



MorphMatrix: A Toolkit Facilitating Shape-Changing Interface Design

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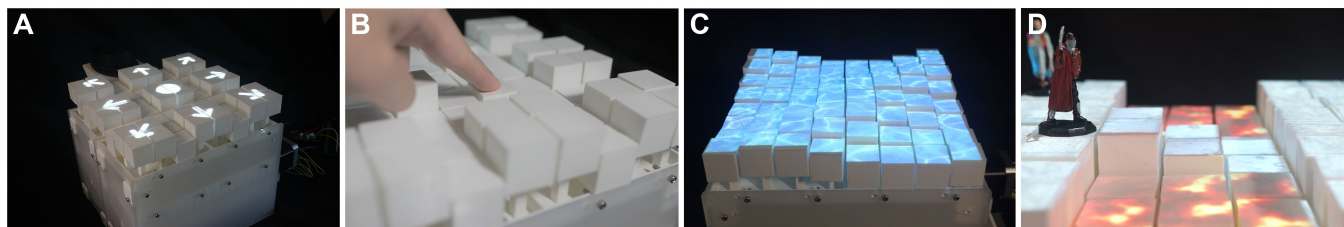


Figure 1: Example application scenarios.(A) Physical interactors with arrow keys implemented by MorphMatrix. (B) Buttons in MorphMatrix being pressed. (C) An implementation of an augmented water surface picture by MorphMatrix. (D) An interactive gameboard implemented by MorphMatrix.

ABSTRACT

Shape-changing interfaces offer transformative potential for user interaction across numerous sectors, facilitating more intuitive and immersive experiences. In parallel, their significant design complexity and cost constrain the widespread adoption of these interfaces. To tackle these challenges, MorphMatrix is a toolkit that lowers the entry barrier for designing and implementing shape-changing interfaces. MorphMatrix includes a software system with customized GUI and simulation capabilities; a flexible physical framework adaptable for various application scenarios; and a kinetic system that governs interface transformations. We illustrate the potential of MorphMatrix through five diverse application scenarios, complemented by a user study validating its effectiveness and usability. MorphMatrix streamlines the design and construction of shape-changing interfaces, thus facilitating broader applicability and potential impacts across interactive computational systems.

CCS CONCEPTS

• **Human-centered computing** → **Interaction design process and methods.**

KEYWORDS

shape-changing interfaces, design toolkit, actuated tangible interfaces

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1 INTRODUCTION

In the rapidly evolving field of Human-Computer Interaction (HCI), shape-changing interfaces are emerging as an advancement offering great potential for transforming user interactions across many sectors[3]. A shape-changing interface is a computer-controlled system that interacts with users by altering its physical shape or materiality, delivering information or invoking responses[37–39]. From enhancing educational tools to providing innovative solutions in healthcare, entertainment, and beyond, the potential applications of shape-changing interfaces are vast and transformative[4, 43–45].

However, the integration and exploration of these interfaces grapple with many challenges [3]. These include technological intricacies such as the heavy reliance on many electromechanical actuators, amplify system complexity, raising questions about efficiency, reliability, and maintenance, and high entry costs for developers. These obstacles stand in the way of design improvements to shape-changing interfaces. Easing access to low-cost entry models for developers and users can address the need for advanced design toolkits that aid in the conception and prototyping of these dynamic interfaces, bridging the gap between theoretical design and practical realization.

In response to these challenges, MorphMatrix is a toolkit aimed at lowering the design and implementation threshold of shape-changing interfaces with pre-defined content. Our toolkit integrates both hardware and software components, providing a resource that

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takes developers from design to construction. A distinguishing feature of MorphMatrix lies in its unique mechanical system, centering upon 3D-printed camshafts. This system enables the realization of complex morphing interfaces while demanding a minimal use of motors. The prototype uses just two motors to animate an 8x8 cube matrix. It can transition rapidly and fluidly between different states, making it a practical tool for small-scale projects, the prototyping of shape-changing interfaces, and beyond.

While the current version of the MorphMatrix system presents several innovative features, it also comes with some limitations. A significant constraint is its reliance on pre-defined content, which tightly constrain dynamic content changes during operation. Moreover, the content displayed in the system is ‘circular,’ with limited information within each circle. The prototype used in this research supports a maximum of 36 frames with a vertical extrusion length of 18 mm (0.70 in). Despite these limitations, the system meets the requirements for applications that work well with pre-defined content, including buttons, text displays, gameboard enhancement and other applications, which we will further discuss in subsequent sections.

The development of the MorphMatrix system contributes to the body of knowledge in the following ways:

- Introducing a cost-effective shape-changing interface, lowering the entry barrier for entities with limited resources, enabling them to utilize shape-changing interfaces.
- Presenting a design tool specifically developed for these low-cost shape-changing interfaces that simplifies the design process and supports the rapid prototyping of shape-changing interfaces.
- Demonstrating the system’s versatility and practical application through five distinct scenarios, ranging from dynamic tangible interfaces to virtual haptic.
- Conducting and presenting an in-depth user study focusing on the design of shape-changing interfaces with finite variable states. This study translates to valuable insights into user experiences and preferences, informing the future development and refinement of shape-changing interfaces.

2 RELATED WORK

2.1 Mechanical Shape-changing Interfaces

Shape-changing interfaces represent a dynamic sub-field within HCI, offering many possibilities for tangible representation of digital information. This literature review focuses on mechanical or pin-based shape-changing interfaces using physical pins that move to create dynamic, tangible expressions of digital information.

Iwata et al. introduced Project FEELEX and FEELEX2, an early pin-based shape-changing interface with an actuator array that used a piston-crank mechanism to increase the resolution of the interface [21]. Poupyrev et al. developed Lumen, a 5x5 array actuated by shape memory alloy, which improved the reaction time, with limited extrusion length [36]. Leithinger and Ishii advanced the field by developing Relief, an actuated tabletop display that could render and animate three-dimensional shapes [26]. Peters presented a design strategy for constructing a more affordable high-resolution reconfigurable pin tool, contributing to developing more cost-effective shape-changing interfaces [35]. Follmer et al.

proposed inFORM, a dynamic shape display that can render 3D content physically, allowing users to interact with digital information tangibly [14]. The authors discuss the limitations of the current inFORM system, such as the limited scalability given the architecture of one actuator per pin. AnimaStage by Nakagaki et al. presented a hands-on animated craft platform based on an actuated stage [33]. Taher et al. explored interactions with physically dynamic bar charts, constructing a 10x10 interactive bar chart and designing interactions that supported fundamental visualization tasks [46]. Siu et al. developed shapeShift, a compact, high-resolution, mobile tabletop shape display that can be mounted on passive rollers allowing for bimanual interaction [41]. Sacramento et al. proposed a solution for pin-based shape displays using a multiplexing strategy to update pins, allowing fewer actuators to efficiently actuate pin-based shape displays [40]. Je et al. introduced Elevate, a floor-scale, walkable pin-array that enhances real-walking VR [22]. It efficiently controls 1200 pins with a limited number of actuators, offering detailed terrain variations.

