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# Shape Acquiring and Editing through an Augmented Reality based Computer-aided Design System

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## ABSTRACT

This paper presents a novel augmented reality (AR) integrated three-dimensional (3D) touchable computer-aided design (CAD) system, which utilizes stereoscopic display and 3D input devices to achieve intuitive and convenient 3D interaction between a user and the system. In the AR environment, physical objects can provide visual and physical feedback to the user. Analysis has been made on the proposed system in the aspects of visual feedback and user input. CAD operations to effectively capture user's intention are developed for shape acquiring and editing. The basic setup of a prototype system is described. Several test cases are presented to demonstrate the functionality of the developed system and its effectiveness.

**Keywords:** augmented reality, CAD, stereoscopic display, position tracking, curve fitting, dental appliance design.

## 1. INTRODUCTION

Most presently used Computer-aided Design (CAD) systems remain to be based on traditional interfaces such as monitor, mouse and keyboard. By using these interfaces, designers cannot freely explore shapes in three-dimensional (3D) space, which limits the designers' creativity. The traditional interface is also difficult to use. For example, it is tedious and time consuming to edit a NURBs surface using a mouse or a keyboard by specifying the shape of its silhouette.

A novel augmented reality (AR) integrated 3D touchable CAD system is presented to provide designers with intuitive and convenient design experience. The desk-top size system consists of a stereoscopic display and two types of 3D input devices, one for each hand. Fig. 1 shows a prototype of the AR-based CAD system. The stereoscopic display used as the visual output helps to create an AR environment for the CAD system; the 3D input devices are able to execute positioning function in 3D space to directly capture user inputs. Details about their implementations will be described in the following sections.

The presented 3D interface can potentially change the way of future designers in using CAD systems to design engineering products. That is, instead of mentally converting between 3D shapes and their two-dimensional (2D) projections displayed on a monitor, designers can directly explore 3D shapes by displaying and touching of physical objects. Thus the new interface would allow designers to focus more on the product shape design itself. Future CAD software systems need to be redesigned to enable creating and editing 3D geometries in a simple and intuitive way. A new 3D interface is presented in the paper; however, how to design CAD operations based on the new interface such that a CAD system can intelligently capture user intention is still an open problem. Our initial investigation of some CAD operations will be discussed in Section 6.

An interesting feature of the new 3D interface is that it allows designers to use physical objects as visual and physical feedback during the design process. Such physical objects may already exist, or can be created using various 3D printers. Recent developments enable the printing of digital models quickly and easily [16]. For a physical object positioned in our AR-based CAD system, its digital model may be displayed based on a user-specified viewing mode. In addition, the physical and digital models are kept aligned with each other during model manipulations such as rotation and translation.

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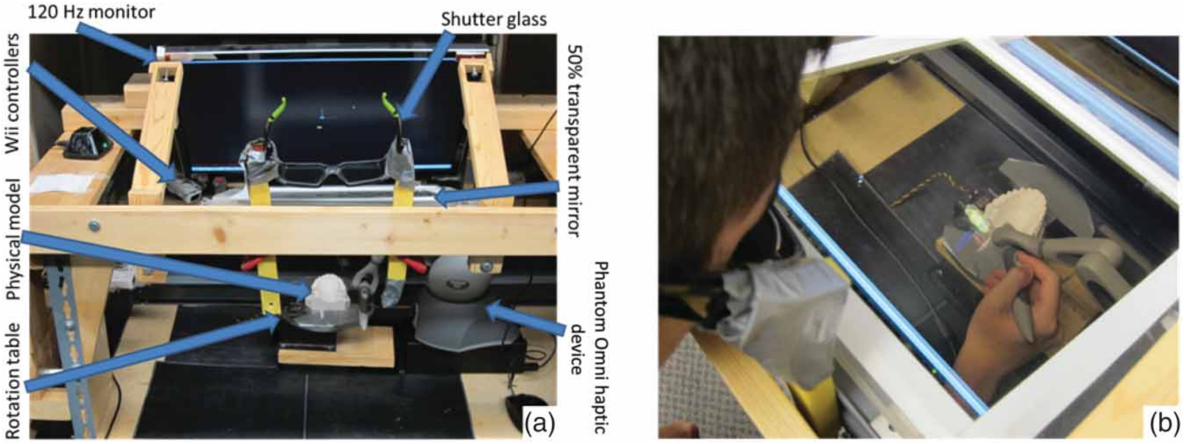

Fig. 1: A prototype AR-based CAD system. (a) Overview of the system; (b) a user can see both physical and virtual objects in the system. In addition, the display of a virtual object is aligned with the related physical object positioned in the system.

A stereoscopic technique based on a 3D monitor is used to display virtual models in the working space of the CAD system. A beam splitter is further used to superimpose the virtual models with physical objects. Thus a user can easily verify his/her designs by using the physical objects as a reference. Fig. 2 shows an example, in which the user needs to design a dental brace wire that is customized for a physical teeth model. The physical teeth model for a patient can be created by 3D printing or other traditional prototyping approaches such as dental impression.

