Shape Synthesis

Physical Object Augmentation and Actuation for Display and Interaction on Shape Changing Interfaces

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Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning, in Partial Fulfillment of the Requirements for the Degree of Master of Science at the Massachusetts Institute of Technology

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Abstract

Pin based shape displays can not only give physical form to digital information, but they have the inherent ability to accurately move and manipulate objects that are placed on top of them. This document presents ways and ideas that show how a shape display's dynamic shape changing ability can work in unison with physical objects that are placed on top of it. First, we introduce the idea of shape synthesis, which is the physical augmentation of inert physical objects with the dynamic shape to create a seemingly new object. This synthesized object combines the advantages of the inert object's natural affordances with the computational power of dynamic shape change. In so doing, we can substitute for passive objects, complement passive objects and enable easier interactions with a shape display. We then show that a shape display can be used to assemble, disassemble and reassemble structures from simple passive building blocks through stacking, scaffolding and catapulting. Then, we introduce special unpowered kinematic modules that can be driven and sensed through the underlying pins. These modules can translate the vertical pin movement into other degrees of freedom like rotation or horizontal movement. This suggests that a shape display can be regarded as a versatile physical control platform that can drive and control a variety of useful mechanisms and objects.

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And especially thank you to my most precious Micha for always putting a smile on my face and for being there, even from afar.

Contents

"The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such room would be fatal. With appropriate programming such a display could literally be the Wonderland into which Alice walked."

(Sutherland, 1965)

1. Introduction

The ultimate display, as Ivan Sutherland describes it, is not made of color changing pixels behind a flat glass screen, but is physical in its nature. With the introduction of the *inFORM* shape display (Follmer, 2013), we came one step closer towards a future where matter is dynamic and can be as easily controlled as pixels on today's common displays. Digital information can now have physical manifestation that one can interact with. This idea of dynamic, computer-controlled shapes that form tangible user interfaces on demand has been proposed in the "Radical Atoms" vision (Ishii, 2012).

The idea of having hundreds or thousands of computationally controlled pins drive up and down to display detailed shapes is not completely novel and has been explored in previous research (Poupyrev, 2004; Nakatani, 2003), as well as in Science Fiction (Figure 1).

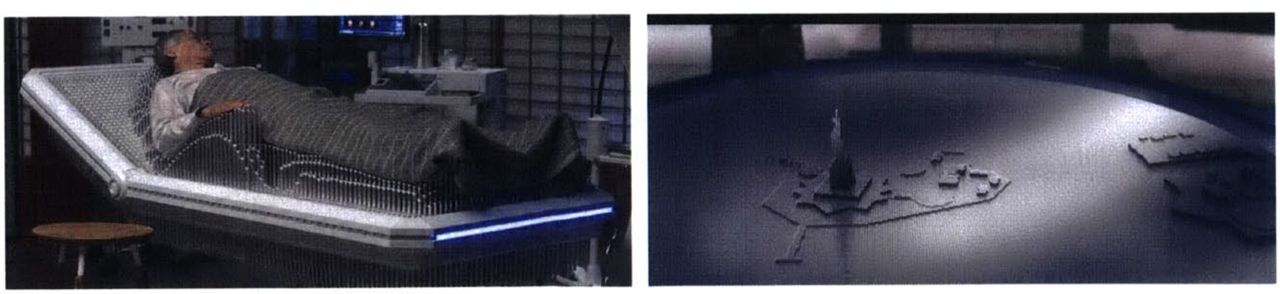


Figure 1. Shape displays (Computer Graphics) used in science-fiction movies (Left: The Wolverine, 2013. Right: X-Men, 2000)

The true strength of shape displays, like the *inFORM*, is their inherent ability to move and manipulate passive physical objects through dynamic shape change. This augmentation of otherwise inert physical objects with kinetic capabilities, which Follmer and Leithinger call "inter-material interaction" (Follmer, 2013) greatly broadens the application space of shape displays. Leithinger and Follmer describe "inter-material interaction" in the context of dynamic physical user interfaces (Follmer, 2013) and for remote physical telepresence (Leithinger, 2014).

In this thesis we try to expand on this rich body of research and argue for a new interaction concept called *Shape Synthesis*. This concept describes the tight coupling of inert objects with dynamic shape to create novel objects which combine the affordance advantages the inert objects with the computational and shape-changing power of shape displays. By designing interfaces that employ the advantages of both, we can create novel ways of interacting with computers. We then expand the concept of Shape Synthesis around the constructive assembly of passive, unpowered building blocks on a shape display. Ultimately, we advocate for regarding a shape display as a versatile physical control platform and further demonstrate this idea on the basis of specially designed kinematic modules that are sensed and controlled by the underlying shape display.

1.1. Thesis Contributions

This thesis expands the research around shape-changing user interfaces with the following contributions:

- The tight coupling of inert objects with dynamic shape to create synthesized objects that combine the affordances of the former with the computational power of the latter.

- A series of application primitives that exemplify the concept of shape synthesis.

- The use of shape-change as means for interactive constructive assembly, disassembly and reassembly of passive building blocks.

- A technical evaluation that proves the reliability of the presented assembly techniques.

- The introduction of the idea of a shape display as a versatile platform for physical control that can drive and sense special kinematic objects for richer input and output.

Additionally, these contributions each present different ways that help overcome inherent limitations of current shape displays, which are described in chapter 2.2.

1.2. Thesis Aims

"That's a good challenge, and the answer you'll find offered here is half technology (how it can be done now) and half philosophy (how it should be done eventually)."

John Underkoffler (The I/O Bulb and the Luminous Room, PhD Thesis, 1999)

This thesis's aims are boiled down to an essence by the above sentence. This thesis provides technical knowledge but also seeks to inspire future researchers in Human Computer Interaction (HCI) to leverage shape-changing interfaces inherent ability to affect and manipulate the physical world. This opens up an interesting new design space and can lead to a large variety of novel interaction scenarios. Our world is filled with inanimate passive objects and if our future surroundings will have dynamic shape-changing capabilities, we have to start thinking about how we can combine the world of passive shapes with tomorrow's world of dynamic shapes.

2. Background

This chapter provides a brief overview of the *TRANSFORM* project, the limitations of current pin-based shaped displays and the concept of programmable matter.

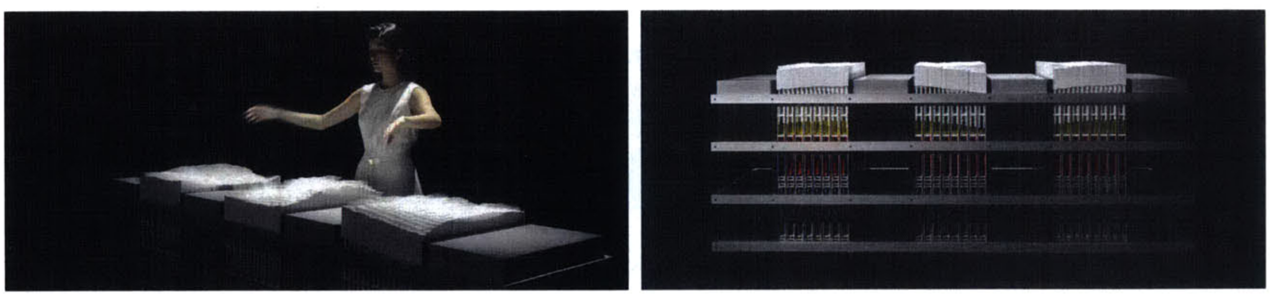


Figure 2. *TRANSFORM* at Milano Design Week 2014. Three shape-changing modules with 1152 pins form an interactive kinetic triptych.

2.1. A Novel Canvas and Paint Brush

The *TRANSFORM* project can be seen as the starting point for the exploration of more complex "inter-material interaction" which ultimately led to many ideas which are further investigated in this thesis. *TRANSFORM* is a shape display that was designed and built in the period of November 2013 to April 2014. It was then exhibited at the" Lexus Design Amazing" event in Milan, Italy during the Milano Design Week. (Figure 2)

In contrast to the *inFORM*, which can be considered a general purpose research platform, the *TRANSFORM's* context is that of a kinetic furniture that carefully plays with the conceptual juxtapositions of static vs. dynamic, hard vs. soft and nature vs. machine.

We explored the creative potential of "Radical Atoms" by regarding the *TRANSFORM* as a novel canvas for artists and designers to draw on (Ishii, 2015). For the exhibit in Milan, with more than five thousand visitors, we implemented three scenarios (Figure 3).

1. In the *Wave* mode, visitors could use their hands to playfully sway and shake the *TRANSFORM's* kinetic surface.

2. In the *Machine* mode, we play back a kinetic choreography that tells the story of "Nature and Machine".

3. In the *Escher* mode, we demonstrate the concept of "inter-material interaction" through actuating a red ball in an aesthetic perpetual motion.

In order to paint on this novel "canvas", we developed a special "paint brush". This "paint brush" is a software tool that leverages the powers of a commercially available professional 3D animation program and lets us create content for the *TRANSFORM* in real time. The tool allowed us to quickly prototype and iterate different ideas, which immensely improved the workflow towards the creation of the *Machine* and *Escher* mode and proved an invaluable tool throughout the making of this thesis.

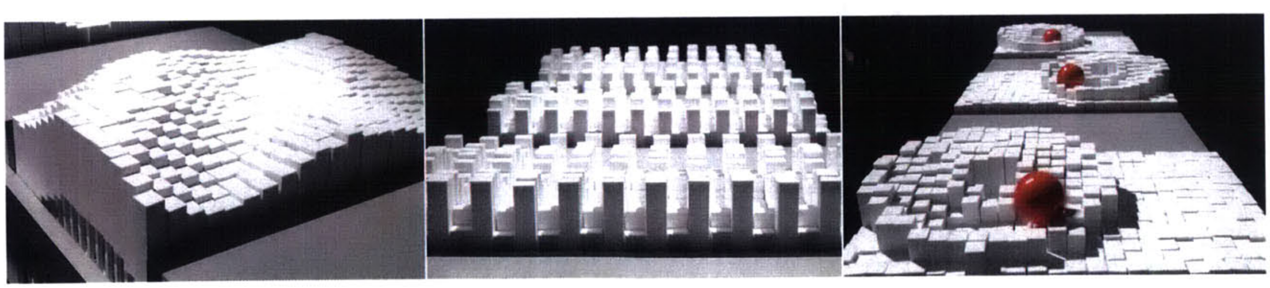


Figure 3. Impressions of the three implemented modes. Left to right: *Wave, Machine, Escher*

To further emphasize the *TRANSFORM's* furniture context, we explored and implemented different potential everyday scenarios that utilize the *TRANSFORM's* shape-changing abilities (Figure 4).

In these scenarios, the *TRANSFORM* actuates passive objects such as fruits, phones, and playing cards to support a variety of use cases in the home and work environment (Vink, 2015). This work presents another example of "inter-material interaction" and shows, in a very applied manner, what a future world with computationally controlled shape-changing abilities might look like.

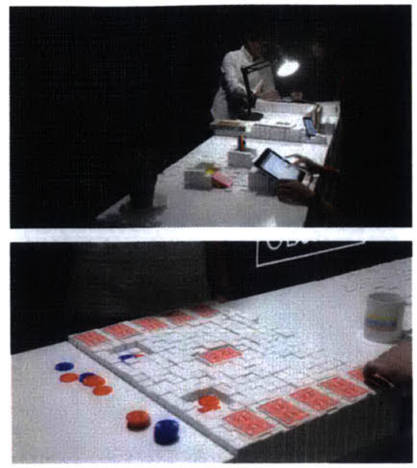


Figure 4. TRANSFORM as a furniture that can adapt to a person's needs and move inert objects.

2.2. Limitations of Pin-Based Shape Displays

"[...] creating highly realistic 3D shapes is the ultimate goal of such displays [...]"

(Poupyrev, 2006)

To better understand the possible potential of shape displays, we also have to look at their limitations. Current shape displays use an array of vertically moving pins to represent different shapes and forms. This method has inherent limitations as to what can be displayed (limited to 2.5D). In general, a pin-based shape display can only correctly render shapes that go up straight or are tapered towards the top. Any form that presents an overhang, overpass or is tapered towards the bottom cannot be displayed correctly (Figure 5). This implies that simple geometries like bridges or tables cannot be represented solely by the pins.

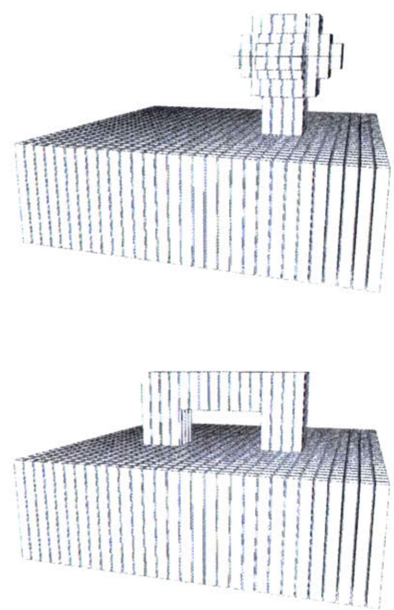


Figure 5. Structures that cannot be displayed on current shape displays: Overhangs and overpasses.

On the interaction side, the shape display's single degree of freedom (DOF) vertical pin movement makes it easy to perform push down interactions but it doesn't allow for any lateral interactions with the generated shape. Hence, we cannot easily translate a presented shape across the shape display using our hands. Leithinger and Follmer try to make up for this limitation by introducing three possible remedies:

Figure 6. Perfect Red and Claytronics (top to bottom). Two fictional materials that present the ideal programmable matter.

1. Using mid air gestures captured by a depth camera (Follmer, 2013).

2. Using passive objects, such as a red ball that serve as a tangible control for the generated shape (Follmer 2013).

3. Utilizing special tools, such as a brush with an attached bend sensor, to move a shape across the shape display (Leithinger 2014).

