary linear actuator for vertical displacement. This design also could support multi-material elements by switching the material for each layer or computationally compound multiple elements for each feeder. On the other hand, the assembly time could increase linearly as the number of vertical layers becomes larger, because even if the connection can be switched instantly, there is still a bottleneck of the horizontal feeder having to travel the entire length of one dimension for each layer.

We prototyped both designs, but in this paper we focus on the first design with a pin-based display due to its fast assembly time.

Connection and Disconnection Mechanism

The next key design component is the connection and disconnection mechanism. A switchable connector is the key to allow the material elements to be reusable for reconstructable shape formation. An appropriate design and selection of the connection mechanism is important for several reasons. First, the speed of switching between connection and disconnection significantly affects the entire assembly time because the formation of each layer depends on the switching time. For example, if switching between connection and disconnection takes 10 seconds, constructing each layer takes more than 10 seconds, and therefore it would take N x 10 seconds to build N-layer objects, which is too slow for real-time interaction. Moreover, the connection mechanism would have the greatest impact on the cost and complexity of manufacturing the elements. Thus, the connector design must be carefully considered with regard to speed and manufacturing complexity.

A variety of switchable connectors have been proposed in the literature of modular self-reconfigurable robots. We summarize some of these approaches in Table 1.

Mechanical latching is the simplest and most common way for reversible connection (e.g., LEGO blocks). While existing systems in modular robots usually achieve mechanical latching with internal motors and actuators [30], past work in digital materials has explored micro-scale mechanical latching by press fitting [4]. As mechanical latching can be achieved with simple mechanical force, elements can be simple to fabricate. However, depending on the design the external assembler can be complicated and switching the connection may be slow.

Magnetic force is another option. The simplest connection uses a permanent magnet to connect and uses external force to push or rotate the magnet to disconnect. This approach has been explored in several systems [42, 56]. Electromagnetic connection can be faster as it can switch states by running current, and it can be fabricated with a standard PCB manufacturing [34, 45, 48]. However, one notable disadvantage of using electromagnets is power consumption: The electromagnet requires continuous current to hold the magnetic force. On the other hand, electrostatic and electro-permanent magnetic connection can maintain the connection. For example, an electro-permanent magnet can be switched to the connection state with pulse current without requiring continuous current [19]. Although these connection mechanisms are appealing due to their speed and size, for millimeter scale (e.g., 1 mm [17] to 10 mm [8]), manufacturing complexity presents difficulty for large numbers of elements.

Thermal and photochromic bonding are other reversible connection methods. These bonding mechanisms leverage phase change of materials between liquid and solid to bond elements. Similar to soldering, thermal bonding uses heating to change the phase of a material from liquid to solid, and cooling to solidify the bond. For fast phase changing, it is common to use a low-temperature melting metal such as Galium or Field's metal, which melts at 40-80C degree [20, 29]. Thermal bonding is used in recent work on liquid metal 3D printing [20, 50]. Existing systems use a heater (e.g., resistive heating [29]), but cooling the metal at room temperature takes time. An alternative phase-changing connection is photochromic bonding, which leverages UV or visible light to change the phase of materials such as azobenzene [1] or liquid crystal materials [40]. We also expect that reversible dry adhesion, which can connect elements with Van der Waals force, could be another approach [22, 31]. Although these methods are promising, they have not been substantially explored for connecting modular robots or digital assembly.

We prototyped 10 mm blocks with three different connectors (permanent magnet, electro-permanent magnet, and thermal bonding using Field's metal). We decided to further explore and implement a design using permanent magnetic connectors due to the simple manufacturing and faster speed of connection and disconnection of this approach.