In addition to visual feedbacks, the physical objects also provide physical guidance for user's 3D input. For instance, the dental braces wire shown in Fig. 2 can be directly drawn by sliding an input tool on the physical teeth model along the desired path. In comparison, using a traditional CAD system to design such a wire for the given dental model would be a tedious job taking a long time.

Another interesting feature worthy of mentioning is that the auxiliary information can be displayed on top of physical objects to assist users in making design decisions. For example, the stress distribution of a digital model can be computed based on Finite Element Analysis (FEA) and projected on its corresponding physical objects. The user can then apply CAD operations to modify related geometry based on the FEA result.

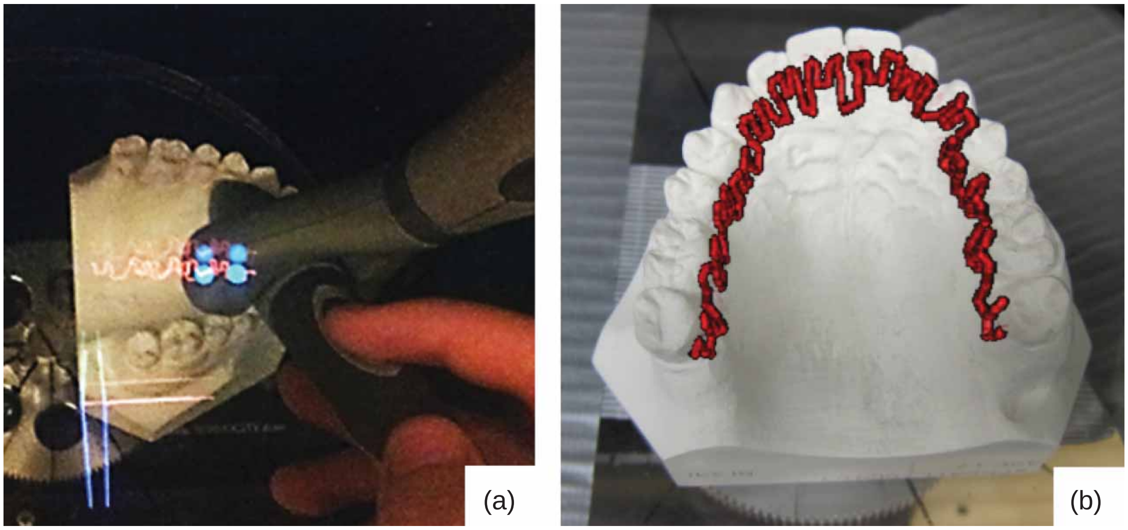

Fig. 2: An example of dental brace wire design. (a) A picture showing the design process of a dental braces wire. A user can directly draw lines on the physical teeth object. Note that the photo was taken by a camera that is positioned above the 3D glasses. Hence the stereo-display as shown in the photo has two rendered images (for both left and right eyes) that are not focused from the viewpoint. (b) The stereo-display is focused from the viewpoint of the 3D shutter glasses. A rendering image of the resultant design is shown that the user will see in the AR environment.

The rest of the paper is organized as follows. A survey of related work is presented in Section 2. Section 3 presents the visual feedback approach used in our CAD system. Section 4 discusses the 3D user input method adopted in the system. Our discussion mainly focuses on system requirements and the selected implementations based on the existing techniques and devices. Section 5 introduces display operations and some CAD operations developed in our system. Based on them, two test cases are presented in section 6 to demonstrate the capability of the developed prototype system. Finally, conclusions are drawn in Section 7 with future work.

## 2. RELATED WORK

There is a large number of research focusing on adopting AR techniques in CAD systems. Van Krevelen and Poelman [23] provided a comprehensive survey of AR technologies, applications and limitations. One of the early works that utilized 3D interface for shape modeling is 3Draw [18]. In [21], a head mounted device (HMD) is used in an immersive design environment, in which the surface can be directly modified by hand gestures. However, this approach cannot allow real-time interaction due to the computational complexity. Dani *et al.* [8] presented the Conceptual Virtual Design System (COVIRDS), which uses multimodal input streams such as gesture, speech and six degrees of freedom (6DoF) device. A large projection wall is used for display in the system.

In recent years, more research was conducted to adopt virtual and augmented reality (VR/AR) in Computer-aided Design. Some approaches such as advanced realism CAD environment (ARCADE) [19, 20] and Construct3D [13] connect existing VR/AR framework ("Studierstube") to CAD core (ACIS). 3DIVS [11] is a semi-immersive modeling environment that is designed specifically for NURBS. It consists of a stereoscopic display and two magnetic trackers in order to recognize gesture. Spacedesign [10] is an immersive system for curve and surface modeling. It uses task-specific configurations to support the design workflow from concept to mock-up evaluation and review. A voxel-based modeling system called virtual clay modeling (VCM) is presented in [14] for conceptual design. Its interaction interface is implemented using tool-like interactive devices and haptic feedback. Weidlich *et al.* provide several methods that can incorporate CAD models into a virtual design environment [26]. A fast interactive reverse engineering system utilizing computer vision is presented in [1] for shape acquisition and reconstruction. A CAD system with similar hardware setup as ours is presented in [9]. It focuses on mesh editing without using any physical objects. Uva *et al.* present a distributed design review system by adopting AR techniques [22]. Recently M. Fuge *et al.* [12] propose a conceptual design system using dual shape representations that are commonly used in AR techniques. The dual representation maintains points set and B-rep at the same time to achieve real-time interaction speed.