The shape display's method of actuation is mostly limited to pushing against passive objects from the bottom. This gives us relatively decent possibilities for translation and manipulation of objects. The ability to lift objects probably presents the most basic method of actuation, though we are limited by the shape displays pin range and force of the motors as to how high objects can be lifted and how heavy they can be. Most objects can be moved across the shape display by creating a slope underneath them so the object can slide down, thereby moving it forward. However, we are not able to rotate most objects around their z-axis nor can we use the shape display to grip and hold an object.

A further limitation is the fact that represented shapes are confined to the shape display's bounds. Being able to lift-up and freely move a generated object using ones hands seems like a natural behavior and would greatly improve the application space. We should be able to evaluate and manipulate objects in a position that seems the most suitable and comfortable to the user. A similar idea was described in the *Claytronics* (Goldstein, 2005) and *Perfect Red* (Ishii, 2012) explorations (Figure 6).

This thesis presents an incremental step towards implementing these missing input and output dimensions through the careful union of a shape display with physical objects.

2.3. Modular Robotics and Programmable Matter

In robotics research, programmable matter is described as the construction of objects from fundamental building blocks controlled by computation. These building blocks are mostly represented by modular robots. The ultimate goal of programmable matter research can be described as making the individual building blocks cheap and so small that they cannot be seen with the naked eye, such that, if we had large number of them we could start calling them a material (Goldstein, 2009). In general, miniaturization is always an important topic in programmable matter research. Unfortunately, this constraint is hard to overcome as most building blocks require some sort of actuation mechanism, which in turn needs a sufficient power source. These factors make the miniaturization of programmable matter the most difficult problem to solve.

Researchers such as Skylar Tibbits at the MIT's Self Assembly Lab have gone a different route to overcome this problem. Instead of relying on internal actuation, they use external actuation such as turbulent water in combination with preprogrammed building blocks that lock into each other by chance (stochastic approach) (Tibbits, 2012). This approach does allow for the miniaturization of building blocks but offers very limited reconfigurability.

In this thesis, we do not offer a permanent solution for the miniaturization of programmable matter but we show that unpowered building blocks in combination with a shape display present a novel approach towards programmable matter.

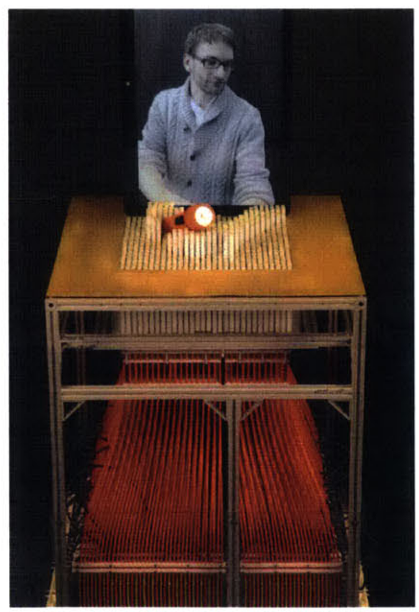


Figure 7. *inFORM* shape display setup. 900 pins are precisely actuated through motorized slide potentiometers.

2.4. System Overview

All described actuation scenarios in this thesis were implemented on the *inFORM* system. 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. It can extend the pins up to 100 mm vertically with a maximum speed of 0.644 m/s (Figure 7).

3. Related Work

This thesis tries to cover a fairly broad spectrum of ideas and therefore builds off of a rich body of research, both in Human Computer Interaction as well as robotics. In our work, we try to synthesize many of these themes.

3.1. Tangible Construction Kits and Tangible Tabletop Interfaces

Interacting with information through a set of building blocks is a common approach in Tangible User Interfaces (TUI) and their precursors (Ullmer, 2000). Examples include the physical CAD construction kits by Frazer et al. (Frazer, 1982), Aish et al.(Aish, 1984), and systems like *MERL blocks* (Anderson, 2000) and *ActiveCubes* (Kitamura, 2000). Construction kits like *Lego Mindstorms* and *Topobo* (Raffle, 2004)(Figure 8) add actuation through motorized bricks. However, these modules move the structure, without aiding in the assembling of it.

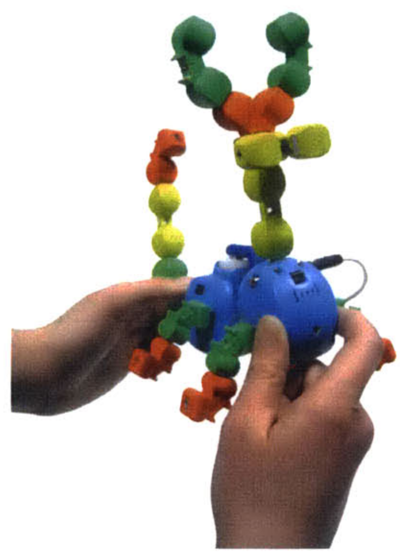


Figure 8. *Topobo* as example for constructive assembly. The user's input movement can be recorded and repeated.

A related form factor based on spatial relationships between blocks is Tangible Tabletop Interfaces (TTI), where the user arranges physical tokens on a horizontal tabletop system. *Bricks* by Fitzmaurice et al. are physical information handles on a tabletop display (Fitzmaurice, 1995) (Figure 9). Ullmer et al. extend bricks to tokens interacting with physical constraints (Ullmer, 2005). *Lumino* by Baudisch et al. is a system to sense multiple tokens stacked on top of each other (Baudisch, 2010).

Most of the listed works are concerned with the sensing of a manually assembled structure to create corresponding virtual representations. The interactive automatic assembly of structures has not yet been focused on.

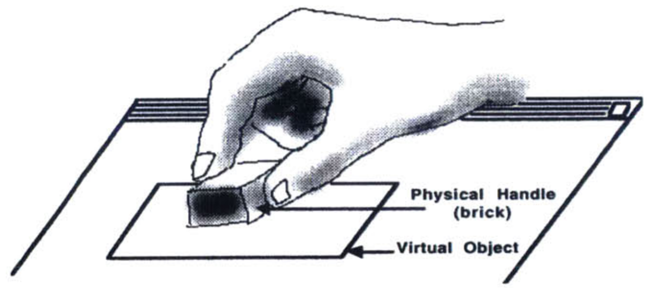


Figure 9. *Bricks* as a physical handle that is tightly coupled to the underlying digital information.

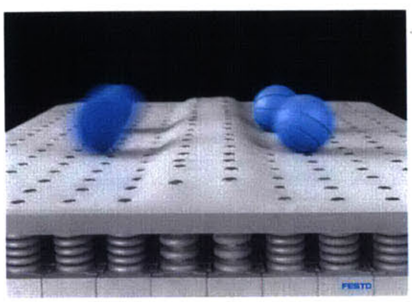


Figure 10. *Festo Wave Handling*. A pneumatically controlled shape-changing surface that moves objects.

3.2. Actuated Tangible Tabletop Interfaces

To overcome the limitations of passive objects, systems like *Pico* by Patten et al. (Patten, 2007) utilize an array of electromagnets underneath a tabletop to computationally move tokens. *Madgets* by Weiss et al. (Weiss, 2010) extends this approach through multi-functional tokens that can be moved, rotated and have their physical state altered through a magnet array. Other techniques for actuation include ultrasonic waves (Marshall, 2012) and wheeled and vibrating robots (Nowacka, 2013). However, these tabletop systems were not designed to construct shapes out of tokens and are unable to stack them on top of each other.

3.3. Shape Displays

While previous shape displays propose to render information through physical shapes (Poupyrev, 2007), *inFORM* also investigates moving various physical objects through shape change (Follmer, 2013). Physical telepresence enables the remote handling of objects through the users shape (Leithinger, 2014). *Festo Wave Handling* proposes object movement through shape actuation for factory automation (Festo, 2013) (Figure 10). *MoleBot* (Lee, 2012) actuates small objects across a table surface through a moving molehill-like shape. While all these systems move objects, they do not assemble them into more complex three-dimensional structures, nor do they investigate the mixing of the inert shape with the dynamic shape.

3.4. Modular Robotics/Self Assembly

Forming complex robots from multiple simple modules was first demonstrated with *CEBOT* by Fukuda et al. (Fukuda, 1990). Modular robots use motorized hinges, or internal flywheels (Romanishin, 2013) (Figure 11), to self-arrange spatially into their target shape. However, at this point, 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 to utilize external actuation to assemble structures. These can be stochastic forces that are combined with active connectors between the blocks (Tolley, 2010), (Gilpin, 2008) or pre-defined structures that lock into each other when tumbled (Tibbits, 2012) (Figure 11). Another approach is to use a swarm of robots to assemble a structure, with examples including Flight Assembled Architecture (D'Andrea, 2013) and Termite Inspired Construction (Werfel, 2014). While programmable matter research provides a lot of technical innovation there is less focus on the interaction with those systems.

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

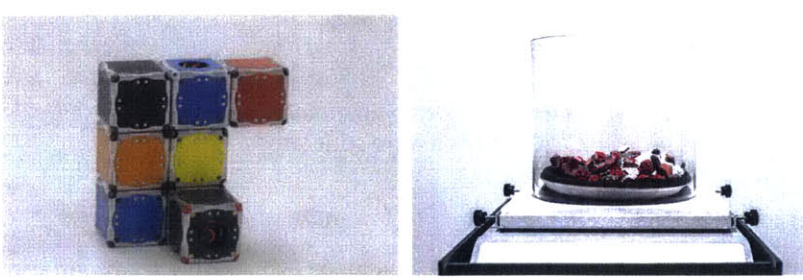


Figure 11. Two examples for programmable matter that demonstrate different assembly approaches. Left: *M-Blocks* uses internal directed actuation. Right: *Autonomous Mass Assembly* uses external undirected energy.

3.5. Kinematic Assemblies

The design of mechanical systems is still mostly a manual task that requires years of experience. More recently, researchers have started to investigate how computation can assist in the design process of complicated mechanical systems. Examples include Ceylan et al. who present an automatic algorithm that generates the design for a mechanical figure that moves according to motion capture data (Ceylan, 2013). Thomaszewski et al. present a design system that allows for easy creation of linkage-based characters (Thomaszewski, 2014). Similarly, Coros et al. describe an interactive design system that allows for the easy creation of sophisticated mechanical characters (Coros, 2013) (Figure 12). Zhu et al. present a method that allows for the synthesization of mechanical toys from the motion of their features (Zhu, 2012). Koo et al. present a software that aids designers in quickly prototyping and testing objects with mechanical parts (Koo, 2014). Though, in this thesis, we design kinematic modules manually, in the future, we hope to have design tools available that let us specify a desired output motion and the computer takes care of designing the required mechanical system.

Figure 12. A realistically moving kinematic cheetah whose mechanical internals were generated computationally.

4. Shape Synthesis

According to the online dictionary the word synthesis can be described as "the combining of the constituent elements of separate material or abstract entities into a single or unified entity."
(http://dictionary.reference.com/)

4.1. Basic Concept

In this thesis, we introduce the concept of *Shape Synthesis* to describe the tight spatial coupling of inert objects with the dynamic shape of a shape display. This combination creates a seemingly new "mixed" object, which combines the richer affordances of the inert object with the computational powers of the dynamic shape (Figure 13). In this chapter, we first attempt a classification of shape synthesis into existing Tangible User Interface (TUI) frameworks. Next, in addition to example scenarios, we describe interaction primitives and applications where the inert physical object is used as both a representational as well as a control object.

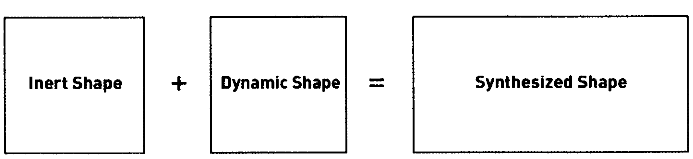


Figure 13. The tight coupling between the inert and dynamic shape creates a synthesized shape.

4.2. TUIs and Physical Augmentation

In their *Bricks* paper, which can be regarded as laying the foundation for the idea of Tangible User Interfaces, Fitzmaurice, Ishii and Buxton describe how Graspable UIs *"[...] are a blend of virtual and physical artifacts, each offering affordances in their respective instantiation"* ((Fitzmaurice, 1995). The bricks present a tangible handle that can be used to manipulate digital content. Ishii further iterated this idea and described the central characteristic of TUIs as the tight coupling of the physical representation ("physical handle") to the underlying ("under the water") digital information (Ishii, 1997).

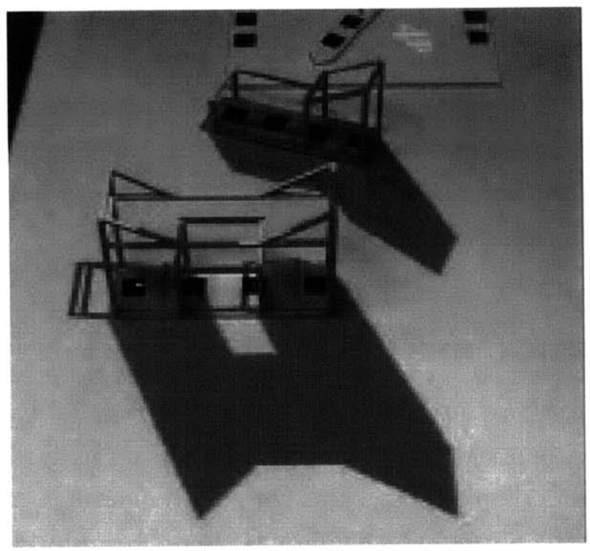


Figure 14. *Urp*: A great example for the combined power of inert object plus computation. A digital shadow is attached to an iconic physical building. Wherever the building moves, the shadow moves.

Many classical TUIs come in the form of interactive table-top-displays in combination with some kind of physical token (Ullmer, 2000). In such interfaces it is very common to graphically augment these physical objects, either to add context specific information to symbolic tokens as in *SLAP Widgets*, (Weiss, 2009), *DataTiles* (Rekimoto, 2001) and *THAW* (Leigh, 2015), or to add digital functionality to more iconic objects as in *Urp* and *Luminous Room* (Underkoffler, 1999) (Figure 14).

