Mechanism Perfboard: An Augmented Reality Environment for Linkage Mechanism Design and Fabrication

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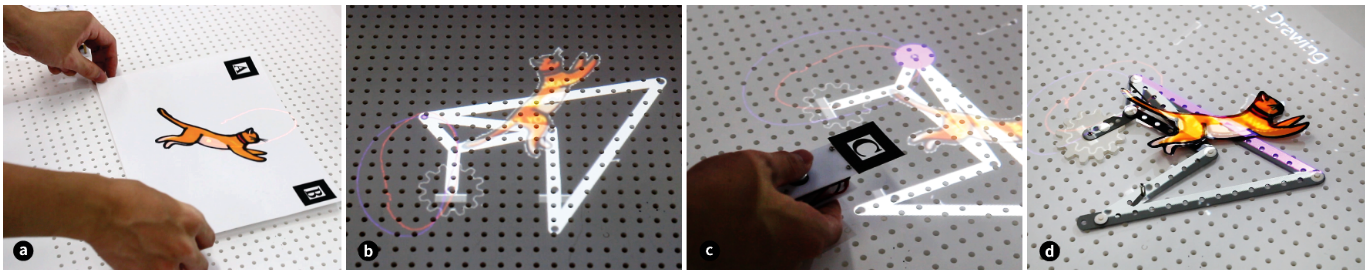

Figure 1. Overall usage process of the Mechanism Perfboard: (a) recording the desired movement of an image or object on an AR marker board, (b) generating initial linkage mechanism for the desired movement with computational support, (c) modifying the initial linkage mechanism with an interface button within the augmented environment, and (d) assembling with augmented fabrication guide using a mechanical parts kit.

ABSTRACT
Prototyping devices with kinetic mechanisms, such as automata and robots, has become common in physical computing projects. However, mechanism design in the early-concept exploration phase is challenging, due to the dynamic and unpredictable characteristics of mechanisms. We present Mechanism Perfboard, an augmented reality environment that supports linkage mechanism design and fabrication. It supports the concretization of ideas by generating the initial desired linkage mechanism from a real world movement. The projection of simulated movement within the environment enables iterative tests and modifications in real scale. Augmented information and accompanying tangible parts help users to fabricate mechanisms. Through a user study with 10 participants, we found that Mechanism Perfboard helped the participant to achieve their desired movement. The augmented environment enabled intuitive modification and fabrication with an understanding of mechanical movement. Based on the tool development and the user study, we discuss implications for mechanism prototyping with augmented reality and computational support.

ACM Classification Keywords
H.5.2. User Interfaces: Prototyping

CHI 2018, April 21–26, 2018, Montreal, QC, Canada
© 2018 ACM. ISBN 978-1-4503-5620-6/18/04...$15.00
DOI: https://doi.org/10.1145/3173574.3173985

Author Keywords
Linkage mechanism; prototyping; fabrication; augmented reality; computational design;

INTRODUCTION
Recently, kinetic mechanism prototyping has become common in physical computing projects by using a sensor and an actuator, and the demand for designing a kinetic mechanism has increased. A kinetic mechanism allows people to build a wide range of products that can move, such as robotic arms, automata, interactive robots, adjustable furniture, and the Internet of things (IoT) products in which sensors and actuators are embedded [17, 19, 20]. Several studies in HCI have proposed tools for building a kinetic mechanism. In order to design and fabricate the kinetic mechanism, these research efforts have provided computational and parametric design tools for digital modeling [8, 15, 27], or a new type of mechanism for material properties [7, 13].

One of the essential configurations for a kinetic structure is a linkage mechanism. A linkage mechanism enables various kinetic movements by connecting rigid linkages and actuating them with other mechanical components, such as gears and motors. It is widely used for basic mechanical systems because it can generate a complex repetitive motion with a single motor attached to the simple linkage mechanism. However, designing a linkage mechanism is difficult because the resulting movement is unpredictable [22]. Small changes in the length of the linkages and the location of points bring about a variety of movement alternatives. Iterative design and modification are necessary for achieving the desired movement. Thus, it takes a lot of time and effort to obtain the desired result. It is difficult for non-experts, who lack knowledge of and experience with mechanism design, to interactively derive the desired movements.

Several researchers have developed algorithms and frameworks for supporting linkage mechanism design [2, 5, 12, 22, 28]. These works enable non-experts to generate a linkage mechanism with computational support. However, it is still difficult to prototype the linkage mechanism in the physical world. There is a gap between a linkage mechanism designed in the software and hardware fabricated in the physical world. In the process of assembling a linkage mechanism in the physical world, the completion time is affected by the planning of the placement and assembly order of the parts. Also, mechanical problems, such as distortion and interference between parts, commonly occurs. Non-experts spend a lot of time and effort fixing these problems with iterative design, reassembly, and testing. Computational support of sophisticated software may address a part of the challenges, but many mechanical problems still remain unsupported. The repetitive trial-and-error process is still required with redesigning and assembling physical prototypes [20].

In this paper, we present Mechanism Perfboard, which is an augmented reality-based environment for linkage mechanism design and fabrication (Figure 1). As an approach for kinetic mechanism design and fabrication, we applied a camera-projection-based augmented reality environment to connect the real-world manipulation and the virtual world simulation. This approach enables users to interactively fabricate the linkage mechanism by integrating the digital and physical fabrication process. Mechanism Perfboard utilizes a real object as a tangible user interface for design. Also, it enables physical testing and virtual simulation within the same environment.

This paper makes several contributions. First, we present an augmented reality environment that supports the interactive process by integrating the virtual world and the physical world for linkage mechanism design and fabrication. Second, it illustrates an approach to support non-experts' design and fabrication with a tangible interface, AR technique, and computational support. The system design details are illustrated, including a mechanism generation from the movement input with real object and augmented contents to support effective mechanism design and fabrication from early ideation to the final fabrication process. Lastly, this paper reports the effect of the augmented reality environment and implications for mechanism prototyping with augmented reality and computational support based on the tool development and the user study.