The above reviewed approaches differentiate from each other by using different 3D input/output interfaces and targeted applications such as shape acquisition and design reviewing. Using similar CAD operations developed for traditional CAD systems, none of the systems adopt 3D physical objects in their system to provide users visual and physical guidance. In our research, shape exploration operations based on the AR integrated CAD system are discussed. Its application in designing customized dental device is demonstrated. Validation in terms of usability and time efficiency from several users is also presented.

## 3. 3D VISUAL FEEDBACK

The display method of an AR-based CAD system plays an important role in providing users with intuitive and immersive visual feedback. In this section, various display methods are discussed and the approach implemented in our system is presented.

Various display techniques have been developed for desk-top size Virtual Reality (VR) based and AR-based systems. Some common techniques adopted in the VR/AR systems include head-attached display, hand-hold display, and spatial display techniques [6]. However, the hand-hold display is not appropriate for an AR-based CAD system because it requires a user use one of his/her hands to hold the device, which leaves only one remaining hand for shape exploration. The head-attached display consists of retinal display, head-mounted display and head-projectors. The retinal display such as *Google* glasses does not support stereoscopic display. It can only display monochrome images. The head-mounted display and the head-projectors suffer from low resolution due to the limitations of the applied miniature displays. In addition, the device is usually heavy to wear. Finally, the spatial display includes video see-through, optical see-through and projection-based display. The projection-based display directly project images on the surfaces of physical objects. Hence using it to create 3D spatial geometry is difficult. The video see-through spatial display is limited by the resolution of the merged image, which is a general disadvantage of the video see-through approach. In comparison, the spatial optical see-through display can align virtual and physical scenes such that a user can see a merged scene within a working environment. Consequently, the optical see-through display approach is adopted in our prototype system. There are several spatial optical see-through display techniques in literatures. They differentiate each other by using different optical combiners including transparent screens [15,3], planar or curved mirror beam combiners [5,4], and optical holograms [2].

There are two disadvantages that are usually associated with the spatial optical see-through display techniques including: (1) the applied optics prevents a direct manipulative interaction with the virtual and real objects in the working space; and (2) a mutual occlusion between real and virtual objects is not supported. That is, virtual objects that supposed to be occluded by the physical objects can still be seen by users.

To address the first issue, a design based on a 50% beam splitter is used in our system. As shown in Fig. 3, a 50% beam splitter is used to reflect the monitor display to user's eyes while allow user to see through the beam splitter. In addition, our setup enables a virtually displayed model to be seen under the mirror. Hence both virtual and physical models are positioned in the same working space. Furthermore, users can easily access the working space without any physical obstacles from the displaying system (refer to a usage scenario as shown Fig. 1b). Note that during the design process physical objects are firmly secured in the system. Hence user's touches will not change their positions in the working volume.

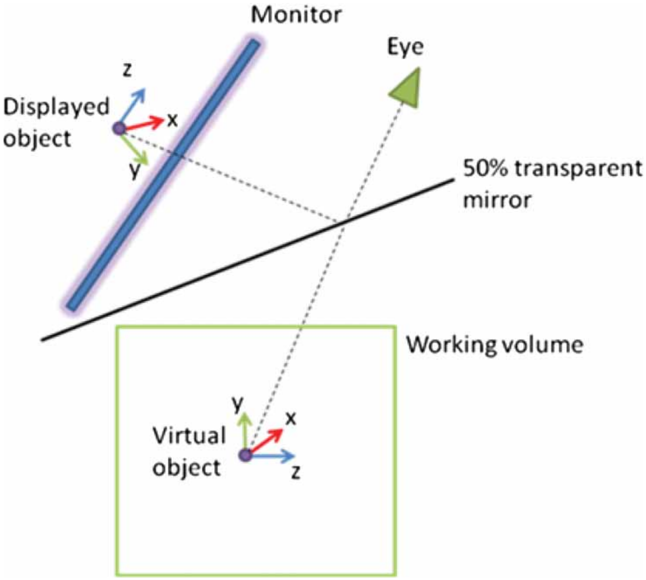

Fig. 3: Working principle of the virtual display.

To overcome the second drawback, a strategy adopted in our system is to create an artificial occlusion in the AR environment. That is, since the digital model of each physical object is known in our system, a digital model can be rendered based on its relative position to all the physical objects. Portions of a virtual scene that are behind physical objects may be displayed using the background color and hence will not be seen. An example is shown in Fig. 4, in which the physical object of a cube is positioned in front of a digital teeth model in the working space. Accordingly a portion of the teeth model should not be rendered such that the cube object can be correctly seen in the AR environment.

