Kinetic Blocks: Actuated Constructive Assembly for Interaction and Display

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ABSTRACT
Pin-based shape displays not only give physical form to digital information, they have the inherent ability to accurately move and manipulate objects placed on top of them. In this paper we focus on such object manipulation: we present ideas and techniques that use the underlying shape change to give kinetic ability to otherwise inanimate objects. First, we describe the shape display's ability to assemble, disassemble, and reassemble structures from simple passive building blocks through stacking, scaffolding, and catapulting. A technical evaluation demonstrates the reliability of the presented techniques. Second, we introduce special kinematic blocks that are actuated and sensed through the underlying pins. These blocks translate vertical pin movements into other degrees of freedom like rotation or horizontal movement. This interplay of the shape display with objects on its surface allows us to render otherwise inaccessible forms, like overhangs, and enables richer input and output.

ACM Classification Keywords
H.5.2 User Interfaces: Haptic I/O, Interaction Styles

Author Keywords
Shape-Changing User Interfaces; Shape Displays; Actuated Tangible Interfaces.

INTRODUCTION
A common form factor of Tangible User Interfaces (TUIs) is construction kits, where the user assembles building blocks spatially to interact with information. Various construction kits have been proposed for applications like Computer Aided Design (CAD) [2], as educational toolkits [22], and for tabletop gaming [16]. Most technical research in this area has investigated sensing techniques to detect how the user interacts with the blocks [2, 12, 3]. However, actuation techniques to move the blocks and computationally rearrange them into shapes have been less researched.

This idea of dynamic, computer-controlled shapes that form TUIs on demand has been proposed in research visions like *Radical Atoms* [13] and *Claytronics* [11] and studied in related fields like modular and swarm robotics. Currently, two approaches for creating dynamic shapes dominate: using shape-changing interfaces, like shape displays, or combining multiple modular elements, like small robots. However, both of these approaches have limitations: shape displays can only render certain types of 2.5D shapes, and the engineering challenges of miniaturizing robust modular robots limit their applicability for computer interfaces.

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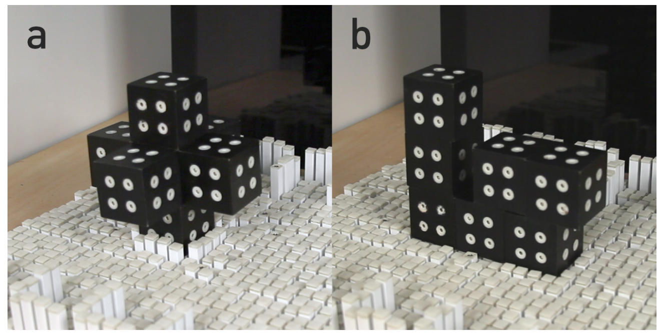


Figure 1. Two structures made from magnetic building blocks that were assembled by the shape display.

We therefore propose combining these two approaches by arranging passive modular building blocks using an underlying shape display (see Figure 1). This technique simplifies the modular blocks in comparison to miniaturized robots while enabling more degrees of freedom for shape rendering and interaction than do current shape displays.

Limitations of Pin-Based Shape Displays
Current shape displays use an array of vertically moving pins to render different shapes and forms. This method has inherent limitations on the types of shapes that can be generated: in general only 2.5D shapes that go straight up or are tapered towards the top are possible. Any form with an overhang or overpass or that is tapered towards the bottom cannot be rendered correctly. Simple geometries like bridges and tables are therefore unavailable. The rendered shapes are also constrained to the shape display and cannot be lifted off, limiting how users can interact with them.

As the individual pins of the shape display only possess a single degree of freedom (DOF) through vertical movement, they cannot apply lateral forces to passive objects placed on top. This means they cannot bend, twist, or push these objects.

Contribution

In this paper we make three main contributions. (1) We describe and evaluate techniques for the constructive assembly of simple, unpowered building blocks into 3D structures via a shape display. These structures extend the shape display's rendering capabilities, and allow for expressive user input. (2) We also present unpowered kinematic blocks that can be driven and sensed through the underlying shape display. These blocks translate the pins' vertical DOF to other DOFs to extend possibilities for shape display input and output or provide special capability like extending pin length to construct higher structures. (3) We introduce the idea of a shape display as an interactive and dynamic physical control engine. We illustrate this idea through applications and example scenarios.

RELATED WORK

Tangible Construction Kits and Tabletop Interfaces

Interacting with information through a set of building blocks is a common approach in TUIs and their precursors [27]. Examples include the physical CAD construction kits by Frazer et al. [8] and Aish et al. [1] and systems like *MERL blocks* [2] and *ActiveCubes* [14]. Construction kits like *Lego Mindstorms* and *Topobo* [22] add actuation through motorized bricks. However, although these modules move structures, they do not aid in their assemblies.