RELATED WORKS

Algorithms and Frameworks for Mechanism Generation

It is challenging for non-experts to design mechanical parts from scratch to derive the desired movements. Several algorithms and frameworks for mechanism generation are available to help non-experts to create kinetic mechanisms with the desired movements. Coros et al. presented a technique that automatically generates mechanism configurations from the motion of an articulated character as an input [5]. When the user draws a desired path, the system creates an appropriate mechanism that is composed of gear-linkage assemblies. Zhu et al. presented a system for creating mechanical automata from the animation of 3D virtual objects [28]. Chacra [12] generated a linkage mechanism from the extreme poses of each geometric part of articulated characters. Thomaszewski et al. presented a system that interactively suggests appropriate topologies of a linkage mechanism during the design process [22]. Previous works enabled a rapid and effective design process for mechanism design because the system automatically generates an appropriate result or several candidates for the desired movement. However, these works focused on algorithms and frameworks for mechanism generation. Our system supports the whole process in designing and fabricating a linkage mechanism and focuses on interface with augmented reality for prototyping it.

Interface to Input Desired Movement

Several tools that support the fabricating mechanism or authoring motion provide interfaces to input the desired movement in a variety of ways. Coros et al. applied an approach using control points to sketch the cyclic desired path that indicates the movement of characters [5]. However, it is difficult to generate sophisticated motion because the path only includes the positional data of a certain point of a target artifact. Chacra [12] provides the motion-defining interface using the extreme pose of the segments. The user can define the start and end positional and rotational properties with the placement of the segments. It is possible to define both the positional and rotational movement of the target artifact. However, its motion may differ with the users' desired motion because the intermediate motion is not defined, but is generated, by interpolation. Ciccone et al. applied various devices, such as a mouse, Leap-motion, and Kinect, to increase the degrees of freedom for capturing looped cycles of motion [4]. Ceylan et al. applied a motion-capture technique as an input for generating mechanical automata [2]. It is intuitive and natural because the user can record the motion with his or her body. Mechanism Perfboard supports the tangible user interface for capturing the movement intuitively. The user can use a real object as an input interface with the augmented reality environment.

Connect the Virtual and Physical Worlds for Fabrication

The digital fabrication process is separated into digital modeling in the software and physical assembly in the real world. Although it is convenient to design with software, there is a gap between the virtual and physical environment and a discontinuity of the fabrication process. Several studies presented tools that connect the virtual and the real environment for supporting fabrication. CopyCAD [6] and MiragePrinter [25] apply tangible user interfaces that integrate digital modeling and a physical design environment for both design and fabrication processes. MixFab [24] provides a mixed-reality environment with a gesture-based interface and existing object for 3D modeling. WireDraw [26] is a virtual reality-based 3D drawing guide tool that provides 3D visual guidance for making a 3D wire sculpture with a 3D extruder pen. SPATA [23] is a measurement tool that connects the virtual and physical environment bidirectionally by measuring, transferring, and presenting the dimension. Previous works enabled an intuitive and rapid fabrication with connection to the virtual and physical environment for static artifacts. We applied this approach by integrating the virtual and the real environments for kinetic artifacts, especially the linkage mechanism.

Building Blocks for Rapid Prototyping

The iterative process involving designing, building, and modifying is common in digital fabrication. A significant amount of time is necessary to complete the prototyping process because iterative fabrication, including editing and post-processing, is time-consuming. One solution for the challenge is to use building blocks. Using existing off-the-shelf parts saves fabrication time in comparison with making new components for fabrication. Several commercial modular kits, such as Lego [9], Meccano [11], and Science Box [21], were commonly used for rapid prototyping [14]. Several tools are available for building a kinetic mechanism with building blocks. Topobo [19], Cubement [3], Kinematics [16], and LINKKI [10] allow the user to create movement with a tangible kit. Our tool supports both the fabrication of custom assembly parts and the use of off-the-shelf mechanical parts for rapid fabrication.

MECHANISM PERFBOARD

Mechanism Perfboard is an augmented reality environment to support the design and fabrication of linkage mechanism for non-experts who lack knowledge and experience about it. The environment can be used to explore kinetic movement in the early stage. It allows non-experts to design and fabricate a linkage mechanism with computational support that generates the linkage mechanism and provides an integrated fabrication environment. The camera receives the information from the physical world in order to design and modify the linkage mechanism and the projector displays the virtual information for animated simulation and guidance on how to assemble the linkage parts. The accompanying hardware parts support the physical testing and fabrication of a final kinetic prototype.

Mechanism Perfboard has three key features. First, it supports a top-down process that prioritizes the movement of the target object for the linkage mechanism design. It is difficult to design the linkage mechanism from scratch without knowledge and experience. Also, an iterative trial-and-error process is necessary to produce a satisfactory result [15, 22]. First the system generates the initial linkage mechanism according to the desired movement, then it provides the modification step for details. The user can easily create the linkage mechanism by recording the desired movement, even though they are not accustomed to the linkage mechanism.

Second, it provides an integrated workbench-type environment by connecting the virtual and physical world with the augmented reality technique. To reduce the gap between the virtual and physical world in the design process, the real-scale virtual linkage mechanism is projected on the environment. The mechanism also includes the captured information of the object in the real world for the bidirectional interactive design process. Also, it allows the user to simulate and modify the linkage mechanism in the environment. The user can design, simulate, test, and assemble the linkage mechanism intuitively and interactively through tangible interfaces of an augmented environment.

Lastly, it supports rapid fabrication with an augmented step-by-step guide and provides a mechanical parts kit for assembly. A step-by-step guide reduces trials and errors in the process of assembly for rapid prototyping. The highlights of the required parts with the real-scale projection supports users' ability to find and place the mechanical parts within the environment. The Mechanism Perfboard's hardware, including the test board and the mechanical parts kit, employs an easy-to-use configuration. The user can assemble and modify the linkage mechanism rapidly with the off-the-shelf assembly parts and building blocks by using Science Box [21], which consists of gears, shafts, linkage frames with holes, etc.