In an AR-based CAD system, the depth perception of virtual objects is essential for 3D shape exploration. In our prototype system a 3D vision wireless glass kit from *nVidia* is used. To achieve depth perception, the stereoscopic display technique use a 120 Hz monitor that is synchronized with a shutter glasses wore by a system user. The active shutter glasses black out the right lens when the left eye view is shown on the display. The glasses black out the left lens when the right eye view is shown on the display. The refresh rate of the display is 60 Hz per eye. The resulting image for the user is a combined image that appears to have depths, which can be in front of and/or behind the stereoscopic 3D display. Hence the stereo effect can be achieved. Since the location of human eyes will have a visible influence on the

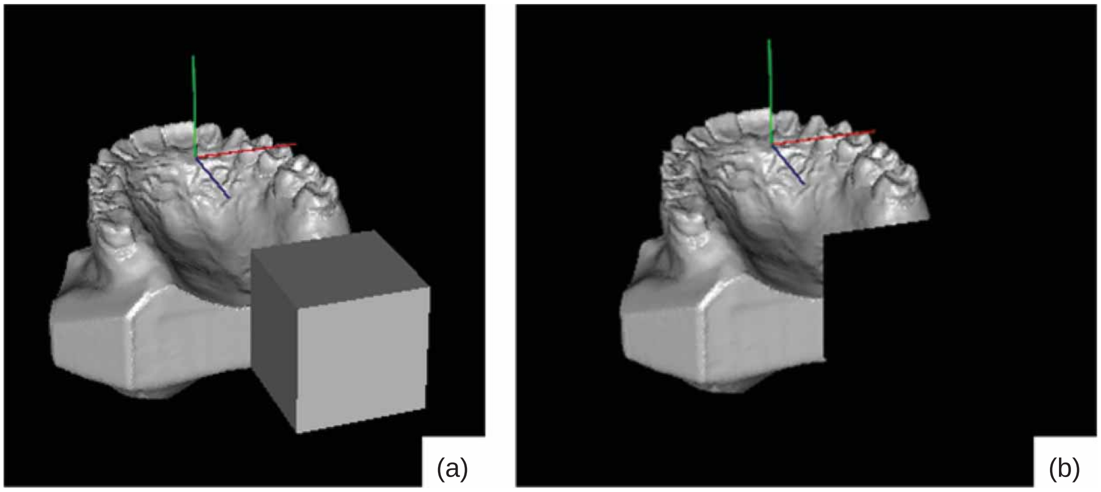

Fig. 4: Artificial occlusion effect in the AR-based CAD system. Suppose the physical object in the working space is a cube and the virtual model of a teeth is positioned behind the cube. (a) The relative position of the teeth and the cube; (b) created occlusion effect by displaying a portion of the teeth model using the background color.

stereoscopic effect, a fixture is used in our system to hold the shutter glasses at a pre-calibrated position. Hence the positions of user's eyes are fixed in our prototype system (refer to Fig. 1). Objects can be rotated in the working volume to achieve different viewing angles.

Note that, in all the figures of the paper (e.g. Fig. 2a), the rendered images for both left and right eyes are shown. The two images look slighted shifted in the photos since the photos are taken by a camera that is position above the shutter glasses. The images for left and right eyes are actually well aligned if looking through the user's shutter glasses (refer to Fig. 2b).

## 4. 3D TRACKING INPUT

The most widely used tracking devices nowadays can be classified into four groups: mechanical, optical, electromagnetic and acoustic tracking. A mechanical tracking system usually employs linkages and joints with encoder/potentiometer to determine the position and orientation of its terminal. Generally, mechanical tracking systems have the advantage of high accuracy [17]. An optical tracking system can calculate the 3D position of an input point based on the triangulation theorem. A typical optical tracking system can achieve ~1 mm accuracy, which can satisfy non-critical 3D tracking requirements such as selecting 3D icons. Although an electromagnetic tracking system and an acoustic system can also provide satisfactory accuracy for such tasks, the electromagnetic tracking is sensitive to the presence of metal object while the acoustic system is sensitive to environment factors such as temperature, humidity and barometric pressure. These limitations make both the electromagnetic and acoustic tracking systems inappropriate for the AR-based CAD systems.

In our prototype system, two position tracking devices, one for each hand, are adopted.

(1) For 3D position input with user's right hand (assume the user is right-handed), a mechanical tracking system (a Phantom Omni from *3D Systems Inc.*) is integrated due to its high accuracy. The interference problem of a mechanical tracking system is alleviated since the physical objects put in our system are held by a rotation table or a robot arm. Hence relative small motions are required for the mechanical tracking system as the physical objects can be rotated and/or translated for accessing different sides of the objects.

(2) An optical tracking system based on five Wii controllers is integrated in the prototype system due to the advantages of its low cost and easy movements in 3D space [7]. The user can use his/her left hand to hold an infrared (IR) pen to freely move around and select any 3D points. Considering the presence of physical objects in the working volume that may block the visibility of the IR pen, multiple Wii controllers (a total of 5) are used in our prototype system.

The setup of the two position tracking devices is shown in Fig. 1. The captured 3D positions using both position tracking devices are treated as the 3D user input. For each device, a 3D cursor is displayed in the working volume for visual feedback to the user. Ideally, the stylus terminals of both devices should be totally coincident with the related 3D cursors. However, as aforementioned, each tracking device has some positioning errors. Accordingly their usages are quite different. In our prototype system, the tracking device for right hand is for geometry selection and editing; while the device for left hand is for function selection and view manipulation. Obviously, the accuracy requirements for geometry selection and editing are much higher than those for function selection and view manipulation.

