

AR-Jig: A Handheld Tangible User Interface for Modification of 3D Digital Form via 2D Physical Curve

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ABSTRACT

We introduce AR-Jig, a new handheld tangible user interface for 3D digital modeling in augmented reality (AR) space. AR-Jig has a pin array that displays a 2D physical curve coincident with a contour of a digitally displayed 3D form. It supports physical interaction with a portion of a 3D digital representation, allowing 3D forms to be directly touched and modified. Traditional tangible user interfaces physically embody all the data; in contrast, this project leaves the majority of the data in the digital domain but gives physicality to any portion of the larger digital dataset via a handheld tool. This tangible intersection enables the flexible manipulation of digital artifacts, both physically and virtually. Through an informal test by end-users and interviews with professionals, we confirmed the potential of the AR-Jig concept while identifying the improvements necessary to make AR-Jig a practical tool for 3D digital design.

Keywords: actuated interface, augmented reality, digital modeling, handheld tool, pin array display

Index Terms: H5.1. [Information Interfaces and Presentation]: Multimedia Information Systems—artificial, augmented, and virtual realities

1 INTRODUCTION

Automobile or product designers use tools to manipulate 3D digital representations of their work. A well-known tool for manipulation is SensAble's PHANTOM [1], a 6-DOF (degree of freedom) articulated arm device to render 3D force feedback. A pen attached to a PHANTOM device allows for interactive sculpting of a digital model with computed volumetric viscosity and surface contact forces. However, it handles only one point of digital form at a time, so a user cannot utilize the wealth of interactions available to sculptors and physical artists, who make use of the physical relationships between the body and the art object.

We are interested in providing users more direct interaction with 3D objects to allow the use of the physical relationships between the body and the digital representations, bypassing the manipulation of parameters or form/element handles typical of traditional CAD GUIs. Furthermore, we are interested in making the modeling of 3D objects more accessible to novice end-users as

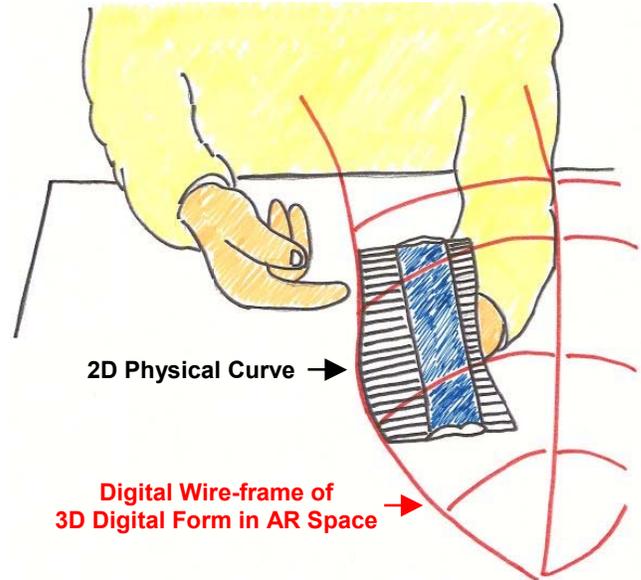


Figure 1. AR-Jig Concept: A physical 2D curve coincident with a contour of a digitally displayed 3D form allows for deforming the 3D form by pin array manipulation.



Figure 2. The first prototype of AR-Jig. The display in the figure shows an image that a user sees through a head mounted display.

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well as experts, so that people inspired by physical forms can easily grab and re-use forms available in both their physical and their digital environments.

To realize a physical relationship between the body and the design target, we use the Tangible User Interface (TUI) [2], which gives physical form to digital information for direct manipulation,

but limit physical contact with the multiple points to take advantage of flexible and dynamic 3D virtual data. Even with a limited number of points, adjacent physical points can represent part of a form. Therefore, we propose to give physicality to any portion of the larger digital dataset via a handheld tool, leaving the rest of the digital data in the digital domain.

First, we focus on a curve as a part of the 3D form and use augmented reality (AR) technology to visualize the spatial relationship between a physical curve and digital 3D form. This system, called AR-Jig, has a handheld pin array that displays a 2D physical curve coincident with a contour of a virtual 3D form shown in an AR space (Figure 1). AR-Jig allows for 3D digital form modification by pin array manipulation, since the 2D physical curve is synchronized with the 3D form. The first prototype of AR-Jig has 12 in-line pins with positions manipulated by hand, measured by sensors, and actuated by motors (Figure 2). The pins physically display a contour of a 3D digital form seen through a head mounted display (HMD).

In this paper, we present AR-Jig's related work, its system design, the first prototype implementation, interaction techniques, and qualitative evaluation to demonstrate the possible use of AR-Jig as a practical tool for 3D digital design.

2 RELATED WORK

Our work is related to previous handheld tools and tangible user interfaces for digital form control. It is also related to pin array displays.

2.1 Handheld Tools for Digital Form Control

The CSIRO haptic workbench [3] uses a PHANTOM device to translate, rotate, and deform a 3D model in an AR space. T'nD [4] is a free-form modeling system with another articulated arm that has two 3-DOF haptic devices connected to a ruler tool by means of spherical joints. This design allows for the scraping of a digital surface by sweeping motions with the ruler. Handheld tools without force feedbacks have also been used for 3D digital form control. Spacedesign [5] is a mixed reality application for the sketching and surfacing of free-form shapes with a pen in the air. Surface Drawing [6] allows the use of a handheld tool and hand gestures for creating organic 3D shapes. This direct interface is known as a good option for artistic 3D digital creations. GeOrb [7] is a ball-shaped tool used to control 3D movement simply by touching the part of the Orb that maps to the desired direction. It allows the user to shape the computer image by simply squeezing the device.

