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Virtual figure model crafting with VR HMD and Leap Motion

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ABSTRACT

Handcrafting has been used for purposes ranging from learning and entertainment to stress relief. However, clay art and handicrafts require specialized space and physical materials. In this paper, we propose a virtual figure model crafting system that is developed to allow users to directly experience the figure model crafting process using a head-mounted, display-based, virtual reality environment. In the proposed system, users can freely generate the shape of a figure and decorate its exterior. In order to provide realistic crafting user experiences, we leverage motion grammar-based gestural input with Leap Motion and consider the support of multiple difficulty levels for user engagement. The preliminary user study results confirm that the proposed system provides immersive and interactive crafting experiences in a virtual environment.

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Introduction

Virtual reality (VR) technologies have attracted significant attention due to the recent introduction of highly advanced, low-cost, head-mounted display (HMD)-based VR devices, and significant investments by technology giants such as Facebook, Google, and Microsoft. The well-known HMD devices include Facebook's Oculus Rift, HTC's Vive, and Sony's PlayStation VR. These devices support naturalistic VR experiences: as users move their head, they can quickly capture their viewpoint and render the scene seamlessly. Furthermore, there are increasing expectations for VR-based game content, because recent game engines such as Unreal, Cry, and Unity are offering improved functionalities that satisfy the visual demands, such as high-resolution graphics and fast rendering of VR content.

The focus of this work is on one important application area of VR HMD: handcrafting, which is used for various purposes, ranging from learning and entertainment to psychotherapy and stress relief [1]. In general, clay art and other handicrafts require specialized space and materials, which can become significant barriers to participation. Fortunately, realistic handcrafting experiences can be easily simulated in a virtual environment by leveraging HMD-based VR systems.

Prior studies have partially examined supporting handcrafting in VR environments. Existing VR clay and deformation techniques have been limited to partial modelling and haptic feedback rather than the overall process or a realistic VR experience [2,3]. The finite element method attempts to mimic the properties of clay [4] using an animation deformation

technique, which deforms an existing shape to a pre-defined shape [5], and sketch-based modelling, which reflects changes to the shapes based on a user's sketch [6]. However, this approach is computationally demanding, and, thus, is less appropriate for real-time handcrafting. Virtual crafting studies [7–12] have also been conducted. Most of these works have been run on PC (personal computer) platforms that seem to fall short with respect to the immersion experienced with the HMD VR platform that we use. For virtual crafting systems, a sense of immersion should be a primary consideration. More details on prior studies will be investigated in the section 'Related work'.

This study aims to build handcrafting systems that can manipulate virtual figures, e.g. representative characters from video games, animations, and movies. Figures have the intrinsic property of being a multi-use source that can make progressive extension to various character markets such as toys, fashion goods, shoes, and theme parks [13,14]. The figures have a central position in promoting those character markets.

Portable VR HMD devices can provide immersive user experiences as well as ease of use. Bowman and McMahan [15] defined immersion as 'the objective level of sensory fidelity'. To increase the immersive experience, which is important for VR, it is necessary to satisfy visual demand. High resolution, accurate stereoscopy, and high frame rates are the key elements in providing visual loyalty. In addition, a VR HMD display is simpler and easier to operate than existing VR devices, and it has interactive advantages because it is easily compatible with other input controllers, such as Leap Motion. Therefore, in this study, the VR

HMD Display Oculus, which has recently achieved remarkable technological progress while satisfying these conditions, has been selected as our platform.

Thus, we believe that the overall process of figure model crafting (FMC), which is popular in the entertainment industry, can be supported with virtual reality and gesture recognition. To our knowledge, none of the prior studies considered supporting the entire process of virtual figure model crafting (VFMC) with natural gesture input using Leap Motion.

Therefore, we built a VFMC system that supports the process of FMC in an immersive and interactive way using the VR environments. VFMC has two primary components: the configuration feature for crafting the shape of a figure, and the decoration feature for colour and decoration. In order to support natural crafting user experiences, the key gestures are defined using Leap Motion [16], which is a commercial device for hand gesture recognition. The system was implemented with a HMD-based VR display. The preliminary user study results confirm that the prototype system provides immersive and interactive crafting experiences in a virtual reality environment.

Related work

The trend of related studies in the virtual crafting field [7–12] will be examined, and they will be compared with our proposed study. To compare the related studies on virtual crafting with the present study, we set the following criteria. If a customized VR device is required for an application, it is inconvenient for general users to use it. If a craft method runs on a PC-based platform, the immersive experience is insufficient compared to the VR platform. Also, the use of a specific device for tracking also lacks extensibility because experiments are only supported in a special laboratory environment. The interest of users and the quality of the final results are also affected if the craft method supports colouring. Supporting both hand and tool interactions also enables more sophisticated crafting. A comprehensive summary of related studies is shown in Table 1. In addition, recent technological

advances in HMD VR will be examined. In particular, we will describe in detail HMD VR technical issues that have been enhanced, making it possible to reduce motion sickness by enabling high frame rates and increasing resolution.

Virtual crafting

One 3D virtual pottery method [7] locates a hand shape with a SoftKinect camera sensor, recognizes hand movements with the point cloud method, and performs object deformation. Also, the Leap Motion controller is used to select the workspace in the work window. There is the advantage of performing object deformation according to the expression of a hand gesture without learning about a specific gesture. However, it is inconvenient to simultaneously operate the main work space, handcraft, and tool craft on the laptop screen. Since it works in a laptop environment, there is also the disadvantage that the 3D pottery cannot be observed on the front and side during work, which makes operations difficult. With our approach, a HMD VR device allows users to function more comfortably in the extended work space because the front, left, and right sides can be displayed with a HMD VR device. In particular, users can always see the prototype of the 3D figure model on the left screen of the VR while working.