Tangible Tabletop Interfaces (TTI) are a related form factor focused on spatial relationships between blocks in which the user arranges physical tokens on a horizontal tabletop system. *Bricks* by Fitzmaurice et al. are physical information handles on a tabletop display [6]. Ullmer et al. extend bricks to tokens interacting with physical constraints [28]. *Lumino* by Baudisch et al. is a system to sense multiple tokens stacked on top of each other [3].

Actuated Tangible Tabletop Interfaces

To overcome the limitations of passive objects, systems like *Pico* by Patten et al. [20] use an array of electromagnets underneath a tabletop to computationally move tokens. *Madgets* by Weiss et al. [29] extends this approach through multi-functional tokens that can be moved, rotated, and made to change their physical state through a magnet array. Other techniques for actuation include ultrasonic waves [17] and wheeled or vibrating robots [19]. However, these tabletop systems are not designed for constructing shapes out of tokens and are unable to stack them on top of each other.

Shape Displays

Previous shape displays propose rendering information through physical shapes [21] and *inFORM* investigates constraining and moving physical objects through shape change [7]. *Physical Telepresence* extends this approach to enables the remote handling of objects through the user's body shape [15]. *Festo Wave Handling* proposes object movement through shape actuation for factory automation [5]. While all these systems move objects, they do not assemble them into more complex multi-story structures.

Figure 2. Users can rearrange the blocks directly with their hands.

Modular Robotics/Self Assembly

Forming complex robots out of simpler modules was first demonstrated with *CEBOT* by Fukuda et al. [9]. Modular robots use motorized hinges or internal flywheels [23] to self-arrange spatially into their target shape. At present, however, the complexity, speed, and power requirements of modular robots prohibit their use as building blocks for an actuated construction kit.

More closely related to our approach, researchers have proposed using external actuation to assemble structures. These can be stochastic forces in combination with active connectors between the blocks [26] [10] or pre-defined structures that lock into each other when tumbled [25]. Another approach is to use a swarm of robots to assemble a structure, with examples including *Flight Assembled Architecture* [4] and *Termite Inspired Construction* [30]. While Programmable Matter research provides exciting technical innovation, there has been little focus on human interaction in those systems.

In contrast to the presented prior work, we try to open a new design space using actuated and self-reconfiguring 3D shapes for tangible interaction.

ACTUATED CONSTRUCTIVE ASSEMBLY

In this section we describe our design criteria, the building blocks we use, and the various techniques that enable actuated constructive assembly on shape displays.

Design Criteria

Unlike systems for additive manufacturing and modular robotics, our setup is guided by the principle that the user should be able to interact with the system at any point, even while it assembles a shape (Figure 2). There were several other design criteria for our system:

- Robustness: No fragile connectors or actuation mechanisms that may break when a user touches them may be exposed.

- Safety: No mechanisms like robot arms should be mounted above the shape to avoid colliding with a user's hands.
- Parallelism: Multiple building blocks should be able to move simultaneously to speed up the assembly process.
- Scalability: The building blocks should be simple; adding more blocks should not significantly increase cost or complexity.

Building Blocks

We explored constructive assembly on shape displays with both non-locking and locking (magnetic) building blocks.

Non-Locking Blocks

The non-locking building blocks are commercially available wooden cubes with 5 cm edges. On the inFORM shape display they cover a 4 x 4 area of pins. In practice, we found this to be the most stable size across a variety of actuation techniques. At 90 g each, the blocks are light enough for the inFORM to easily lift four vertically-stacked blocks while heavy enough that control of the blocks is maintained through sudden changes on the underlying shape display (e.g. a change of direction when traversing). The non-locking blocks are ideal for the assembly of temporary structures and can be easily disassembled.

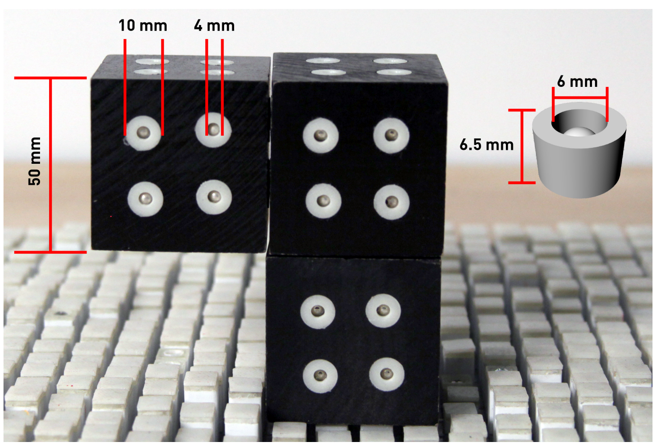


Figure 3. Locking blocks are made with spherical magnets inside a 3D printed plastic shell.