Several studies suggest modular approaches to simplify the system. Jin et al. introduced a compact surface display system that uses a set of linear actuators connected to pins to create a high-resolution actuated tangible 3D object [24]. Kim and Nam introduced G-raff, an elevating tangible block that supports spatial interaction in a tabletop computing environment [25]. Tiab et al. proposed TiltStacks, a concept for vertically stacking tilt-enabled modules composing shape-changing interfaces [47]. Vijaykumar et al. focused on cost and scalability using custom-designed modular linear actuators and sensor packages, implementing a 16x16 shape-changing interface with a top surface covered with a pressure sensor [50]. In 2021, Suzuki et al. presented HapticBots, a novel encountered-type haptic approach for Virtual Reality (VR) based on multiple tabletop-size shape-changing robots [44].

As illustrated in Table 1, most other solutions require an actuator for each pixel, leading to a dramatic increase in costs for large matrices. Our method improves this by utilizing only two motors to control a 64-pixel array, thereby reducing costs substantially. Technologies such as Elevate and Bezeal offer the advantage of generating an infinite number of shapes with fewer actuators. However, the time required to transition from one shape to another limits this solution. MagneShape employs magnetic modules to minimize the number of actuators and facilitate quick responsiveness [53]. However, the physical constraints of magnet size and magnetic force limit its ability to sustain loads, such as finger presses. Compared to these, MorphMatrix maintains a short reaction time while also maintaining load-bearing ability. MorphMatrix does exhibit limitations in its capacity for real-time shape generation, which consequently restricts its applicability in domains that demand real-time individually addressable shape manipulation and interactivity.

2.2 Motion Information Encoding in Physical Materials

Everyday objects store information in physical forms across diverse communication, machinery operation, and entertainment systems. Keys are coded information with their unique pattern of cuts and grooves. Music boxes store melodies in bumps and grooves on

Related Works	MorphMatrix	FEELEX	Lumen	inFORM	shapeShift	Elevate	Bezalel	MagneShape
Number of Pixels	64	36	25	900	288	1200	9	100
Number of Actuators	2	36	25	900	288	52	6	1
Transition Duration	Short	Short	Short	Short	Short	Long	Long	Short
Number of States	Finite	Infinite	Infinite	Infinite	Infinite	Infinite	Infinite	Finite

Table 1: Comparison between related works

a rotating disc. Barcodes and QR codes use patterns of lines or squares to retrieve diverse information [16, 48]. Thomas Edison’s wax cylinders, used in early phonographs, encoded sound waves as mechanical grooves to playback audio [12]. These examples highlight the diverse ways data can be physically encoded.

HCI widely employs 3D printing technologies to store movement patterns in tangible objects. For example, metamaterial mechanisms developed by Ion et al. utilize internal 3D printing microstructures to achieve specific mechanical movements [18, 19]. Ondulé uses 3D-printed springs to achieve designed movement patterns [17]. Li et al proposed a method to convert arbitrary solid shapes into 3D printing models with certain motion functions [27]. 4D printing extends this concept by using responsive materials that alter shape under different environmental stimuli, triggering specific movements or responses [30, 31, 51]. MagneShape and Mixels offer another method for encoding motion information in magnetic fields [34, 53]. Research has explored using deformable objects and varying pressure fluids to create interactive interfaces that encode motion information through material characteristics [28, 32]. In addition, research on encoding motion information have used origami, linkage mechanisms, and gear trains [7, 8, 23].

Our prototype leverages the mature and widely used technology of 3D printing to record motion information in a camshaft. This approach allows precise and customizable motion information encoding, lowering the implementation and application threshold. Similar to Thomas Edison’s phonograph wax cylinders, the replaceable design of the camshaft in the MorphMatrix system allows for interchangeable introduction of new content. In contrast to methods that rely on magnetic fields [34, 53]. Physical mechanics can be less prone to external disturbances. Although 4D printing technologies are pioneering in their responsiveness to environmental stimuli [30, 31, 51], they often require specialized materials and are not as widely accessible. In summary, our system utilizes a technology that is already well-established and accessible, making the benefits of physical motion information encoding more readily available for a wide range of applications.

3 IMPLEMENTATION

Our toolkit incorporates three systems: an interactive software design environment, a modular physical framework, and a flexible kinetic system. With its GUI, our software system simplifies the design process, enabling even novices to conceptualize and easily design shape-changing interfaces. The physical framework provides the adaptability to tailor the shape-changing interfaces to various application scenarios. The kinetic system offers a cost-effective and practical solution to control and drive interface transformations.

Like the rotating drum of a music box, the system uses a camshaft marked with depressions and protrusions. These physical variations

act like a disk that encodes and stores the motion of the cube matrix. This camshaft plays a vital role in the shape-changing interface. As the camshaft turns, the height variations on its surface trigger a specially designed lever system. The lever system converts these variations into vertical displacements, moving each cube in a well-defined way.

3.1 Software System

Inspired by the animation concept of ‘frames,’ the MorphMatrix software system enables users to shape their shape-changing interfaces. The system operates in a frame-by-frame manner, where users dictate the vertical position of each cube within the 8x8 matrix for a particular frame. This flexibility offers the ability to craft complex transformations across time, as one would choreograph movements in an animation sequence.

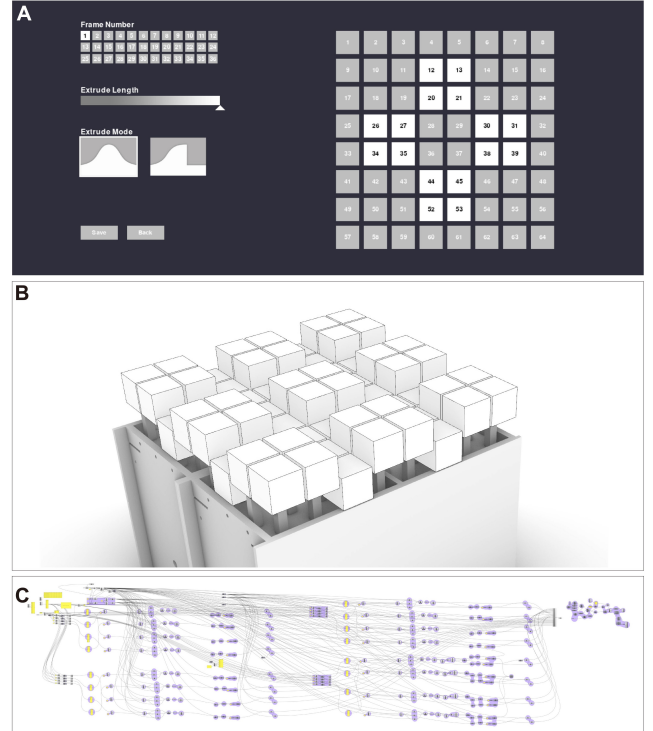


Figure 2: Software system. (A) GUI allowing developers to design each cube state in the matrix. (B) 3D simulation providing real-time visualization of shape-changing interface designs. (C) The Grasshopper code employed to translate cube states into specific camshaft shapes.