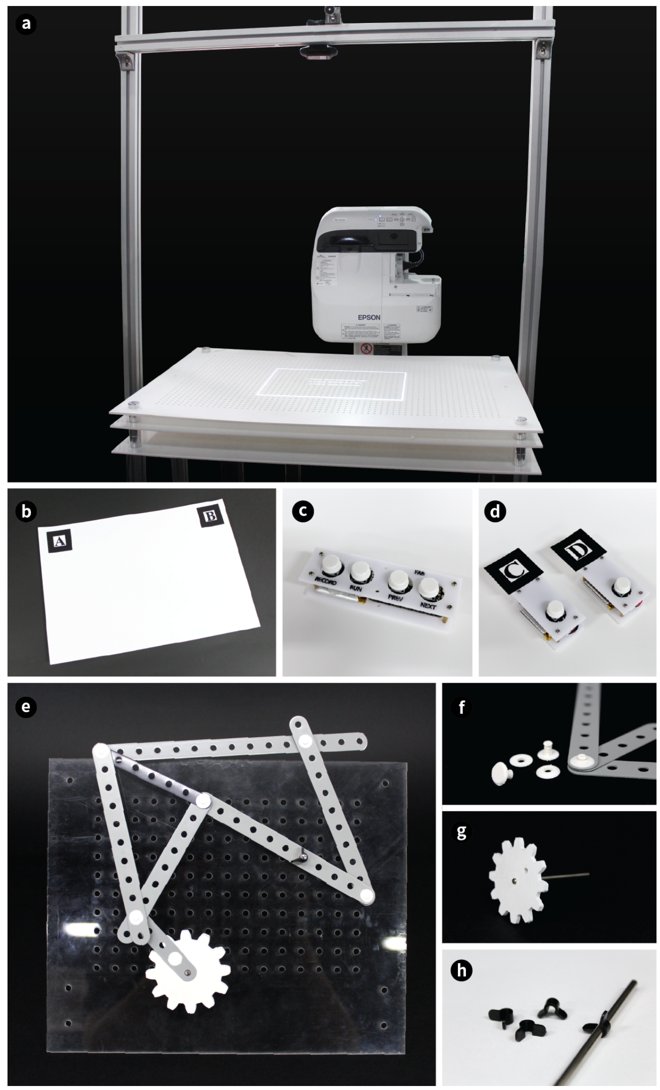

Figure 2. Hardware components of Mechanism Perfboard: (a) workbench with test board, camera and projector configuration, (b) AR marker board, (c) system button module, (d) modification button modules, (e) assembled linkage mechanism, (f) snap-fit joints and linkage, (g) gear, and (h) shaft and clip.

Hardware Components of System

Workbench

The main hardware of Mechanism Perfboard consists of a test board, a projector, and a camera (Figure 2a). The test board features double-stacked acrylic plates with holes to insert shaft parts easily and is designed to support the whole process that can be conducted on the test board. The camera is installed at the top of the test board to detect the AR marker and capture the image of the object on the AR marker board. The marker is used to capture the movement of the object and manipulate the system. The projector displays the linkage mechanism and assembly guide on the test board.

AR Marker Board

To capture the movement of the real object, an AR marker board with printed markers on two corners is used (Figure 2b). The user can employ this marker board to make the system recognize the real object by printing, drawing, and attaching images or object on it. The user can record both positional and rotational movement by manipulating the AR marker board above the test board to generate the linkage mechanism.

Interface Buttons

The button modules consist of a system button module (record, run, previous, and next, Figure 2c) and two modification button modules (move and scale, Figure 2d). The record button is used to start and finish the recording of the movement with the marker board. The run button is used to start and finish animated simulation of the linkage mechanism. The previous and next button are used to change the progress of guides for assembly. Two types of modification button modules allow the user to modify the linkage mechanism within the environment. The user can move the point of linkage mechanism with the move button module and scale the linkage mechanism based on the gear with the scale button module.

Mechanical Parts Kit for Assembly

The mechanical parts kit consists of a linkage, a snap-fit joint, a gear and a shaft to support rapid assembly (Figure 2e-h). We utilized the linkage and shaft part of Science Box, one of the most popular commercial modular kits in Korea. A linkage part of Science Box is a steel plate with holes (0.5-inch gap) to be assembled with other parts. The snap-fit joint is designed to connect the linkages at once, and the gear is designed to actuate the linkage mechanism with an other gear, motor, or handle by hand.

WALKTHROUGH: PROTOTYPING KINETIC SIGNAGE

Step1: Ideation and Drawing

To record the movement of the drawing, the user draws the object on the AR marker board. To capture the object clearly, it is better to draw with thick lines and vivid colors.

Use Case: A pet shop owner, Amy, wants to build kinetic signage with two objects (a cat and a toy) that move as shown in Figure 3. She draws the cat and toy on the AR marker board one by one. She draws a thick outline with a black marker pen and fills the inside of the drawing with a colored marker pen.

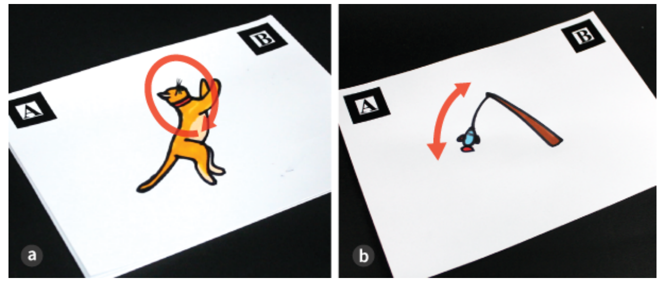

Figure 3. Drawing the object on the AR marker board: (a) cat and (b) toy. The red line is the desired movement.

Step2: Movement Recording and Mechanism Generation

In the initial page of the system, there is a rectangular guide and instructions for the linkage generation. To start recording the movement of the drawing, the user puts the AR marker board in the rectangular guide and presses the record button (Figure 4a). At this time, an image of the object in the rectangular guide is captured. The user can move the AR marker board to record the desired movement (Figure 4b). To finish recording, the record button is pressed again. Then the system generates the most similar linkage mechanism by comparing the trajectory and rotation angle of the desired movement with the mechanism data set (Figure 4c). The captured image is snapped to the target linkage.