These tools provide indirect virtual contacts with digital data to control a digital form. In contrast, AR-Jig provides direct real contacts with digital data, even though the contact area is partial.

2.2 Tangible User Interfaces for Digital Form Control

Free-form modeling is one application target of TUI. Digital Tape Drawing [8] is a 3D digital drawing tool designed with knowledge of the conventional tape drawing. Illuminating Clay [9] is a 3D (2.5D) digital modeling interface based on the knowledge of well-known clay modeling. Another promising approach to direct free-form modeling involves the use of physical building blocks embedded with computation such as Anderson's blocks [10] and ActiveCube [11]. Tangible Augmented Reality Modeling (TARM) [12] also uses building blocks that can be virtually copied in an AR space to make a virtual model. ShapeTape [13] is a unique tangible form input device that is a bendable and twistable sensitive strip allowing for direct manipulation of digital curves and surfaces.

All these TUIs have been well received in design and/or educational domains because they preserve the fundamental interactions of easy-to-use traditional physical media while leveraging the power of digital media. These interfaces are limited, however, to creation. In contrast, AR-Jig can instantly adopt the contour of an existing digital form and produce a malleable physical representation of that contour, allowing for modification.

TUIs that computationally modify the physical environment do exist, but they are confined to the tabletop. The Actuated Workbench [14] and Planar Manipulator Display [15] move physical points on a table to display digital data in user-manipulable forms. In contrast, AR-Jig actuates a curve instead of point objects. Free from the table, the handheld AR-Jig can actuate any curve in space within reach.

2.3 Pin Array Displays

AR-Jig displays a 2D digital curve with an actuated pin array. This idea is inspired by the contour gauge (a conventional profile measurement tool), pin art of children's toys, and the following actuated pin matrix displays. FEELEX [16] and Wanger's displays [17] are typical early pin matrix displays that use RC servomotors to actuate pins. Nakatani's display [18] actuates long stroke pins using a coil-form Shape Memory Alloy (SMA). Haga's display [19], which also uses an SMA as a pin actuator, is used as a Braille display. Application findings of a pin array display have already been initiated. Northrop Grumman's TerrainTable [20] is a large table on the top of which an array of vertical pins creates a curved surface to represent 2.5D topographic geometry. Lumen [21] is an interactive pin array display that presents visual images and physical moving shapes, each controlled independently. Also, many patents involve a 3D surface using an actuated pin array [22] [23] [24].

AR-Jig features a far simpler mechanical implementation. Our 1D array has fewer pins (and therefore fewer actuators) than 2D matrices; therefore, it is light enough to be handheld. This mobility allows AR-Jig to display aspects of a fully 3D digital object, whereas tabletop arrays are typically limited to 2.5D massing models.

3 SYSTEM DESIGN

Digital representations in design work are primarily visual, usually occupying the 2D space on computer monitors. Thus, many TUIs have been proposed to give physical embodiments to digital representation. TUI allows users to interact with digital representations within a physical 3D space. However, TUI has limitations: giving physical embodiment to large-scale 3D digital data is often impractical, difficult, and expensive. It is also generally difficult to give physical form to dynamic digital representations.

The best way to give physical embodiment to a 3D dynamic digital form would be, perhaps, to invent a 3D physical display that could represent the 3D digital form inclusively. However even with the most advanced technology available, it is currently impossible to make such a 3D physical display. As a substitute, one-point haptic displays such as PHANTOM have been invented. By moving a mechanical force-feedback stylus, users can feel the shape of a 3D digital form through the one-dimensional point at its tip. However, one-point representation is far from the whole 3D data representation. Providing more than one-point physical embodiment is one way to achieve the benefits of TUI.

Our approach gives versatile physical embodiment to part of a 3D digital form. As the embodiment, we chose a 2D curve because 2D representations are sometimes helpful in understanding and controlling a 3D form. In fact, most 3D

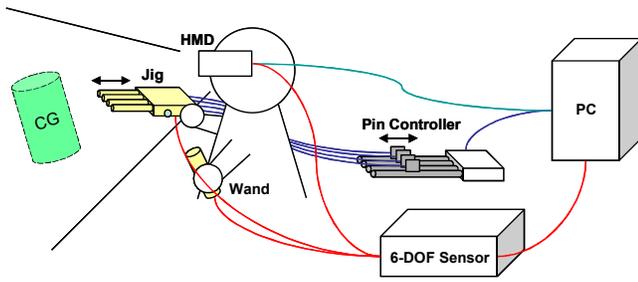


Figure 3. Hardware architecture.

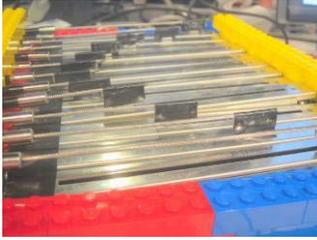


Figure 4. Pin Controller.