Pan et al. [8] proposed metaballs-based organ deformation for virtual surgery training. To accomplish this, the authors converted the polygonal mesh of a Voronoi Diagram into metaballs and perform local optimization. In order to perform the desired deformation, position-base dynamics (PBD) were applied while preserving the Laplacian coordinates and local volume properties. However, this method has limitations; it is inconvenient to manually create blob-like objects, such as human organs. Therefore, it difficult to expect a good result: the deformation of a high-resolution object.

A virtual wood handcrafting system [9] that imitated real-life woodworking was proposed. The authors employed a hand tool metaphor for three interactive

Table 1. Comparison with related studies.

| Work/year | Display platform | Tracking/controller | Colouring function | Hand craft | Tool craft | Output result |
|--------------------------------------|--------------------|---|--------------------|---------------|---------------|----------------------|
| 3D virtual pottery [7] | Laptop | SoftKinect/Leap Motion | Not supported | Supported | Supported | Virtual pottery |
| Virtual surgery [8] | PC screen | Grasper, scissor, hook cauterly | Not supported | Supported | Supported | Virtual Human Organ |
| Virtual hand crafting [9] | HMD VR (Cannon VH) | Hand tool | Supported | Not supported | Supported | Wood craft |
| Virtual pottery [10] | LED screen | Kinect/real wheel | Not supported | Supported | Not supported | Virtual pottery |
| Virtual 3D sculpting [11] | PC screen | Vicon Motion Capture/Finger Marker Tracking | Not supported | Supported | Supported | Virtual sculpture |
| Virtual clay [12] | PC screen | PHANToM haptic | Supported | Supported | Not supported | Virtual sculpture |
| Virtual figure model crafting [ours] | HMD VR (Oculus) | Leap Motion | Supported | Supported | Supported | Virtual figure model |

devices: TweezersDevice, KnifeDevice, and HammerDevice. These tools provide for various woodworking operations, such as pick up, move, cut, and join. To achieve this, they used a binocular video see-through HMD (Cannon VH-2002). The position and orientation of the HMD and ToolDevice had to be tracked using Polhemus LIBERTY. However, the HMD VR devices used seem to be older models, compared to the currently available HMD VR devices that fully support head tracking, high resolution, and a high frame rate.

Virtual pottery with a real spinning wheel [10] demonstrates a technique to create virtual pottery while displaying a virtual cylinder in an LED display panel. In fact, it is a way to create a desired shape by touching the virtual clay with the left hand while using the right hand to rotate the wheel used in pottery generation. In this approach, a Kinect sensor is used to track the movement of the hand, and a mouse is attached to the wheel to detect the rotation. However, this method introduces only an interesting production environment, compared to VR technology that requires both an interesting production environment and the feeling of immersion.

Sheng et al. [11] proposed a virtual 3D sculpture method to create a 3D clay virtual model that transforms an object by attaching a marker to a finger and tracking it using four Vicon Motion Capture Cameras. Object deformation uses free form deformations that can be conducted in real time according to displacement. However, since the goal is to design a rough virtual model, there is a limitation in creating a high-level model because the burden of using expensive motion capture equipment is imposed.

A virtual clay method [12] was proposed to reproduce the shape of a sculpture by measuring a user's force using a PHANTOM haptic device. A physics-based dynamic subdivision solid model was presented for shape modification. By sensing force, a semi-elastic illusion was created by manipulating the virtual clay. The authors also added a tool function to effectively communicate 3D interaction using haptic force. However, in the conventional 2D display environment, there might be a limited ability to fully feel the immersion of the VR clay. Also, the mouse interaction might be less suited to selecting from a menu during sculpture production.

Technical advancement in HMD VR devices

In recent years, the dominant HMD VR device manufacturers have announced significantly improved technologies. Facebook's Oculus Rift, HTC's VIVE and Sony's PSVR have seen technological advances. Improved graphic quality is one of the major advances because the distance between the eyes and the display is very small, and it is necessary to satisfy at least 90 fps so that the optic nerve can smoothly receive input and

reduce dizziness. HMD VR device manufacturers are known to be working with graphics card developers to continuously improve quality [17]. For example, the amount of graphic data rendered with VR is 7.5 times the amount of graphic data rendered on a PC screen. In addition, NVIDIA technology such as VR SLI (the technology that assigns the rendering of two eyes to another GPU or Multi-Res Shading) and the technology that renders each part of the image to match the pixel density of the distorted image necessary for VR have been introduced [18]. It is also possible to reduce workload by rendering the centre of the image as much as possible while scaling down the outer part. Finally, there has been a significant improvement in rendering latency, which may result in visual sickness, particularly when a VR user's field of vision moves [19]. In order to solve the latency problem, a technique that simultaneously reproduces the current frame scene while tracking the position of a camera and predicting the next frame is used. This predictive method can reduce the delay to 20 ms by locating the camera in advance and using it as an input for the rendering. Furthermore, in order for VR users to settle smoothly into the virtual space, designers must create a scene that gives the users a sense of comfort.

Virtual figure model crafting

The process of virtual figure model crafting has two sub-processes: the preliminary process and the figure model crafting process. In the preliminary process, a user can learn how to use the VFMC system through viewing the tutorial program and can then select their crafting difficulty level.