MAGNETIC CONNECT-DISCONNECT MECHANISM

Block Design

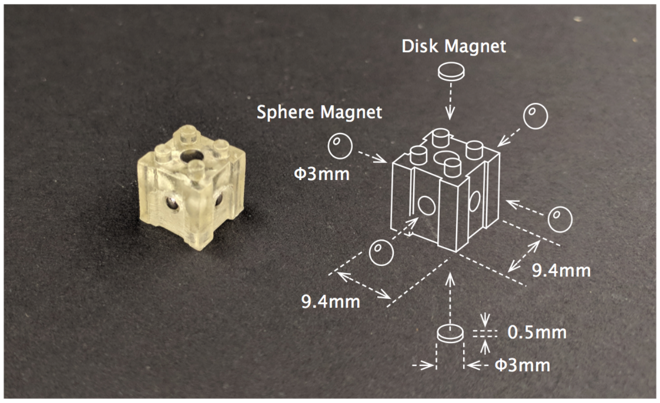

Figure 5. Design of a single Dynablock.

Each element of Dynablock is a 9.4 mm 3D printed block. We chose a simple magnetic connection for easy and fast manufacturing. It is also inexpensive, which allows for scalability. Systems, like ours, that employ fixed magnets for connection must address the problem of polarity: in order to attract and connect, the two mating faces must always have opposite polarity. Inspired by [42], we use an omni-directional magnetic connector for horizontal connection to address this problem. Each horizontal face has a spherical pocket containing an N35 spherical magnet with a 3 mm diameter. The diameter of the pocket is slightly larger (3.3 mm) than the magnet inside, allowing the magnet to rotate freely within the pocket, while

Type	Connection	Disconnection	Time	Manufacturing	Examples
Mechanical Latching	Push / Rotate	Pull / Rotate	1 - 10s	Simple	[4, 36]
Permanent Magnet	None	Push / Rotate	0.1 - 1s	Simple	[28, 39, 42, 56]
Electromagnet	Run Current	Turn off Current	0 - 0.1s	Complex	[3, 18, 51]
Electrostatic	Apply Voltage	Turn off Voltage	0 - 0.1s	Complex	[16, 17]
Electro-permanent magnet	Run Pulse Current	Pulse Current	0 - 0.1s	Complex	[8]
Thermal bonding	Heat and Cool	Heat	1 - 30s	Simple	[10, 20, 29, 53]
Photochromic bonding	Expose Visible Light	Expose UV Light / Heat	1 - 10s	Simple	[1, 40]
Dry Adhesion	Surface Contact	Reduce the Contact Area	1 - 10s	Simple	[22, 31]

Table 1. A list of switchable connectors.

the (2.5 mm) hole on the face is small enough to prevent the magnet from escaping. Because each spherical magnet can rotate freely, when two faces are brought together, their two magnetic connectors can rotate and align their polarities. Each horizontal face also has a slit with 0.5 mm in depth and 4 mm in width, which receives a spacer to separate blocks during assembly. To support vertical connection, we embed a thin (ϕ3 mm x 0.5 mm thickness) disc-shaped magnet in both top and bottom faces. Each block has four studs (ϕ1 mm x 1 mm thickness) on the top and mating cylindrical holes (ϕ1.4 mm x 1.2 mm thickness) on the bottom. These studs prevent horizontal rotation between vertically stacked blocks.

Mechanism for Horizontal Connection and Disconnection

Next, we describe the mechanism for connection and disconnection using the shape-display. The block elements of Dynablock are stacked on top of the pin arrays. As described in the design section, each pin can push the vertically connected stacked blocks.

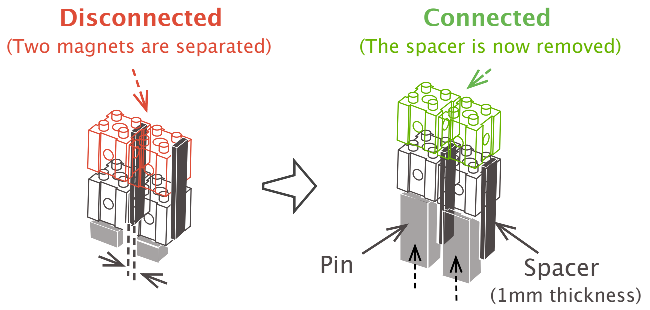

Figure 6. Horizontal connection is achieved by a pair of rotatable sphere magnets.

Figure 6 illustrates the mechanical design. As described above, each block has a 0.5 mm deep slit, which receives a 1 mm thick spacer attached to the bottom of the plate that serves as an obstacle to horizontal connection. Although there is still magnetic attraction between blocks, it is too weak to connect the blocks. This horizontal separation mechanism allows each pin to individually push the stacked blocks without interfering with nearby stacks.