In our prototype system, the accuracy of the right-hand device is within an error of 0.3 mm based on our experimental tests. Note that the stylus of such a device should have at least 5 degree of freedom in order to achieve convenient manipulation on the external surfaces of physical objects. In addition, the shape of the stylus should allow it to conveniently access any points on the surface of physical objects. In order to achieve accurate touch and avoid interferences with other portions of physical objects, the stylus terminal is desired to be slim with a small tip. Some modifications to the existing stylus of the Phantom Omni may be needed, e.g. by assembling a sharp and slim stylus terminal to replace the existing one. Accordingly, the touch positions corresponding to the newly installed terminal need to be calibrated.

The main function of the left-hand device in our system is to select menu buttons and to conduct view operations such as rotation, zoom in and zoom out. Such operations require fast and large movements. For such purpose, an optical tracking system by using an IR pen is appropriate and more convenient than a mechanical tracking system. In our prototype system, the left-hand device has a relatively large positioning error (~2 mm). In addition, the used IR pen has a relatively large stylus size (with a diameter of ~5 mm).

Generally, the user's intention for 3D input can be classified into moving, picking, dragging and erasing. One button on the input device is desired in order to capture the user's intention. Precisely and intuitively picking feature points (e.g. control vertex for spline, middle/end point for line segment and so on) is crucial for any CAD system. With a button on the input tool, user can pick any point by press the button. Based on our experiments, this design works well when the stylus is in direct contact with a physical object. However, pressing a button in the virtual environment will cause a slight movement due to the force applied on/released from the button. The issue can be resolved by introducing a magnetic attaching

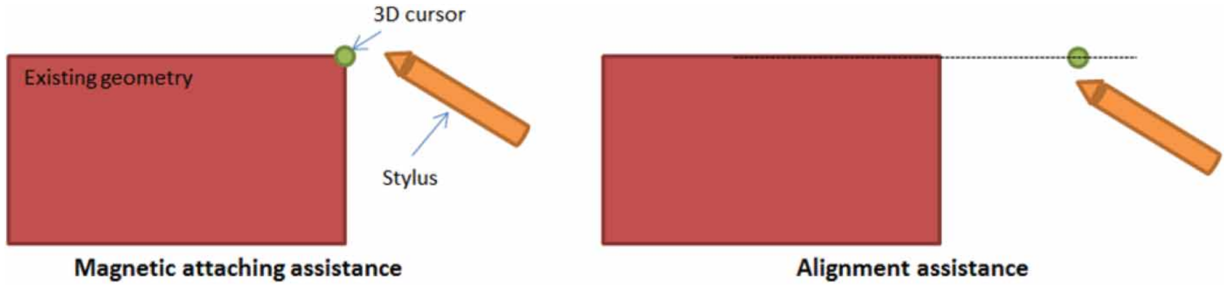

Fig. 5: Illustration of magnetric attaching assistance and alignment assistance.

assistance (see Fig. 5-left), which will detect feature points and attach the 3D cursor onto them once it gets close to them. Similarly an alignment assistance function (refer to Fig. 5-right) can also be turned on in order to pick a point aligned with any other geometry feature along orthogonal directions. The moving and dragging input can be conducted by moving the 3D input tool with and without pressing the button respectively. For conveniently erasing geometry entities, the user just need to change the 3D cursor into the erasing mode by double-clicking the button. Accordingly any geometry entity can be destroyed by holding the button.

## 5. CAD INTERFACE AND OPERATIONS

### 5.1. Display Operations and Model-View Manipulations

Traditional CAD systems provide display operations and rendering modes such as shading and wireframe for digital models. In our AR-based CAD system, such display operations and modes can also be used for all virtual objects. For each physical object placed in the working volume, users can specify whether to display its corresponding digital model. In addition, as mentioned in Section 3, artificial occlusion effect needs to be considered in the AR environment by computing the relative positions of the physical objects and virtual models.

For the model-view manipulations such as rotation, translation and zoom in/out, a physical object needs to be synchronized with its digital model; otherwise, the transformed object and the related digital model will be misaligned. To avoid the recalibration of a transformed object and its related digital model, a motion system is used in our system such that the related model-view transformation matrices are always known in order to keep the physical object and the virtual model aligned. For example, Fig. 1 shows a rotation table is integrated in our prototype system. Hence, for the rotation operation, the physical object positioned on the rotation table can be freely rotated along the upward axis. Fig. 6 shows a picture of the user interface for the allowed model-view manipulations. Currently the system only allows the rotation mode. Note that the button for rotation is highlighted using a different color. The user can use the left-hand device to pick a button and to drag the virtual trackball to rotate the physical object to desired positions. For a desired rotation angle, the CAD system will communicate with a motion controller, which will then drive the servo motor of the rotation table accordingly. For the translation and zoom in/out, we plan to incorporate a robot arm to freely translate the physical object in the working space of the system.