Locking Blocks

We also created building blocks that magnetically connect. Constructions composed of these blocks are more permanent, retaining their shape when taken off the shape display, but they can be easily reassembled by users' hands. The blocks' locking also allows the construction of otherwise unachievable architectures. A key design requirement was for connections to be strong enough that one building block can carry another laterally, enabling constructions with overhangs. Balancing this, the connections had to be weak enough that the shape display's pins could split blocks apart during disassembly.

To meet these requirements we designed ungendered connectors recessed into the sides of the cubes, four connectors per face. Each connector houses a 6 mm diameter spherical neodymium magnet inside a 3D-printed, 6.5 mm long cylindrical shell with a 10 mm diameter. The magnets rotate freely within their shells to pair with other blocks in any orientation. The design permits precisely controlled magnetic connection strengths by varying the diameter of the outward-facing shell opening. For our design criteria, we experimentally determined the opening's ideal diameter and wall thickness as 4 mm and 1.5 mm, creating a distance of 2 mm between paired magnets. The connection strength of two blocks joined at all four points ranges from 3.15 to 3.25 N. Since each locking block weighs 105 g, this meets our design requirements admirably.

To install the connectors, we used a CNC machine to drill holes 6 mm deep, 4 per face, into the wooden cubes. (We used the same wooden cubes as for the non-locking blocks.) We placed the magnets into their shells and press-fit the shells into the holes. No adhesive was necessary. We spaced the shells 1 cm apart from each other and with a 1 cm margin from the block's edge. This separates magnets within a block sufficiently to prevent them from substantially attracting each other through the wood. (Figure 3). This spacing restricts any face of a block to forming connections with just one other block at a time, but the connection may be offset, using only two or one connection points instead of the full four. In all, this design allows us to connect a block to up to six others at once. The magnetic connections help with precise alignment when assembling larger structures.

System Overview

All described experiments and actuation scenarios were done using the inFORM system [7]. The inFORM shape display consists of 30 x 30 motorized pins that cover an area of 381 X 381 mm. Each pin has a size of 9.5 x 9.5 mm with a 3.175 mm spacing between them. The motors can extend pins up to 100 mm vertically with a maximum speed of 0.644 m/s and a maximum strength of 100 g.

Assembly Techniques

The general ability of pin-based shaped displays to move and rotate objects of different size and shape has already been described by prior work [7] [15].

In this paper, we focus on the described building blocks and identify fast and reliable ways to move and rotate these specific objects. The techniques presented in the following sections present a set of fundamental maneuvers that allow for assembly of structures in three dimensions. While this does not constitute a comprehensive exploration of the design space of constructive assembly on shape displays, we are confident in having identified many of the best techniques afforded by systems like ours.

Translation

Since 2.5D shape displays cannot laterally push objects, we move a rectangular or cubical object across the surface by creating a ramp sloped at 45 degrees. The object is continuously lifted on this ramp and, like a cardboard box sliding down a staircase, the object slides forward in order to satisfy gravity.

Due to variations in the ramp surface, the blocks may start to tumble when moving at high speeds. In order to move blocks precisely at faster speeds we developed the *Sled* (Figure 4a). The *Sled* combines a ramp to move the block forward with guiding rails on both its sides and at the front. Its total footprint is 6 x 10 pins. This physically constrains the block from tumbling too far forward or off to the sides and achieves reliable block tumbling at speeds up to 0.2 m/s (16 pins/s).

When moving the block around corners or before performing other manipulations, it is crucial for the block to rest flat on one of its sides inside the *Sled's* boundaries. Therefore, before each change of direction we realign the block by raising all the pins in the ramp to a height of 6 cm, tumbling the block off the ramp and trapping it against the *Sled's* front guide rail. This short maneuver perfectly aligns the block and increases accuracy of subsequent manipulations.