Currently, the proposed system supports three levels of difficulty: beginner, intermediate, and advanced levels. The virtual figure model crafting process supports the configuration and decoration steps. In the configuration step, a user forms and manipulates the shape of the figure model. This configuration step has two sub-stages: a handcraft stage for forming the overall shape, and a tool craft stage for carving details. In the decoration step, the user can add colours or attach accessories to the figure formed during the configuration step for artistic expressions. The overall figure model crafting production process is depicted in Figure 1. In this section, the components are illustrated in detail and then the VR interfaces and gesture inputs for crafting with Leap Motion are presented. It should be noted that during the design process, some critical considerations are made in order that the user interface and the layout are suitable for the Leap Motion interaction framework for the FMC process and the VR HMD environment.

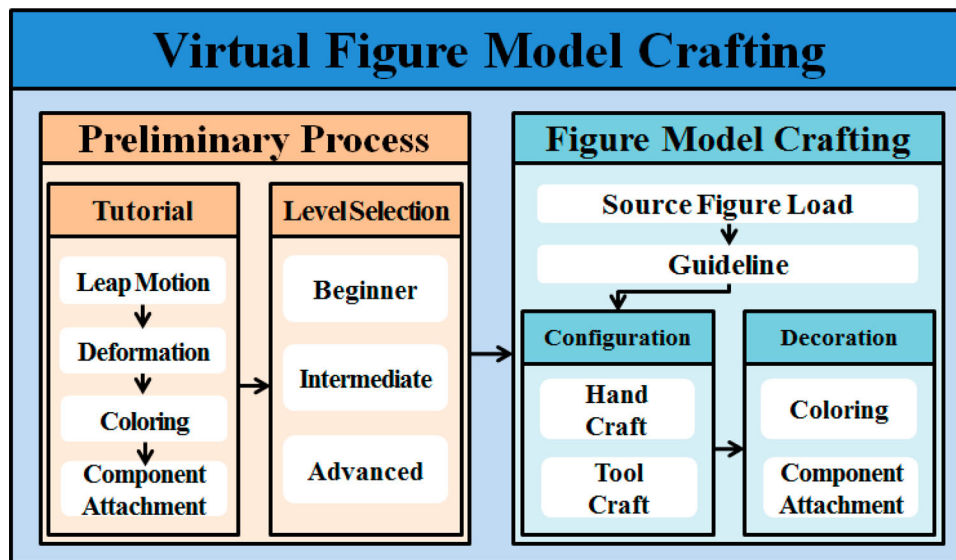


Figure 1. The virtual figure model crafting process.

Preliminary process

A tutorial is provided to help users to become familiar with the VFMC system. The tutorial consists of four stages. The first stage is to learn how to use the Leap Motion. The user practices the Leap Motion gestures that have been defined specifically for the FMC process. The second stage is to learn how to use the deformation feature, or the method of deforming the figure materials. The third stage is colouring; i.e. the user practices the process of applying one of the two colours, red and blue, to the model formed during the deformation stage. Lastly, in the component attachment stage, the user is given the task of attaching a carrot component to the figure material. Note that the accessories, which are typically difficult for the user to create, are provided as components in the VFMC.

After the tutorial, the user is asked to select a suitable difficulty level for FMC according to their skills. Currently, the proposed system has the three difficulty levels (beginner, intermediate, and advanced), which have been carefully tuned by the researchers. Afterwards, figure model crafting production stage is presented, where a figure whose crafting requirements are suitable to the skill level can be produced.

Figure model crafting

FMC is the stage where the user can select their desired figure and begin producing the figure. First, the menus and features related to producing a figure are presented. The spatial interface was designed by utilizing the screen layout of the HMD-based VR. On the upper left-hand side, a guideline menu is provided, which the user can refer to if difficulties arise during the production. The component and tool menus are placed on the right side; these are necessary for the figure production. The user notes the locations of

each menu and proceeds to the configuration process (hand craft and tool craft). The configuration process refers to the task of forming the overall shape, where Leap Motion is used to help users to deform the intricate shapes using their hands and fingers. The tools include a knife spatula, a round spatula, and a digging spatula, with each tool having different uses.

Configuration process

The most important component in the VFMC production process is the deformation technique, which determines the exterior shape of a figure. The deformation technique expresses the desired features of the figure using hands and tools (knife, round, and digging spatulas). During the configuration process, the location of the material where the hands, fingers, or the tools touch must be detected, and the deformation must be applied around this location. In this study, grid-based spherical coordinates were used, and each grid point is referred as a vertex.

The mass-spring model was customized to implement deformation activities with both hands and tools. Mass-spring techniques [20] have been broadly used in cloth [21], hair [22] and surgery [23] simulations. In order to extract a touching vertex, the Raycast [24] collision detection method was used to limit the area of collision in order that a real-time change can be applied quickly and more accurately. Unlike the proposed approach, previously geometric collision detection methods [25,26] are less suitable for FMC because unnecessary collision detections caused by more installed colliders could occur frequently, which results in the use of more memory space and computing time. For example, if three colliders (box, circle, etc.) are installed in a finger, and one collider in a palm, then there is a total of 16 colliders

for one hand. However, the Raycast uses only one collider for one finger and one collider for one palm; thus, there are only six colliders in total. Therefore, fewer comparisons are needed.