After the linkage mechanism generation, the user can simulate the generated mechanism to verify that it is correct. The user presses the run button to start the simulation of the mechanism, and presses it again to finish the simulation. During the simulation, the user can check the movement of the linkage, the captured image, and the trajectory. The captured image is moved according to the position and angle of the target linkage. The trajectory is drawn with a purple line. If the generated linkage mechanism is unsatisfactory, then the user can record the movement by pressing the record button again.

Use Case: After drawing the object, Amy put the AR marker board in the center of the rectangular guide to start recording. She presses the record button and moves the AR marker board as she desires. To finish the recording, she presses the record button again. The system generates the linkage mechanism after several seconds. To check the movement of generated linkage mechanism, she presses the run button. She thinks that the movement of the generated linkage mechanism and the desired movements are quite different, so she decides to record the movement again. She presses the run button to finish the simulation and presses the record button to change the initial page of the system. Then, she records the movement again. The second generated linkage mechanism is a little bit different. However, she thinks that it would be possible to achieve the desired movement by modifying the process with the modification button modules and decides to continue to the next step.

Step3: Modification Linkage Mechanism

The user can modify the linkage mechanism with the move and scale button. The purple circle indicates the target point when the move button module is detected on the test board.

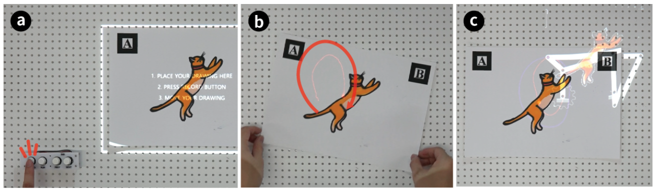

Figure 4. Generating a linkage mechanism through (a) placing the AR marker board on the test board and pressing the record button, (b) moving the AR marker board, and (c) pressing the record button again. Then, the system generates the linkage mechanism.

To move the point of the linkage mechanism, the user selects the point by pressing the move button and then moves and releases it (Figure 5a). When the user edits the displacement of the points, the trajectory is instantly changed. If a trajectory is broken or disappears, it means that the linkage mechanism is not valid. To change the scale of the linkage mechanism, the user presses, moves, and releases the scale button (Figure 5b). The scale of the linkage mechanism changes based on the gear as a center. Also, it is possible to simulate the movement with the run button.

Use Case: In this step, Amy modifies the linkage mechanism by using the move and scale button modules. She modifies the position of each point with the move button while checking the trajectory to make sure that it is similar to the desired movement. Also, she simulates the movement of the image with the run button. After that, she magnifies the linkage mechanism with the scale button.

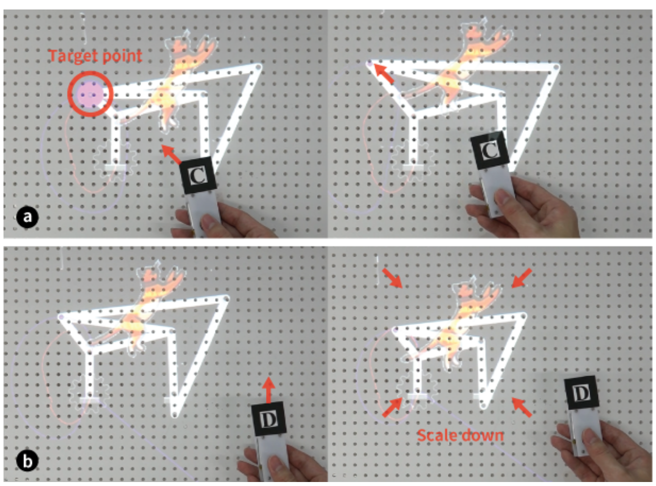

Figure 5. Modifying the generated mechanism by (a) moving the point and (b) changing the scale

Step4: Prototyping with the Fabrication Guide

After designing the linkage mechanism, the user assembles the linkage mechanism with the fabrication guide. Mechanism Perfboard illustrates how to assemble the linkage mechanism step by step. The user can move the progress of the fabrication with the next and the prev buttons. At first, the user needs to assemble the linkage. The linkage that should be assembled highlights its color to purple, and the used linkage changes its color to light purple (Figure 6a). The user can find the mechanical parts with the annotated length number or by direct placement on the test board. The user needs to assemble the purple linkages with the snap-fit joint. The linkage assembly procedure begins with a four-bar linkage and transitions to a coupler linkage. After the linkage assembly, the user assembles the gear and inserts the shaft into the right position according to the guidance of the system (Figure 6b & 6c). Lastly, the target link changes to purple. The user attaches the drawing and tests it by rotating the gear.

Use Case: Amy presses the next button to start prototyping. She checks the numbering length of the linkage to find the proper Science Box linkage. She also puts the linkage on the displayed linkage mechanism. After finding the three linkages, she simulates the linkage mechanism to determine the stacking order and assemble it with the joint. Then, she compares the assembled linkage by putting it onto the displayed linkage mechanism. She continues to assemble all linkages and gears and inserts the gear and shaft according to the guidance. Lastly, she cuts out the drawing, attaches it to the target linkage, and actuates the linkage mechanism.

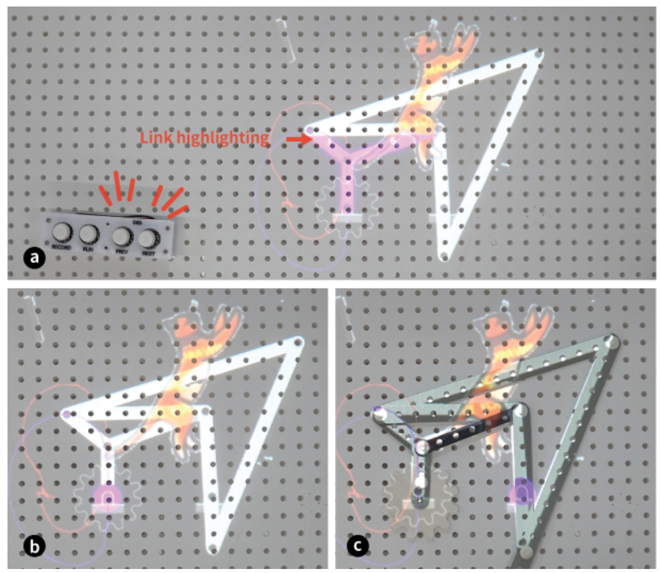

Figure 6. Augmented guide for fabrication: (a) assembling linkage, inserting (b) gear and (c) shaft.