Figure 2 A illustrates the software system GUI constructed using the Pygame Zero library, providing a design environment for the shape-changing interfaces. The right section of the GUI displays the state of the 64 cubes, with the extrusion height indicated by each square's color. The left segment of the GUI enables users to switch between different frames, allowing them to define the extrusion height for each cube.

Once completed in the GUI, the system transmits all cube information to the Rhino software via the Rhino3dm and computeRhino3d libraries. Specifically, Rhino3dm is used for the direct manipulation of the Rhino's native 3DM files; while computeRhino3d enables remote access to Rhino's geometry engine, allowing for advanced computational tasks. Additionally, the system enables 3D simulation of the user's design through the Grasshopper platform, a graphical algorithm editor tightly integrated with Rhino software. This feature provides users with an interactive preview of the shape-changing interface in motion, allowing for real-time adjustments and optimization. With inverse kinematics algorithms implemented within Rhino, this translates the state of each cube into the shape of the camshaft. The camshaft's shape has been optimized for printing without support structures, significantly reducing the system assembly time. The MorphMatrix software system simplifies and accelerates the design and implementation of shape-changing interfaces through this streamlined process.

3.2 Physical Framework

The physical framework of MorphMatrix uses 3D printing and laser cutting technology, chosen for efficiency and cost-effectiveness to lower the threshold for building the system. As depicted in Figure 3, the framework is composed of several key components: (a) the cube matrix, designed to move up and down; (b) the fixing mechanism, ensuring that the cube movement is strictly vertical; (c) the lever mechanism, serving to amplify the shape changes on the camshaft; (d) the 3D printed camshaft, which encodes the motion information of each cube; and (e) the acrylic frame, utilized to secure these components together and protect the internal mechanism.

At the framework's heart is our lever system, demonstrated in Figure 5. Using the protrusion on the camshaft to drive cube movement results in the cube travel distance being almost identical to the camshaft's protrusion distance (as shown in Figure 5 D). This arrangement creates substantial camshaft shape fluctuations when needed for a relatively large cube movement distance. Given a constant camshaft radius, such pronounced undulations would lead to fewer protrusions or depressions, significantly restricting the number of frames the shape-changing interface could contain. In response, the lever system (shown in Figure 5 A), employs the principle of mechanical advantage to translate relative small fluctuations on the camshaft into substantial cube movements. As shown in Figure 4 A, the pin extrusion height h is determined by the protrusion distance of the camshaft d , the distance from the support point to the lever axis R_1 , and the distance from the pin to the lever axis R_2 . We can use the following equation to calculate the pin extrusion height h .

$$h = R_2 \cdot \tan(\cos^{-1}(\frac{2R_1^2 - d^2}{2R_1^2})) + d \cdot \sqrt{(\tan(\cos^{-1}(\frac{2R_1^2 - d^2}{2R_1^2})))^2 + 1} \quad (1)$$

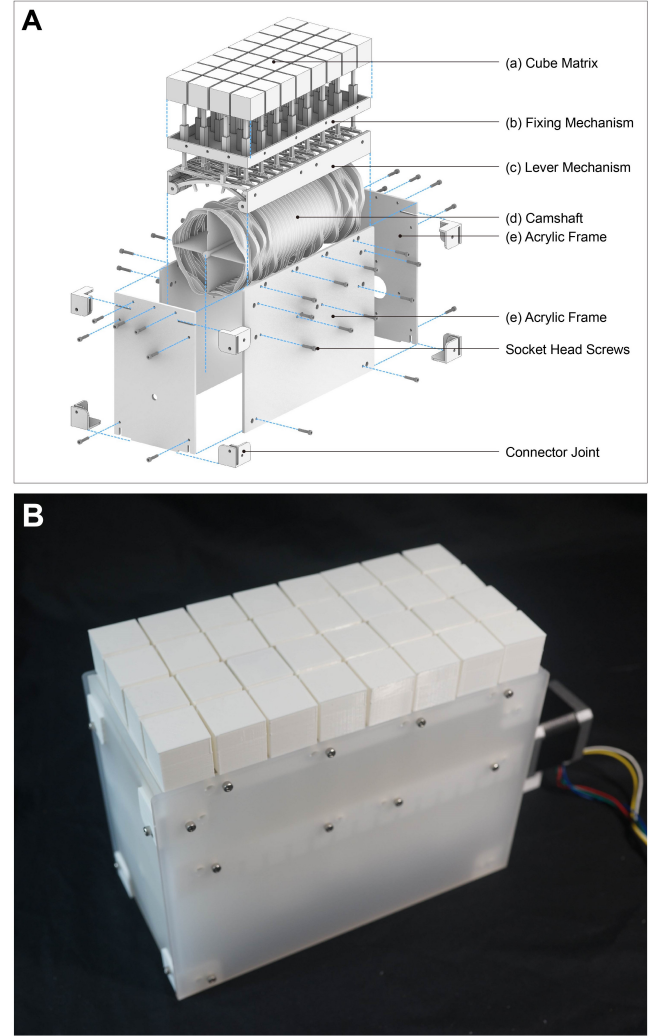


Figure 3: Physical framework. (A) The composition of the physical framework, illustrating its modular structure. (B) An 8x4 physical frame module utilized in the prototype, exemplifying its modularity.

Based on the equation for pin height, increasing the value of R_2 allows for a greater pin height, albeit at the expense of enlarging the overall device size. Reducing the value of R_1 can similarly result in a taller pin but imposes higher strength requirements on the 3D-printed components. In the design of the MorphMatrix prototype, one of our objectives was to increase the resolution of the shape display, which requires a smaller cube size. However, several factors limit this objective, such as the dimensions of the camshaft and the overall device size. Moreover, the 3D-printed lever must be sufficiently robust to lift the pin, requiring a certain thickness. Given these considerations, we designed a cube size of 1 inch x 1 inch (25.4mm x 25.4mm). Increasing the cube size would be a more straightforward task, leading also to higher pin heights and an increased number of frames, as indicated by the governing equations.

The print bed dimensions and the material's strength constrain the maximum pin size.