On the other hand, a shape synthesized object can be described as physically augmented. Instead of augmenting the object through pixels, the shape display creates a dynamic physical extension that is seemingly attached to the object. This extension can either represent a missing part of an object (shape substitution) or add additional functionality to the object. For instance, a designer who is tasked with reiterating the design of a toaster lever could place the toaster's already finished parts on a shape display and physically augment it with different versions of the lever design to get a better sense of the finished object (Figure 15). Moreover, the toaster lever's input mechanism operation could be simulated by pushing down on the pins. We could also imagine, the other way around, where an already created toaster handle mechanism can be physically augmented with different toaster designs. This time, the dynamic shape could simulate the toasters output mechanism by popping a piece of toast (Figure 15). Though, the example might seem rather randomly specific, it very nicely demonstrates the powers that shape synthesis affords.

Figure 15. Renderings of a shape synthesized toaster. Left: The lever is represented by the shape display and can be changed dynamically. Right: The lever is static and toaster is dynamic, simulating the popping mechanism.

4.3. Classification

At this point we would like to define the concept of Shape Synthesis to provide a better view on where this concept can be situated within the vast research space of Tangible User Interfaces. This also allows us to make a clearer distinction between the concept of Shape Synthesis and Follmer's and Leithinger's work with physical objects on shape displays (Follmer, 2013).

4.3.1. Strong Degree of Coherence for Increased Reality Based Interaction

The tight spatial coupling of the inert object to the dynamic shape makes for a coherently strong interface. Here, the "degree of coherence", can be described as the level at which a coupled physical and digital object are perceived as the same thing (Koleva, 2003). The stronger the coherence the more the user's knowledge and skills of interaction with the real world are leveraged when using the interface. Following Kovela's framework we can make a distinction between Follmer's and Leithinger's work (Follmer, 2013) and the concept of shape synthesis. Follmer and Leithinger use physical objects as a multi purpose "tool" for performing different tasks, which would categorize the TUI as coherently weak. Shape synthesized objects, on the other hand, rather afford more specialized tasks while giving the illusion of being the same object, which places this concept on the opposite end of the spectrum (Figure 16).

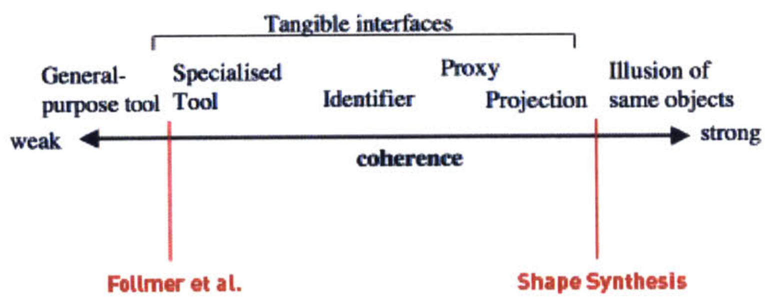


Figure 16. Koleva et al.'s framework appended. Shape synthesis is coherently strong whereas Follmer et al.'s work focuses on the inert object as a general purpose tool, which categorizes it as a coherently weak tangible user interface.

Building upon that, Jacob et al., in their paper, describe their observation that current HCI research is dominated by the idea of taking advantage of the human's inherent skills of interacting with the "real" world (Jacob, 2008). They present a framework for reality-based interaction, trying to tie together the different categories of interaction, such as virtual reality, augmented reality, ubiquitous computing and tangible interaction. According to them, basing interaction on pre-existing skills will decrease a user's mental effort when interacting with computer systems.

Yet, Jacob et al. suggest scaling back on reality-mimicking metaphors and interactions if the power of computation presents a substantial advantage to performing a task. He urges designers to find the right balance between "realism" and the computer's versatility and malleability (Jacob, 2008).

In the concept of *Shape Synthesis*, we follow a similar route. We try to dissolve the boundary between the "real" and the "digital" to leverage both the user's skill to interact with physical objects and the computational power of the dynamic shape. While we can use a synthesized shape to simulate an object's real world behavior (see 4.5.2.), we can also leverage the computational power to go beyond constraints of reality (see 4.5.1.).

4.3.2. Spatial and Iconic

In their framework, Ullmer and Ishii (Ullmer, 2000) classify different TUI related works into four categories: *Spatial*, *Constructive*, *Relational*, *Associative*. In this section, we focus on the most relevant categories, *Spatial* and *Relational*. In short, a spatial TUI can be described as an interface where a physical object's position and orientation is spatially concurrent with the displayed digital information, exemplified in the *Luminous Room* (Figure 17) and *Urp* project (Underkoffler, 1999).

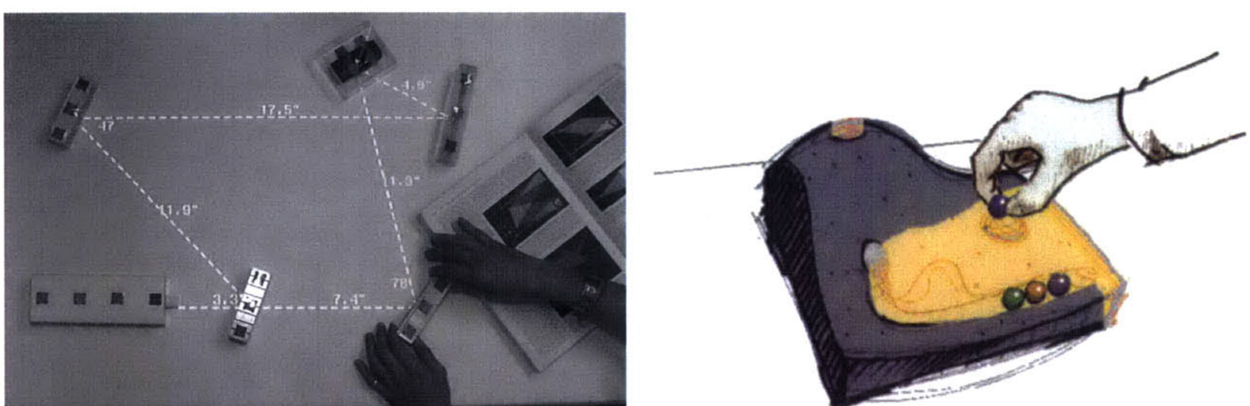


Figure 17. Left: *Luminous Room* as example of a spatial TUI. The information follows the token. Right: Marble answering machine as example of a relational TUI. The token's position is mapped to abstract tasks.

By contrast, in a relational TUI the physical object's position or proximity to objects or elements is mapped to certain, often more abstract, computational tasks. Good examples for relational TUIs are tangible programming blocks such as *AlgoBlocks* (Suzuki, 1993) and *Programming Bricks* (McNerney, 2000) or as a non-educational application, Durrell Bishop's marble answering machine (Abrams, 1999)(Figure 17). These categories are not mutually exclusive and TUIs often times share features from each other.

Within each category, a TUI can be described as either symbolic or iconic. In symbolic TUIs, the physical objects are abstract and do not have surface or visual features that provide any indications about their coupled digital information, similar to how an ordinary number or letter can be used as a symbol that can represent anything. Exemplary TUIs are *Bricks* (Fitzmaurice, 1995) and *LegoWall* (Fitzmaurice, 1996) (Figure 18).

Figure 18. Left: *LegoWall* uses symbolic tokens that each can have different functionalities. Right: *metaDESK* uses iconic tokes that have a more specialized functionality.

In iconic TUIs the physical object has some representational resemblance to their coupled digital information. Examples include *Urp* (Underkoffler, 1999) and *metaDESK* (Ullmer, 1997) (Figure 18).

Follmer and Leithinger's work with objects on shape displays (Follmer, 2013) can be described as a relational and symbolic

TUI. Since their work mostly focuses on dynamic physical user interfaces, objects are used for their symbolic value. A red ball represents a handle to an interface element rendered by the shape display, such as a slider or circular control. The inert object does not offer any visual or physical reference to the shape that is displayed. Their work can be regarded as a relational TUI inasmuch as the physical translation and manipulation of the object controls abstracted actions such as scaling the dynamic shape or for moving through a "Cover Flow" like menu.

The concept of *Shape Synthesis* can be classified as a spatial and iconic TUI. The inert object is usually spatially tightly coupled to the digital information (dynamic shape). Additionally, in *Shape Synthesis*, the inert object is most often part of a larger physical object, which makes it iconic in nature. For instance, in chapter 5.5.3. we describe how a cylindrical shaped token represents the joint of a larger mechanical system.

4.4. Overcoming Limitations and Richer Affordances

Shape displays offer great novelty, as they make a part of the physical world appear to be dynamic and adaptable. One could argue, why would we need to combine this new dynamic "material" with a static and rigid objects if we can just use the shape display to render the object?

The fact is that current shape displays are still very limited in their input and output capabilities, with the input limitation probably being the most restricting. Objects that are displayed on the shape display cannot be moved in a way that would correspond to our experience of moving objects in the real, non-digital world. Pushing against a rendered shape to move it around the shape display feels jerky and discontinuous. The same applies to interactions that cause the rotation of a rendered shape around any of its axes.

Using real world objects and their richer affordances allow for smoother interactions with the shape display. In *Shape Synthesis,* the dynamic shape updates according to the passive object's manipulation. Furthermore, the shape display can actuate the object together with the dynamic shape and thus help keeping the inert object's state in sync with the digital state (Pangaro, 2002).

In one of our application examples, we use a cylindrical object as an iconic representation for a joint. The pieces connected by the joint are represented through the shape display. The cylindrical object allows us to rotate it using our hands which, in turn, will rotate the tightly coupled dynamic shape. This would not be possible without an inert object. Additionally, the dynamic shape can be used to create physical barriers which can constrain or prevent a user's actions (Follmer, 2013).

4.5. Shape Synthesis Primitives

To explore the idea of *Shape Synthesis,* we have implemented several proof of concept primitives that let a user move synthesized blocks and cylinders on a shape display, where the augmented shape can perform different computational tasks and simulations. The presented primitives cannot be regarded as a complete set of all possible primitives but a small collection of a larger application space. We divided the primitives into three categories: *Compound, Material* and *Mechanical.*

4.5.1. Compound

In this category we, describe interactions with two colliding synthesized shapes (Figures 19 – 26). The collisions can either behave in a realistic way (simulation) or leverage the computational power to create new shapes through common CAD inspired operations (compound objects).

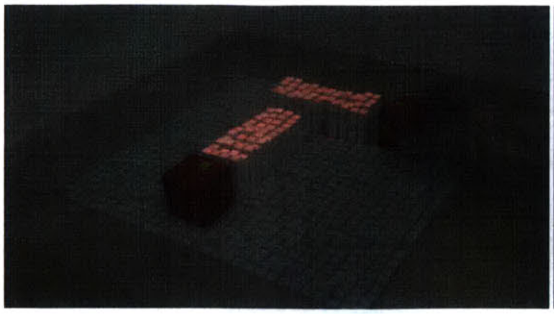


Figure 19. Standard setup. Using specially painted blocks we can track their position and update the dynamic shapes accordingly

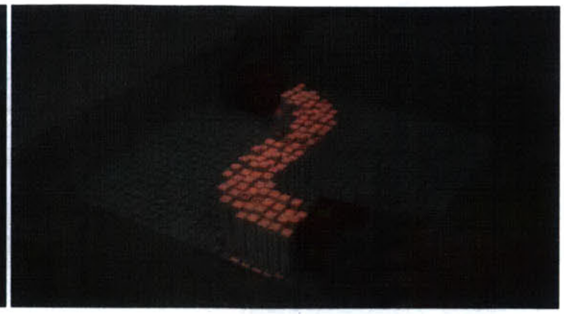


Figure 20. A shape synthesized object can consist of more than one inert object. Here we simulate a lasso whose two ends are blocks.

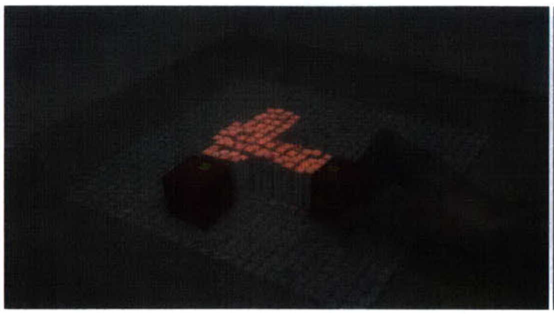


Figure 21. *Union*: The dynamic shapes can overlap as if they were not a physical object.

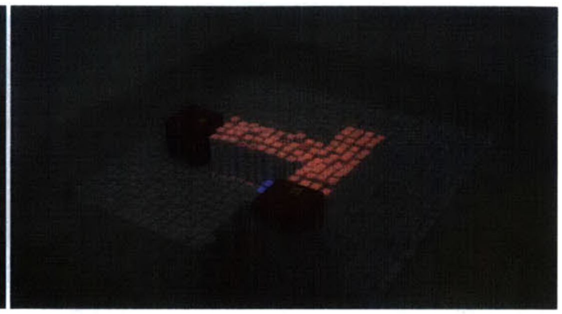


Figure 22. *Constraint*: Opposite to Union, we can create the illusion of physical constraints by using the pins (blue).

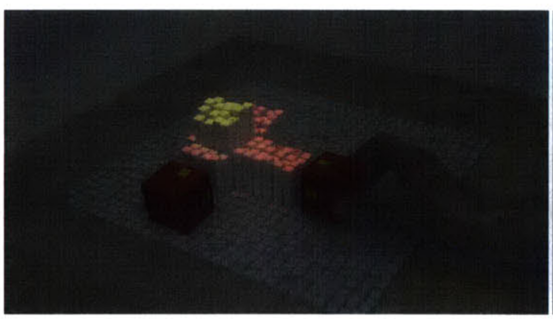


Figure 23. *Add*: The area of intersection between two synthesized shapes are added together.