Step5: Move to the Small Test Board and Actuate

After assembly, the user moves the linkage mechanism to the small test board with a clip. It is possible to actuate the linkage mechanism vertically with the small test board (Figure 7).

Use Case: Amy moves the linkage mechanism to the small test board. Then, she designs and fabricates one more linkage mechanism and actuates them together.

IMPLEMENTATION

Hardware

The test board was built with double-stacked acrylic plates with holes for the stable assembly of the shaft parts. The thickness of the plates was 5 mm and the distance between the two plates was 25 mm. The radius of the holes was 4 mm, which corresponded to the shaft parts, and the holes

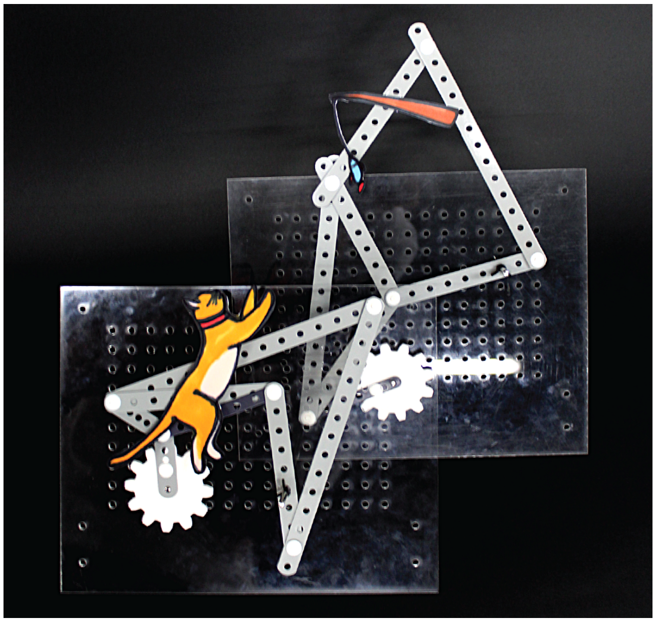

Figure 7. Final result of the prototyping kinetic signage (a cat and a toy).

were arranged in a 58-by-35 configuration with a distance of 0.5 inch (produced by laser cut). The mechanical parts kit (gears and snap-fit joints) were designed with 3D modeling software and were 3D printed. The joint parts were designed to be flat and rounded to minimize the interference with the linkage parts when the linkages were actuating. The small test board was designed to be smaller with 3-mm-thick, transparent acrylic plates and 15-by-10 holes. The button modules were implemented to be wireless and portable with an Adafruit Feather HUZZAH ESP8266 board, tact switches, and a 3.7-V lithium ion battery. The AR markers, from the template markers of AR.js, were printed and attached on the modules. A Logitech C920 webcam and an EPSON EB-585Wi short-throw projector were used for the AR environment and were manually calibrated with grids. Each hardware component was assembled on aluminum frame (Figure 2a).

Software

The software for Mechanism Perfboard was developed as a web application with JavaScript. AR marker detection was implemented using AR.js to capture the movement of the object on the AR marker board. The center position and rotation angle were obtained by two AR markers at two corners of the board. The image captured from the board was processed to eliminate the outer area from the color value of the board. Then the captured image was attached on the target linkage to represent the movement. The hardware control buttons were connected via a socket server of Node.js.

Mechanism Generation from Movement

Movement Features

Mechanism Perfboard applies a six-bar Watt-1 linkage mechanism to deal with both the position and rotation features of movement. A simple circular movement can be generated by a four-bar linkage (*Link ABCD*), but rotation of the coupler is constrained by the position. Two additional couplers (*Link EGF*) with Watt-1 mechanism can generate another coupler curve (Figure 8, left) which has the potential for a wider range of movement [18]. We designate a point on the four-bar coupler as the pivot point of the target object, and apply this Watt-1 coupler curve as a pivot handle of the target object (Figure 8, right). Therefore, the target image is attached on *Link FG*. The angle of the target object for time t is obtained as, $\theta(t) = \arctan(\ (\ y_F(t) - y_G(t)\ )\ /\ (\ x_F(t) - x_G(t)\ )\ )$. We use two arrays of the coordinates of point F $(P_{F1}, P_{F2}, ..., P_{Fn})$ and angles of the target object $(\theta_1, \theta_2, ..., \theta_n)$ as features to derive a linkage mechanism.

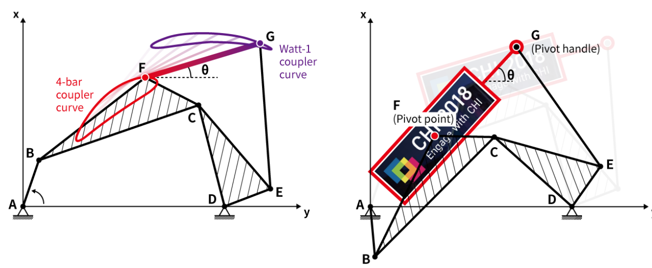

Figure 8. Configuration of the six-bar mechanism. Point F of the four-bar linkage was used as the pivot point of the target object and point G on the Watt coupler served as the pivot handle to enable a movement from both positional and rotational features.

Data Generation and Mechanism Selection

To create the mechanism for the users' desired movement, based on the movement features, our approach was to find a mechanism that had the most similar movement in the data set. We generated various Watt-1 mechanisms that had different lengths for the linkages, as shown in Figure 9. For using the mechanical parts kit of Mechanism Perfboard, the lengths of the linkage parts were constrained for a unit of 0.5 inch and the rocker for the Watt coupler was linear (Figure 9a). For each generated mechanism configuration, eight sample variations of rotated and flipped mechanisms were obtained to save arrays of coordinates and rotations of the target object. The samples were excluded where the linkage configuration was broken or not valid. The array of movement features was normalized into the range from -1 and 1. The total sample mechanisms were 54,585.