Figure 5. Jig (in-Line pins).

modeling software has a “wire-frame” mode to show 2D profiles of 3D forms, as well as a 3D surface control method using a 2D control curve. To apply the embodiment to any portion of the 3D digital form, we selected a handheld style. Actuating a wire in the air is too difficult, instead of a wire; we chose multiple points to display any 2D curve physically.

Although one TUI merit of simultaneous control by multiple persons cannot be achieved, our approach realizes three TUI merits for design tasks. Multi-point representation allows for direct designer expression. The physical embodiment of design media allows a designer to use her/his fingers, palms, and even objects around her/him to modify the design media. The representation can be controlled not only by a designer but also by a computer so that the designer’s input can be optimized under numerical constraints. These merits of tangible interaction provide unique modification of digital data that cannot be achieved with conventional digital design tools.

4 PROTOTYPE IMPLEMENTATION

We implemented a prototype system to confirm the potential of the AR-Jig concept. This section describes the system architecture.

4.1 Hardware

AR-Jig hardware consists of six parts (Figure 3): a 6-DOF sensor, a Pin Controller, a Jig (in-line pins), a Wand, an HMD, and a PC. We use the POLHEMUS Fastrak as the 6-DOF sensor to track three objects (Jig, Wand, and HMD). The Pin Controller (Figure 4) consists of 12 motor-driven slide potentiometers (ALPS RSA0N11M9A05) connected to a custom electronic board, which reads the 12 potentiometers and controls the 12 motors operated by 24 V DC. The travel length of the slider is 100 mm. The spacing between sliders is 1.75 mm. The actuating torque is about 5 N. The Wand is simply a plastic hand-made handle with another tracker of the 6-DOF sensor. The HMD is a video see-through head mounted stereo display (Canon VH-2002) with VGA (640x480) resolutions and NTSC cameras. The other tracker of the 6-DOF sensor is attached to it. The PC is a Linux-based Intel Pentium 4 Processor 3.60 GHz computer with an NVIDIA Quadro FX 3400 graphics card.



Figure 6. Pin Controller and Jig.

The total weight of the 12 motor-driven slide potentiometers is too heavy (612 g) to be held with the hand. Thus, we make the Jig (Figure 5) with long (1.78 m) wire-in-tubes, which were originally used for bicycle breaks, to separate it from the Pin Controller (Figure 6). The middle of the bundled wires is hung on a tripod. As a result, the total weight of the Jig is about 200 g. This is light enough to be handheld so as to select a part of 3D form directly, although selectable space is limited. A tracker with a button of the 6-DOF sensor is attached to the Jig.

4.2 Software

AR-Jig software consists of seven parts (Figure 7): a Head Tracker, an AR Base System, a Jig Tracker, a Wand Tracker, a Pin Tracker, a Pin Actuator, and a Form Controller.

The Head Tracker sends the AR Base System the user’s head (HMD) position and orientation measured by the 6-DOF sensor.

According to the head position and orientation, the AR Base System renders a Computer Graphics (CG) model provided by the Form Controller on real scene images captured by cameras of the HMD. The AR Base System also renders semitransparent virtual objects representing the Jig (Figure 8) and the Wand (the orange sphere in Figure 9(a)) based on their position and orientation as provided by the Jig Tracker and Wand Tracker. The virtual object for the Jig changes its color based on interaction techniques, which are described in Section 5.3. The color helps a user understand which technique is activated.

The Head, Jig, Wand Trackers, and AR Base System are implemented based on an AR software development kit called “MR Platform SDK” [25].

The Pin Tracker communicates with the custom electronic board of the Pin Controller to get the Jig’s pin positions (i.e., the potentiometer values) and to send them to the Form Controller, where those positions are used to control a CG model shape.

The Pin Actuator communicates with the custom board to control the motors of the Pin Controller and move the Jig’s pins to new positions requested by the Form Controller. The Jig’s pins are actuated one by one.

The Form Controller modifies a CG model form. The CG model is composed of polygonal data in the IV file format. If a form optimization is activated, the Form Controller re-modifies the CG model form based on predefined numerical constraints. When the form is modified, the Form Controller communicate with the Pin Actuator to control the Jig’s pin positions to fit the

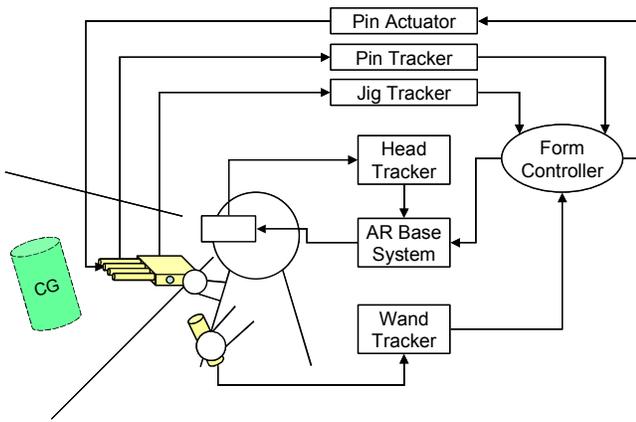


Figure 7. Software architecture.



Figure 8. Physical Jig (left) and visually augmented Jig seen through an HMD (right).

re-modified model shape. The detailed modification techniques are described in Section 5.1.3.