For systems where the values of $R1$ and $R2$ are fixed, we can still modify the pin height by changing the value of d . When considering the surface of the camshaft as a continuous wave shape, the angle α (as shown in Figure 4 B) between the line connecting adjacent wave crests and troughs, and the line connecting the wave crest and the center of the camshaft, should not be too small. After our experiments, the camshaft can maintain a smooth rotation effect when α is greater than 50 degrees. Additionally, the relationship between α and the protrusion value of the camshaft surface d , as well as the number of frames that this camshaft can represent N (which is also the number of waves on the surface of the camshaft), can be expressed by the following equation.

$$\alpha = \cos^{-1} \left(\frac{R - (R - d) \cos(2\pi/N)}{\sqrt{2R(1 - \cos(2\pi/N))(R - d) + d^2}} \right) \quad (2)$$

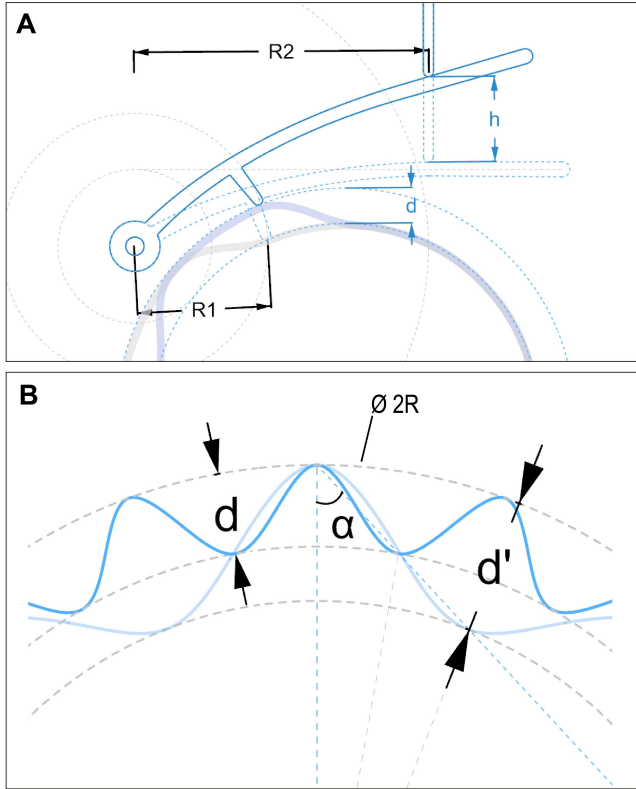


Figure 4: Geometric relationships in the system. (A) Geometric relationship between the pin extrusion length and design parameters of the system. (B) Camshaft with a different protrusion value.

Based on the upper equations, we can see that all parameters in the system are interdependent. When we aim to achieve more frames while ensuring that the angle α remains more significant than 50 degrees, we can accomplish this goal by reducing the value of d . Similarly, securing a more significant d value (and consequently, a taller pin height) in each system can be achieved by decreasing the N value (such as d' in Figure 4 B) or decreasing the

angle α . The constructed prototype balances movement distance and frame number, resulting in a model that can support a maximum of 36 frames with an 18 mm extrusion length, taking these factors into account.

The design philosophy embraces modularity to enhance MorphMatrix's flexibility and scalability. Based on considerations of the camshaft's dimensions and the overall device size, the module has four cubes in the direction perpendicular to the camshaft axis. Meanwhile, the number of cubes in the camshaft axis direction is adjustable according to the camshaft's length. The prototype assembles a 4x8 matrix into a module and creates the required 8x8 matrix by integrating two modules. In addition to the 4x8 matrix, the team experimented with 4x4 and 4x16 module configurations. This approach means each module requires only a single motor for operation and can function independently. The modular and scalable design significantly contributes to the system's versatility, extending the reach of MorphMatrix's applicability.

We fine-tuned the camshaft's design and printed the prototype using a Dremel 3D45 printer. With settings at a layer height of 0.3mm and a speed of 60mm/s, the camshafts for an 8x8 matrix took approximately 8 hours to print. Using high-speed 3D printers further reduces printing time. Additionally, the 3D-printed lever has inherent elasticity when the pressure compresses and lifts the cubes rebound. This feature enables the system to mimic the tactile sensation of pressing a spring-loaded button. Furthermore, altering the lever's material or structure tailors the responsiveness of the blocks under pressure, an avenue we plan to explore in future research.

3.3 Kinetic System

MorphMatrix's kinetic mechanism integrates stepper motors, controllers, and connector nodes. The prototype utilizes two NEMA23 stepper motors and two Pololu Tic T500 controllers powered by a 5V, 10A external power source. As depicted in Figure 6, each motor drives a rotational movement of the camshaft, thus physically transforming the interface. Fine adjustments to the camshaft's rotation — in terms of angle, velocity, and direction — offer users varied control over the dynamics of the shape-changing interface, enabling the generation of diverse effects.

MorphMatrix extends beyond automated control, allowing users to rotate the camshaft by hand and change the state of the shape-changing interface. This feature enhances the system's flexibility and inclusivity, facilitating use across a broader range of scenarios. In providing both motor-driven and manual control options, MorphMatrix sets the stage for shape-changing interface deployment in diverse applications.

4 APPLICATION SCENARIOS

This section explores five application scenarios that illustrate MorphMatrix's potential across varying contexts. These applications, bolstered by the integration of projectors and LiDAR sensors, are hopefully suggestive of MorphMatrix's practicality, adaptability, and versatility.