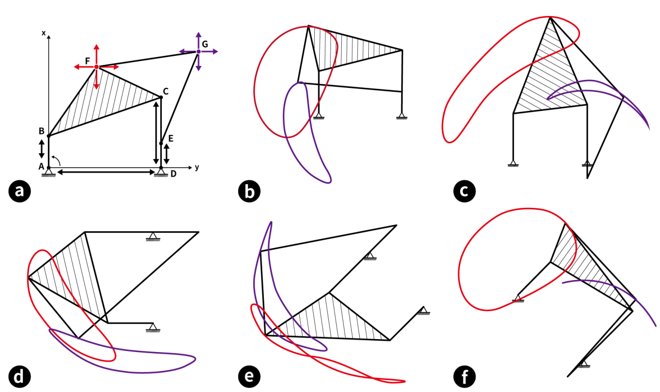

Figure 9. Data generation for mechanism generation: (a) variation of linkage configurations and (b-f) example mechanisms in the data set.

The mechanism that was the most similar to the desired movement was obtained by dynamic time warping from the generated data set. It is challenging to find a six-bar mechanism that has the exact same movement of the both position and rotation features. Therefore, we empirically set the distance weight between the position and rotation as 2:1 for a satisfactory result: $Distance(M_1,M_2) = Weight_P \times DTW(P_1,P_2) + Weight_R \times DTW(R_1,R_2)$. The mechanism that has the lowest weighted distance was selected as the nearest neighbor with dynamic time warping. The measured time to obtain a mechanism using a total of 54,585 samples varied in the range of 8 to 30 sec.

USER STUDY

We conducted a lab-based user study to evaluate the effectiveness and usability of Mechanism Perfboard and to find areas of improvement. Specific questions regarding the study included: (1) How does the top-down design process using real object affect the participants' design activity? (2) How does the augmented reality integrating software simulation and physical environment affect the mechanism design? (3) How do the augmented assembly guide and mechanical parts kit help them? (4) What are the system's effectiveness, usability, and areas of improvement? We recruited 10 participants to make a kinetic prototype with a linkage mechanism. We observed the participants' activities while using the system, collected the outcomes of the kinetic prototypes, and conducted the survey and interviews.

Participants and Assignment

Ten undergraduate and graduate students participated in the study (8 males and 2 females, ages 21-25, M=23.00, SD=1.00). Five participants (P1, P3, P4, P6 & P10) had a knowledge of the linkage mechanism. They had learned about the concept and basic kinematics. However, they lacked knowledge and experience related to the actual design and fabrication of the tangible mechanism. Two of them (P1 & P10) had experience with designing and building the linkage mechanism, such as very simple automata and pre-designed mechanisms such as the Theo-Jansen mechanism. Five (P2, P5, P7, P8 & P9) had no experience of designing and building a linkage mechanism, except through the process of assembling toys or pre-designed products.

The participants were asked to build kinetic signage by using the linkage mechanism. We chose kinetic signage because designing it includes both a concept idea for expression and the movement of the signage itself. We let the participants choose one target shop or brand then build the kinetic signage with two moving objects. The objects were drawn on the given AR marker board. Each object was included in one six-bar mechanism, so the participants completed two six-bar mechanisms as the assignment.

Procedure

Before using the system, we took 5 minutes to introduce the linkage mechanism and its related components, including the linkage, driving part, anchor point, and joints. We showed examples of a linkage mechanism (Figure 2e) and how it actuated. Then the participants watched a video that introduce the usage walkthrough, and they saw a 10-minute demonstration of the system. After the introduction, the participants had 10 minutes to think of an idea and sketch what they wanted to build. The participants were free to generate ideas of movement without mechanical limitations in order to figure out their desired movement. They sketched two objects and were asked to annotate their desired movement freely in order to figure out their initial plan. Then they drew two objects that would be moved on the provided AR marker board. After drawing, the participants proceeded to build kinetic signage with the two moving objects. We guided the participants' progress as they completed the first mechanism while using the system (e.g., how to use the mechanical parts kit for assembly), then let them use it alone. After creating their mechanisms, the participants cut and attached their drawn images on a target linkage and actuated the mechanism with the given gear modules.

We conducted a survey and semi-structured interview for 20 minutes after the prototyping session. The survey included aspects of usability, effectiveness of the system, and a self-evaluation of how their result compared with their initial desired movement as listed in Figure 11. The questions were rated on a 5-point Likert scale (ranging from 1 = strongly disagree to 5 = strongly agree). During the interview, we asked questions that were structured into five aspects: effects of the top-down design process with real objects' movement, effects of the augmented environment using projection, effect of the augmented guide and mechanical parts kit, improvement points for further development, and potential applications and domain areas.

Data Collection

We analyzed the results from the observations of the participants' usage, surveys, and interviews. The initial sketches and prototype outcomes were collected and photos were taken. The entire procedure of the study was video recorded. We measured the time and the number of attempts to generate mechanisms until they obtained a satisfactory result in the design process. We also measured time for assembling and actuating the designed mechanisms. The collected data (survey results, transcribed interviews, activities in prototyping sessions, and prototyping outcomes) were analyzed by the research team with iterative analytic induction.

Results

Design Outcomes

Most participants could successfully build their kinetic signage with two linkage mechanisms. The average time of generating the mechanism by the real movement was 3.15 minutes (SD=1.97), with two to four trials of generation to obtain the satisfactory result. P3 took 10 minutes to get the final result after several modifications. Fabricating the designed mechanism took an average of 10.85 minutes (SD=1.87).