5 INTERACTION TECHNIQUES

The prototype system of AR-Jig provides three types of tangible interaction techniques utilizing three TUI merits: (1) direct manipulation, (2) physical embodiment, and (3) computationally controlled physical representation. It also provides intangible interaction techniques as general functions for digital modeling.

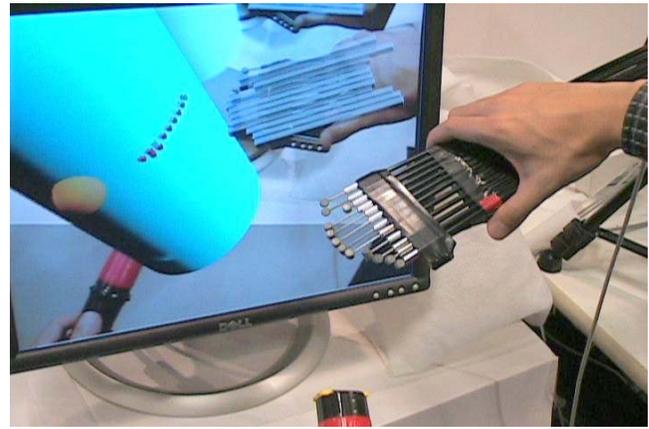
5.1 Tangible Interactions

In 3D digital design domain, the tangible interactions of AR-Jig aim to utilize three merits of TUI. The first interaction technique of AR-Jig allows for *manual direct manipulation* of the 3D digital form. The second utilizes *physical embodiment* of design media to copy a profile of a physical object and paste it on to a digital object. The third allows a user to feel a design suggestion based on *computational simulation through haptic feelings* as well as visual feelings.

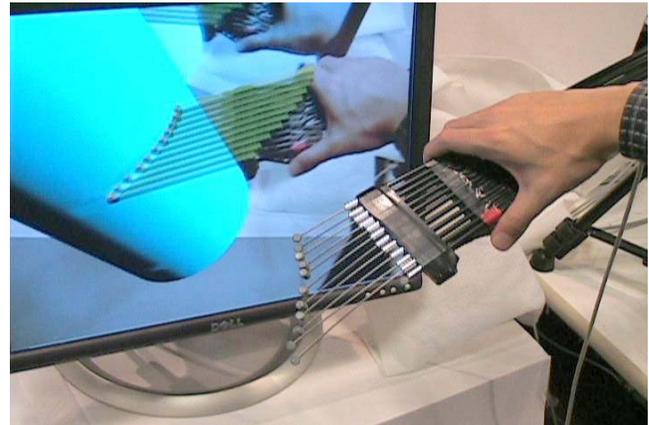
5.1.1 Hand Modification

AR-Jig acts both as a handle for a digital object and as a physically manipulable aspect of that object's surface. When molding a lump of clay, one often reorients the piece during modification. The sculptor can push her/his fingers into her/his piece, or the piece into her/his fingers. The pins' slight resistance to movement causes a physical feedback loop that facilitates control over molding. Locally, the digital object behaves as if it were a plastic medium.

The hand modification to utilize the first merit of TUI starts from curve selection with the Jig held with one hand. If the Jig is close enough (less than 12 cm) to a CG model and the Jig's button is pushed, the nearest points to each pin of the Jig are searched on



(a) A digital curve is selected.



(b) The pins are actuated to display a 2D tangible curve that has the same form as the selected digital curve.



(c) A user modifies the selected digital curve by manipulating the tangible curve.

Figure 9. Modify a digital 3D form via 2D physical curve by hand.

the CG model surface and shown with virtual red cubes (Figure 9(a)). When the button is released, a virtual curve, including the nearest points, is selected. We use a polygonal curve as the virtual curve for quick implementation of the first prototype; however a higher-level mathematical curve, such as a NURBS curve, would be appropriated for fine modification.



Figure 10. Physical Copy (left): push the pins against a real glass to make the same contour. Digital Paste (middle): heap up a form with the copied contour. Compare the physical contour and the pasted digital contour (right).

After the curve selection, the pins are actuated to represent a 2D tangible curve that has the same form as the selected digital curve. Then the CG model moves to the pins so that the selected digital curve and tangible curve overlap (Figure 9(b)). If a user manipulates the Jig's pins to change the tangible curve shape, the selected digital curve shape is also changed to preserve the overlapping (Figure 9(c)). The surrounding digital surfaces as well as the selected curve are modified to make the entire CG model smooth, and thus minimize discontinuity. If the Jig's button is pushed during the curve selection, the curve is released and another curve becomes ready to be selected.

5.1.2 Physical Copy and Digital Paste

"Copy and paste" is a fundamental technique in design and other tasks. The second merit of TUI--physical embodiment of design media--realizes a similar but new interaction technique called "physical copy and digital paste" that copies a physical contour of a real object and pastes it onto the surface of a digital form (Figure 10). When a good physical contour on a real object is found, a user can push the pins against the contour to make the same contour with the pins. Then the user can paste the physical contour shape onto the surface of a 3D digital form by pushing the Jig onto the surface, and then deform the surface with the new contour by turning the digital form (similar to throwing pottery).

AR-Jig allows everyday objects to behave as "French curves" (templates composed of many different curves) of a sort. Varying the angle at which the Jig meets a bottle of soda offers a wide range of elliptical curves. Similarly, a conical object can be used to generate hyperbolas and parabolas. Finally, the edge of a box can quickly produce any angle from 90 to 180 degrees.