Table 2 describes the logical details to make a deformation. With the hit point (P_h), the strength (S_i) of each vertex within the range of the strength offset (S_o) is calculated, and then the final deformed vertex is obtained by adding V_i to $S_i \Delta f$ with the time interval Δf .

Figure 2 illustrates the Raycast detection method. By generating a ray R in the direction of the hand, the distance D to an object lying on a straight line can be detected. When the distance D becomes less than equal to zero, the corresponding vertex is set as the hit point P_h , which is the reference point for deformation. In Figure 3, the deformable vertices are denoted as the hit vertices detected using the Raycast detection method, and the static vertices are included within the strength offset (S) as depicted in Figure 3(a). The deformable vertices are indicated in red in Figure 3(b). As described earlier, a non-deformable vertex changes to a deformable vertex after detection; then, strength is applied to the deformable vertex with a magnitude inversely proportional to the offset distance from the hit vertex, which dislocates the deformable vertex. Figure 4 illustrates the process of a non-deformable vertex changing to a deformable vertex; the set of vertices near the hit point (P_h) is included in the deformable vertex set $\{V_i\}$, as the strength is applied. Finally, the deformation occurs with the application of strength, which results in the deformed vertex set denoted as $\{V'_i\}$.

Table 2. Algorithm of configuration.

| Algorithm: Configuration Process |
|---|
| Input: H (Hand), T (Tool) |
| Output: the Deformed Vertices $\{V'_i\}$ |
| Begin |
| Detect_Hit_Point&Activate () |
| { |
| Notation: R (Ray to the front), |
| D (Distance from H or T to a vertex), |
| S_o (Strength offset), P_h (Hit point); |
| Detect the method between H and T ; |
| Shoot the ray R from H or T ; |
| If $D \leq 0.0$ then gain the hit point P_h ; |
| Else wait until finding P_h ; |
| Set the Strength offset S_o ; |
| Activate the Deformable Vertices $\{V_i\}$ |
| } |
| Move_Deformable_Vertex () |
| { |
| Notation: d_i (Distance from P_h to each |
| Deformable Vertex in $\{V_i\}$), |
| S (Strength), S_i (Vertex Strength), |
| Δf (Frame Interval), k (Constant); |
| Calculate each Deformable Vertex Strength, |
| $S_i = S/(k + d_i^2)$; |
| Move each Deformable Vertex in $\{V_i\}$ to the Deformed Vertex in $\{V'_i\}$, using |
| $V'_i = V_i + S_i \cdot \Delta f$; |
| } |
| End |

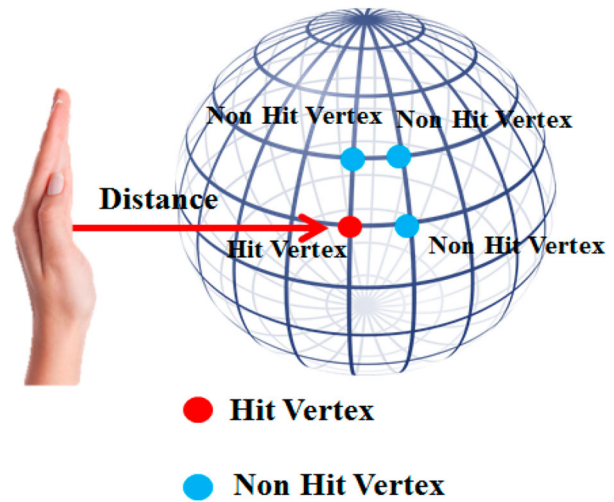


Figure 2. Detection of the hit vertex.

Here, an external input is required for any deformation to occur. The strength input values can be generated from the hands/fingers and tools (i.e. knife spatula, round spatula, and digging spatula). The hands and tools are typically used for different tasks during the crafting process, due to their different physical strength.

This is realized in the deformation through configuring the strength offsets of the hands/fingers and tools differently. The hands deform a wide area with a constant strength. The knife spatula applies a strong strength to a long, narrow area and is therefore useful when a relatively strong deformation with a short duration is desired. The round spatula is used to apply a constant, weak strength to a wide area. Lastly, the digging spatula is used to deform a single point with a very strong strength. For example, as depicted in Figure 5, different strength offset values are assigned to the hand and tools. Thus, the activated deformable vertices differ from one another.

In addition, a tessellation shader [27,28], which is the process of breaking a polygon or patch down into smaller parts such as triangles, is used to provide a further scalable level of detail.

Decoration process

After the configuration process, the user then proceeds to the decoration task, which can be described as the process of applying colours or additional accessories to the completed overall shape of a figure for artistic expression. The decoration task consists of colouring, when colours are applied, and component attachment, for which built-in components are provided that are difficult for the user to create. The user can select a colour from the colour table and the palette. Frequently used colours are placed on the palette for convenient access. During the component attachment stage, the user can attach accessory components that are provided by the system.