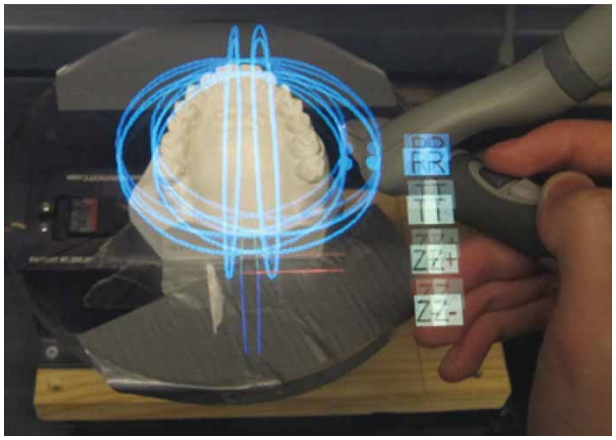

Fig. 6: The graphics user interface for model-view manipulations. The four buttons with the letter “R”, “T”, “Z+” and “Z-” represent rotations, translation, zoom in and zoom out, respectively.

### 5.2. CAD Operations

In the newly developed CAD system, how to design shape editing operations that can intelligently capture user’s intention in the AR environment and how to achieve convenient design process based on such 3D interface are still open questions. In this paper, we investigate a set of CAD operations for defining and modifying geometry by using physical objects that are positioned in the AR environment.

(1) For shape creation, the user can create primitives by first selecting the type of the primitive and then, picking several points on the physical objects to create it [7]. The system

will try to generate the primitive using the points provided by the user. Various numbers of points may be required for defining different primitive shapes. Our system will try to construct the desired shapes as long as the input points can provide sufficient information. Fig. 7 shows a simple example of creating a rectangular box. The system generates the desired shape after 5 points are picked from the physical wood block.

(2) For creating freeform shapes, the user can draw 3D sampling points directly on the surfaces of a given physical object. Accordingly a curve fitting process is applied on the sampling points using a specified curve type such as B-spline or NURBS. User can further edit these fitted curves by changing the positions of the control points, or by adding/removing some control points. Fig. 8 shows an illustration of the curve fitting process and its modification. Multiple curves can form a loop to create a surface patch; and several patches can be enclosed to create a solid. In any stage of the design, the generated freeform shapes are dynamically displayed. Users can edit those curves. The related surfaces or solids will be updated according to the edited curves (refer to a test case as shown in Fig. 9 in Section 6).

(3) We also integrate a set of mesh operations into the prototype system including mesh cutting, mesh offsetting, surface thickening, and Boolean operations. Meshes can be imported from files or generated by tessellating the input shapes that the user has designed. Using the 3D interface, the user can intuitively apply mesh operations in the AR environment. For example, cutting a surface patch from the digital model of a physical object can be performed by directly drawing the boundary of the desired patch on the physical object. Test case 2 in Section 6 shows an application by adopting such an operation. In our implementation of such mesh operations, the mesh thickening and Boolean operations are based on the algorithms that were presented in our previous work (refer to [25] and [24]).

## 6. TEST CASES

Various test cases have been performed. Three of the test cases are presented as follows to demonstrate the capability of the developed AR-based CAD system.

Figure 9 shows the first test case, in which a user is trying to re-design a car seat based on an existing car seat model. Sampling points on the five signature curves are first retrieved from the physical model by sliding the stylus of the Phatom Omni device directly on the car seat surface (refer to Fig. 9a-9b). According to the sampling points generated by the right-hand device, five B-spline curves are generated as shown in Fig. 9c. After that, user can modify the control points of the fitting curves (refer to Fig. 9d). As can be seen from this test case, user can conveniently capture the signature curves from the existing physical car seat object and modify them to the desired shape as what he/she likes. During the modification process, the digital model of the changed shapes can be see through the user's shutter glasses while the physical object can still be seen as a reference. Thus the user can

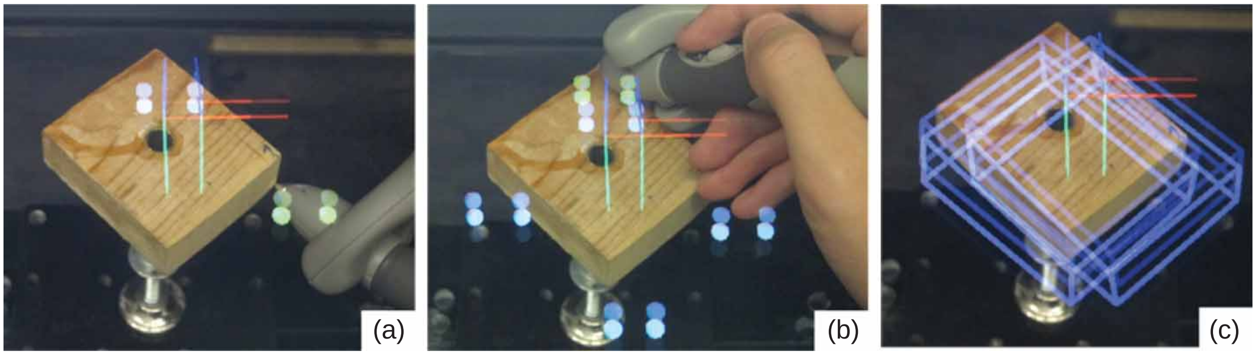

Fig. 7: Primitive creation using picked points. (a) Picking the second point; (b) picking the fifth point; (c) a rectangular block is created.