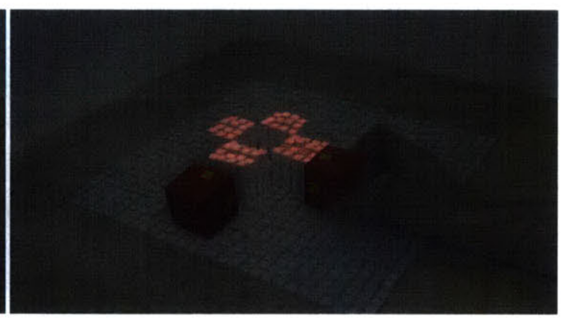


Figure 24. *Subtract*: Here the area of intersection is subtracted from the form.

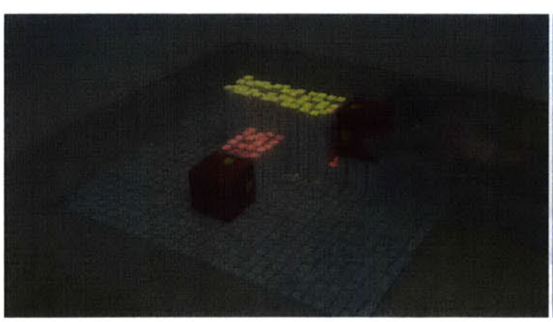


Figure 25. Stack: We can stack two synthesized shapes on top of each other. As in *Constraint*, this simulates the behavior of real objects.

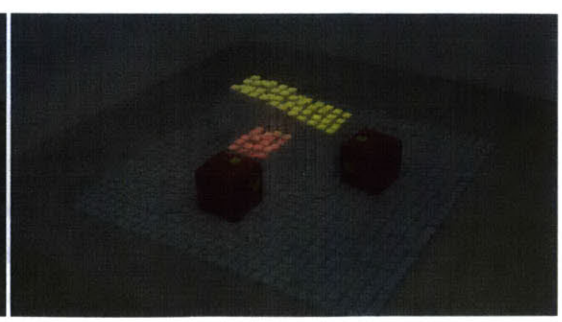


Figure 26. If the center of mass is off, the top synthesized object will tilt accordingly.

4.5.3. Mechanical

Here we introduce cylinders as objects on the shape display. The cylinders are iconic objects for joints that allow us to create simple mechanical structures where the dynamic shape presents the levers around the joint (Figures 27 – 30). Its orientation determines the direction of rotation.

Figure 27. We track the position, orientation and rotation of a specially painted cylinder. Here the vertical position lets us rotate the shape levers around their z-axis.

Figure 28. Orienting the cylinder in a horizontally changes the dynamic shapes axis of rotation to be x or y.

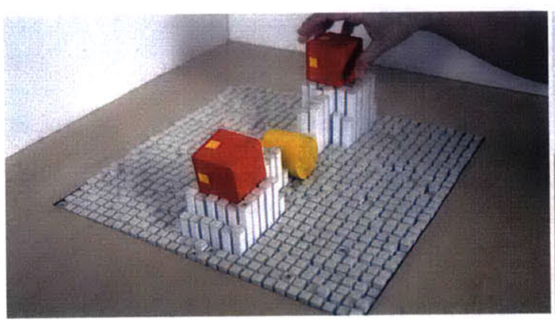


Figure 29. One application could be a shape synthesized scale where the cylinder represents the scale's axis.

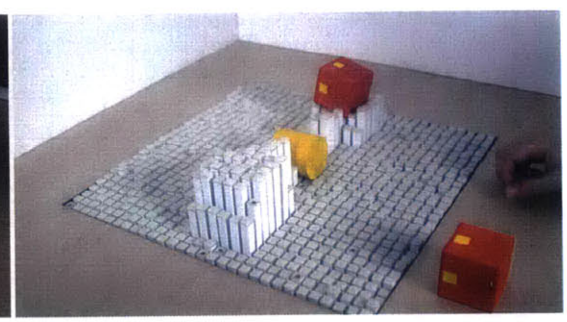


Figure 30. We use the specially painted blocks as weights. The scale adjusts accordingly.

4.5.2. Material

We can not only introduce gravity into the dynamic shape but also simulate material properties, such as friction, mass, flexibility and elasticity (Figures 31 – 34). We demonstrate this concept by colliding two synthesized shapes. These application primitives are not yet implemented and are therefore represented by 3D renderings.

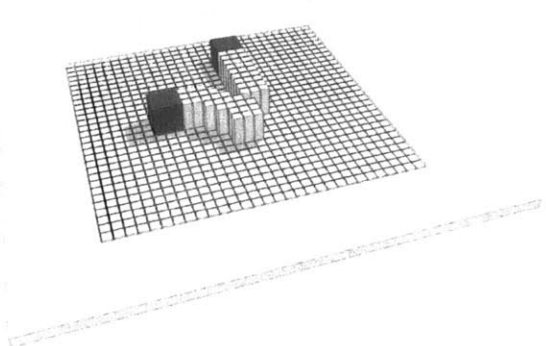


Figure 31.The dynamic shapes can simulate different material properties. Here one is hard while the other is soft and rebounds when a collision appears.

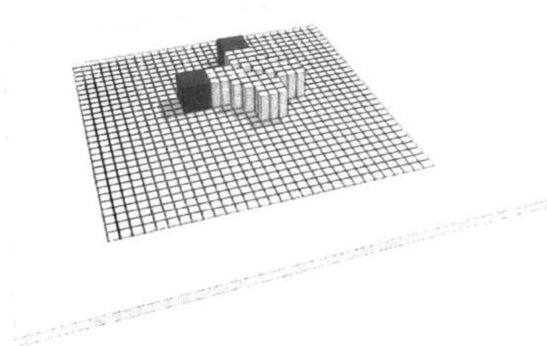


Figure 32. When two shapes have the same material properties, they behave accordingly.

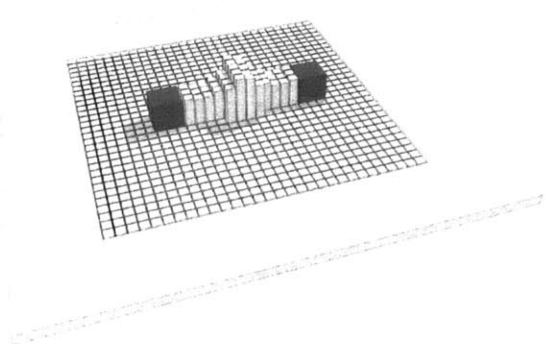


Figure 33. Material extension can appear in all three dimensions.

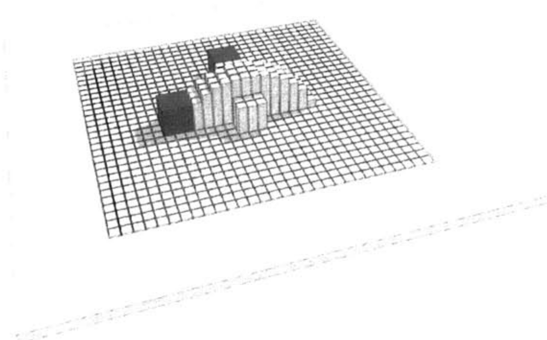


Figure 34. A softer material is put on top of a harder material.

4.6. Application Scenarios

Since we are limited by the shape display's technical constraints such as low resolution and latencies due to camera tracking, in this section we would like present example scenarios that describe the use of shape synthesis in a more applied context. We believe, once shape displays mature and object recognition technologies improve, these applications could be implemented.

4.6.1. Industrial Design

We imagine shape display as a tool for industrial designers. Similar to the aforementioned toaster example, other design prototypes that were created using CAD tools could be displayed as a whole or combined with already manufactured objects through shape synthesis. The shape rendered by the shape display does not need to be static but can simulate moving parts. In Figure 35, you can see a concept rendering of garden shears on a shape display. The handle part is already designed and fabricated but the blades are still in the process of realization. Designers can easily test the final garden shears functionality and quickly iterate through different blade designs.

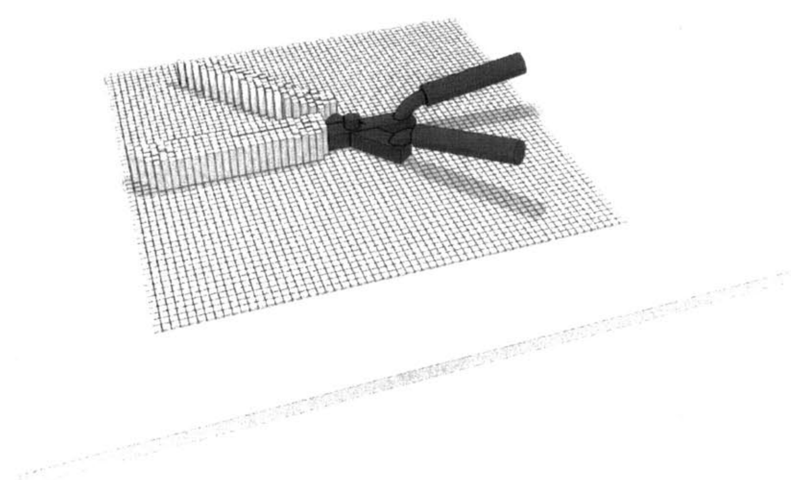


Figure 35. A shape synthesized garden shear that could simulate the cutting mechanism.

4.6.2. Reconstructive Surgery and Archeology

For surgeons, a shape display could present a very useful tool for planning reconstructive surgery. Prostheses or other artificial body replacements could be fitted and tested on a shape display before surgery takes place (Figure 36). In the concept renderings, we show how an artificial bone replacement is fitted to the rendered shape of a patient's MRI data. The shape synthesized object can be moved in real time to determine if the replacement part will be fully functional after surgery.

Similarly, an archaeologist could match bones found in the field against the physical representation of skeletal data from other specimens to determine the species or the period the animal or human lived in.

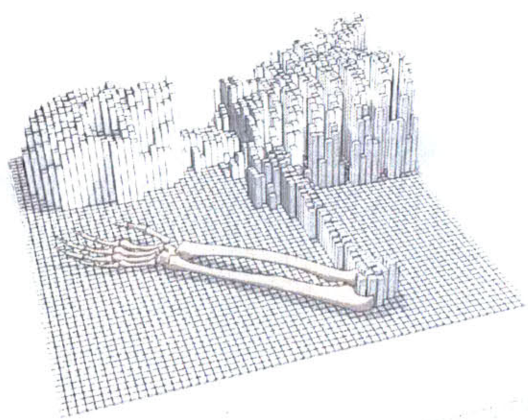


Figure 36. Real bones are combined with a rendered skeleton. Joint connection and degrees of freedom of movement could be simulated.

4.6.3. Mixed Tools

If we imagine the use of a shape display for 3D modelling and texturing, it would be convenient to have tangible tools that leverage a human's fine motor skills and thereby in the creation process. Shape synthesis allows us to augment an ergonomically formed handle with multiple tools such as a different brush tips (Figures 37). This allows us to combine the rich affordances of a handle with the dynamic shape.

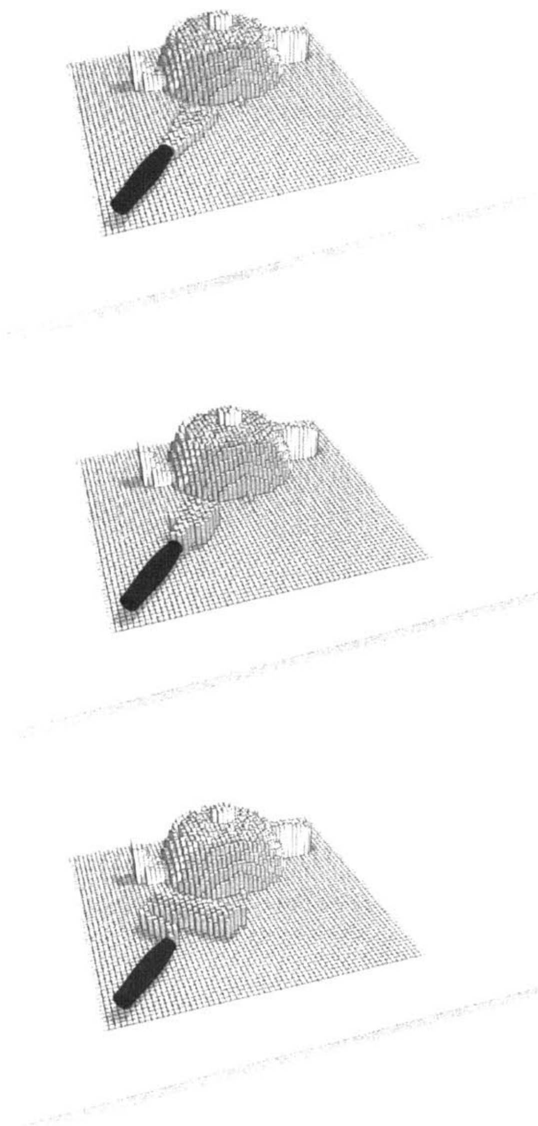


Figure 37. A tool's handle can be augmented with different brush tips for texturing a 3D model.

4.7. Implementation

For the implementation of the presented applications we use cube and cylinder shaped wooden blocks that have a size of 50 x 50 x 50 mm. The software is written using C++/openFrameworks and OpenCV (Figure 38). We get color and depth images from a Kinect depth camera. We threshold the depth image just above the table surface to isolate content regions. We black out corresponding non-content regions in the color image. The cubes are painted red with yellow markers specifying a preferred direction. The cylinders are painted yellow with a blue marker to determine orientation and rotation angle.

4.7.1. Object Detection

For each object type we want to detect, we threshold the color image in HSV space. Cubes and markers are matched on hue; touched cubes are detected as low-brightness content, since the only objects other than cubes touching cubes are pins with bright graphics projected onto them.

Using these color-thresholded images, we detect blobs of valid size. We then track the blobs and find their minimum bounding angled rectangles using the open-source Community Core Vision (CCV) library developed by the NUI Group Community. CCV uses OpenCV findContours and minAreaRect functions under the hood.

Cubes are recognized from red cube blobs, with blobs matched to cubes across video frames using CCV's blob tracking. The cube angle is determined from the blob's minimum bounding rectangle and the cube orientation from the nearest detected marker blob. We determine whether the cube is being touched by testing for a corresponding touched cube blob. Depth parallax causes distortion in the perceived x-y coordinates of the cube, so we correct this using pre-calibrated reprojection equations. To limit noise, we only update cube properties frame-to-frame when the difference against old properties passes a hysteresis threshold.