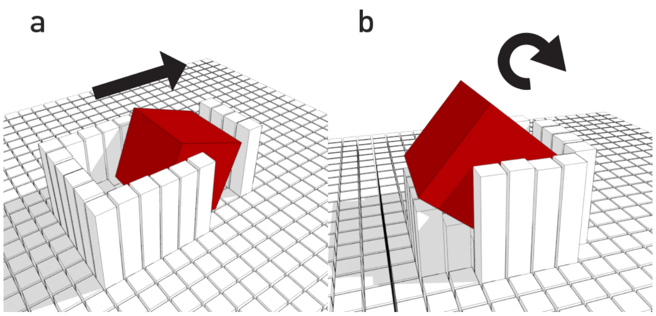


Figure 4. a) Using the shape display's pins we create a *Sled* to rapidly move a block across the surface. b) Lifting a block from one side while physically constraining the opposite side lets us rotate it around its x, y and z axes.

Rotation
To rotate the block 90 degrees around its x or y axis we create guiding rails 6 cm high around the block. We then lift the block from one side, tumbling it onto its perpendicular side while retaining its original location (Figure 4b). Because we cannot create lateral forces on a shape display, rotation around a block's z-axis requires x-y-x or y-x-y compound rotations. Single rotations have a footprint of 6 x 7 pins and can be performed 80 times per minute; the compound z-rotation has a footprint of 7 x 7 pins and can be performed 26 times per minute.

Stacking
While the precise translation of blocks on a 2D plane lets us create single layer structures, we can build more sophisticated multi-story structures by constructing in the z direction as well. The simplest 3D construction technique uses a bottom-up approach of lifting a block vertically then tumbling it on top of another. The stacked object must be lifted 0.5 cm above the top of the base object. Pins on the stacked object's far side then extend farther up to tumble it onto the base object (Figure 10c).

This maneuver lacks precise control of the stacked block's velocity when it tumbles onto the base object and occasionally leaves the two misaligned. As with the ramp *Sled*, we can use extra pins to establish guide rails around the base block. This physical barrier guides the stacking object into place. Such guidance is unnecessary when constructing with the locking blocks as they naturally snap into place.

With either kind of block, the 10 cm actuation limitation on the inFORM's pin heights restrict this method of stacking to two-story-high constructions. We can improve on this limitation in multiple ways.

Stacking with Helpers
We can create three-story structures by lifting a two-story tower and tipping it onto another two-story structure. This causes the top block in the lifted tower to tumble on top of the resting structure, creating a third story (Figure 10e). The helper block collides with the base structure, but placing guide rails behind the base protects it from being displaced. A starting distance of half a block's width between the structures produces the best results. We could not reliably extend this to construct four-story structures because inFORM can only produce two-story guide rails, so third-story blocks in base structures are frequently knocked backwards by helper blocks.

Stacking by Catapult
Another way to stack a block is to catapult it into its target position by raising the pins under its rear half at maximum speed. This technique can reliably construct two and three story structures. Our current system can apply enough force to launch individual blocks one story high. To launch a block two-stories high we employ a helper cube technique and catapult a two-story tower as a unit. The top block lands squarely on a two-story base structure, and the helper comes to rest at its base (Figure 5). We found the ideal starting distance for catapulting a second story stacking is half a block width (2.5 cm) and for third-story stacking is one block width (5 cm).

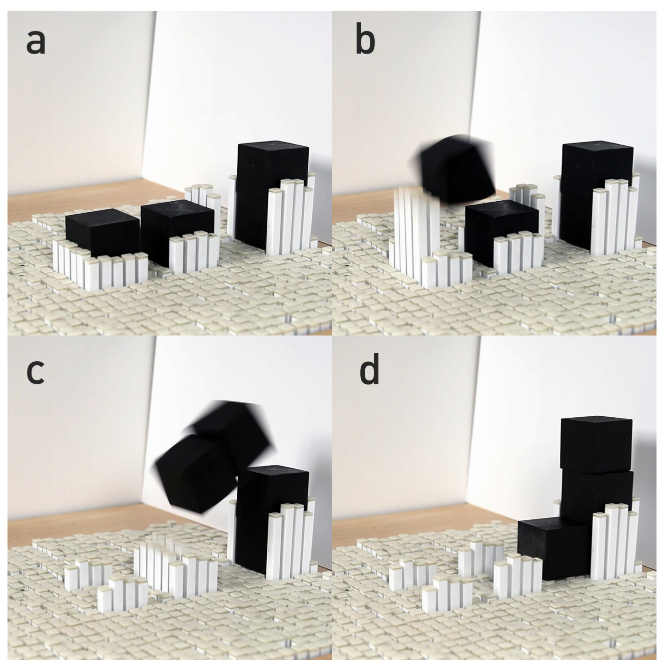


Figure 5. Catapulting the blocks on top of each other lets us create up to three-story structures by using an additional building block as a helper.