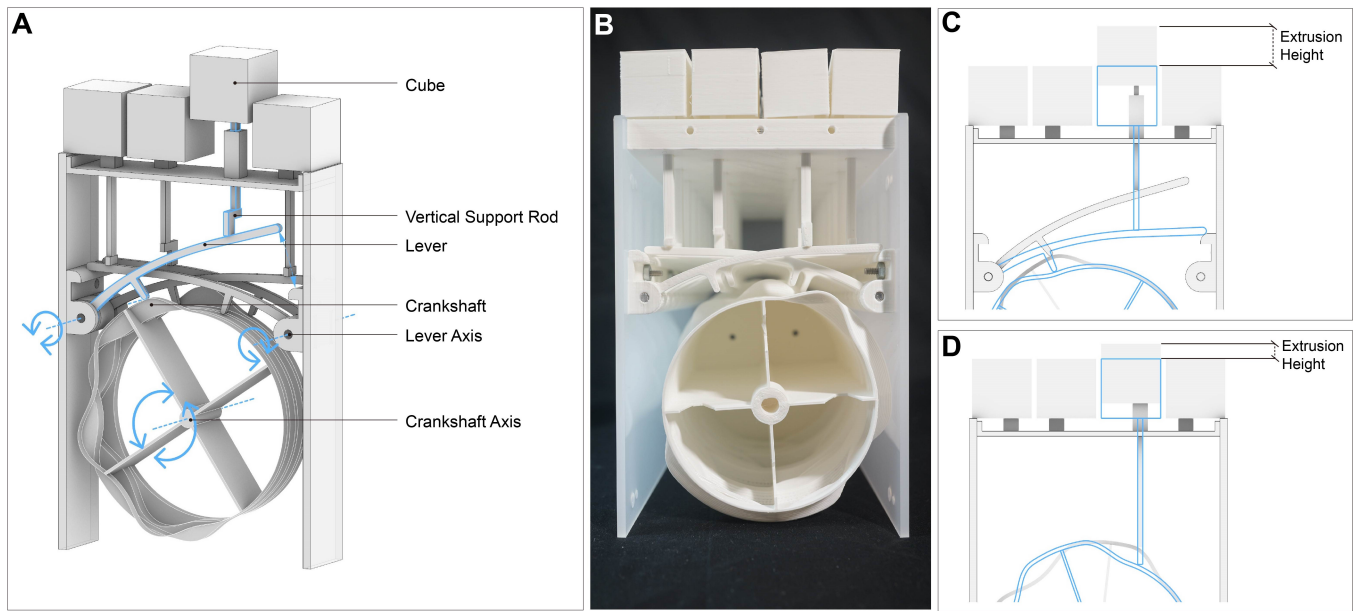


Figure 5: Lever system. (A) The composition of the lever system, essential for efficient cube movement. (B) Photo depicting the lever system. (C) Illustration of extrusion height achieved with the lever system. (D) Comparison diagram displaying the extrusion height without the lever system.

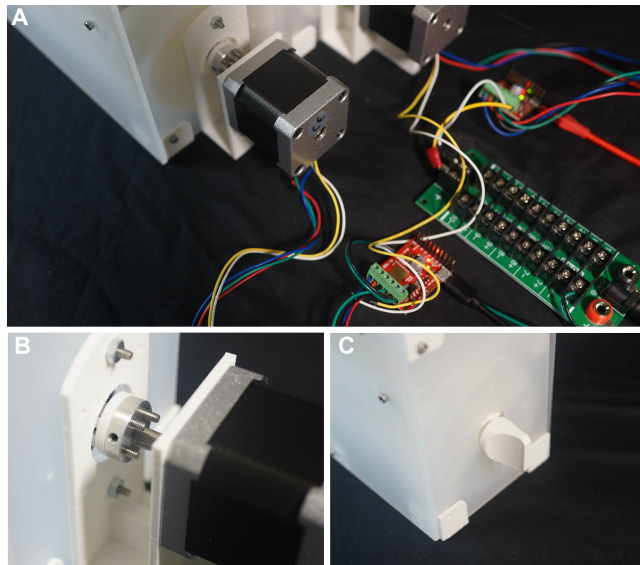


Figure 6: Kinetic system. (A) A detailed photograph of the kinetic system in action. (B) Close-up of the joint connecting the motor to the camshaft. (C) Manual handle for turning the camshaft when needed.

4.1 Dynamic Tangible Interfaces

This application extends the MorphMatrix system with a 2D LiDAR sensor and projector to create a dynamic tangible interface. It is built on the Pygame Zero library and leverages the combined capacities

of the LiDAR sensor, projector, and shape-changing interface. When the user puts their finger/hand on the shape-changing interface, the LiDAR sensor detects hand positions and triggers the corresponding reaction. Meanwhile, the projector provides visual cues by projecting button icons onto the interface. The shape-changing interface enhances these cues, adding a layer of tactile feedback to the user experience. By embodying the digital information within a tangible form, the MorphMatrix system expands the sensory engagement and enhances the interaction affordance of the interface.

Figure 7 represents seven distinctive interactors within this application scenario, encompassing buttons, arrow keys, numeric keyboards, and music playback functionality.

4.2 Gameboard Enhancement

MorphMatrix's potential applications prospectively include gaming, allowing for the transformation of static 2D gameboards into immersive 3D experiences. This application brings forth multiple dynamic effects to augment the gaming experience. An example includes emulating the rising of a bridge within the gameboard (shown in Figure 9 C), thereby providing a visually and physically evocative representation that also advances the state of the game.

The 2D content of the gameboard translates dynamically into a 3D surface. For instance, elements such as magma or staircases can emerge in real-time during gameplay, adding a layer of tangible interaction to the gaming experience. The possibility for dynamic play allows for modifying established game rules, such as chess or checkers. By adding a third dimension, the extruded z-axis necessitates new regulations within traditional gameplay.

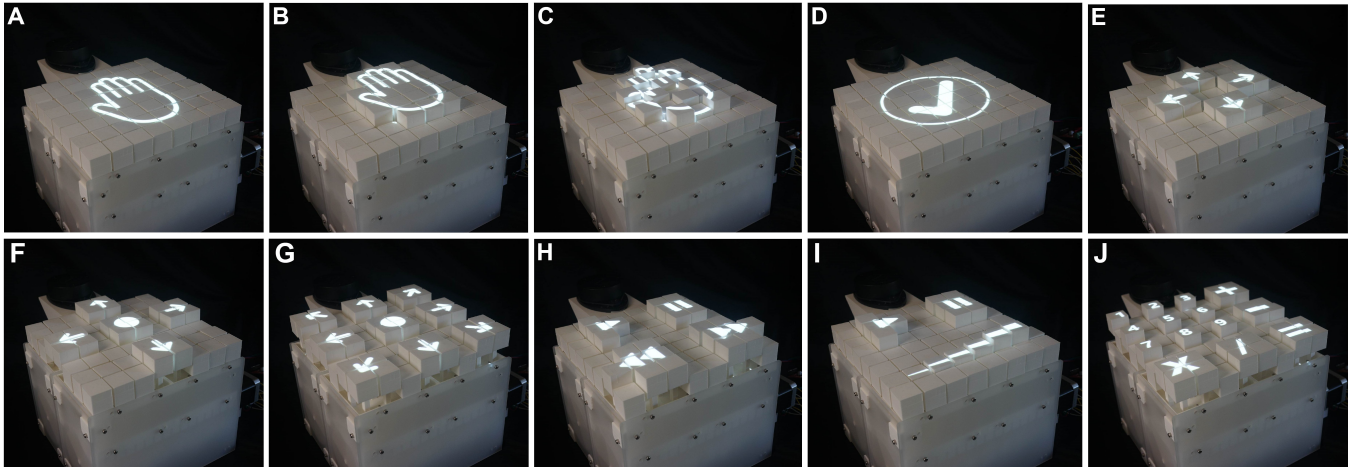


Figure 7: Implementation of various physical interactors. (A-D) Multi-stage dynamic button showcasing different dynamic effects. (E-G) Functional set of arrow keys. (H-I) Intuitive music control interface. (J) Practical calculator interface.