Among the 20 desired movements, 9 were swing movements, 4 were one-way movements, 5 were cycled movements, and 2 were zigzag movements. Most desired movement could be realized with a six-bar mechanism supported by the Mechanism Perfboard system. However, two participants

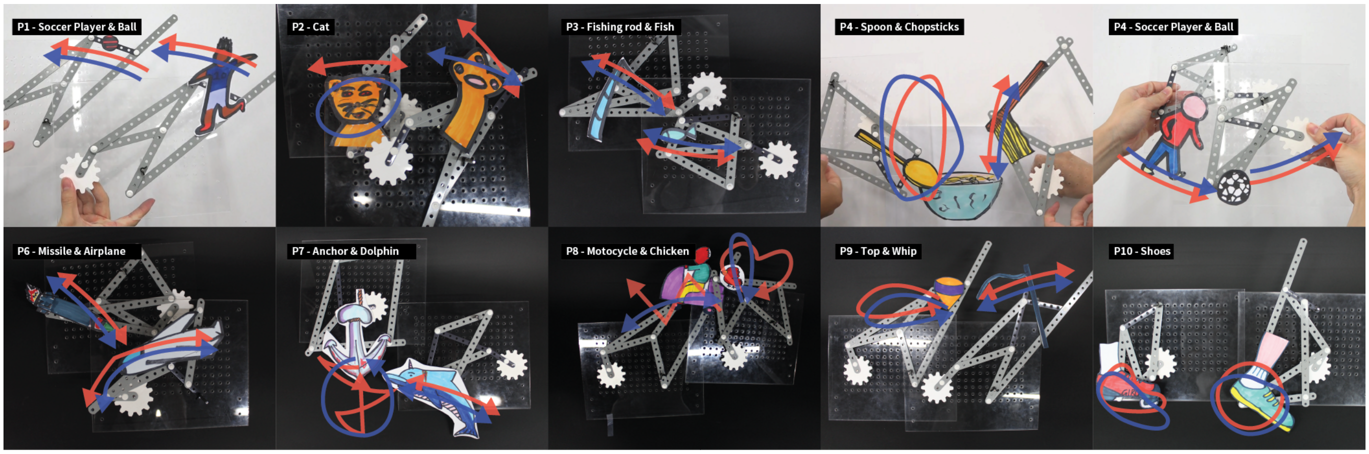

Figure 10. Kinetic signage built by user study participants. The red line is the desired movement and the blue line is the movement that was built with Mechanism Perfboard.

intended to design zigzag movements that were not supported by the system. Each movement was replaced with cycled and swing movement after the first trial of the mechanism generation. Several mechanisms interfered with the shaft parts (anchor points), so partial movement was allowed.

Design with a Real Object

The participants could easily generate a linkage mechanism by using their drawn images and felt that the process to input the movement was intuitive. They highly valued digitization of their desired movement without any additional devices. P3 said, "*It is hard to express what I want by using a mouse or something when I use a computer*." Some participants were concerned about completing the task at the beginning of the study, but they were interested in the automated generation and were able to finish their design. Most participants commonly said that the automated mechanism generation played a role to lower the barrier to start the mechanism design. P9 said, "*I didn't know how to design it at all, but it was good to create the linkages (by the system) at first*." When the generated mechanism was not exactly same as the participants' desired movement, they tried two or more times to generate it again. Repetitive generation was effective for some participants who did not have any knowledge of a linkage mechanism. The participants said that the mechanism generation process was easy and intuitive and that they had an acceptable time to retry to obtain better result.

Augmented Software Simulation

When the participants started to modify the generated mechanism, we observed that the participants mainly concentrated on the resulting movement instead of understanding the mechanism actuation. The projection of real-time simulation on the test board could help the participants to repeatedly adjust the resulting path to their desired movement. Since the participants were unfamiliar with mechanism design, they tried to move the points to check how the movement trajectory or rotation of the target image were altered. P8 said, "*I liked the projection of the path when I wanted to change the scale or shape of movement*." Similarly, we observed that the participants thought aloud about how the movement should be changed instead of understanding the configuration of the linkage (e.g., "*it (path) should be stretched vertically*." P10).

Animated simulation of the mechanism also helped the participants to fabricate the linkage parts. Comparing to the static schematic drawing of mechanism, animation of the mechanism actuation allowed them to expect the stacking order of linkages that were connected to a joint. The participants could avoid interference caused by crossovers of links despite the simulation was two dimensional projected animation. P4 mentioned, "*I could decide what linkage was best to be placed on top during the simulation*." Since it was hard to challenge the designed linkage mechanism before the completion of fabrication, they spent enough time checking the simulation results and thinking about their next step.

Fabrication Support

Mechanism Perfboard provided fabrication support by using an augmented assembly guide and mechanical parts kit. Real-scale projection on the test board was intuitive and it was easy to find and place the parts. The participants placed several parts on the test board to compare it with the projected virtual parts instead of measuring. The participants felt that fabricating with Mechanism Perfboard provided experience as *shape-by-shape* that is the name of the puzzle used to find a shape that fits the frame.

The participants felt that the system helped them to become immersed in the fabrication with the step-by-step guide via projection. Some participants compared this feature with previous experience, such as referring to a schematic drawing on a monitor screen. P9 mentioned, referring to other instruction caused an interruption of the work flow because they had to make sure that it was properly assembled. However, highlighting the linkage of the current step helped the participants to avoid the confusion with the previously assembled parts enabled them to feel comfortable with the process of adding new parts. P8 said, "*At first, I worried about how to assemble this. But it was easy by looking at the step-by-step guide*."

Usability

The overall easiness (μ=4.10) and the usefulness (μ=4.00) of the system to the prototyping linkage mechanism was positively rated (Figure 11a). For specific features (Figure 11b), the participants responded that the automated mechanism generation (μ=4.30) and simulation with the captured image (μ=4.60) were useful. To input movement with the drawing was also positively rated (μ=3.70, 80% agree). During the interview, several participants mentioned that using the real object was intuitive. P4 said, "*It was good because I could use my hand to move the drawing easily*." P1 and P7, who rated the process negatively, mentioned that they were uncomfortable with the settled starting point and the pivot point of the AR marker board. The similarity between the desired movement and the achieved movement was relatively low (μ=3.10). The participants commented that the system could not provide identical movement, but it was not a serious challenge.