Stacking with Scaffolds

We can use the shape display's pins to create temporary scaffolds that assist in assembly tasks. For instance, we can create a bridge by lifting a rectangular block three standard blocks long (15 x 5 x 5 cm) with 4 x 4 pins at its center of mass. We then tumble blocks for the bridge's pillars underneath each of the lifted rectangular block's sides. After removing the scaffold by lowering the pins back to their zero position the bridge rests stably on the pillars (Figure 10g).

Ground Assembly with Locking Blocks

Locking blocks allow structures in the 2D plane to be lifted as a unit to stand vertically. This enables the ground assembly of structures unattainable if built upright from the start. With this pattern we can create structures up to four blocks in height. We can also use locked structures as movable components for constructing larger structures, such as the three-block-long rectangular component described in the previous section for constructing a bridge.

Overhangs with Locking Blocks

To create overhangs with locking blocks we move a block within one pin distance of a higher base structure. In the free space between the block and base structure we create a pin barrier to prevent the two opposite blocks from connecting. We then lift the bottom block to the desired height and, row by row towards the base structure, raise the pins underneath the block one more centimeter. This motion moves the block slightly towards the base structure and forms a connection. Once the blocks are connected we retract the pin barrier.

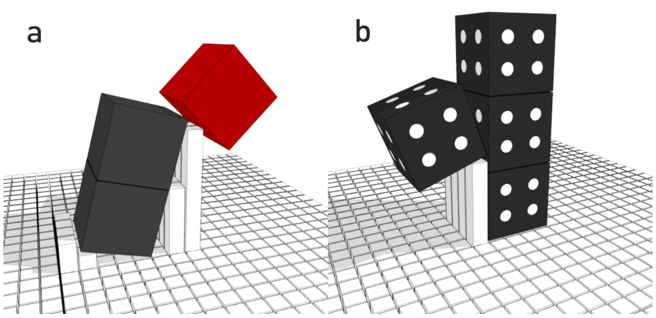


Figure 6. a) We unstack a non-locking structure by toppling it so that the top block can slide off. b) Bumping pins against a locking block breaks its magnetic connection.

Disassembling

In order to reuse blocks or reconfigure structures we need to disassemble them. Structures of non-locking blocks can be disassembled by toppling the entire assembly. To disassemble structures selectively we can slightly tilt the whole structure and raise a scaffold for the blocks we want to stay assembled. The unsupported blocks will slide down while the rest remain intact. The remaining assembly can then be tilted back to its original position.

We found the best technique for disassembling locking blocks was to bump a row of four pins into a block at the points closest to its connection site (Figure 6b). The sudden impact causes the magnets to disconnect and the block will fall off. This technique works best for overhanging blocks. When removing the topmost block of a multi-story structure the full assembly must be tilted into a horizontal position before applying the bumping technique.

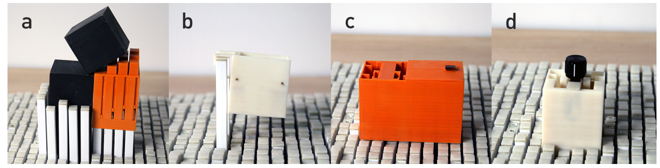


Figure 7. a) The *Extender* can be used to create higher structures. b) The *Hanger* has retractable flaps that let us lift it to create overhangs. c) The *Slider* can be used for horizontal input and output. d) The *Rotator* provides rotational input and output

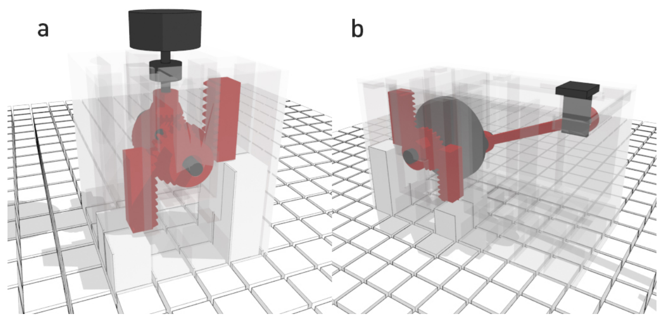


Figure 8. a) Inside view of *Rotator's* mechanical system. Two linear gears are driven by the pins which translates into rotation using a gear train b) Gears and a lever create horizontal movement in the *Slider* block.

KINEMATIC BLOCKS

In this section, we introduce the idea of using a shape display as a computational physical control engine to drive special unpowered kinematic blocks. Similar to mechanical automata, these blocks are mechanical systems made from gears and levers that convert vertical pin motions into other desired movements. The shape display's pins provide the required input energy to drive the kinematic blocks. Because the inFORM's pins are made from motorized slide potentiometers, we can use the pins as sensors. This enables kinematic blocks to serve as input as well as output devices.