For stable connection and disconnection, a careful design must be considered. For example, if the spacer and slit are too thin, then the distance between two magnets could be too short to maintain strong magnetic attraction. On the other hand, if the spacer and slit are too thick, then it can be difficult to attract and connect with nearby magnets once the spacer is removed. We found that the 1 mm thick spacer and 0.5 mm thick slit are thick enough to reduce the magnetic attraction, while thin enough to allow stable connection when the spacer is removed.

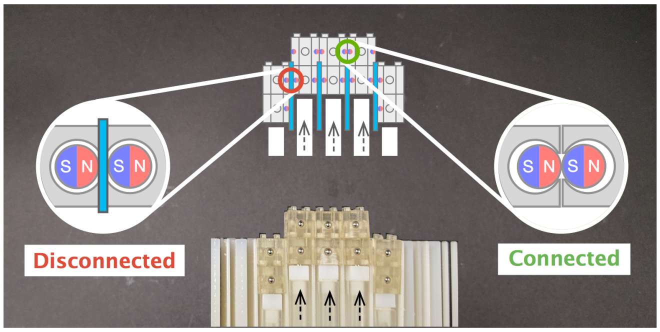

Figure 7. Mechanism for horizontal connection.

Figure 7 shows a photo of the system viewed from the side, along with an illustration of the horizontal magnet connections. In the stacked state, all five magnets on the top layer are disconnected due to the white 1 mm spacer. Therefore, an actuated pin can individually push up the blocks on top of it without affecting neighboring blocks. The photo in figure 7 depicts the state after the three center blocks are pushed up with the pin. At the top of the block holder, there is no longer a spacer to prevent the magnets from forming a connection, so the three blocks connect horizontally. Note that the separating spacer only exists at the center to fit within each slit, so that the blocks can be densely packed within the block holder and don't shift when pushed up.

Mechanism for Vertical Connection and Disconnection

By default, the blocks connect vertically when stacked in the block holder. Thus, to create an overhang or internal hole structure, blocks must be disconnected in the vertical dimension.

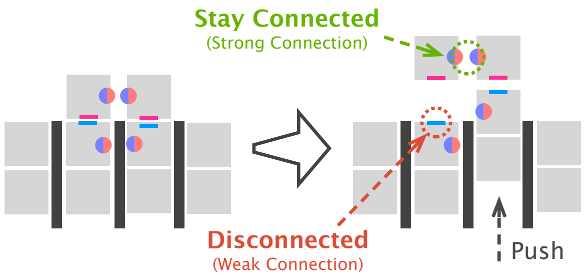

Figure 8. Sketch of vertical disconnection.

For vertical disconnection, we take advantage of the difference in the attraction force between slightly different magnets on horizontal and vertical surfaces. We use N35 3 mm sphere magnets for horizontal connection, and N45 3 mm with 0.5 mm thick disc magnets for vertical connection. The attraction force of the vertical connections is smaller than that of the horizontal connections. The pull force and surface field of the vertical connection (N45 3 mm x 0.5 mm disk magnet) are 0.10 kgf and 1,650 gauss, while the horizontal connection (N35 3mm sphere magnet) achieves 0.16 kgf and 8,060 gauss respectively. This allows the vertically connected blocks to be detached while maintaining the horizontal connection.

Figure 8 shows a side view of this mechanism. On the left, the two top blocks are horizontally connected while also vertically connected to the blocks in the layer below. When pushing up only one block, the horizontal connection is stronger than the vertical connection. This makes it possible to create an overhanging structure without needing a support structure.

Note that the vertical disconnection is only invoked to detach blocks from the underlying layer, but in an assembled object the vertical connection between blocks is maintained. This allows the rendered object to be stable without breaking when grasped.

To disassemble the rendered object, the system drops each pin to its initial position. Then, the object is pushed down into the block holder, breaking the horizontal connections between the blocks. Once the blocks are in their initial positions, the system can reconstruct and render a new shape.

DYNABLOCK: SYSTEM AND IMPLEMENTATION

In this section, we describe the design and implementation of Dynablock.