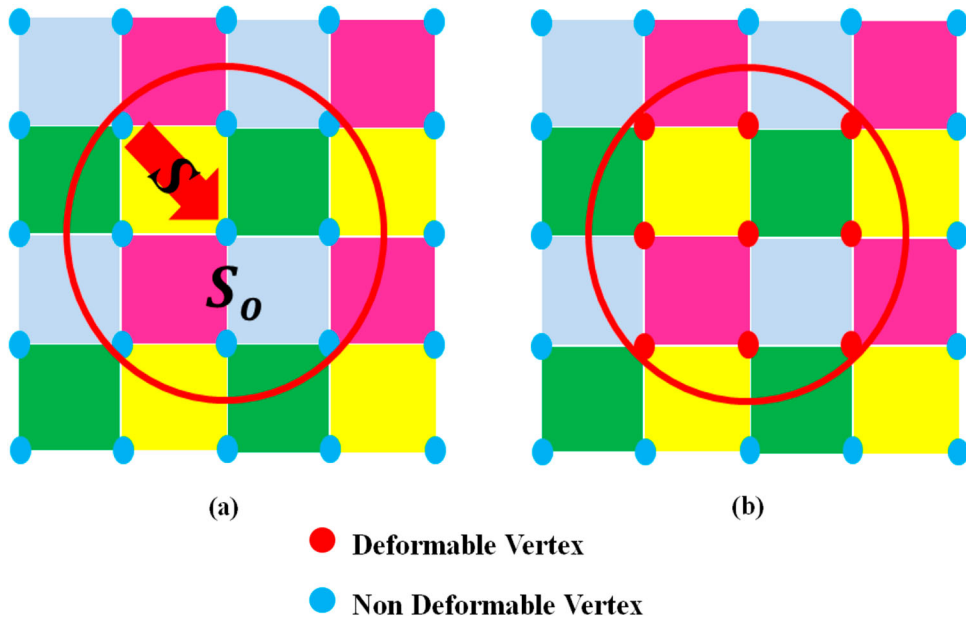


Figure 3. (a) Hit vertex and (b) the strength offset range.

The proposed system provides these components because it is difficult to handcraft detailed objects.

Figure 6 presents the process of performing the decoration task using the finger motion feature from Leap Motion. In the top figures, using the palette and the colour table, the user selects black

and applies this colour to a hat component. The bottom figures depict an example of a component attachment. The hat component selected from the component menu on the right (coloured in black in the previous step) is now attached to the figure.

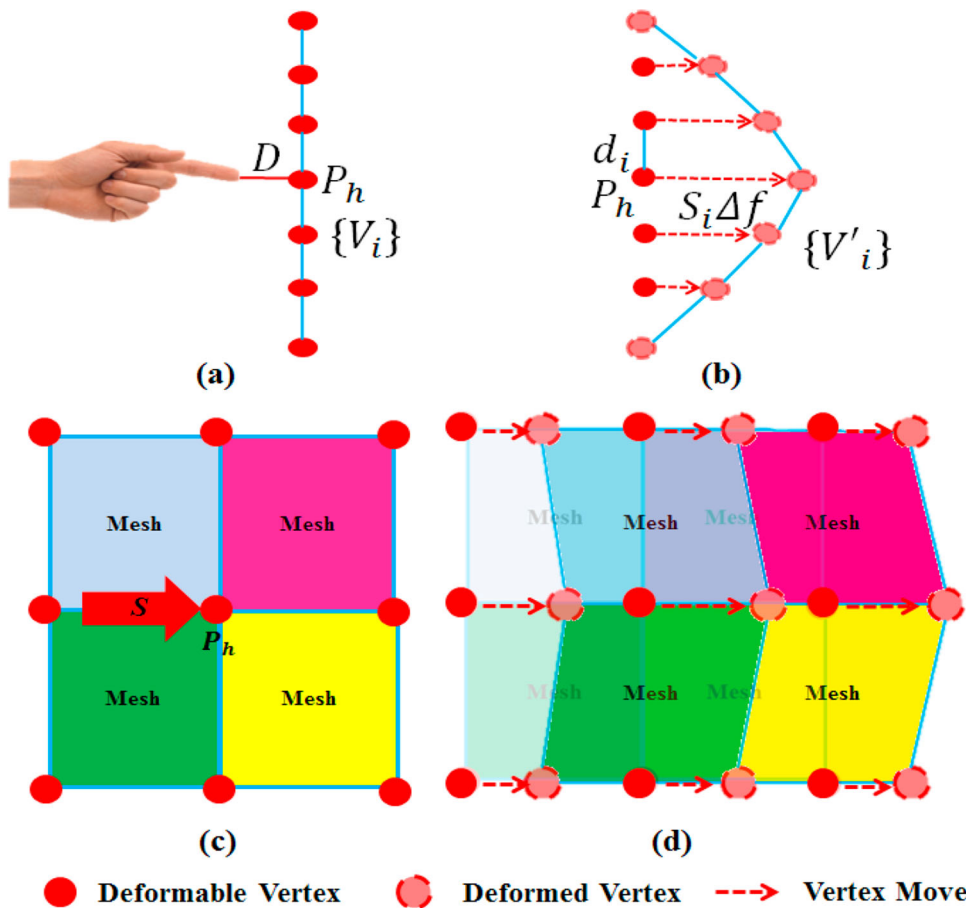


Figure 4. (a) Hit point detection, (b) vertex move, (c) hit point detection and adding strength, and (d) deformable vertex move.