Regarding the use of the interface button modules after the mechanism generation process (Figure 11c), the easiness (μ=3.90) and the usefulness (μ=3.70) were positively rated. Most participants could achieve their desired movement in this phase. However, some participants had trouble getting better results or some spoiled the generated mechanism. P2 said, "... *I have no idea how to move to get what I want*." The augmented fabrication guide for real-scale projection (μ=4.60), the numbering length of the linkage (μ=4.60), and the step-by-step assembly guide (μ=4.50) were also highly rated (Figure 11d). On the other hand, the participants negatively responded to the ease of using the mechanical parts kit (μ=2.90). They were satisfied with the test board for rapid fabrication, but they mentioned that the provided linkage parts and snap-fit joint had a limitation when attempting to actuate their mechanism smoothly. Despite the fact that the snap-fit joint was designed to minimize interference, it was determined that the problem still existed. Actuating vertically with the small test board reduced this interference.

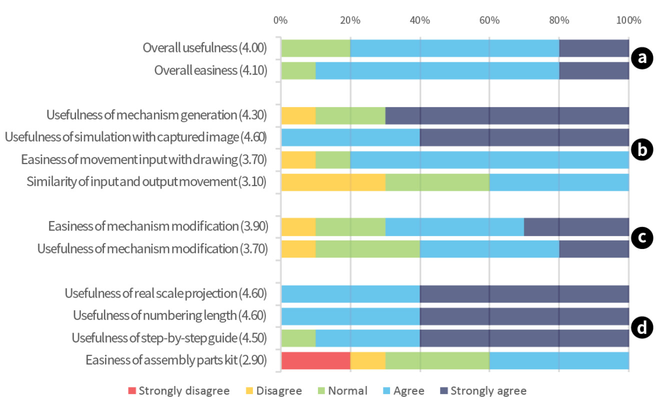

Figure 11. User assessment of easiness and usefulness of Mechanism Perfboard (5-point Likert scale, average in parentheses).

DISCUSSION AND FUTURE WORK

Helping Non-Experts Using Computational Support

Mechanism Perfboard supports the top-down design of the linkage mechanism to obtain the desired movement. We found that the generation of the initial mechanism that was similar to the desired movement played a role as a starting point without knowledge of it. However, the automated generation of the mechanism is not always effective. It is challenging to obtain exactly the same movement from computational support with limited movement features. Therefore, support for its iterative modification for finding the desired movement should be allowed for users. The current system let the users change the positions of the joints with real-time simulation. We assume that there are several ways to apply a top-down approach to support modification. The change of the linkage configuration from the change of the movement path or angles, as demonstrated by Bächer et al. [1], can be adapted to the system because the participants wanted to edit the movement. Meanwhile, it is also feasible that the system let the participants select one result among the alternatives provided by the computation results [22], not the nearest neighbor selection.

User Engagement with Different Knowledge Levels

We found that there was no critical difference between the experienced and non-experienced groups in the user study. The task completion time was not affected by skill level, but rather depended on the participants' satisfaction with the mechanism generated by the system. P3 wanted to modify the linkage mechanism with the modification button instead of generating the linkage mechanism and spent 10 minutes to get desired movements. On the other hand, some participants were satisfied with the generated movement by the system and moved on to the prototyping phase without modification. However, we found that the non-experienced group performed the task more passively than the experienced group, especially when modifying the linkage mechanism and finding the stacking order. The non-experienced group more depended on the guide and they wanted a more detail guide about the modification and stacking order.

Integration of the Virtual and Real Environment

Our system applied a camera-projection augmented reality technique for integrating movement design and fabrication. The physical linkages are assembled and actuated in 3D space with the thickness and depth position of each linkage part. The participants used the projected simulation to foresee the stacking order, but they felt uncomfortable with the obstruction of the projection by parts or hands during the fabrication. There is some way to improve the expression level. Virtual reality with a head-mounted display or augmented reality with a hand-held device has the potential to explore the information in 3D space without interference as well as by minimizing the physical scale of the system. In terms of recognition, the system detected the position and rotation of the movement. The participants also mentioned that the recognition of the linkage parts would provide more interactive fabrication. If the system recognizes the assembled parts in the real world, then it can provide a guide to solving the potential trouble as well as to complete fabrication rapidly and easily with augmented information. Each function of the system could be implemented with an on-screen application, and it might be more practical in the aspects of accessibility rather than augmented reality setup. However, the integrated workbench was more effective for the rapid and iterative process with an augmented reality techniques. We found that the participants were able to maintain their viewpoint during the fabrication, which helped them to concentrate on the task and prevented confusion.

Fidelity and Domain Areas

There remains some future works to improve the system and study. Mechanism Perfboard supports a 2D planar linkage mechanism with simple circular movement. The 2D planar linkage mechanism is widely used as an essential configuration of the movement of various everyday products such as the windshield wiper of a car, a trash can, and adjustable furniture. We expect that Mechanism Perfboard is useful to explore and concretize the idea with kinetic movement in the early stage of the fabrication process. The linkage mechanisms are also used for educational purposes in designing with kinetic materials. The participants mentioned that Mechanism Perfboard could be used for educational purposes. However, the mechanism designed by the system has limited practical applications. Additional mechanical components, such as sliders, gears, and cams, can expand the expression of the designed mechanism. Moreover, more sophisticated mechanisms beyond the six-bar mechanism can be applied for the data set for the automated mechanism generation. Meanwhile, the prototype built with Mechanism Perfboard can be improved in terms of hardware quality. The participants commented that the stable part components and special housing for the designed mechanism supports the makers' prototyping. Mechanism Perfboard, with an improved quality of outcomes, can be evaluated by potential users while creating various examples beyond kinetic signage to investigate the applications of linkage mechanism design.

CONCLUSION

Our motivation for conducting this research was that there are many difficulties in the linkage mechanism fabrication process and it is difficult for non-experts, who lack knowledge of and experience with mechanism design, to employ it. In this paper, we have presented an augmented reality environment and a top-down approach with a novel movement input interface that enables non-experts to design and fabricate linkage mechanisms with ease. Also, we explored how the features of Mechanism Perfboard, including computational support, augmented reality, and a fabrication guide, could be involved with the linkage mechanism fabrication process. We expect this research to inspire the development of tools for kinetic mechanisms, as well as systems that use augmented reality and computational support.

ACKNOWLEDGMENTS

This research was supported by the EDISON Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (No.2014M3C1A6038802).

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