We imagine the shape displays of the future will control a multitude of kinematic blocks to assist in accomplishing various kinds of physical assembly tasks and provide richer input capabilities. Mechanical logic will be specified in this richer I/O space and be automatically compiled into programs of kinematic blocks and vertical pin actuations.

As a proof of concept we created four kinematic blocks that are controlled by the underlying shape display. We selected block functionalities demonstrating the shape display's ability to control mechanical systems that can overcome the display's inherent limitations. These functionalities address the shape display's limited pin height and its lack of overhangs, rotational movement, and lateral movement.

All four kinematic blocks were designed in Rhinoceros and printed on the Stratasys Dimension 1200es FDM 3D printer.

Extender

The *Extender* gives us the ability to extend the shape display's pin height (Figure 7a). The *Extender* is placed on top of the shape display such that the underlying display's pins can push against the *Extender's* pins. These blocks can be stacked to increase their pin length. We can use the *Extender* as a tool that lets us overcome the pin height limitation and build higher stacking structures. We can also stack other kinematic blocks on the *Extender* if required for a certain task.

Hanger

The *Hanger* (Figure 7b) is a simple block that can create overhangs by mechanically hooking into a set of pins. Unlike the locking blocks that construct overhangs by attaching to each other, the *Hanger* builds overhangs directly onto the pins. It covers an area of 4 x 4 pins on the shape display. The top and bottom of the block are open and the top half contains two special flaps that form hooks and are connected to hinges. Similar to opening a cardboard box, these flaps can be folded out by pushing against them from inside using the underlying pins. The *Hanger* can be lifted by raising external pins underneath the folded out flaps, hooking onto the lifting pins and creating an overhang. Lowering the pins will lower the *Hanger* and unhook the pins. The shape display can fold the flaps back in by pressing a lever that folded out with the flaps.

Rotator

The *Rotator* block (Figure 7d) translates vertical pin movements into rotational movements. Internally, two linear gears allow for left and right rotations. Each gear can be driven by two pins for increased strength. These linear gears drive a spur gear connected to a set of bevel gears which create rotational movement around the z-axis (Figure 8a). The gear ratios currently allow for 315 degrees of rotation in both directions. We can use the *Rotator* as input device as well, providing a new degree of freedom for interaction with shape displays.

Slider

To translate the pin's vertical movement into horizontal movement, the *Slider* block (Figure 7c) contains two linear gears and a spur gear that rotates a disc with an attached lever (Figure 8b). The lever is fixed on a rail and drives a small slider horizontally. Similar to the *Rotator*, the *Slider's* internal linear gears are driven by two pins each to increase force, and the gears allow forward and reverse sliding. The *Slider* is useful for both input and output.

Sliders' and *Rotators'* simple movements comprise the fundamental actuations that enable six-degree-of-freedom position and orientation control. More complex blocks could potentially produce such control.

DEMONSTRATIONS OF ACTUATED ASSEMBLY

In this section we describe applications and example scenarios demonstrating how a shape display can be used for actuated constructive assembly.

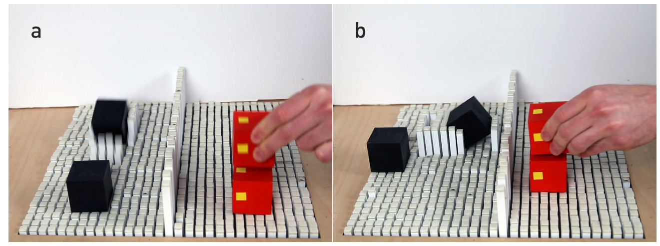


Figure 9. a) Remote assembly scenario where the user's local movement guides the assembly. b) Remote assembly where the local structure is analyzed and the system determines how to assemble the structure.

Programmable Matter

In robotics research, programmable matter is described as the computationally controlled construction of objects from fundamental building blocks. In most programmable matter research, the building blocks are self contained units that can actuate themselves to the their target position [23], whereas our approach uses outside actuation to transport the blocks. This allows the building blocks to be simple, cheap, and robust and allows a user to directly manipulate the building blocks without the fear of breaking them. It further provides for a wide range of construction materials to be used.

To demonstrate programmable matter using our blocks, we created an application that lets the user choose between two structures displayed on a tablet computer. The shape display automatically assembles the selected structure using seven locking blocks (Figure 1). Once the first structure is assembled and another is selected, the shape display will disassemble the current structure and reassemble the blocks to match the newly selected structure.