5.1.3 Tangible Collaboration with a Computer

In the product design process, it is important to keep numerical constraints, such as regulations and requirements in manufacturing. However, it is practically difficult for human designers to attend to all constraints at any one time. If a computer helps to keep such constraints, designers can concentrate on finding a better design. AR-Jig has a real-time form optimization with the third merit of TUI (computationally controlled physical representation). When form optimization is activated, the Jig's pin positions are actuated to modify the CG model form to fit a predefined numerical constraint. Once a user modifies a form with her/his hands, a computer can optimize the form and let the user feel the optimization tangibly. The user can guess the underlying numerical constraint and try to find a form that satisfies both the intended design and the numerical constraint. This process is a kind of collaboration between a user and a computer.

The first AR-Jig prototype has three form optimizations.

- Smoothing: If the curvature change of a digital surface around a pin of the Jig is bigger than a threshold value, the pin is actuated to make the curvature smaller.
- Access control: If access of a core area of a CG model is not allowed but the Jig's pins go inside the area by user manipulation, the pins are automatically actuated to go outside.
- Numerical adjustment: When a user manipulates the pins, the pin positions are automatically adjusted to the nearest round number (e.g., 12.0). This optimization allows for a kind of numerical control.

"Smoothing" and "access control" occur immediately when the condition is met. "Numerical adjustment" occurs for every user manipulation. Therefore, the user-created form is not significantly changed by the optimization.

5.2 Intangible Interactions

AR-Jig also enables intangible interactions to support design work from the digital side. As is the case for conventional handheld tools, with AR-Jig a user can translate, rotate, deform, and scale a digital form using a handheld device. Redo, undo, and reset operations are also available.

5.2.1 Translate and Rotate

If the Wand touches a CG model, the CG model is attached to the Wand so that the model can be translated and rotated with the Wand. If a user shakes the Wand quickly (faster than 3 m/s), the CG model is released from the Wand. The released CG model is placed in the last position before the Wand began moving faster than 3 m/s.

5.2.2 Deform

If the Jig's pin heads touch and push a CG model surface without selecting a curve, the area around the contact points caves in (Figure 11). When the pin heads are inside a CG model and the pin sides touch the CG model surface, the contacted points also cave in towards the pin heads. Nothing happens if the pins are far outside the CG model.

If the Jig's pins touch a CG model surface without selecting a curve and the Jig's button is pushed, the nearest surface area heaps up to attach the pins (Figure 12).

The style of these two techniques is similar to that of conventional digital design tools such as PHANTOM. Thus, it is expected that AR-Jig allows designers to utilize their digital skills as well.

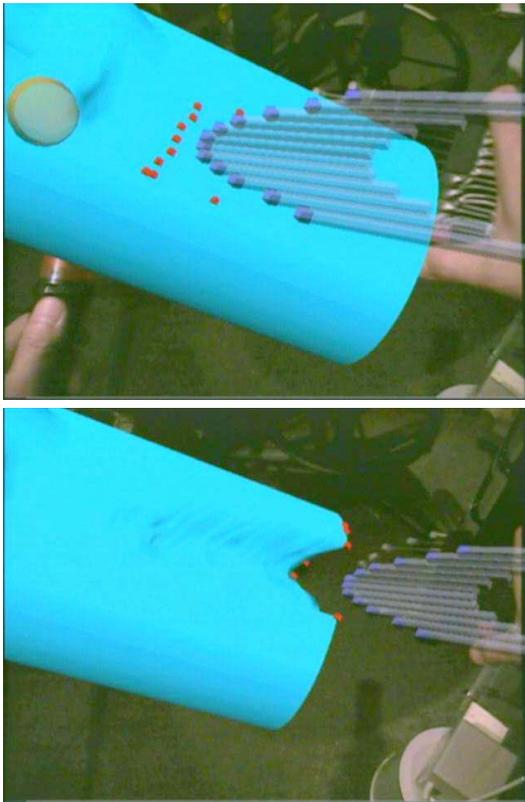


Figure 11. Cave in a form (top: before, bottom: after).

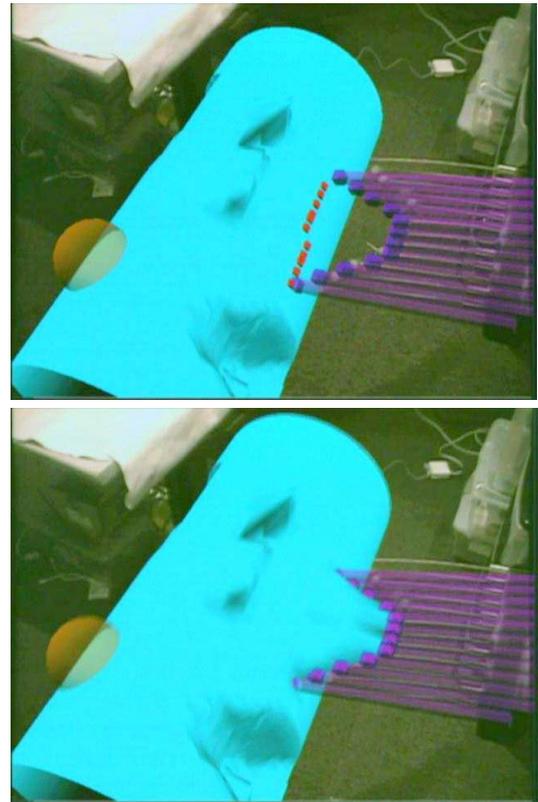


Figure 12. Heap up a form (top: before, bottom: after).