Parallel Assembly with a Pin-based Shape Display

For the parallel assembler, we built a pin-based shape display. Taking inspiration from FEELEX [15] and shapeShift [44], we used a geared DC motor and a motorized lead screw for linear actuation.

The blocks are held within the 3D printed block holder, as shown in Figure 10. In each cell, the block holder has a 4 mm wide, 1 mm thick spacer to separate neighboring blocks. This spacer prevents them from connecting horizontally.

The assembler consists of a 24 x 16 array of motor-driven pins. Each pin moves up and down, driven by a small DC motor (TTMotors TGPP06-D700) and a 3D printed lead screw (2 mm pitch, 4 starts, 120 mm in length). TGPP06-D700 is 6 mm in diameter and 29 mm in length and can rotate 47 rpm with 1:700 gear ratio. The 2 mm 4 starts lead screw can travel 12 mm per second without load, and each motor consumes approximately 60 mA. The pins are 3D printed with a nut at the bottom to travel along the lead screw. Each pin is 120 mm long and has a 7mm square cross section with a 5 mm diameter hole from top to bottom, and an N45 disk magnet (ϕ 3mm x 2.4 mm thickness) is attached at the top. Guide grids at the top prevent pins from rotating and ensure that pins travel vertically. The 24 x 16 guide grids have 7.5 mm square holes with 10.16 mm pitch and are cut from a 5 mm acrylic plate.

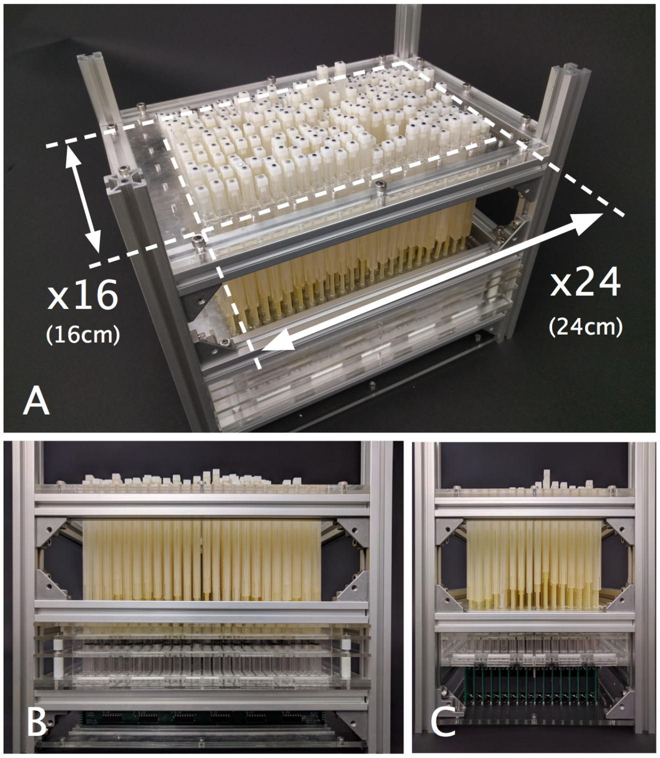

Figure 9. Dynablock's parallel assembler implemented using a shape display. Perspective (A) Front (B) Side (C)

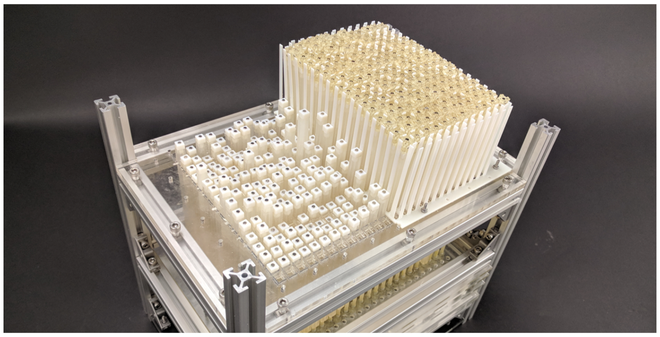

Figure 10. The shape display with the block holder on the right half.