Remote Assembly

Another application domain with potential for actuated constructive assembly is remote physical teleoperation. We implemented an application that lets a user remotely stack two building blocks on top of each other. We explored two conceptual approaches.

1) The user creates a structure from building blocks locally. The remote shape display follows the user's movements and assembles the structure ad hoc.

2) The system ignores the user's movements and actions and solely analyzes the local structures. The remote shape display system determines the optimal path and assembly technique for replicating the remote structures and build them wholesale.

Kinematic Blocks to extend DOF

To showcase the kinematic blocks functionality we implemented proof of concept applications demonstrating their capabilities as input and output devices.

We attached a knob on the *Rotator* block which a user can turn to control a red ball's position within a circle around the block. In the reverse scenario, a user can move the red ball around the block and the *Rotator* will point an attached red arrow at the ball, tracking it like a compass.

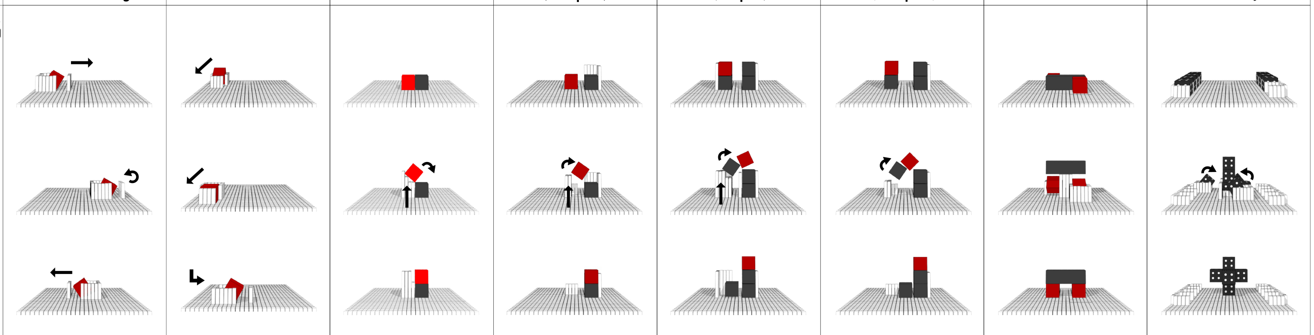
	a) traverse with direction change	b) traverse around corners	c) two story stack	d) two story stack (catapult)	e) three story stack (helper)	f) three story stack (catapult)	g) overpass with scaffold	h) star structure assembly
Illustrations (top to bottom)								
Attempts	100	100	100	100	100	100	100	40
Success	99%	82%	100%	99%	100%	99%	100%	82.5%

Figure 10. This table shows the results from controlled tests of the various translation and assembly techniques. All tests were performed using the non-locking building blocks except for test h) where we used the locking blocks.

In a similar fashion we use the *Slider* to move a building block from left to right direction across the shape display. The position of the *Slider* determines the block's position and vice versa.

Example Scenarios

While our current system is limited in resolution, actuator strength and sensing, we see great potential for applying our proposed methods to various domains in the future. In this section, we discuss how they could enhance computer-aided design (CAD), educational toolkits, music interfaces, and tabletop gaming.

CAD with self assembly

We envision a bi-directional CAD system where the computer not only senses user input, but enters a tangible conversation with the user through actuated feedback. Such a system would be similar in shape to previously proposed block-based CAD interfaces by Aish et al. [1], Frazer et al. [8] and Kitamura et al. [14]. As proposed in the previous section, it could load and build geometries from files or keep two remote models in sync, but it could furthermore computationally optimize models. It could rearrange blocks to improve a statically unsound user-defined building. It could fill in geometry outlined by the user, such as building walls between corners of a building, or repeating building patterns. The system could make such physical modifications much faster than current 3D printers, enabling a physical dialogue between designer and system.

Educational Toolkits

Physical building blocks, such as *AlgoBlocks* by Suzuki and Kato, allow students to learn programming concepts [24]. Through our systems ability to move blocks, it could provide feedback on what combinations are allowed in the programming environment. It could move false connections when the user asks for advice or provide hints through vibration when placing down blocks.

Music Interfaces

Tangible music interfaces like BlockJams by Newton-Dunn et al. [18] elegantly demonstrate music creation through building blocks. An actuated system can extend this approach by arranging the blocks into sound sculptures that represent a music piece and then letting the user modify the blocks to change the music. Kinematic blocks like rotators and sliders add additional degrees of freedom for music improvisation.