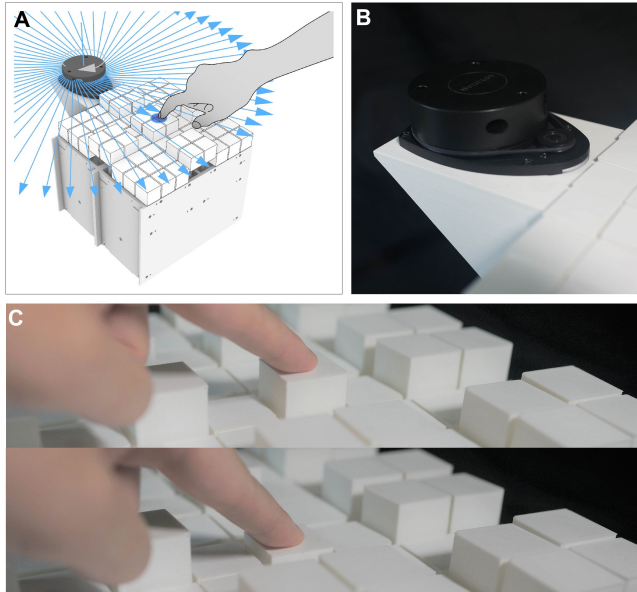


Figure 8: Dynamic tangible interfaces with LiDAR. (A) The operating mechanism of the tangible interfaces. The LiDAR's sensing plane is set just above the extruded cubes, permitting precise detection of touch-based interactions. (B) The RPLiDAR A1 sensor utilized for interaction detection. (C) Demonstration of buttons in tangible interfaces being pressed, enabled by the unique mechanical system.

4.3 Augmenting Images

This application uses a shape-changing interface with a projector to enhance the display of conventional static images. The synergy of the two technologies provides a three-dimensional dynamism that animates the pictures. The prototype employs the projector to overlay static water ripple patterns on the shape-changing interface,

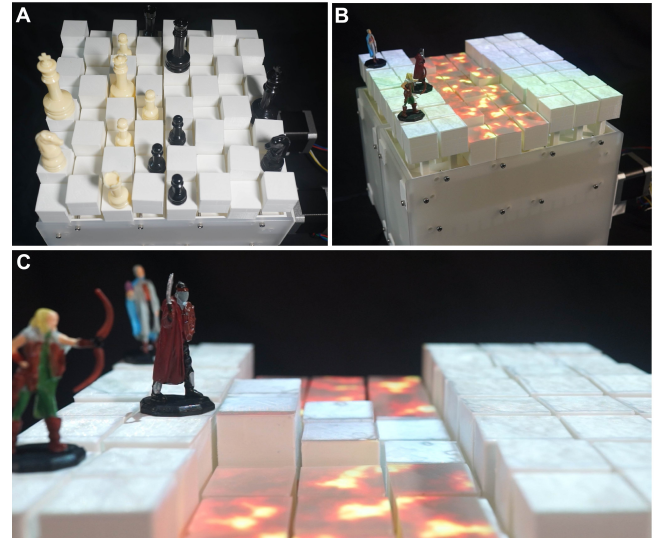


Figure 9: Enhanced gameboards. (A) Innovative 3D chessboard design. (B) Engaging gameboard featuring rolling flow magma. (C) Interactive gameboard with a rising bridge.

simulating the undulating wave movement via the choreographed vertical displacements of the cubes. This combination of visual and tactile stimuli creates an enriched, expressive representation of a static image. Expanding on this idea, the frame-based design of MorphMatrix enables pairing it with animated GIFs, toward display of dynamic three-dimensional expressive content.

4.4 Dynamic Dot-matrix display

Dot-matrix displays permeate daily lives, from simple digital clocks to billboard advertisements. This application harnesses the potential of MorphMatrix to elevate the traditional dot-matrix display to an interactive, dynamic 3D realm. MorphMatrix utilizes an 8x8 matrix

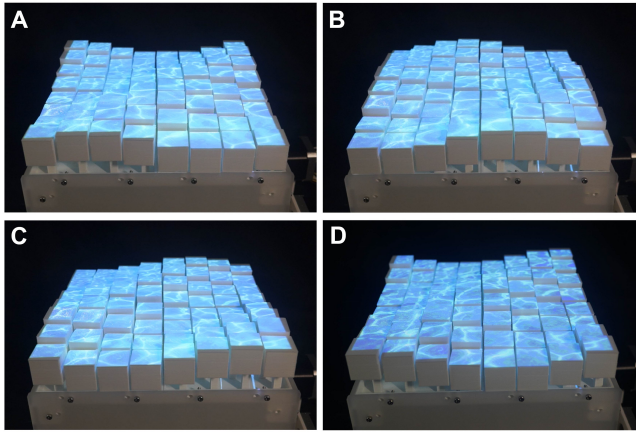


Figure 10: Augmented water surface picture. (A-D) Various stages of dynamic wave simulations

configuration, allowing for the three-dimensional representation of letters, numbers, and characters. Figure 11 depicts the prototype demonstrating the dynamic 3D display of the letters "TEI", providing a tangible, motile rendition of these characters.

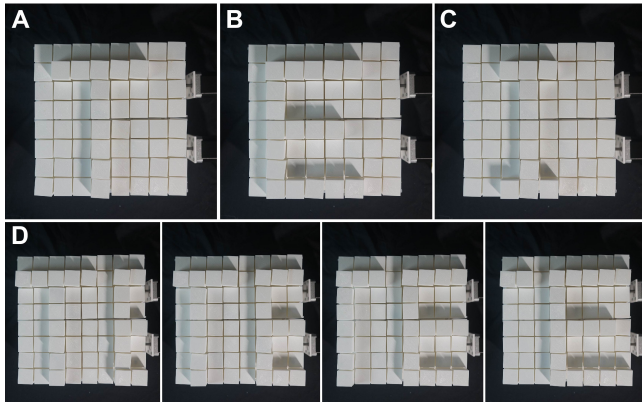


Figure 11: Dot-Matrix display of text. (A-C) Segmented display of the letters "TEI" on the dot-matrix interface. (D) Continuous scroll display of "TEI".

Given MorphMatrix's design flexibility, it can be horizontally extended, enhancing its capacity to display more complex or lengthier text information. Furthermore, additional intricacies of the text display—including dynamics and temporal aspects—can be tailored within the MorphMatrix GUI.

4.5 Encountered-type Haptics

The challenge of delivering tactile feedback within virtual reality (VR) environments is a topic of considerable research attention, with most present solutions requiring sophisticated systems and high costs. MorphMatrix offers a novel, affordable approach to address this challenge.