We fabricated the pins, the lead screws, and blocks with an inkjet 3D printer (Keyence Agilista 3200) with water soluble support material. In total, we fabricated 384 (= 24 x 16) pins and lead screws, and 3,072 (= 24 x 16 x 8 layers) blocks. To create the magnetic blocks, we embedded spherical magnets in each block by hand and inserted disk magnets using a bench vice.

In order to connect motors to a printed circuit board (PCB), we designed and fabricated a custom motor holder. A 3D printed motor holder is attached to each DC motor, soldered with a 2.54 mm pitch female pin header at the bottom for simple fabrication and assembly. Each motor holder is fixed with a 3mm acrylic plate with an 8mm hole. The motor holder has clutches to fix the motor's position and prevent it from rotating. The motor is connected to a printed circuit board and aligned vertically through an L-shaped male pin header, aligned horizontally with a 10.16 mm (= 2.54 mm x 4) pitch.

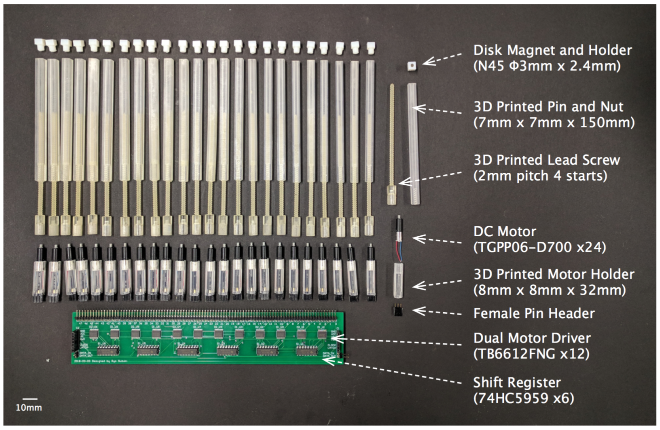

Figure 11. Components of our implementation of Dynablock's parallel assembler.

Motor holders are fabricated with the Form 2 3D printers using standard clear resin.

Each controller PCB comprises twelve dual motor drivers (TB6612FNG) and six shift registers (74HC5959). Each motor driver can switch the direction of two motors using an H-bridge and each shift register can individually control three of the dual motor drivers (i.e., six motors). Thus, for each row, one PCB can independently control the direction of 24 motors. The speed of each motor can be also controlled through pulse-width modulation (PWM). The shift register is controlled through a daisy-chained serial-in parallel-out signal, sharing the latch and clock among all PCBs. Thus, all the shift registers are controlled with three digital pins from an Arduino Uno. The VCC of the controller is connected to 5V and the external voltage for DC motors is connected to a DC 5V power supply . These low-cost components support scalable production (in our prototype, a DC motor, a motor driver, and a shift register costs US $3.10, $0.90, and $0.30 respectively).

Software

We built an interactive voxel editor and simulator (Figure 12). The voxel editor allows the interactive design of objects that can be formed by Dynablock. The user imports an 3D design as an STL file which our software converts to voxels at an appropriate resolution. The user also can interactively edit the shape of imported object or create a shape from scratch. Once the user confirms the shape to be rendered, then the simulator shows and tracks the current position of the array of 24 x 16 actuated pins.

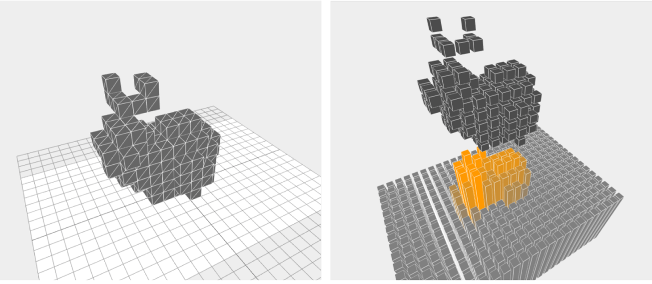

Figure 12. Interactive voxel editor and simulator.