4.7.2. Shape Generation

Pin heights are specified as a grayscale bitmap with one pixel per pin. Applications draw pin heights and graphics based on detected objects and remembered history.

We maintain a one-pin-width clearing around cubes at all times to facilitate movement of the shape synthesized object. Additionally, touched cubes are lifted slightly above their surroundings by the shape display, to let them slide easily.

4.7.3. Projection

We project graphics onto raised pins to both emphasize discrete objects and increase the effect of synthesis. Graphics are first calculated as x-y graphic maps, then are reprojected according to the current pin heights so as to land at the correct 3D pin surface coordinates. As with the parallax corrections to cube location, x-y graphics are corrected using pre-calibrated reprojection equations.

To avoid accidental projection onto cubes, which would disrupt cube detection, cube footprints are blacked out of the x-y graphic maps before reprojection, and cube heights are accounted for in the table surface height map.

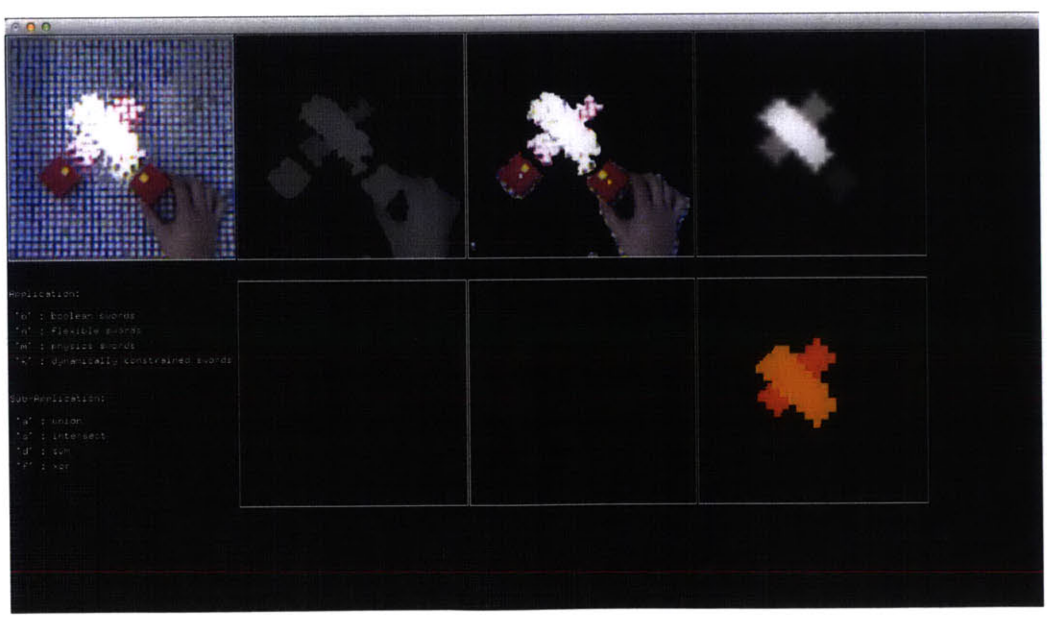


Figure 38. Screenshot of Computer Vision pipeline

4.8. Limitations

The object tracking is still very limited and rudimentary. If we move an object too fast, the system induces a noticeable lag. This is caused by the depth camera's relatively low frame rate (30 fps) and latency due to internal image processing (50 ms). Newer generations of depth cameras will surely be able to track objects with a higher precision and at faster speeds.

When tracking objects using a camera from above, occlusion is always a big issue. This could be avoided using multiple cameras from different angles or embedding sensors into the shape display that could determine a placed object's orientation.

5. Shape Displays for Actuated Constructive Assembly

In this chapter we will expand the concept of *Shape Synthesis* by presenting ideas and techniques that utilize the *inFORM's* 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. We then discuss the reliability of our presented techniques through a technical evaluation and a description of applications and example scenarios.

5.1. Rationale

The idea of dynamic, computer-controlled shapes that form tangible user interfaces on demand has been proposed in research visions like *Radical Atoms* (Ishii, 2012) and *Claytronics* (Goldstein, 2005), and studied in related fields like modular and swarm robotics. But the complexity of arranging multiple building blocks in three dimensions while allowing for direct human input has so far limited their practical implementation as computer interfaces.

Currently, two technical approaches to create dynamic shapes dominate: multiple modular elements, and shape-changing interfaces. We propose to combine these two techniques to arrange simple passive unpowered building blocks through an underlying shape display. This approach circumvents some of the engineering challenges of modular robots, while enabling more degrees of freedom for rendering and interaction than current shape displays.

5.2. Design Criteria

We identified several design criteria for our system. Unlike systems for additive manufacturing and modular robotics, the design of 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.

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

- *Safety*: No mechanisms like robot arms should be mounted above the shape to avoid colliding with the user's hands.

- *Parallelism*: To speed up the assembly process, multiple building blocks should be able to move simultaneously.

- *Scalability*: The building blocks should be simple, so adding more does not significantly increase cost and complexity.

5.3. Effecter Affordances

Before we describe the different techniques that allow us to assemble structures on the *inFORM* system we would like to explain the concept of effector affordances, which play an important role in determining how a shape display can handle and manipulate different objects.

According to Gibson affordances are all possible actions that an object offers to an agent. However, these affordances are always in relation to the agent that is using the object (Gibson, 1986). For example, a set of stairs does not afford climbing if the agent is a baby that cannot even walk. In constructive assembly, the agent is the shape display and the object is the building blocks. What the building block affords to the shape display is relative to the shape display's technical specifications. For example, strong motors can catapult objects, whereas weaker motors might only be able to stack objects.

This leads to the question: Can we regard a technical object as the agent? The answer to that question is offered by Kaptelinin et. al., who introduce the concept of *instrumental affordances* (Kaptelinin, 2012). A user can, through the interaction with technology, indirectly cause an effect on another object. The technology acts as a mediator between the human and the object. The affordances for interacting with the technology (*handling affordances*) and the possibilities of the technology to have an effect on the object (*effecter affordances*) are comprised under the umbrella of *instrumental affordances* (Figure 39). This concept gets clearer if we regard it with reference to a simple object like a knife. Knives are comprised of two distinct parts, one for affecting the object (blade) and one for handling the instrument (handle). A user directly interacts with a knife's handle (Person - Technology) according to its affordances and the attached blade affects an object according to it's affordances (Technology - Object).

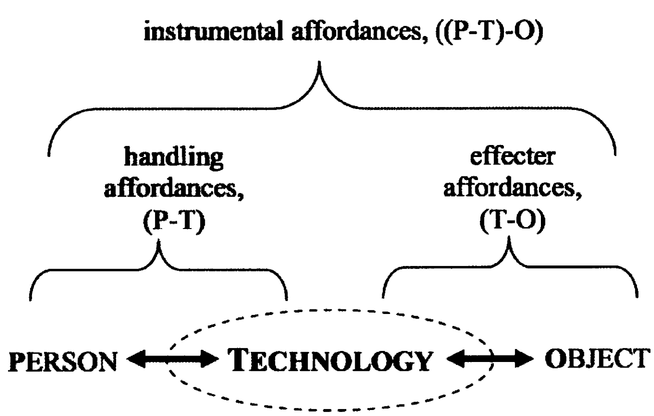


Figure 39. Kaptelinin et al.'s framework of instrumental affordances. The effecter affordances determine how a technology interacts with an object.

For actuated constructive assembly, we are interested in the *effecter affordances* (Technology - Object, i.e. Shape Display - Building Block). The building blocks shape, weight and size as well as the shape display's resolution, pin spacing and strength present factors that determine the actuation possibilities. If the building block is too heavy, the shape display cannot lift it. If it is too big, the shape display cannot stack it. A round object affords rolling, whereas an angular object affords tumbling. If, for example, we would introduce relatively small changes to the building blocks, e.g. rounded edges, the assembly techniques presented in this document would no longer work.

5.4. 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 (Follmer, 2013) (Leithinger, 2014). In this document, we try to identify the fastest yet most reliable way to move and rotate these building blocks.

5.4.1. Translation and Rotation

On a shape display, we can move rectangular or cubical objects by creating a ramp that lifts one end of the object so that gravity will slide it forward. At higher speeds the objects will start to tumble uncontrollably which can be a problem when trying to move it to an exact position. To still be able to move the blocks precisely at faster speeds we developed the sled (Figure 40). The sled has a has a 6 x 10 pin footprint and provides a guiding rail on either of its sides and at the front, which prevents the block from tumbling off the ramp. When moving around corners or before performing any other actuation to the building block, we have to make sure it is aligned correctly inside the sled's boundaries. We do that by raising the ramp inside the sled which causes the cube to rotate onto one of its sides, which aligns it precisely to be ready for further actions. We found the top speed to reliably translate the blocks across the surface to be 0.2 m/s.

To rotate the block 90 degrees around its x or y axis, we first create a guiding rail around the block and lift it from one side until it lands onto its perpendicular side (Figure 39). The rotation technique has a footprint of 6 x 7 pins and we can perform 80 x- or y-rotations per minute, or 26 z-rotations. As we are unable to create any lateral forces on a shape display, the rotation around the blocks z-axis requires an x-y-x or y-x-y rotation.

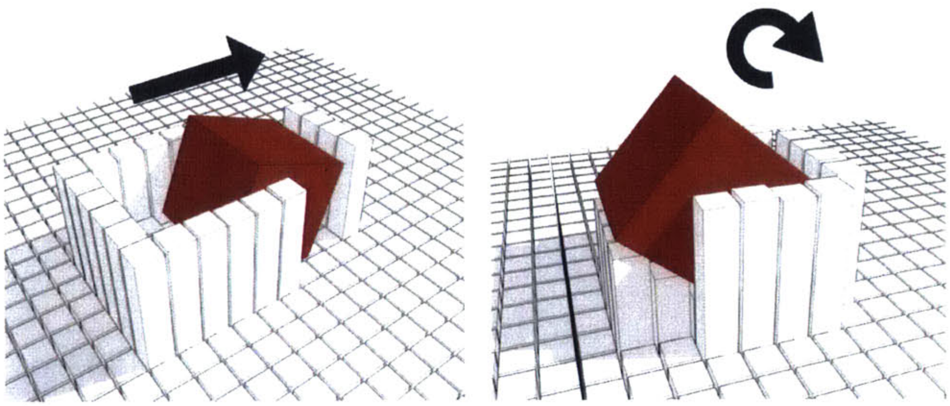


Figure 40. Left: Using the shape display's pins, we create a sled that can move the blocks across it. b) Lifting a block from one side and physically constraining it on the opposite side lets us rotate it around its x, y and z axis.

5.4.2. Stacking

While the precise translation and rotation of cubes on a 2D plane enables us to create single-layer structures, to build more sophisticated multi-layer, three dimensional structures, it is necessary to construct in z direction as well. Shape displays do not allow us to place building blocks on top of each other from above as a robotic arm would do. To be able to stack one block onto another, we first lift it using the pins. The lifted block needs to be slightly higher (5.5 cm) than the block one wishes to build upon. We then tumble it on top of the other using a ramp. We cannot precisely control the block's velocity when it tumbles on top of the other which can cause a misalignment of the two. We therefore use the surrounding pins to construct a guiding-rail structure around the blocks similar to Figure 40.

Blocks as Helpers

On pin-based shape displays, the pin actuation height presents a limiting factor when stacking blocks. In our current system the maximum pin height is 10 cm. Considering the blocks height of 5cm, we are limited to two-story structures. We can, however, overcome the pin height limitation constraint to a certain degree by utilizing a building blocks as a helper object (Figure 48e). Lifting and tumbling a two-layer structure onto another two layer structure will cause the top block of the lifted structure to tumble onto the resting structure, thus creating a third layer. We could not reliably create a four-layer structure using this method. This is due to the fact that we could not support the resting structure with a high enough surrounding guiding rail causing it to collapse when we tried to stack the fourth block.

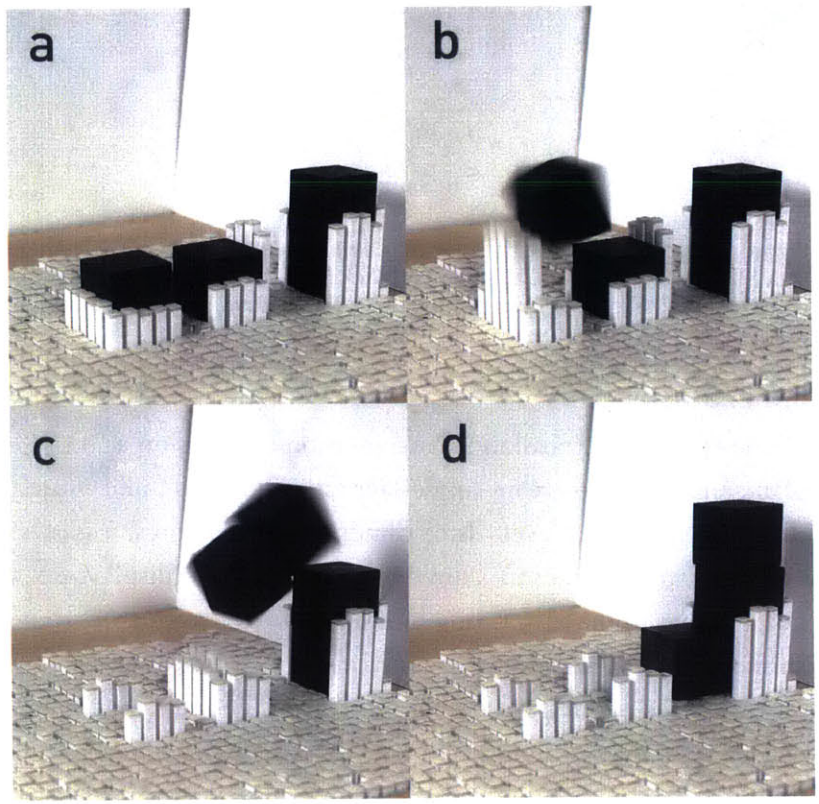


Figure 41. Catapulting the blocks on top of each other lets us create up to three story structures when utilizing an additional building block as helper object.