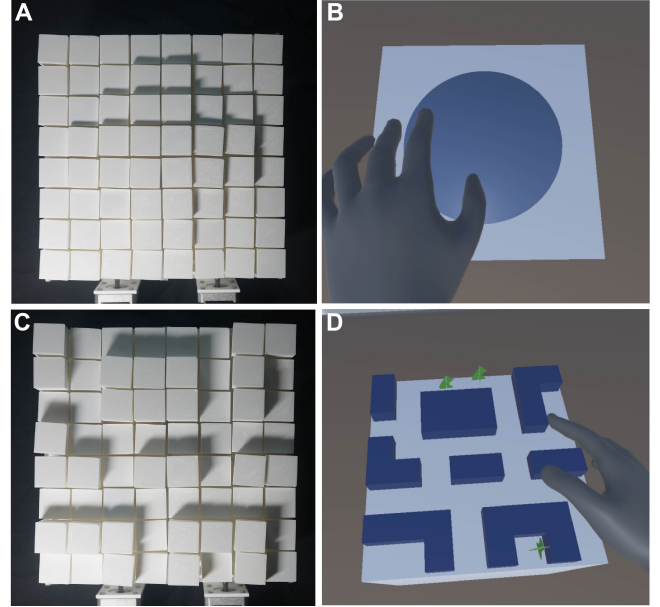


Figure 12: Haptic within VR. (A) Shape-changing interface exhibiting a rounded bump. (B) Representation of the rounded bump within Unity VR. (C) Urban scene displayed on the shape-changing interface. (D) The corresponding urban scene within Unity VR.

MorphMatrix expresses a wide array of 3D shapes by carefully controlling cube heights and providing tactile feedback for pre-encoded VR objects or scenarios. This dimensional space allows users to experience haptic interactions with virtual elements, enhancing the immersive qualities of VR environments.

This application utilized the Oculus Quest 2 VR platform, leveraging its built-in hand-tracking capabilities to capture the user's hand position and movements. This information synchronizes with the physical part of MorphMatrix and the virtual model in Unity, enabling the successful implementation of encountered-type haptics. Figure 12 shows that this integration provided tangible feedback for diverse VR content, including a simple shape and a urban scene.

5 USER STUDY

The user study aims to begin exploring the kinds of content users might design using the shape-changing interface toolkit and to perceive potential real-world applications of this technology through a qualitative research approach. By gathering early feedback, the team hopes to gauge the toolkit's usability, identify possible enhancements, and streamline its user experience for future users, both toward understanding usage scenarios and facilitating continual improvement.

5.1 Participant Recruitment

Recruitment utilized flyers and posters in educational buildings and word-of-mouth in-person recruitment. This approach facilitated a diverse participant pool from various backgrounds. Interested individuals approached the researcher via email, recruiting 12 participants (age 24-54, female n=6).

The participants had a broad range of professional backgrounds, primarily focused on design disciplines. Participants came from fields such as architectural design (P2, P10, P11), landscape design (P1, P12), urban design (P3, P4, P8), and interior design (P6), with one participant (P5) having a background in game design. Moreover, the study included participants from software development (P7) and engineering (P9) fields to diversify the range of perspectives. Most participants, brought experience using design software like Photoshop and Rhino, bringing an understanding of design principles and practices to the study.

5.2 Procedure

The user study started with the introduction of the MorphMatrix toolkit. A training session acquainted participants with the concepts of shape-changing interfaces and the functionalities of the toolkit. After the training, participants engaged a hands-on design exercise using the toolkit, toward creating content for the shape-changing interface. They were encouraged to explore different themes and use the MorphMatrix GUI to bring their designs to life. This exercise provided initial experience and prepared them for the subsequent step: semi-structured interviews. These interviews elicited feedback, participant experiences, perceived challenges, and possible improvements to the toolkit. Semi-structured interviews allowed for open discussions facilitated by guiding questions.

5.3 Results

The qualitative data collected from semi-structured interviews were analyzed using a thematic analysis approach, as outlined by Braun and Clarke [6]. The method involved several stages to pursue understanding of the dataset. First, interviews were transcribed and the transcriptions were reviewed by the researchers to familiarize themselves with the content. Next, initial codes were generated by identifying significant phrases or sentences that capture key thoughts or concepts. NVivo software was utilized to manage and code the data systematically. Initial codes led to potential themes, which were then reviewed for accuracy and relevance to the data set. Digressive themes were merged, separated, or discarded, and the remaining ones were clearly defined and named. In accordance with these themes, user insights were organized into five distinct categories: User Interface, Expressiveness, Design Applications, System Appreciation, and Improvement Suggestions.

5.3.1 User Interface. Most participants (P2, 4-7, 11, 12) found the toolkit's GUI to be straightforward and logically structured. Its novelty was acknowledged (P8, P9) and was generally considered easy to use (P2, P5, P6, P10). However, some participants (P1, P3) suggested the addition of more interactive elements to enhance its appeal.

5.3.2 Expressiveness. Most participants said the toolkit was practical in expressing their design ideas. The primary perceived limitations were system resolution (P1, P4, P5) and the number of frames displayed (P2, P3). Participant P11 noted that limited vertical cube movement constrained design possibilities.

5.3.3 Design Applications. In the design exercise, participants proposed diverse applications for the toolkit (As shown in Figure 13). Some (P1, P4, P12) suggested musical applications, such as

deformable musical instruments or music visualization. P3 suggested using it for stage design to simulate elevating platforms. Participants (P2, P6, P10) proposed its use for displaying information like text or traffic data. Others (P5, P7, P10, P11) designed it as a flexible display rack for objects like succulent plants, watches, jewelry, or artwork.

5.3.4 System Appreciation. Several participants (P2, P3, P5, P6, P8, P11) expressed their appreciation for the design freedom provided by the toolkit, accommodating a wide variety of designs and scenarios. The dynamic deformation effects that the toolkit could achieve were favored by others (P4, P6, P7, P9, P10).

5.3.5 Improvement Suggestions. Participants made several improvement suggestions. Some (P1, P3, P6) called for a more modern design style for the GUI, including animation and sound effects. Others (P5, P7, P8, P12) suggested adding more functionality, like picture input, function-based block control, frame copying, and integration with other systems. There were hardware-related suggestions (P2, P7), including optimizing the cube shape and integrating LED lights for color display.

6 DISCUSSION

MorphMatrix system allows users to build prototypes of shape-changing interfaces at a low cost quickly, and is well suited for applications that require a limited number of frames. It has the potential to lower the entry threshold for the application of shape-changing interfaces. Next, we consider present limitations of the MorphMatrix system and explore future work to overcome these limitations.

6.1 Limitations

The user study and subsequent reflection upon MorphMatrix suggested several limitations of the current toolkit to address in future versions:

- **Frame number limitation:** MorphMatrix system, unlike other shape-changing interfaces, can only display a fixed number of states or frames at a given time due to its system characteristics.
- **Pin stroke limitation:** The system's mechanical properties do not allow long-distance extrusions.
- **Resolution limitation:** The mechanical stability of the 3D printing structure is affected when it is too small. A larger device volume is necessary for a more significant number of cubes, creating a resolution-to-cost trade-off.