The user interface of the software is built using Three.js and React.js, and communicates with the Arduino controller through a Node.js server. The Node.js server logs commands sent to the Arduino, such as the running time and the direction of each motor. The log is stored as JSON data and tracks the duration of pushing each pin, and based on these data we can compute the pin positions. The Node.js server feeds the information to the front-end to simulate and visualize the current positions of the pins in a browser through websocket. To track the user interaction and vertical displacement, we mounted a Kinect depth camera above the system. Figure 13 illustrates the entire architecture of software and hardware of Dynablock.

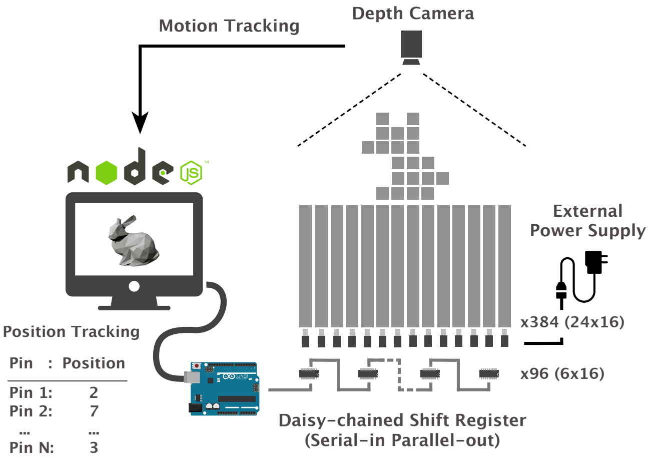

Figure 13. System architecture of our dynamic 3D printing prototype.

Stability of Connection

Dynablock has a unique ability to assemble a 3D shape with overhanging parts. However, it depends on the stability of the magnetic connectors. Our prototype uses N35 3mm neodymium sphere magnets. The force required to detach two magnets was 80 g. We conducted a test to find out how many magnets can hold each other horizontally without collapsing. We found that the maximum number of blocks in horizontal cantilever was eight (Figure 14). We also tested a vertical overhanging structure like an icicle growing downwards: these magnets hold together at most 25 blocks.

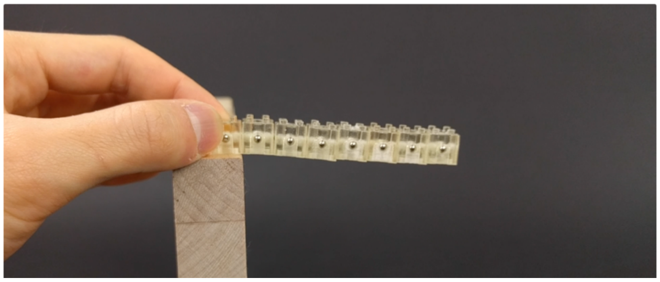

Figure 14. Horizontal overhanging.

APPLICATION SCENARIOS

In this section, we illustrate several possible application scenarios with dynamic 3D printers.

Dynamic Physicalizable Textbook

Today, an augmented reality system can show an interactive 3D image for a textbook. For example, a natural history textbook can show an animated Brontosaurus, a chemistry textbook can show a water molecule, and an architecture textbook can show Mies van der Rohe's Barcelona Pavilion.

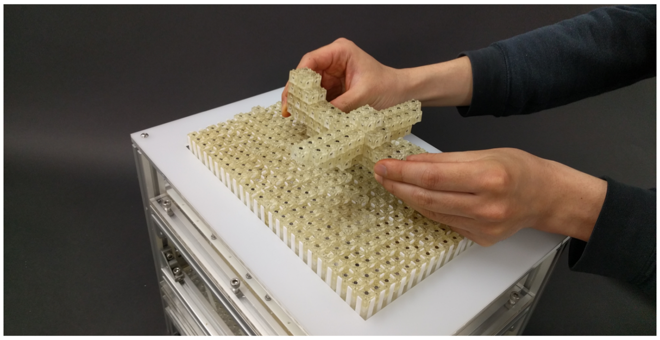

Figure 15. Airplane model rendered with dynamic physicalizable textbook.