Catapult

An alternative way of stacking blocks is to catapult blocks on top of each other by quickly raising and lowering the pins underneath the block's half that is opposite to the desired flight direction. On our current system, we can create two story and three story structures reliably, using this method. The three story structures are constructed by employing the helper cube technique. We catapult an already two story structure onto another two story structure whereby the top block will land on the two story structure (Figure 41). Through trial and error method, we found the ideal distance between the blocks for the two layer structure to be 2.5 cm and 5 cm for the three story structure.

Scaffold

We can use the pins to create a temporary scaffold for assembly tasks. For instance, we can create a bridge by lifting a rectangular block that is (150 x 50 x 50 mm) with 4 x 4 pins at its center of mass. We then tumble blocks that represent the bridge's pillars underneath each of the lifted block's sides. After removing the scaffold by driving the pins to their zero position, the bridge will rest on the pillars (Figure 48g).

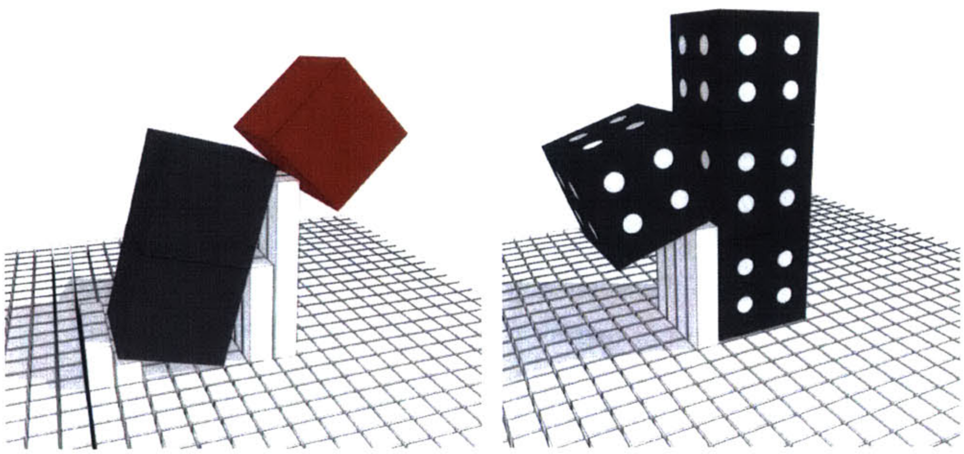


Figure 42. Left: We unstack the structure by toppling it so that the top block can slide off. Right: Bumping the pins against the locking block breaks the magnetic connection.

Disassembly

To be able to reuse blocks or reconfigure structures, we need to disassemble them. We can disassemble non-locking block structures by simply toppling it completely. Or, if we need to more selectively disassemble blocks, we can slightly tilt the structure and create a scaffold for the blocks that are supposed to stay assembled. The non-supported blocks will slide down. We then tilt the remaining assembly back into its previous stable position. The locking blocks can be disassembled by quickly bumping four pins in a row against their connected side. This sudden impact causes the magnets to disconnect and the part to come off (Figure 42).

5.5. Building Blocks

We explore actuated constructive assembly on shape displays with non-locking and locking (magnetic) building blocks. We determined the building block's size to be 50 x 50 x 50 mm, according to MacKenzie's findings that square blocks with a width of 50 mm are easy to hold and support a precision grip (MacKenzie, 1994). The blocks have a footprint of 4 x 4 pins, which in practice proves to be the best size for reliable actuation and manipulation compared to smaller or bigger blocks.

5.5.1. Non-Locking Blocks

The non-locking building blocks are just plain wooden blocks without any special mechanism. We use them to assemble more temporary structures that can easily be disassembled. The blocks have a weight of 90 g each, which is light enough for the *inFORM* to still lift up to four blocks that are stacked onto each other and heavy enough so that the blocks will not bounce uncontrollably when sudden changes on the underlying shape display occur (e.g. a change of direction when traversing).

5.5.2. Locking Blocks

We created building blocks that can be connected magnetically. One important design requirement was for the connections to provide enough force to carry at least one other building block to create overhangs. At the same time they needed to be weak enough so that we can break the connections using the shape display's pins. The connectors we designed consist of a spherical neodymium magnet with a 6 mm diameter which is housed in a 3D printed 6.5 mm long cylindrical shell with a 10 mm diameter. This allows the magnets to freely rotate within the shell which lets us create ungendered connections that can connect to any of the block's sides in any orientation. Additionally, the shell helps us to control the magnet's connection strength by varying its top opening diameter. This opening physically constraints the magnet from moving too close to an attracting magnet which would cause the connections to be too strong. We experimentally determined the shell's ideal diameter and wall thickness to be 4 mm and 1.5 mm respectively. We drilled 24 holes into the wooden cubes using a CNC machine and inserted four magnetic connectors in each of the cube's sides in a symmetrical orientation (Figure 43). This design allows us to connect up to six other blocks to a single block, while the magnets help with the precise alignment of connected blocks. Furthermore, the locking blocks allow for an additional assembly technique by assembling structures in the horizontal plane, which can then be brought into vertical orientation using the underlying pins.

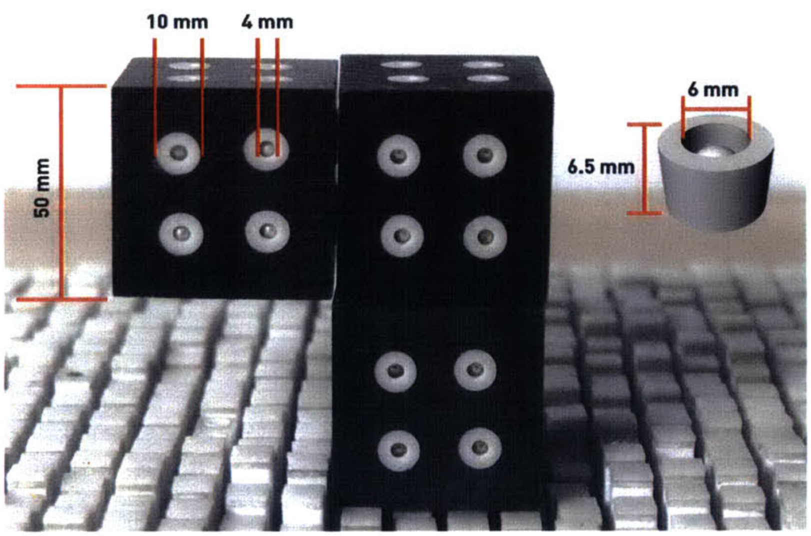


Figure 43. Locking blocks are made with spherical magnets inside a 3D printed plastic shell.

5.6. Demonstration of Actuated Assembly

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

5.6.1. Constructive Assembly and Shape Synthesis

We can not only utilize the shape display's pins to move and stack the building blocks, but we can also combine them to create shape synthesized structures. The ability to create these "mixed" structures presents a powerful concept. We can use the shape display to either substitute for missing building blocks or to create more temporary structures. For instance, a castle assembled from building blocks could have a gate that is represented by the shape display to allow it to open and close automatically (Figure 44).

Furthermore, *Shape Synthesis* allows us to give kinetic ability to otherwise static structures. In our examples, we created a bird that could flap its wings and a moving worm (Figure 44).

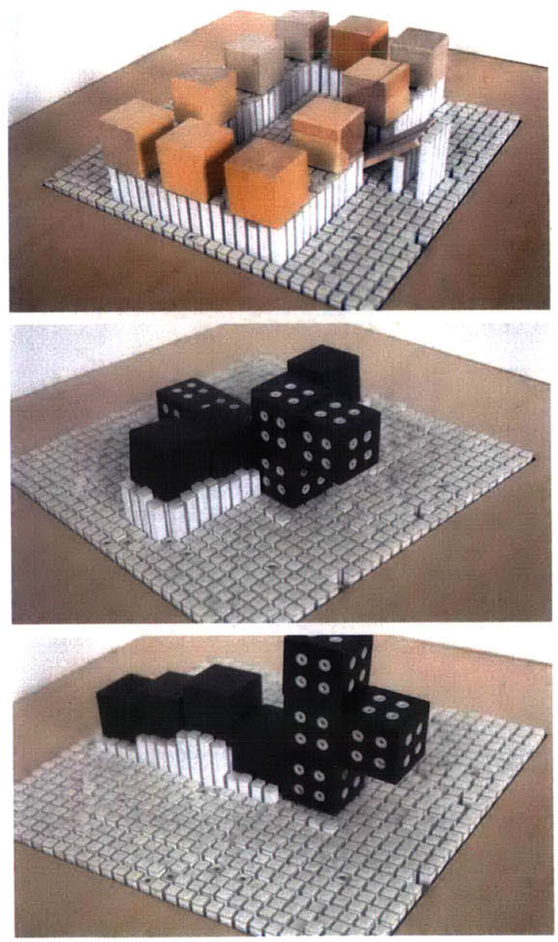


Figure 44. Top: A castle made from inert objects and dynamic shape. The draw bridge is operated by the shape display. Middle: A bird made from locking and non-locking building blocks that can flap its wings. Bottom: A worm that has a moving body.

5.6.2. Programmable Matter

In robotics research, programmable matter is described as computationally controlled construction of objects from fundamental building blocks. In our research, the computation and actuation happens external to the building block itself. Programmable matter research such as *Fluid Crystallization* (Tibbits, 2012) uses external undirected energy for actuation and assembly whereas *M-Blocks* (Romanishin, 2013) uses internal directed energy. Our approach can be described as using directed and external energy for actuation and assembly, which, conceptually, situates us between the two aforementioned approaches (Figure 45).

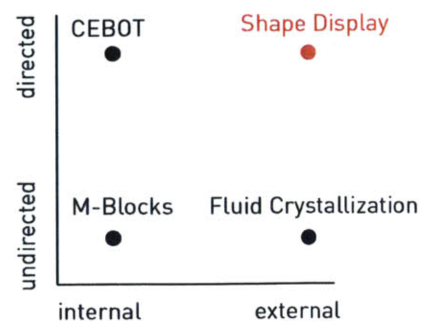


Figure 45. Actuation energy graph. Shape displays present a novel approach towards programmable matter.

To demonstrate this method of programmable assembly through directed external actuation, we created an application which lets a user choose between two structures that are displayed on a tablet computer. The shape display will then automatically assemble the selected, structure using seven locking blocks (Figure 46). Once the first structure is assembled and another one is selected the shape display will disassemble the current structure to then reassemble the blocks to match the newly selected structure.

Figure 46. Two structures that can be automatically assembled, disassembled and reassembled by the shape display. The user chooses a structure using the tablet computer.

5.6.3. Remote Assembly

Another application domain where we see potential for actuated constructive assembly is remote physical teleoperation. We implemented an application that lets a user remotely stack two building block on top of each other. We explored two conceptual approaches (Figure 47).

1) The user locally creates a structure from building blocks. 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 only analyzes the local structure. The remote shape display system then determines the best path and assembly technique needed to recreate the remote structure.

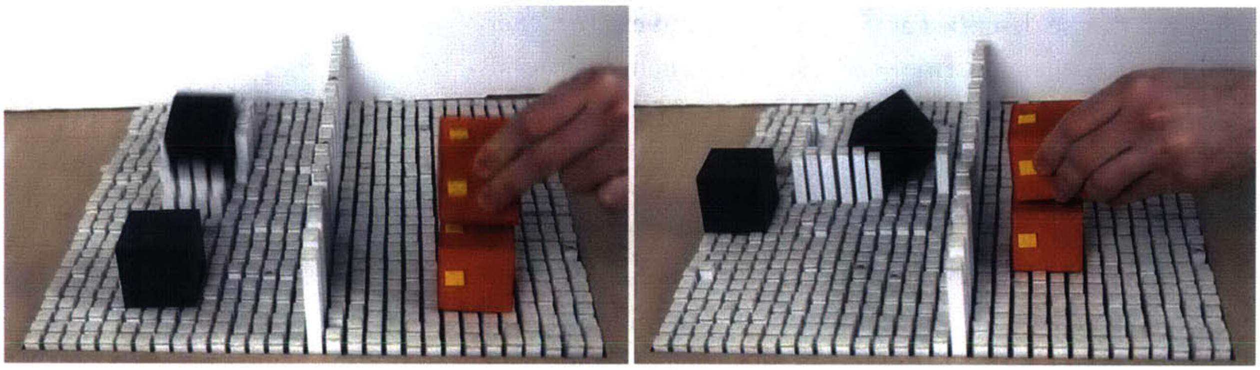


Figure 47. Left: Remote assembly scenario where the users local movement guides the assembly. Right: Remote assembly where the local structure is analyzed and the system determines how to best assemble the structure.

5.7. Application Scenarios

We are limited by the shape display's low resolution and relatively weak motors in the extent of our implementation. Here, we would like to describe two example scenarios which are not implemented at the moment but show the potential for actuated constructive assembly.

5.7.1. CAD System with Self Assembly

One possible application is a bidirectional CAD system that can correct and direct a user's decision. The user, an architect, creates a model of a new building using tangible building blocks. The created structure is recognized by the system to be statically unsound. It notifies the user who decides to let the system automatically disassemble the part because it suggested a more suitable position. The user then decides to load a different version of the building to check a certain part and the table starts to reassemble the selected structure to match the loaded structure.