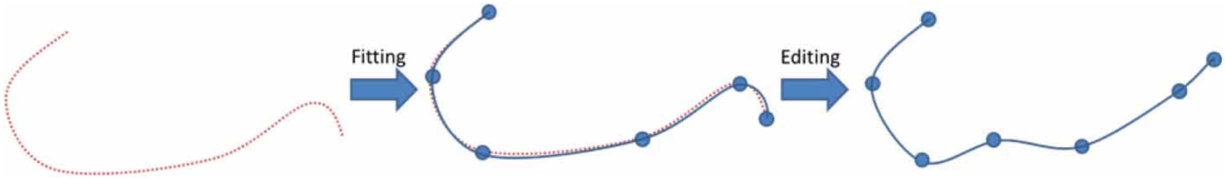

Fig. 8: An illustration of the curve fitting and editing process.

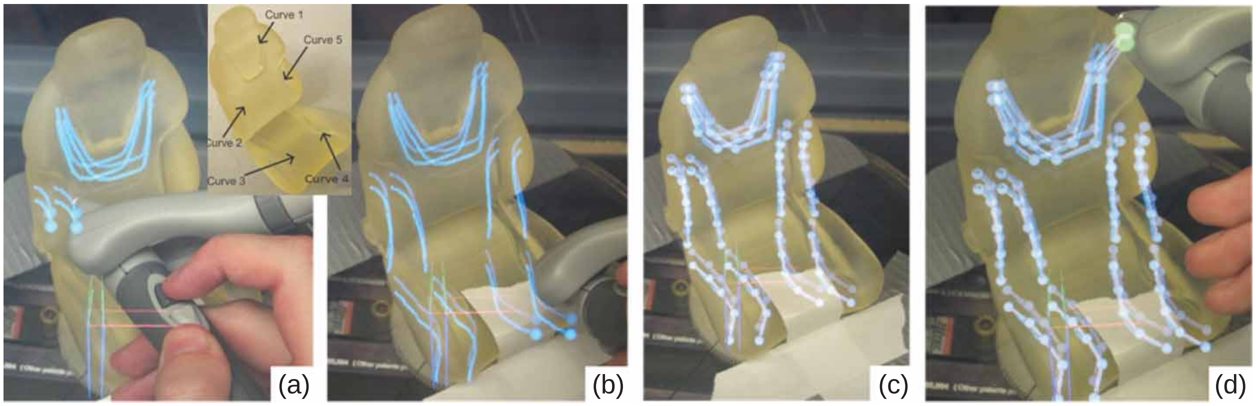

Fig. 9: A test case of an existing car seat re-design. In the test case, signature curves are fitted and modified. (a) and (b) collecting sampling points of the signature curves by sliding the stylus of the haptic device on the physical object; (c) five B-spline are produced based on the sampling points; and (d) modify the shape of the B-spline by changing its control point position. Note that the user can change the position by directly dragging the point in 3D space to a desired location.