The Jig shape for caving in or heaping up is computationally controllable. When the Jig is far (more than 12 cm) from a CG model and the Jig's button is pushed, the pins represent ten predefined shape templates in rotation: edges (triangular, circle), notches (V-shape, U-shape), lines (flat, slope right up, slope left up), and combs (one tooth, two teeth, and three teeth).

5.2.3 Scale

If the Jig's button is pushed and the Wand touches a CG model surface, the CG model is attached to both the Jig's pins and the Wand. To preserve these attachments, the CG model's scale is changed based on the distance between the Jig and Wand (Figure 13). This technique is just for scale changing. To zoom into some part of a CG model, the user may scale up the model with this interaction technique, then translate and/or rotate the CG model, and focus on the part.

5.2.4 Redo, Undo, and Reset

Undo, redo, and reset operations of AR-Jig's modeling operation occur when a CG model is not attached to the Wand and a user shakes the Wand quickly (faster than 3 m/s). If the Wand moves down from above (i.e., its vertical motion is longer than its horizontal motion), the undo operation occurs. If the Wand moves up from the bottom (i.e., its vertical motion is longer than its horizontal motion), the redo operation occurs. If the Wand moves horizontally (i.e., its horizontal motion is longer than its vertical motion), the reset operation occurs.

5.3 Interaction Selection

AR-Jig provides several interaction techniques, so interaction selection methods are needed. One well-known selection method in AR application involves touching a menu on a plate-type

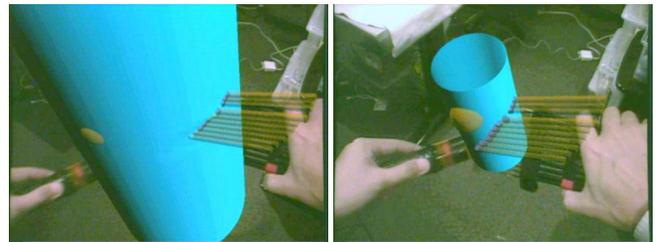


Figure 13. Scale down a model (left: before, right: after).

device with a pen-type device [5]. We did not use such a method because a handheld plate-type device cannot be held, since the two handheld tools (the Jig and Wand) and a stationary plate-type device would prevent users from moving in 3D space freely.

We use the distance between the Jig and a CG model surface, the Jig's button, and the other distance between the Wand and a CG model surface to select an interaction technique. If the distance between the Jig and a CG model surface is less than a threshold (12 cm) but more than zero, the "hand modification" technique can be selected by pushing the Jig's button. If the distance is zero, the "cave in" technique is selected. If the distance is zero and the Jig's button is pushed, the "heap up" technique is selected. If the Jig's button is pushed and the other distance between the Wand and a CG model surface is also zero when the "hand modification" technique is selected, the "scale" technique is selected.

To let a user know which interaction technique is selected, a virtual Jig model is shown and its color is changed. For example, the virtual Jig's basic color (no interaction is selected) is green,



Figure 14. Artwork made with AR-Jig by the subjects (from left): “Bird,” “Face,” “Cow,” “Bunny,” “TENGU (long-nosed monster).”

and the virtual Jig model becomes yellow when the “hand modification” technique is selected.

6 EVALUATION

Although the prototype is still at the early stage of development, we believe the concept of AR-Jig has a strong potential to improve 3D design. To explore such potential and identify the requirements of improvements, we conducted preliminary qualitative experiments/evaluation sessions. One evaluation by end-users (mainly novices), revealed the pros and cons of the system in general. The other evaluation involved interviews with professionals to determine the improvements necessary to make AR-Jig a practical design tool.

6.1 Testing by End-users

6.1.1 Process

Eleven people were asked to use the first prototype system of AR-Jig to model forms from a 3D cylinder model. Every subject except one (a CAD expert) was unfamiliar with conventional 3D digital design tools (e.g., Maya). The subjects were graduate university students, and researchers and developers visiting a university from automotive or consumer electronics companies.

First, the subjects learned to use the system through a five-minute demonstration by an experimenter. Then the subjects practiced using the system for five minutes. They were allowed to ask questions of the experimenter during this practice time. Next, the experimenter presented a five-minute explanation about the three form optimizations: smoothing, access control, and numerical adjustment. Then the subjects practiced again for five minutes with the three form optimizations.

Next, the subjects were asked to model two free forms: one without form optimization, and the other with one shape optimization selected by each subject. The subjects were allowed 15 minutes for each shape.

After completing the modeling tasks, the subjects responded to a questionnaire. The questionnaire asked the subjects to evaluate AR-Jig’s ease of use, speed, control, optimization, reversibility, and scalability. After completing the questionnaire, the subjects were interviewed by the experimenter.

Figure 14 shows some artwork modeled by the subjects during their evaluation. In general, all subjects were satisfied with their 3D modeling results.

6.1.2 Questionnaire Responses

The following is a discussion of the 11 subjects’ responses regarding the six aspects that we asked them to evaluate in the questionnaire.