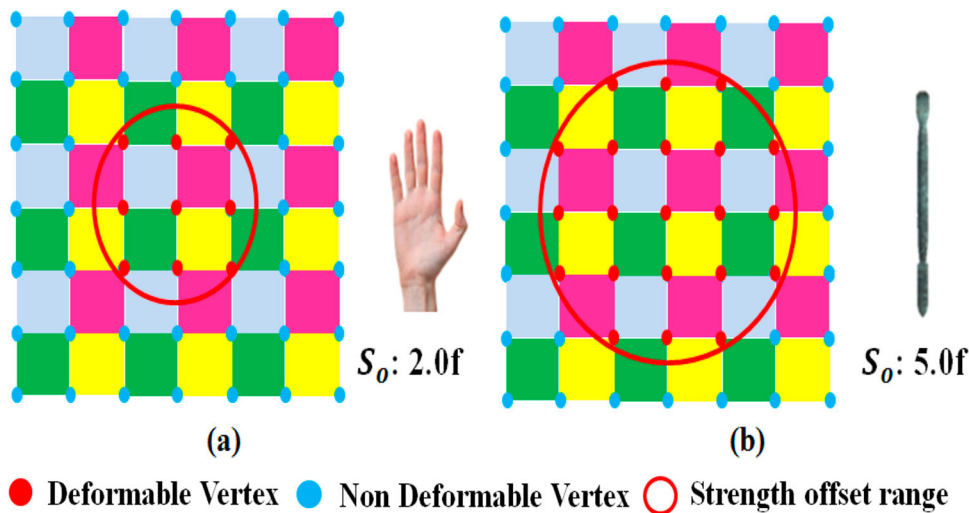


Figure 5. (a) Hand deformation strength offset, and (b) round spatula tool deformation strength offset.

VR interface

In most previous studies, handicraft content was delivered to the user in a 2D environment. In the VFMC proposed in this study, we can provide a more immersive user experience over a 3D environment with a VR HMD. The key benefits of a VR environment are that it not only provides an immersive experience, but it also allows the user to experience the content without being limited to the user's current location. These properties improve the usability through overcoming the spatial limitations. Figure 7 presents the FMC content implemented in a VR environment.

Moreover, the interface structure and layout were designed to maximize the interaction efficiency within the VR environment. As depicted in Figure 8, the VR screen consists of three views. The left view provides the menus that allow a more detailed

examination of the figure. The arrow direction menu on the bottom can be used to examine the figure from a different perspective. The guideline step menu (in three steps) is for viewing the production process in more detail. In the centre view, a workspace is provided where the figure can be manipulated. On the right, the palette, component, and tool features are visualized in order to allow execution of the decoration task.

Leap motion for crafting gestures

The six most frequently used gestures during the FMC process are carefully defined as FMC gestures. These gestures are based on the standardized motion lexicon for Leap Motion [29].

For the left-hand operations, six motions are defined as depicted in Table 3. The rotation motion rotates a

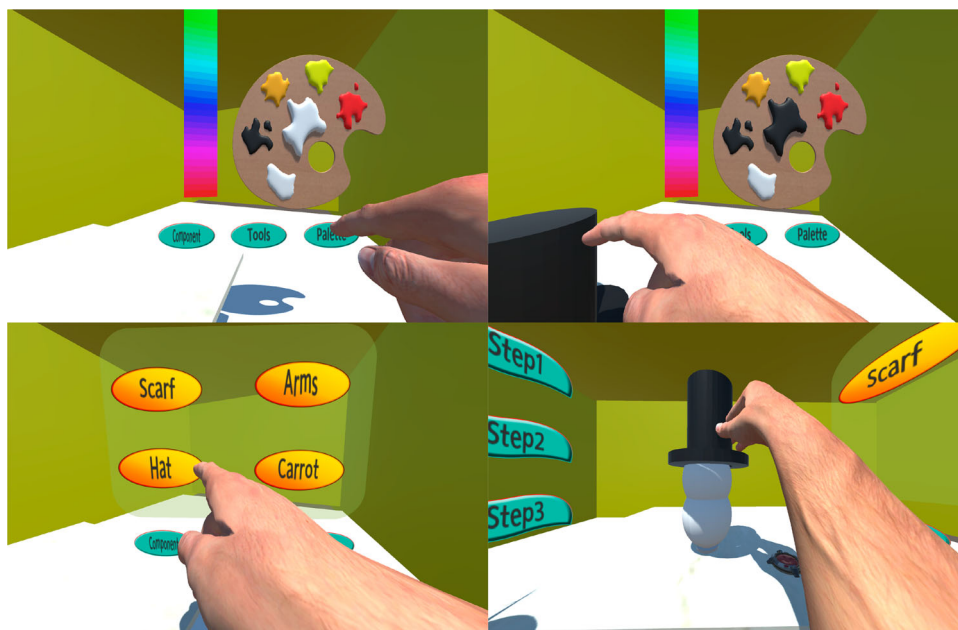


Figure 6. Colouring and component attachment. Images generated by the authors using their self-developed software VFMC: Virtual Figure Model Crafting, which was implemented with Unity engine, a copyright licence free game.