5.7.2. Remote Assembly with Shape Substitution

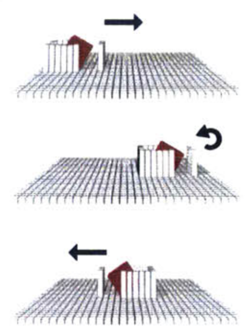
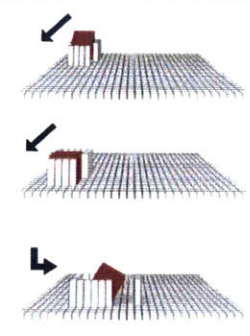
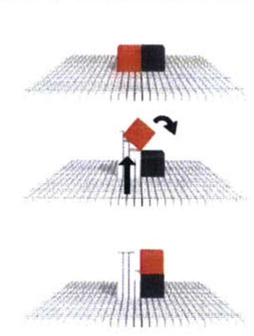
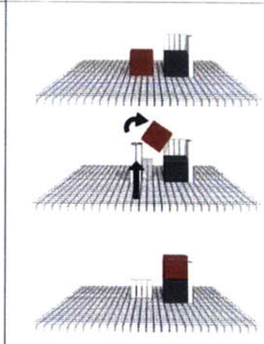
In this scenario two kids play together with building blocks through two remote shape displays. Kid A constructs a tower which is replicated on Kid B's shape display. Kid B decides that the tower is not high enough and adds an additional block on top of it. This decision will be replicated on Kid A's shape display but it ran out of building blocks. The shape display can recreate the missing blocks by substituting them through raising pins at the required position. Now Kid B's dog runs over his shape display thereby destroying the tower. Luckily Kid B can tell the system to automatically rebuild the tower.

5.8. Technical Evaluation

To evaluate the reliability of the described actuation techniques, we tested them multiple times and recorded the errors and successes. Figure 48 describes the results of different attempted actuation techniques. The most common cause for failure was that some pins that could not reach their final height due to friction in the *inFORM* system that has started to appear over time due to wear and tear from extensive use. All attempts except the star construction (Figure 48h) were performed using the plain, non-locking wooden blocks. We regarded an attempt to be unsuccessful if the block did not arrive at its target destination or if it arrived in an unwanted orientation so that the system would not be able to further use the block for assembly without having to realign it first.

The results clearly show the reliability of our open-loop system techniques. However, one drawback of open-loop systems is the fact that a single error in the sequence of movements compromises the whole assembly task. We believe that, in the future, with a closed-loop system (computer vision, sensors on pins, etc.) the reliability of constructing more complex forms will increase.

We also observed that in the movements needed to create three story structures (with a helper object or catapult), it is hard to perfectly align the top block with the underlying block. This is caused by the limited pin height, which prevents us from creating a guiding rail around the structure that would catch the cube. This problem doesn't exist when performing the assembly techniques with magnetic blocks as they tend to automatically align when close enough to another magnetic block.

	a) traverse with direction change	b) traverse around corners	c) two story stack	d) two story stack (catapult)
Illustrations (top to bottom)				
Attempts	100	100	100	100
Success	99%	82%	100%	99%

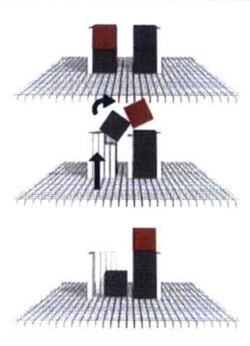
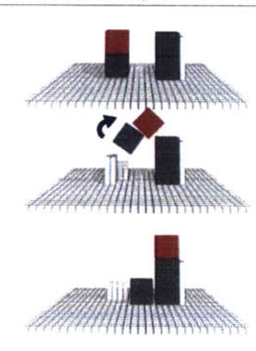
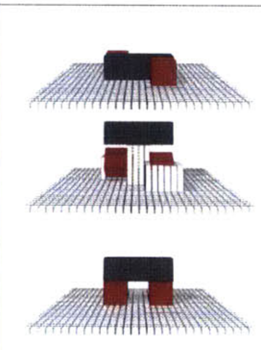
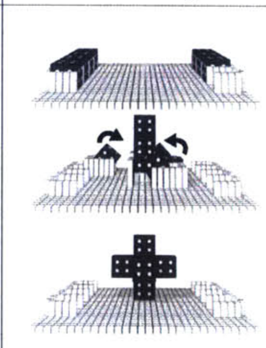
	e) three story stack (helper)	f) three story stack (catapult)	g) overpass with scaffold	h) star structure assembly
Illustrations (top to bottom)				
Attempts	100	100	100	40
Success	100%	99%	100%	82.5%

Figure 48. 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.

5.9. Implementation/Software

To quickly and reliably prototype and test movement patterns on the *inFORM,* we used MAXscript to create a network connection via TCP between the *inFORM* software (C++/open-Frameworks) and the modeling and animation software 3ds Max. This allowed us to use a feature rich professional animation software to create forms and animations in virtual 3D space and display them in real-time on the *inFORM.* The software uses ray-casting to determine the distance of 3D geometry from the virtual camera's near clipping plane and maps these values to a value between 0 and 255 which is sent to the *inFORM.* The *inFORM* which, in turn renders the form on the shape display. We then iteratively create and optimize 3D animation clips that would perform the described assembly tasks.

For tracking the blocks position in the remote-assembly application, we use a Microsoft Kinect depth camera mounted above the shape display. We crop the input image to fit the shape display and use depth and color information to determine the height of the stacked structure. Next, we use openCV's contour recognition algorithms to detect if a user is grasping the block or not.

5.10. Future Directions

The presented applications are still relatively simple but support the notion that a shape display can be used for interactive constructive assembly. Here, we would like to point out possible technical improvements as well as interesting future work.

5.10.1. Closed Loop System

The presented assembly applications are performed in an open-loop system, meaning there is no feedback from sensors whether the actuation was performed correctly or not. We rely purely on the tested reliability of the described assembly techniques. In the future, we hope to implement a closed-loop system which could provide real-time error correction. This could be achieved by embedding sensors into the shape display's pins or implementing more sophisticated computer vision techniques (Gupta, 2012). On the software side, we plan to implement more advanced path planning and decision making algorithms.

5.10.2. Different Building Blocks

In this document, we focused on cube shaped building blocks. These might not be the ideal shape for certain structures. We would like to explore actuated constructive assembly with more diverse shapes like cylinders or triangular shaped objects. Along those lines we are also interested in giving the shape display the ability to assemble arbitrary objects. One could imagine placing screws, gears and levers on the shape display and having it assemble a mechanical object or a tool that the shape display could use itself to accomplish other, more sophisticated tasks. Moreover, we plan to investigate different connector types such as semi-permanent magnetic or mechanical connectors. These could provide stronger connections and also enable larger overhangs for more permanent and detailed structures.

Using active blocks in synergy with the shape display presents another interesting approach to be further explored. These blocks could provide electromagnetic connectors. The pins can have conductive caps that provide external electrical power to the blocks placed on top of the shape display. This elegant solution would ensure that the blocks could have a relatively small size. One drawback from using active blocks is their complexity and cost.

We are limited by the shape displays size to the number of building blocks we can handle at once. Even with seven blocks it proved to be challenging to create animations that wouldn't collide with each other while performing the assembly. Higher resolution shape displays could enable constructive assembly with smaller building blocks allowing the construction of more detailed structures.

6. Shape Displays as Versatile Platform For Physical Control

In this chapter we introduce the idea of a shape display as a versatile physical control platform. Similar to how our computers today are a versatile platform for graphic based applications, we imagine a shape display can be a platform for handling a manifold of different physical tasks. These tasks could involve the assembly of parts (as demonstrated in the previous chapter) but also the precise control of special modules which extend the shape display's capabilities.

Each individual pin on a shape display is a precise actuator and sensor. Here, we utilize this power to drive and sense special kinematic modules that sit on top of the shape display. These modules can translate the pin's single vertical degree of freedom (DOF) into other DOFs and thereby extend a shape display's possibilities for input and output.

We developed four unpowered kinematic modules as a proof of concept and illustrate their use through implemented applications and an example scenario.

6.1. Simple Machines and Kinematic Synthesis

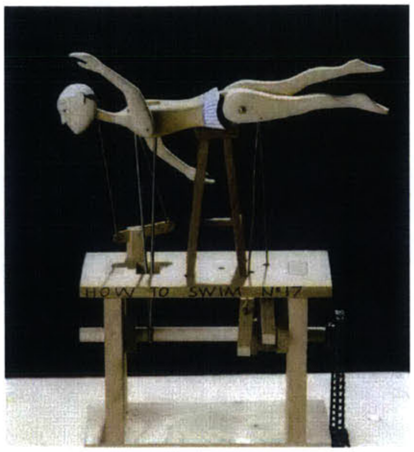


Figure 49. Mechanical Automaton. Rotational movement is translated into more complex movement patterns.

In mechanical engineering, so called *Simple Machines* present the fundamental building blocks of more sophisticated machines which in turn are called *Compound Machines* (Hartenberg, 1964). There exist six defined simple machines: Lever, wheel and axle, pulley, inclined plane, wedge and screw.

To create any kind of *Compound Machine*, one has to put multiple *Simple Machines* in series. The process of determining the correct size and configuration of these parts is called kinematic synthesis. For instance, in *Mechanical Automata* the combination of cranks, gears and pulleys converts a driving force into a desired movement (Figure 49). In a sense, the kinematic modules we developed for the *inFORM* are *Mechanical Automata* that are driven by a vertically moving mechanical force.

The modules can be regarded a shape synthesized object as the interplay between the inert module and the dynamic shape create a novel kinematic object.

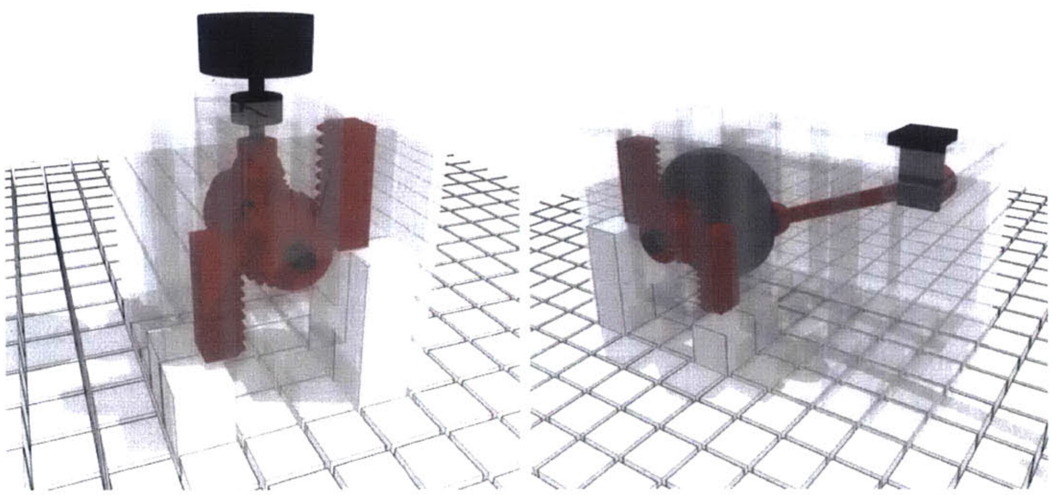


Figure 50. Left: Inside view of *Rotator's* mechanical system. Two linear gears are driven by the pins which translates into rotation using a gear train. Right: Gears and a lever create horizontal movement in the *Slider* block.

6.4. Prototypes

We created four kinematic modules that exemplify the power of using the underlying shape display as an engine which potentially can precisely control all sorts of mechanisms. All four kinematic blocks were designed in Rhinoceros and were then printed on the Stratasys Dimension 1200es FDM 3D printer.

6.4.1. Extender

The *Extender* gives us the ability to extend the shape display's pin height (Figure 51). The *Extender* is placed on top of the shape display so that the underlying pins can push against the *Extender's* pins. These modules can be stacked to increase the pin length. We can use the *Extender* as a tool that lets us overcome the pin height limitation and build higher stacking structures or put other kinematic modules on top of the initial structure if required for a certain task.

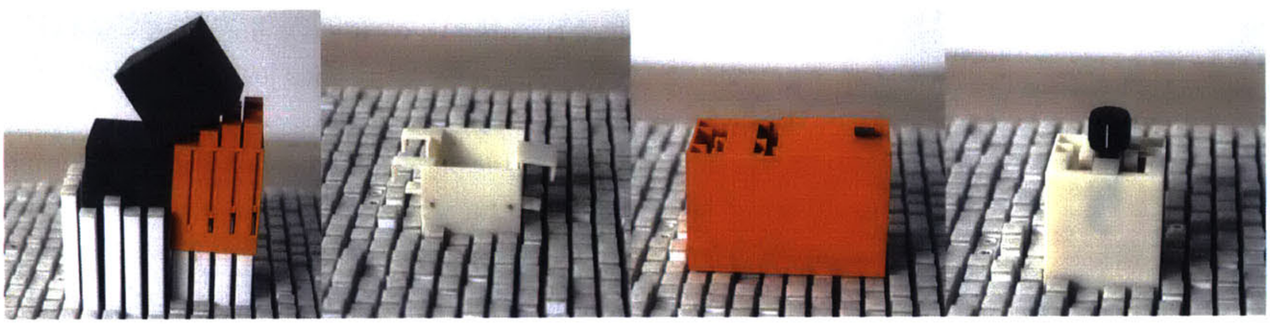


Figure 51: From left to right: *Extender, Stacker, Slider* and *Rotator*. The *Extender* can be used to create higher structures. The *Stacker* has retractable flaps that let us lift it and create overhangs. The *Slider* can be used for horizontal input and output. The *Rotator* provides rotational input and output.

6.4.2. Stacker

The *Stacker* (Figure 51) is a simple module that can hang from raised pins to create overhangs or can be lifted up so that other blocks can move underneath it. Raising the pins inside the Stacker will fold out special flaps that can then hook into a set of pins so the whole module can be lifted up. The hook flaps can be collapsed back by pushing on little retriever flaps that are situated next to the hooks.

6.4.3. Rotator

The *Rotator* module (Figure 51) translates the vertical pin movement into rotational movements. Its internals are made up of two linear gears that are driven by two pins each to maximize strength. The linear gears drive a spur gear which is connected to a set of bevel gears which create rotational movement around the z-axis (Figure 50). At the moment, the gear ratios allow for 315 degrees of rotation in both directions. We can also use the *Rotator* as input device, which provides a new DOF when interacting with shape displays. Attaching a knob on top of the *Rotator* transforms it into a dial that translates a turning motion performed by a user into vertical movement pushing down the pins. This is sensed by the *inFORM* and the sensed value can, in turn, then be mapped to different tasks.