Ease of use Nine subjects indicated that the AR-Jig was easy to use and pointed out that AR-Jig was intuitive. Three subjects mentioned that they need more time to get used to AR-Jig because the modeling style (especially pulling a point on a surface, or

“heaping up”) was different from the conventional physical modeling style, such as clay modeling.

Speed Although seven subjects rated AR-Jig positively with respect to its speed of use, three of those subjects complained about the slowness of modifying a form manually, in comparison with caving in and heaping up a form.

Control While seven subjects were satisfied with their 3D form control, four subjects had reservations. Those four subjects suggested that we render more mathematically appropriate forms to express users’ ideas.

Optimization Eight subjects understood the value of the haptic feedback based on the form optimization. One subject indicated that the automatic adjustment was good when his stroke was far from his intention (keeping the constraint). Another subject compared the modeling with AR-Jig to modeling with someone’s help. The subject who was a CAD expert commented, “I felt feedback force avoided my modeling. If constraints match our task, it might work well.”

Reversibility All the subjects rated AR-Jig positively with respect to reversibility (redo, undo, and reset). In fact, during the evaluation the subjects used this feature extensively with few problems.

Scalability On the whole, subjects did not often use the scalability features of AR-Jig. According to the subjects’ comments, the problem was not with usability: the difficulty lay in scaling a form. However, seven subjects did acknowledge the usefulness of the scaling function in the 3D form modeling.

6.1.3 Evaluator’s Observations

Here are our observations as a result of the subjects’ trial and interviews.

Physicality The physicality of the pins was utilized. Five subjects made positive comments about physicality. For example, they indicate that the physical pins made it easy to understand the digital surface and sculpting shape, and that they helped imagine the modeling process.

Four subjects used their bodies or objects around them to change the Jig’s shape (the physical copy and digital paste). One subject modified a digital curve by hand and pasted it onto another area because the Jig shape was maintained after the hand modification (i.e., physical copy and multiple digital pastes). Another subject let the pins display a digital curve and pasted it onto another area without modification (i.e., digital copy and digital paste via physical pins).

The weight of the pins was also utilized. One subject said he enjoyed the change of gravity center of the Jig.

Strategy Five subjects had more experience using 3D digital modeling tools or AR/VR systems than the other subjects; they used the three modeling techniques properly, based on a strategy. They caved in and heaped up a form roughly at the beginning, and

modified the rough form into a detailed form by hand at the end. In contrast, the six other subjects used mainly one technique: one used hand modification; three used cave in, and two used heap up. Those six subjects seemed somewhat frustrated by the AR-Jig's multi-usability.

Comparison with Other Digital Tools Five subjects mentioned that AR-Jig allowed them to model an object that could not be modeled with a conventional digital modeling tool.

The CAD expert subject had a positive impression of AR-Jig. He said, "It may be impossible to model a similar form with conventional tools. I always let mathematical functions make a curve and give up modifying it even if it does not fit my intention. But I would not give up with AR-Jig. I can model a form without limits."

Fun All the subjects enjoyed modeling with AR-Jig. Nine subjects commented that modeling with AR-Jig was like playing with clay or sculpting. One subject pointed out that this modeling could be a hobby, and he wanted to have the CG data he modeled during the evaluation. Another subject mentioned that AR-Jig could be a digital modeling tool for children.

Form Factor Five subjects commented negatively on the Jig's form. "The pins are rough and not accurate." "Finer pins would be appreciated." "The resolution of the physical curve is too rough." "The width of the physical curve is too short." "The finger size would be better for each pin." "Just one line is not enough to express my idea." "I wanted to curl up the pins into a circle or spiral to deal with compound surfaces." "A pin grid would be good."

Gesture The subjects effectively utilized the gestures to translate, rotate, and deform a CG model. However, the gestures for scale, redo, undo, and reset sometimes confused the subjects. For example, we observed that several subjects gestured for redo or reset when they wanted to undo. Two subjects mentioned that the scaling function was unintentionally selected when they released a CG model from the Jig.

Interaction Selection All the subjects had some difficulty understanding interaction selection. One subject commented that showing the current interaction mode using the virtual Jig's color was understandable, but it was difficult to remember each color's meaning. Another subject suggested that more input interfaces (e.g., button and slider) and feedbacks (e.g., vibration, sound, and virtual icon) would be helpful for interaction selection.

Fatigue The current prototype showed less aptitude for long-term modeling. Three subjects complained about fatigue. A female subject said that the Jig's handle was too heavy and too large to hold.

6.1.4 Pros and Cons

Below is a summary of the pros and cons of AR-Jig, based on the subjects' questionnaire responses and our observations.

Pros The trial uses showed that even novices could use AR-Jig. Tangible interaction techniques (e.g., haptic feedback based on form optimization, and physical copy and digital paste) were well received. Reversibility was also well received. AR-Jig seems to have both tangible and digital merits.

According to trial uses, AR-Jig has the three merits of TUI. As the CAD expert mentioned when comparing AR-Jig with other digital tools, AR-Jig allows for free-form expressions without limit. Thus, AR-Jig could bring the first merit of TUI (direct manipulation) into 3D digital modeling. Five subjects gave a



Figure 15. Car model modification with AR-Jig.

positive evaluation of the physicality of the pins, and five other subjects utilized it during their modeling. This result indicates that AR-Jig can also bring the second merit of TUI (physical embodiment) into 3D modeling. The third merit of TUI (computationally controlled physical representation) was also well received by the subjects, although mathematical implementation is needed.