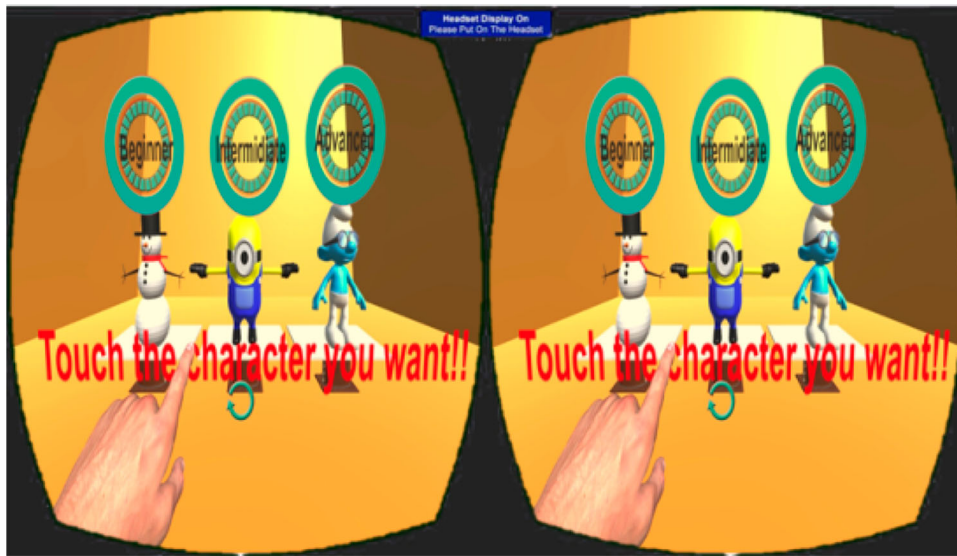


Figure 7. VR HMD view. Images generated by the authors using their self-developed software VFMC: Virtual Figure Model Crafting, which was implemented with Unity engine, a copyright licence free game.

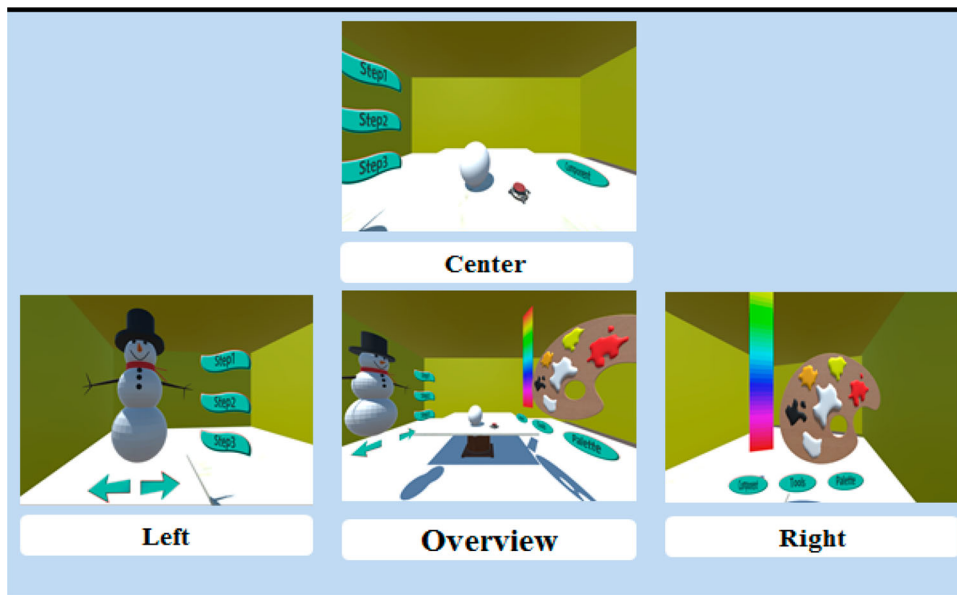


Figure 8. Interface view. Images generated by the authors using their self-developed software VFMC: Virtual Figure Model Crafting, which was implemented with Unity engine, a copyright licence free game.

Figure fixed to the hand in the left and right directions so that it can be examined from various perspectives. The stop motion can stop the rotation of a figure being rotated using the rotation motion. The rewind motion can restore the changes to the shape of a figure made by the push motion. The push motion applies a deformation to the figure through creating a contact between the hand and the figure. The attach motion attaches the elements provided as components to the surface of a figure. Finally, the detach motion can detach a component attached to the material using the attach motion. Three motions are defined for the right hand as described in Table 4. Finally, the motion lexicon defined for both hands, i.e. the create material, is presented in Table 5. This

Table 3. Left-hand motion lexicon.

| | Motion | Image | Function |
|-----------|----------|-------|----------------------|
| Left hand | Rotation | | Rotate the figure |
| | Stop | | Stop the rotation |
| | Rewind | | Move back |
| | Push | | Push the figure |
| | Attach | | Component attachment |
| | Detach | | Component detachment |

Table 4. Right hand motion lexicon.





| | Motion | Image | Function |
|------------|----------|---|----------------------|
| Right hand | Rotation |  | Rotate the figure |
| | Attach |  | Component attachment |
| | Detach |  | Component detachment |

Table 5. Both hands motion lexicon.

| | Motion | Image | Function |
|------------|-----------------|---|-----------------------|
| Both hands | Create material |  | Create a new material |

motion is used when additional material is required during the FMC process.

Moreover, through combining different motions, new compound motion lexicon (CML) can be used. For example, the gesture shown in Figure 9 is created through combining the stop motion of the left hand and the push motion of the right hand, which results in a new CML that is $Pu + St$.

Experimental results

The following environment was set up to evaluate the user experience of the VFMC content developed in this study. A desktop computer installed with Windows 10 64-bit and a GeForce GTX 1060 as graphics card was used. An Oculus Rift DK2 model was used for the VR HMD. The VFMC system was implemented using C# along with Unity 5.4.1f.

Figure modelling crafting system

Figure 10 depicts the overall FMC process. First, the figure material is generated, and a configuration is created in accordance with the figure production process with reference to the guideline. During the decoration step, components are attached, and colours are applied using the colour table and palette, which complete the figure.