What if a textbook could generate physical 3D shapes with which a student can interactively explore a concept? For example, imagine a student reading a design textbook explaining the aerodynamics of an airplane. The student pushes a "render" button, and the book immediately generates a physical aircraft model. The actual physical object can leverage direct manipulation. For example, the system can synchronize a projector and a depth camera to visualize a computational fluid dynamics simulation and project the air flow around the model. In contrast to using only visual information, a student can explore complex ideas by directly manipulating tangible objects. We can also leverage a Hall effect sensor array like GaussSense [25] to detect the position and the orientation of the assembled object on a flat surface. This way, the physical object can be used as a tangible controller for various education and design applications.

On-demand Haptic Proxy Objects for VR

While virtual reality is emerging in various applications, a key research topic is how to provide rich and high resolution haptic feedback synchronized with visual information [44, 56]. For example, when playing a game in virtual reality, a controller may be used to represent different objects depending on the situation: a steering wheel, a fishing rod, or a guitar. In such cases, dynamic 3D printing could create on-demand haptic proxy objects for VR. Inspired by the the robotic assembly of haptic proxy objects [56], we envision that a dynamic 3D printer enables a user to immediately create a custom physical object and use it as a haptic proxy for the visual image presented in the head-mounted display. While this object would not dynamically change its shape in real-time, the user could form different physical controllers to match the visual appearance.

Direct Interactive Fabrication

Dynamic 3D printing would enable a new design workflow for digital fabrication. One notable advantage of dynamic 3D printing is the capability of connecting and disconnecting building blocks through direct manipulation. The user can also define variables or abstract attributes for parametric design through direct and gestural interaction [24, 47]. By leveraging this capability, the user could interactively design and fabricate in a physical space, similar to the man-machine dialogue proposed by Frazer et al. and later tangible CAD interfaces [5, 7].

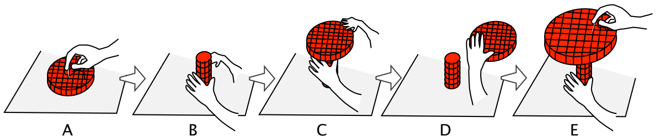

Figure 16. Direct interactive fabrication.

For example, when designing a table, a user can first create a large disk for the table top (Figure 16 A), then create a cylinder for the table's leg (Figure 16 B). The user can easily attach the table top and the leg (Figure 16 C). If the table top is too small, the user can detach and disassemble it (Figure 16 D), then design and generate a larger version (Figure 16 E). This new workflow can introduce direct touch interaction to the current interactive fabrication workflow [52]. Moreover, similar to faBrickation [27], the user can attach 3D printed parts into the object rendered by Dynablock to achieve a higher resolution or embed different materials.

DISCUSSION

Resolution

While our current implementation uses 9 mm blocks, the size of blocks depends on the size of embedded magnets. Our first prototype uses 3 mm sphere magnets, but the block size can be reduced by using smaller magnets. For example, we prototyped 3 mm size blocks with commercially available N50 1 mm sphere neodymium magnets. However, to reduce the element size, the parallel assembler must also be scaled down, which requires overcoming the engineering problem to miniaturize the assembler's various electrical and mechanical parts. The geared motor used in our prototype has a 6 mm diameter, so in our current design the pitch between two blocks cannot be smaller than 6 mm. To further reduce the pitch size, we might use push-pull flexible linkages, similar to the inFORM system [6]. Alternatively, prior work suggests that it is possible to implement a more closely packed, higher resolution pin-based display using a fusible alloy clutch array [35]. Thus, we believe our design of Dynablock can be scaled to 3 mm block resolution without fundamental design changes.

Speed

While our current prototype can form a shape in seconds, the shape has at most only eight layers. However, if the element size becomes smaller, the required number of layers would also increase. Then, does the assembly time also increase linearly with resolution? We note that the assembly time would only depend on the travel speed of actuated pins (i.e., how long it takes to go up eight layers), assuming the connection and disconnection time is negligible. For example, if the time to push each layer is longer than the time to switch the connection, then the completion time of one layer depends solely on the actuation speed. Assuming the assembly time of one layer is constant and independent of the horizontal resolution, we expect the speed of formation in dynamic 3D printing would be fast enough even in higher resolution.