TECHNICAL EVALUATION

We evaluated the reliability of the described actuation techniques by testing them multiple times and recording their errors and successes. Figure 10 describes the results of different attempted actuation techniques. All attempts except h) were performed using the non-locking blocks. We regarded an attempt as unsuccessful if the block did not arrive at its target destination or if it arrived in an orientation that would have prevented further assembly without first realigning it. Specifically, we considered a misalignment failure to occur when more than 20% of a block's bottom surface area protruded off the base block. The most common cause of failure were pins that couldn't reach their final height due to friction that has developed in the inFORM system from the wear and tear of extensive use. The most common type of failure was misalignment.

The results show that our open-loop system techniques are reliable. However, a single error in a larger sequence of movements can compromise the whole assembly task. This was especially true for h) (Figure 10h). A closed-loop system (using computer vision, sensors on pins, etc.) would increase the reliability of constructing complex forms.

IMPLEMENTATION/SOFTWARE

To prototype and test movement patterns quickly and reliably on the inFORM we created a network connection via TCP between the inFORM software (C++/openFrameworks) and the modeling and animation software 3ds Max using MAXscript. This allowed us to use feature-rich professional animation software to create forms and animations in virtual 3D space and display them in real-time on the inFORM. The program determines the distance of the 3D geometry from the virtual camera's near clipping plane using ray-casting, normalizes these values in the range 0 to 255, then sends them to the inFORM. The inFORM outputs these values as rendered 3D form. We iteratively created and optimized 3D animation clips that would perform the described assembly tasks.

For tracking the blocks' positions for remote-assembly we used a Microsoft Kinect depth camera mounted above the shape display. We crop the input image to fit the shape display, use depth and color information to determine the height of the stacked structure, and apply contour recognition to detect whether a user is grasping a block.

GENERAL FINDINGS

Most research findings presented in this paper are tailored towards the inFORM shape display and future systems with different form factors or technical specifications might enable different assembly techniques. Here we compiled findings that hold true across different systems.

- Building blocks should be at least four times the length of a single pin for optimal manipulability.
- Building blocks should have a weight about equal to the maximum force a single pin can apply. This avoids unwanted tumbling while allowing catapulting.
- Dynamic physical barriers constraining or guiding blocks greatly improve the speed and accuracy of the assembly process.
- Block realignment operations are critical for constructing reliable sequences of manipulations in an open-loop system.

LIMITATIONS AND FUTURE WORK

The current assemblies are performed in an open-loop system, meaning there is no feedback from sensors about the results of an actuation. We rely purely on the reliability of the described assembly techniques. In the future we hope to implement a closed-loop system and real-time error correction. This could mean embedding sensors in the shape display's pins or implementing more sophisticated computer vision techniques [12]. In software we plan to implement more advanced path planning and decision-making algorithms.

In this paper, we focused on cube-shaped building blocks. We plan to explore actuated constructive assembly with more diverse shapes like cylinders or triangular objects. A long-term goal is for shape displays to assemble arbitrary objects. One could imagine placing screws, gears and levers on the shape display to have it assemble a mechanical tool it could use for further tasks.

Another extension of the building materials we'd like to to investigate is using different locking types such as semi-permanent magnets or mechanical connections. Stronger connections could enable larger overhangs and more permanent and detailed structures. Using active blocks in combination with the shape display opens another interesting realm. Active blocks could provide electromagnetic connections [23]. The shape display's pins could have conductive connectors providing external electrical power to the blocks. This solution could enable building blocks smaller than can be usefully manipulated by the pins. Active blocks' complexity and cost are a drawback, however.

The shape display's size limits the number of building blocks we can handle at once. Even with only seven blocks it was challenging to avoid collisions during assembly. Higher resolution shape displays could enable constructive assembly with smaller building blocks and allow the construction of more detailed structures.

Stronger and more precise pin actuating motors would enhance interaction with the kinematic blocks. The kinematic blocks controlled by the inFORM shape display were too weak to reliably assist in actuated assembly scenarios. The ability to move kinematic blocks on the shape display out of the way or to a required position is necessary for general-purpose unaided construction with them. We will also explore more complex applications for using shape displays with kinematic blocks to manipulate physical objects.

CONCLUSION

In this paper we presented actuated constructive assembly, disassembly and reassembly with passive building blocks on pin-based shape displays. We described different assembly techniques and, through a technical evaluation, showed that our open-loop techniques perform extremely reliably. We introduced special kinematic blocks that can be driven and sensed through the shape display and that extend its degrees of freedom for both output and input. We provided evidence that shape displays can serve as interactive dynamic physical control engines for a range of assembly tasks. We believe that this research not only presents a valuable contribution to the HCI community but furthermore shows promising novel approaches for further exploration by robotics and programmable matter researchers.

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