Beyond our expectation, the subjects were entertained by modeling with AR-Jig. Therefore, AR-Jig may have a potential to be a fun digital toy or art tool, like many previous TUIs.

Cons On the negative side, less quantitative representation and difficult operations for interaction selection were recommended. The former is a drawback of tangible user interface; the latter arises from digital malleability, which sometime confuses novice users. The trial uses showed that the combination of tangibility and digitality provides not only tangible and digital merits but also tangible and digital demerits.

Although we believe in-line form can be practical with some improvement, some subjects' comments indicated that this form did not always satisfy essential modeling demands. The form factor of AR-Jig is a drawback in comparison with conventional versatile digital modeling tools. Like other TUIs, AR-Jig is not a general tool but a special tool. Preparing several Jigs with different forms could potentially avoid this drawback.

6.2 Interviews with Professionals

6.2.1 Process

We made a simple application where a car model could be modified with AR-Jig (Figure 15). We demonstrated this application to a car designer and a prosthetic modeler; then we interviewed them. After trying to use the system, these two professionals had basically the same impressions in the testing as the end-users. In addition, they gave us further guidance to improve the system for practical use.

6.2.2 Car Designer's Feedback

The car designer mentioned the usefulness of manipulating a curve to modify a 3D form. He said designers often use section images for simplifying the view because a 3D appearance is much too complex. He suggested it would be more helpful to use not only a 2D curve on a plane but also a 3D curve in a space, so that more flexible forms could be expressed.

The designer also mentioned the importance of numerical accuracy in manipulating the tool in a 3D space. A user may want

to keep AR-Jig at a fixed point or move it horizontally during modification. He suggested using a rail to support the position, orientation, and motion of AR-Jig.

6.2.3 Prosthetic Modeler's Feedback

A prosthetic has a socket for a receiving and holding body (e.g., leg). According to the prosthetic modeler, the current digital modeling method such as extruding is not useful for socket modeling, because a socket should be an organic form in order to adjust to the human body. Therefore, socket modelers use the physical modeling method with their skilled hands to sculpt a socket. However, digital modeling would provide many merits for prosthetic design as well as the other design domains. The modeler appreciated that AR-Jig allowed him to model a prosthetic digitally with his skilled hands with a physical rapid prototyping of a customer's body or even customer's own body.

If only a geometric adjustment is needed when making prosthetics, an automatic method to create a model from a captured digital body would be helpful. However, the modeler mentioned that such a method would not be useful because a body form changes (becomes slim) through everyday prosthetic use. He pointed out the necessity of implicit modeling know-how to predict a future body form and make a suitable socket. Because such know-how is too difficult to represent mathematically, the modeler highly valued direct modification using skilled hands.

7 FUTURE WORK

The end-users and professionals positively evaluated the possibility of the AR-Jig concept, but noted that the current prototype system was not adequate for practical use. Making a practical version of AR-Jig is the next step.

Handheld-ness is an important feature of AR-Jig, but the first prototype is not truly handheld. It is an obvious drawback that the control requires a tripod for support because of its weight. Therefore, we will implement a lightweight AR-Jig. We will also use a rail or force-feedback device to support the AR-Jig motion numerically, as the car designer suggested. We will make AR-Jig available as a handheld tool for quick modeling, and as a grounded tool for numerical modeling.

As feedback from the end-users and professionals revealed, simple tangible media sometimes conflict with malleable and numerical digital media. We hope to find a good balance between physicality and digitality. For example, the next system will have improved software for mathematical form deformation and buttons for easier selection of interaction techniques.

Our first evaluation was qualitative. Quantitative evaluation is also necessary in order to determine the value of AR-Jig. We plan to ask professional designers to perform some 3D digital design tasks with AR-Jig and evaluate the results in comparison with traditional 3D techniques using hand gestures and force-feedback tools.

It would be also interesting to observe other intersections along a similar design space. For example, we would like to explore the implementation of a 2D matrix or bendable interface.

The target of AR-Jig is 3D digital modeling, which has been used in various domains. The functions that AR-Jig can provide are limited in comparison with conventional digital modeling tools; therefore, finding domains (e.g., prosthetic modeling) where AR-Jig's abilities are useful will also be our future work.

8 CONCLUSION

Currently, 3D digital modeling is becoming critical in every type of design. Traditional TUIs, which try to embody digital data, have inherent limitations in the design of large-scale, complex,

and dynamic 3D digital forms. Instead of making data tangible, AR-Jig focuses on a handheld tool that makes only a portion (in this case a 2D curve) of a large 3D form tangible, while leaving the rest of the 3D form virtual, as can be seen through HMD. This approach allows for a novel combination of benefits of malleable 3D digital form and tangible modification interface. Traditional TUIs stay away from AR, but AR-Jig can be considered the first TUI that preserves malleability while providing tangibility to a tool in hand. Whereas digital data is basically intangible, we enable part of the digital data to make it tangible.

One of the subjects compared AR-Jig to a light beam from a special flashlight in a user's hand, which makes cave paintings in the dark visible. Unlike regular flashlights that display only an object, AR-Jig gives special properties to the virtual object so that it becomes physically embodied. In the case of AR-Jig, "photons" make the 2D curve tangible instead of only visible, so that the user can touch and modify the curve.

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