6.4.4. Slider

In the *Slider* block (Figure 51), we use two linear gears and a spur gear to rotate a disc with an attached lever (Figure 50). This mechanically translates the pin's vertical movement into horizontal movement. The *Slider's* internal linear gears are again driven by two pins each to increase force. In similar fashion to the *Rotator*, the slider can be used input and output, or both.

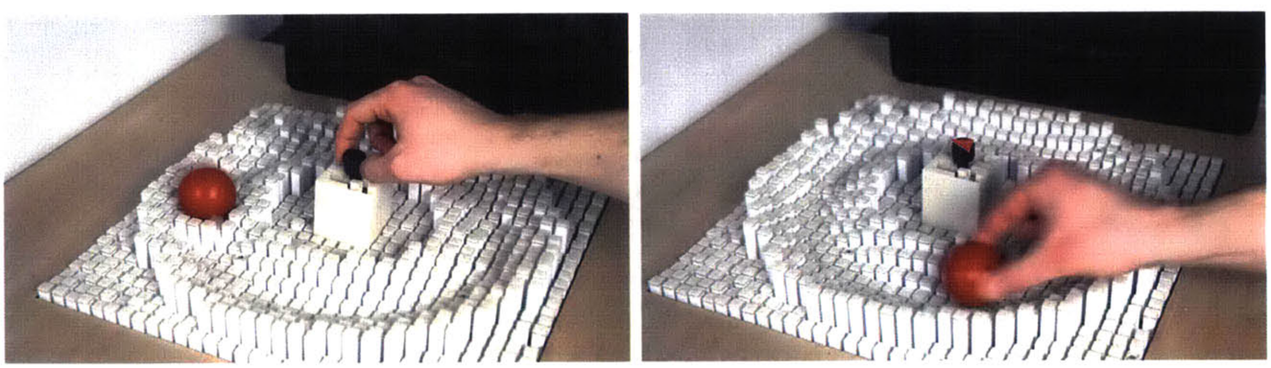


Figure 52. Left: The *Rotator* module is used as input device. Turning the knob moves the ball around the circle. Right: *Rotator* a output device. The *Rotator* always points in the red ball's direction.

6.5. Applications

Weiss et al. developed SLAP Widgets (Weiss, 2009), which are passive and unpowered physical widgets that can be used as input devices on multi-touch screens. In a similar fashion, we regard our kinematic blocks as specialized input and output devices for shape displays. To showcase our kinematic block prototypes, we implemented proof of concept applications.

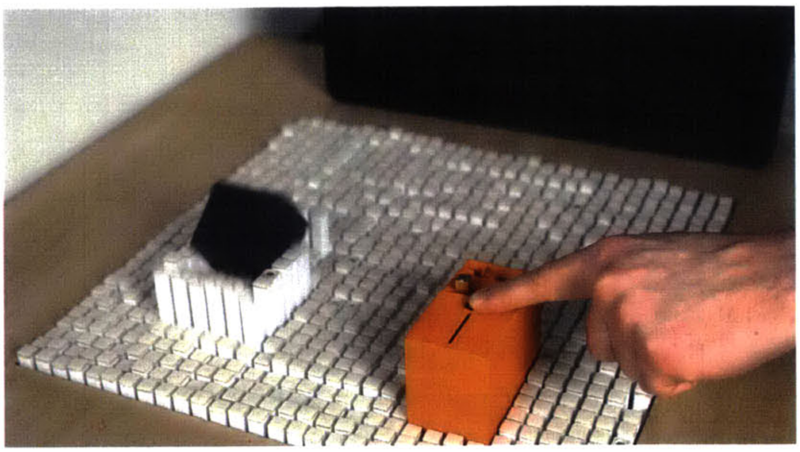


Figure 53. Using the *Slider* module to move the black block across the shape display.

In this first application we attach a knob onto the *Rotator* to control the position of a red ball in a circle around the module. In the reverse scenario, the user moves the red ball with his hands, while the *Rotator* moves an attached red arrow to always point in the direction of the red ball (Figure 52).

In a similar fashion, we use the *Slider* in this second application. Operating the *Slider* will move a building block in horizontal direction across the shape display. The position of the *Slider* determines the blocks position (Figure 53).

The kinematic modules we describe here present the first prototypes of their kind and they are still very limited. The force that the modules generate is very weak, which limits us in what we can actuate with them. We therefore would like to present one example scenario, which describes how we imagine these modules to be used:

"A physics student would like to do an experiment that requires multiple lasers that reflect off moving mirrors to redirect the light. She mounts mirrors on kinematic blocks that can rotate and horizontally move the mirrors. She then uses other kinematic blocks as input device. In particular, the Rotator with a knob proves useful because she can just place it on the shape display next to the mirror to dial in the exact angle such that the lasers reflect off it perfectly."

6.6. Future Direction

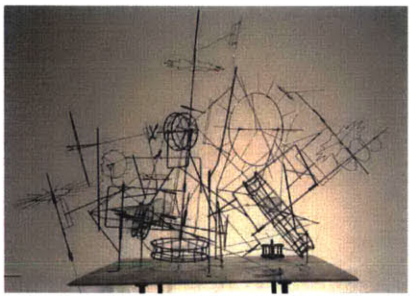


Figure 54: Mechanical automation hand made by Arthur Ganson.

The idea of using a shape display as a versatile platform for physical control is still not matured and this chapter presents one incremental step towards a deeper exploration of this topic. Here we would like to mention possible future steps.

One of the masters of contemporary mechanical automata is Arthur Ganson. The artist creates complex machines and all their complex movement patterns by hand (Figure 54). In general, the design of *Mechanical Automata* requires years of knowledge of motion planning and mechanism design. However, recent research has investigated the automation of mechanical system design. Researchers are developing algorithms that let a user define the desired movement pattern and the computer then determines the necessary configuration of gears and levers to recreate movement from an input (Thomaszewski, 2014).

In the future, we imagine a physical API where the user can define a physical task (e.g. fabrication of some part or bio-lab automation) and get a result that shows him what modules are needed and where on a shape display they need to be placed.

The ability to move kinetic blocks on top of the shape display out of the way or to a required position presents another interesting idea we plan to explore.

Furthermore, stronger and more precise motors would enhance the interaction with the kinematic modules. The motors in the current *inFORM* shape display proved too weak to allow the kinematic modules to be a reliable part in our actuated assembly scenarios.

7. Looking ahead

In this thesis we have proven that the combination of a shape display with inert physical objects opens up a novel and rich space for interactive applications. Though we claimed that the presented techniques would help overcome many of a shape display's inherent limitations, the current technology presented us with restrictions in implementation.

Shape displays present a relatively new field within HCI research. We are currently striving to identify new application scenarios and contexts. Here we try to suggest different ideas that could, as shape displays mature, lead to new applications.

7.1. Technology

Though the *inFORM* and *TRANSFORM* are some of the first shape displays of their kind, there are still a lot of technical improvements that can be made. For instance, increasing the resolution and shrinking the shape display's form factor are the most obvious. Increasing the motor strength and precision would tremendously improve actuated assembly and actuation of the kinematic modules. Furthermore, we could start embedding sensors into the shape displays pins to make up for the limitations of vision based sensing, such as occlusion, frame rate and precision.

At the time of writing we are in the early stages of building a new shape displays that would address some of the mentioned improvements. It will have smaller, more precise and stronger motors as well as special pins that utilize capacitive sensing to detect touch gestures. Additionally, the pins will be made transparent and will have embedded LEDs inside them. By quickly moving the motors up and down, we can utilize the persistence of vision (POV) effect to render shapes that are inside the shape display. Similar to *Sublimate* (Leithinger, 2013), we plan to combine virtual 3D graphics with dynamic physical shapes to create novel display and interaction scenarios.

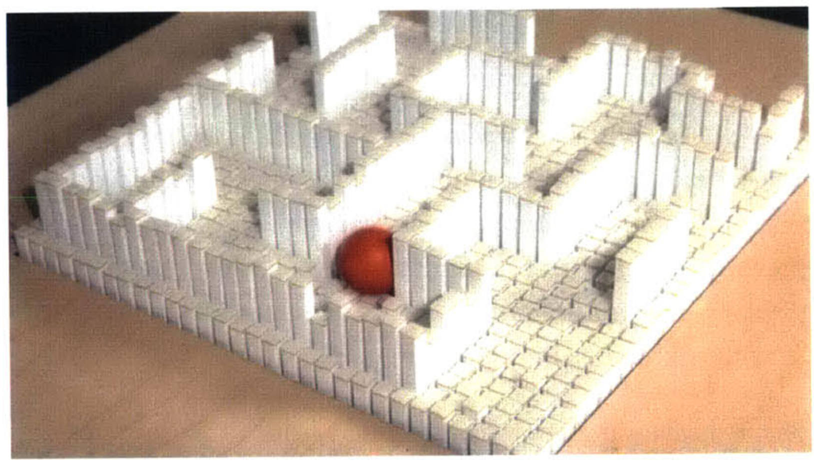


Figure 55. The ball and maze move at the same time. The ball moves in a confined space that, through its constant reconfiguration, appears to be infinite.

7.2. Context

Where a shape display is deployed, as well as its form factor, determines and allows us to think of new applications. Two good examples are the exploration of the *TRANSFORM* as dynamic piece of furniture (Vink, 2015) and the *inFORM 2* as an installation in the Cooper Hewitt Design Museum. Giving a shape display a specific context allows us to create ideas with a useful constraint. For instance, how could a shape display be used in a restaurant, hospital, in outer space, in a car or hung from the ceiling? Asking and exploring these questions will help us to create ideas for shape displays that can then be communicated to the public to gain a better understanding of the future potential of shape displays.

7.3. Scale

A shape display's size and resolution presents another important factor that needs to be explored in future work. We can imagine room-sized shape displays as briefly presented in the space generator project (Malitskaya, 2014). What if a room could dynamically reconfigure itself? Furniture and chairs would just appear where needed. We could create spaces that seem infinitely large (Figure 55). Every time one goes around a corner, the room would reconfigure itself and look different. Small apartments could transform into a palace. Smaller shape displays could have the form factor of current smartphones. At the time of this writing, we are at the beginning of pursuing a research direction that investigates the potential of a one dimensional array of moving motores integrated into a smartphone.

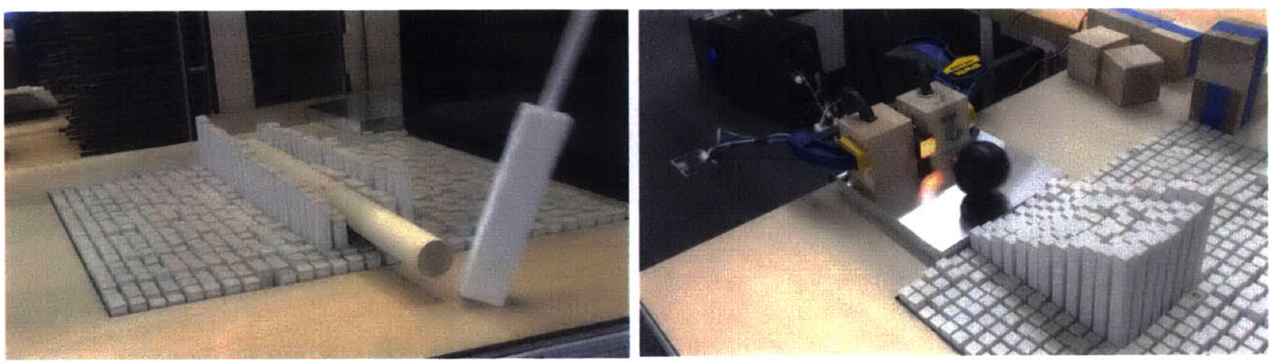


Figure 56. Left: A stick on a shape display can be used to manipulate objects outside of its physical boundaries. Right: A ramp on the shape display used to accelerate a ball that operates the switch outside its physical bounds.

7.4. Extending Reach

We have started to look into a shape display's ability to manipulate objects that are outside of its physical boundaries. The shape display can use objects as tools to accomplish a certain task. For instance, it can manipulate objects using a long object, such as in Figure 56. By stacking objects on top of each other a shape display can operate a light switch that is situated too high for it to reach otherwise. If a button needs to be pressed, the shape display could either catapult an object onto it or flip its whole casing to be able to reach the button using the pins.

7.5. Materiality

Using a shape display, we cannot only render shapes but we can potentially simulate different materiality. Materiality can be experienced visually or haptically. In our first experiments we created a water and a cloth simulation where one could throw a ball onto the shape display and it would appear to swim or sink into the simulated cloth. Once we have shape displays with embedded sensors, we will be able to simulate different materials that respond to a user's touch. For example, touching a hand that is rendered from a remote location could feel like skin. To identify materials that will be rendered remotely we could use special sensors similar to the *SpecTrans* (Sato, 2015). We would then not only display red, green, blue and height (RGBH) information but also material information (RGBHM). The shape display would enable us to switch materiality in an instance, such as switching from solid to liquid.

8. Conclusion

This thesis presented the idea of shape synthesis around three main topics. We showed that the tight coupling of passive object with dynamic shape has interesting potential for additional shape display applications. It lets us combine the affordances of physical objects with the computational power of dynamic shape to create new hybrid objects.

We presented actuated constructive assembly, disassembly and reassembly with passive building blocks on pin-based shape displays. Structures can be constructed interactively and remotely. Through a technical evaluation, we show the presented techniques' reliability.

Next, we introduced special kinematic modules that can be driven and sensed through the shape display and extend its DOF for input as well as output. This supports the claim that, in the future, shape displays can be used as an interactive versatile platform for different physical tasks.

Finally, we described potential future directions for shapes displays, should they continue to be interesting and mature on a technical level. We hope that this research not only presents a valuable contribution to the HCI field but also shows promising and novel approaches to be further explored by robotics and programmable matter researchers.

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