Regarding the actuation speed, faster motors exist with the same 6 mm diameter (1:24, 1:136). Although using these fast geared motors may decrease the compilation time to a speed comparable to current shape displays [44], there is a trade-off between travel speed and torque as the faster geared motors may be too weak to lift the magnetic blocks. Thus, faster motors may require a different connection method or design.

Connector

As we discussed, the connection mechanism plays an important role in assembly speed. If it takes a long time for elements to connect or disconnect with neighbors, assembly will be too slow. In this prototype, we chose permanent magnets and mechanical disconnection for simplicity and ease of construction. While we note this method works at the millimeter scale, further reduction in size to sub-millimeter or even micrometer scale may require a different connection mechanism. There are several promising alternatives. For example, one possible connection mechanism is dry adhesion leveraging the Van der Waals force in a hair or gecko-like structure [31]. Another possible solution is to use MEMS or ASIC based electro-permanent magnets discussed in [8]. We are interested in exploring these alternative connection methods.

LIMITATIONS AND FUTURE WORK

Error Handling and Correction

The current implementation is an open-loop system in both pin positioning and error handling. We plan to implement a limit switch for each motorized lead screw and reset the position when it reaches the bottom. This would enable the software to detect the pin positions for more reliable actuation. Also, in our prototype, we did not implement a mechanism to detect errors. By using more sophisticated computer vision techniques or embedded sensing, we plan to implement more advanced error correction. Such a closed-loop system will increase the stability and reliability of the assembly.

Usefulness and Stability of the Objects

Although the printed objects can be held and manipulated without falling apart, they are not as sturdy as conventional 3D printed objects. Thus, we do not think the current system could immediately replace conventional 3D printing. However, we think our tool could better support design and prototyping (playing a similar role to LEGO or clay), which does not require a stable final product.

Process for Reconstruction

To disassemble the printed object, the tool currently requires the user to manually push the blocks down to below the table. This process is tedious and error prone. In the future, this could be automated using a single plate that automatically clears the object by moving from the top of the table to the surface. Another limitation of the object clearing is that the user cannot add external blocks after printing since there is no additional room to clear the added external blocks, which results in the different level after the clearing. We could alleviate this problem by changing the initial position of the pins to provide additional free space (e.g., set the initial position three blocks higher, so that the tool can hold an additional three blocks for each pin). Moreover, the tool cannot currently scan the precise shape of the modified object. However, if we can add a sensor in the separator to detect the block, we could scan the three dimensional shape while clearing the object. As future work, we plan to address these limitations.

Smart Blocks with Embedded Electronics

Although the ultimate goal of dynamic 3D printing is to create objects that can dynamically transform, as discussed in previous sections, a self-reconfiguring module is out of scope in the near future. Miniaturized flying or wheel-based robots [21] have been explored in the literature, but it is still difficult for them to assemble and disassemble in seconds. However, it may be possible to create "smart" block elements in this size, by embedding micro-electronic components. For example, we can embed a multi-colored LED into each block to dynamically change the appearance of the printed object. One technological challenge to achieve this is power supply, but it should be possible by creating a path similar to [10] or by using wireless power supply [49]. Similar to prior work that integrates electronic components into 3D printed objects [32, 33], we are also interested in embedding sensors into individual components for touch sensing or distributed shape detection. In the future, this may enable digital clay, which can be assembled through direct manipulation, and shapes that can be synchronously detected and encoded digitally for further computation.

CONCLUSION

In this paper, we proposed Dynamic 3D Printing, a new class a class of systems for rapid and reconstructable shape formation. Our main contribution is the design exploration of a Dynamic 3D Printing system, by introducing two key elements: 1) a parallel assembler and 2) fast switchable connectors. To demonstrate the idea, we developed Dynablock, a proof-of-concept prototype that leverages a 24 x 16 pin-based shape display as a parallel assembler. Dynablock assembles and disassembles 3,000 9 mm individual blocks. We describe the design and implementation of a switchable connection method using permanent magnets, which enables small and low-cost block elements. We discussed how the Dynablock's capability of fast and reconstructable shape formation can open new application scenarios, which have not been explored in the current fabrication research. In the future, we envision that a dynamic 3D printer could become an interactive medium, in which the user can think, design, explore, and communicate through dynamic and interactive physical representation.

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