6.2 Future Work

The limitations identified in this study present avenues for future improvements and enhancements to MorphMatrix:

- **Longer pin stroke and more frames:** Using multiple levers (like a scissors structure) in this system amplifies the shape changes on the camshaft. This modification increases the complexity of the mechanical system but allows for a higher pin stroke or more frames.
- **Higher resolution:** Altering the mechanical structure and employing other materials and manufacturing processes to

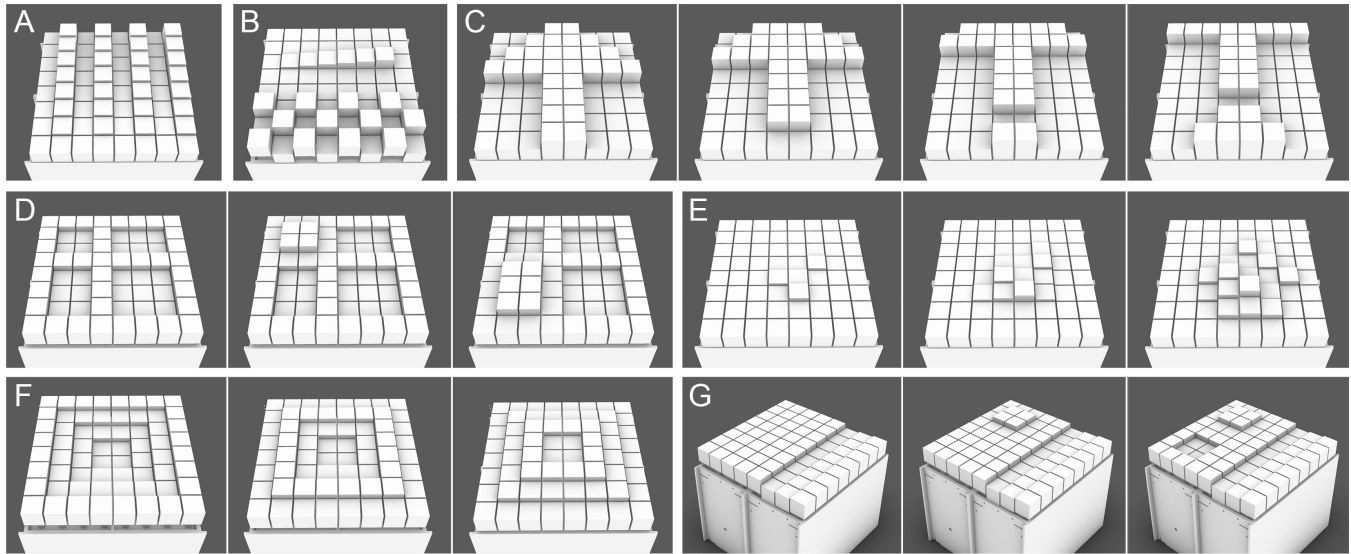


Figure 13: Example design outcomes from user study. (A) Music instrument based on MorphMatrix: Cubes with different heights represent different pitches, and different columns represent different musical instruments. Sounds are triggered by touching the cubes. (B) Another music instrument design also uses cubes of different heights to represent pitches. In addition, different instruments can be selected by touching the spaced cubes below. (C) The design of a dynamic traffic sign that guides users by dynamically displaying an arrow. (D) A jewelry display device that dynamically displays jewelry by placing jewelry of different sizes on cubes that can move up and down. (E) Using MorphMatrix to dynamically display urban population data. Each box represents a different area in the city, and the height of the box represents the population in that area to dynamically display changes in urban population over time. (F) Art display device: place a small-sized artwork in the center of the device; it will move up and down as the device runs to attract the audience's attention. (G) Using MorphMatrix to assist in the design of the lifting stage; the designer can set stage lifting height for different areas and get an intuitive feel with deformable stage models.

reduce the size of each cube and achieve a higher display resolution.

- Expansion of prototype sizes: The current model demonstrates an 8x8 prototype; however, the characteristics of the system can efficiently accommodate larger scales. For instance, exploring prototypes with dimensions of 12x12 or 8x12 could provide further possibilities.
- Incorporation of additional sensors and actuators: Future versions of MorphMatrix could benefit from integrating more sensors and actuators into the system, broadening its capabilities and applications.

7 CONCLUSION

In 2012, Ishii et al. introduced Radical Atoms: "our vision of human interactions with dynamic physical materials that can transform their shape... [where] the interface itself [acts as a] material" [20]. This vision has deeply inspired and informed our approach and aspirations. Where MorphMatrix is not nearly as general as Ishii et al.'s "Perfect Red," perhaps analogistic to an embodied koan (公案) that provokes the "great doubt" and initial insight [15], we have sought to understand and illustrate approaches toward maximizing the ratio of physical, interactive material expressiveness to underlying motile actuation. Engaging Goethe's renowned observation "architecture is frozen music," we hope MorphMatrix, as a special genre of Radical Atom, illustrates both pragmatic and poetic paths,

both today and tomorrow, toward un-bounding architecture's music into interactive, responsive form. More prescient and specific is Sigfried Ebling's suggestion that if architecture is a machine, like machines, it will need to increase performance and convert energy sources – in short, it must be plasmatic, flowing between a fixed state and a responsive skin enfolding the environment, not separate from it [11].

In 1984, Aish and Noakes introduced a LEGO-like tangible interface that not only graphically replicated (twinned) the shape of physical elements but also their "music" – the predicted energy dynamics across hour and season [2]. Aish and Noake wrote that their approach should "only be a transitional phase," as were Edison's wax cylinders, where (e.g.) the 16,500 cylinders remaining in the US Library of Congress have begotten the 3.5 million audio recordings in the Library's entire collections, and the estimated billion recordings presently in YouTube [1, 29, 42]; and US Atlas's cylindrical 1950 data storage [5], begetting today's semi-boundless mixed-media data clouds. These, too, hold analogs between MorphMatrix and its aspirational descendants. Or, recollecting Feynman [13], Drexler [9], Vettiger [49], Woolf [52], and Dyson [10], perhaps cylinders may sometimes be less anachronisms than harbingers of future milli-, mezzo, and mega-scale progeny.

Aish and Noakes wrote, "It is not suggested that a layman using this system will create a 'better' building than an inventive architect or engineer; [but rather,] the wider interest generated by

this form of CAAD... can be expected to develop into a greater understanding by both professional and laypeople of the complex underlying relationships which exist between design, performance and perceptual variables that characterize architectural design" [2]. In the journey toward, though, and upon Radical Atoms that will span decades and centuries, with both creators and audiences ranging from school children to senators, we hope MorphMatrix illustrates an evocative synthesis of form, behavior, dynamics, and interactivity, particularly for domains where the interplay between constellations of states that can both inform and inspire, move toward realms of application spanning the playful to the profound.

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