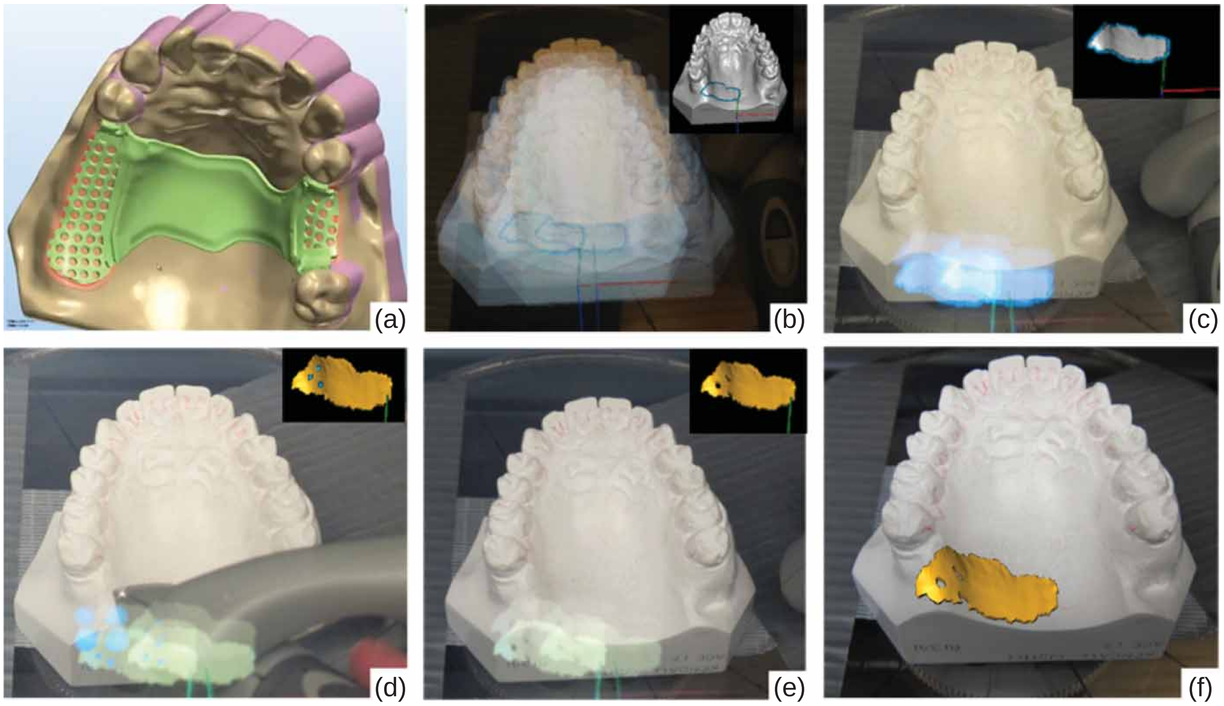

Fig. 10: RPDF design demonstration, for (b)-(e) the big picture shows the physical object together with the stereo-display reflected by the 50% mirror and the small figure at right top corner shows the image rendered for the virtual display. Note that the photos are taken from other angles, in which the virtual and physical models seem to be misaligned. (a) The CAD model for RPDF, (b) the selected boundary for mesh cutting by directly drawing on the physical teeth model, (c) the mesh patch after mesh cutting, (d) the thickened patch with the specified holes' location on it (indicated by the blue dots), (e) the resultant design after Boolean operations for drilling the holes, (f) the design in the AR environment, this is the scene seen by the user wearing the shutter glasses.

re-design the curved surface based on a comparison of the modified version with the original one.

The second test case demonstrates the design of a Removable Partial Denture Framework (RPDF) for dental applications. RPDF is a dental device that is used to hold the replacement teeth. Fig. 10 shows a digital model of a typical RPDF design. Note that the bottom surface of a designed RPDF needs to fit the oral cavity well in order to achieve comfortable wearing. This requires using the surface patch cut from the original teeth model in order to create the bottom surface of the RPDF. A dental technician can use a dental impression to create a replica of the patient anatomy. A digital version of the patient model can also be generated by using 3D scanners with significant efforts. Note that the availability of such a digital model is not required in order to use our AR-based CAD system.

The following three steps are taken during the design of an RPDF using the AR-based CAD system. Step one is to select an appropriate region based on the patient's physical dental model. Based on such a selection, a surface is directly constructed from the physical object, or cut as a mesh patch of the digital model if it is available. In the second step, a surface thickening algorithm is used to convert the selected patch into a solid with desired thickness. Finally, several holes may be drilled on the constructed solid model.

As shown in Fig. 10, all the three steps can be easily performed in our CAD system. To select desired region for RPDF, user simply draws the region boundary on the physical dental object (refer to Fig. 10b). Then the mesh patch related to the selected region is cut from the teeth digital model (as shown in Fig. 10c). After the mesh patch is thickened into a solid patch, user can provide the location of the holes by directly tapping on the physical object (refer to Fig. 10d). Accordingly several holes are drilled at the selected locations by the subtraction operation (refer to Fig. 10e).

Finally, in order to evaluate the usability and performance of the proposed system, five experienced CAD users were invited to design a dental brace wire as shown in Fig. 2. Each user first spent 5 minutes to learn how to use our prototype system to draw 3D curves. Each user then spent another 5 minutes to learn the expected design of a dental wire for a given teeth model. Afterwards, the users began to design the wire. In average, it took each user less than 5 minutes to finish the wire design as shown in Fig. 2b. Afterwards, the five users were required to use the CAD software systems they are familiar with including Solidworks and IronCAD to design the same brace wire. All the users took over 2 hours to finish the wire design for the given teeth model.

A 30 minutes discussion is held with each user on their design experience. All the users strongly agree that the AR-based CAD system is much more intuitive and convenient than the current CAD software systems for designing such a wire. One main reason is the physical guidance provided by the plaster teeth model makes drawing points on the model surface extremely easy and efficient. In comparison, it requires a lot of view rotation followed by position adjustment when using conventional CAD system in drawing such points at expected positions. Among the five users, three users complained the size of the 3D input stylus of our system is too large. It often blocks user's view as well as collides with the teeth model. One user also pointed out the stylus tip need to be smoother in order to better control the stylus movement on the physical teeth object.

## 7. CONCLUSION AND FUTURE WORK

An augmented reality based CAD system has been presented in the paper. The new system uses stereoscopic display for virtual visual feedback, and two position tracking devices for 3D user input. Physical objects are used in the system to provide visual and physical guidance in the AR environment. Analysis has been made on the proposed system in the aspects of visual feedback and 3D user input. A set of displaying and CAD operations have been developed to capture user's intention in shape creation and editing. The implementation of a prototype CAD system has been described. Several test cases have been performed to demonstrate the intuitiveness and effectiveness of the AR-based CAD system. Due to its intuitiveness, the presented CAD system has significant potentials for the customized dental appliance design, in which most dental technicians have little CAD training.

Some future work includes: (1) investigating intelligent CAD operations to fully utilize the convenience presented by the AR environment; (2) further improving the prototype system such as the input stylus for dental applications; and (3) integrating the force feedback of a haptic device into our system such that a user can directly draw on a virtual model based on the haptic force guidance.

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