To allow the user to select the FMC difficulty level appropriate for their skill, beginner, intermediate, and advanced levels are provided. The figures in each level were selected based on popularity and were classified in terms of production difficulty. As depicted in Figure 11(a), relatively easy figures, such as a snowman, were created in the beginner level. The snowman can be created using basic deformation and component attachment. The Minion in the intermediate level can be created through adding various components to a simple shape. As shown in Figure 11(b), the arms and legs are created using deformation, and the decoration is completed through component attachment.

As presented in Figure 11(c), the Smurf in the advanced level has relatively complicated exterior features, and most parts, including the arms, legs, and face, are created by the user without guidelines. Furthermore, Figure 11(d–f) are figure models completed with tessellation that is described in the section ‘Configuration process’.

User study

To assess the validity of the proposed methods, a user evaluation was conducted. The user evaluation test was conducted with 23 participants (13 male and 10 female; aged 21–26) who were interested in figure

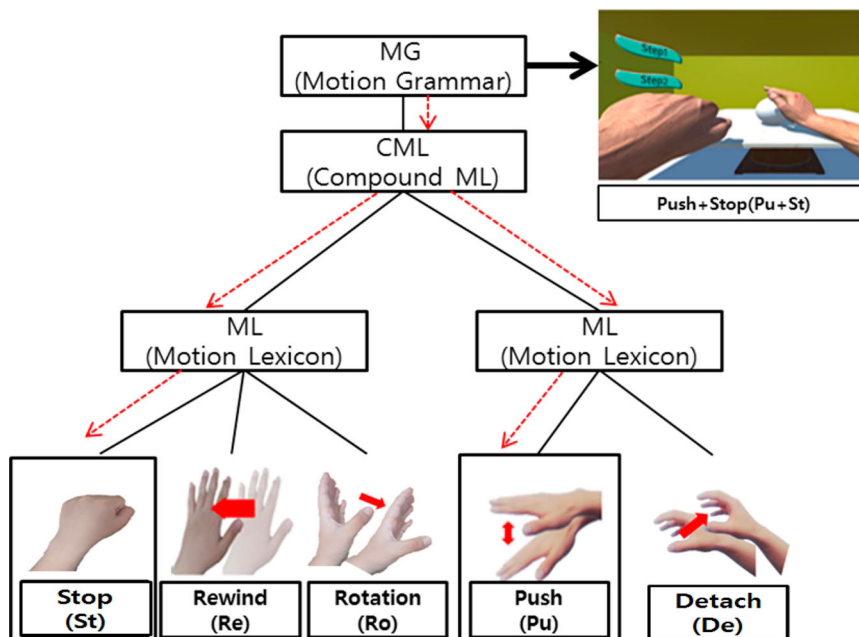


Figure 9. CML motion grammar.

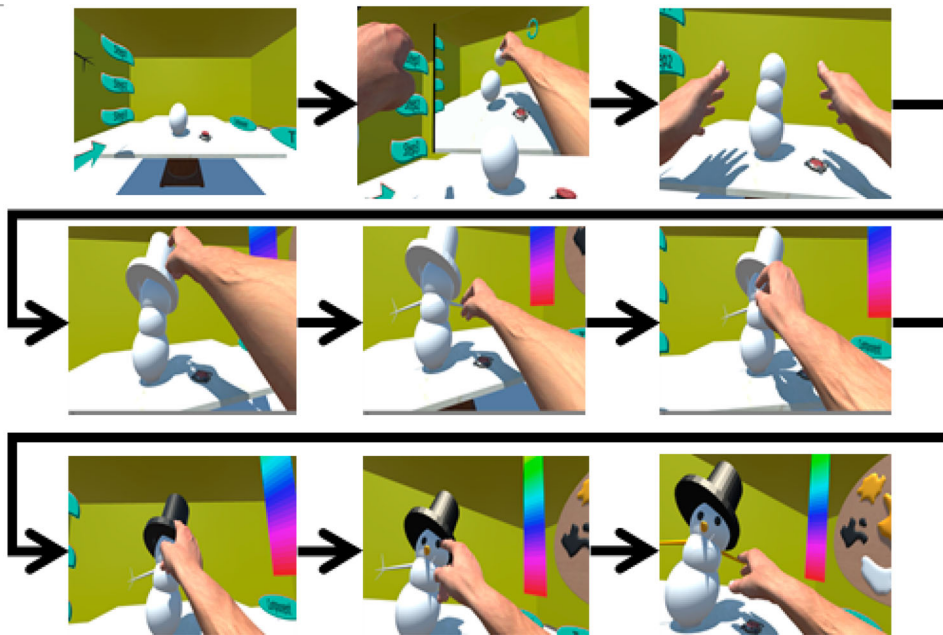


Figure 10. Figure model crafting process implemented. Images generated by the authors using their self-developed software VFMC: Virtual Figure Model Crafting, which was implemented with Unity engine, a copyright licence free game.

collection and crafting, including VR. The experimental method was given as follows. As shown in Figure 12, the participants were provided with basic user instructions for VR HMD (Oculus Rift) and Leap Motion. The tutorial was provided to introduce the participants to the basic FMC content production process. After the tutorial, the participants were asked to go through the content from the beginner level to the advanced level one-by-one.

The primary focus of the experiment was to evaluate the immersion in the VR environment, and the

interaction between the interface and the user. A questionnaire about immersion was designed through considering critical perspectives: the convenience of the production process, the interest associated with the content, the cyber-sickness from the VR device, and the content variety.

There were also significant perspectives relating to interaction: the difficulty of the interface control, the sensitivity in responding to user input in real-time, the convenience of the interface, the ability to recognize and respond correctly to user input, and finally

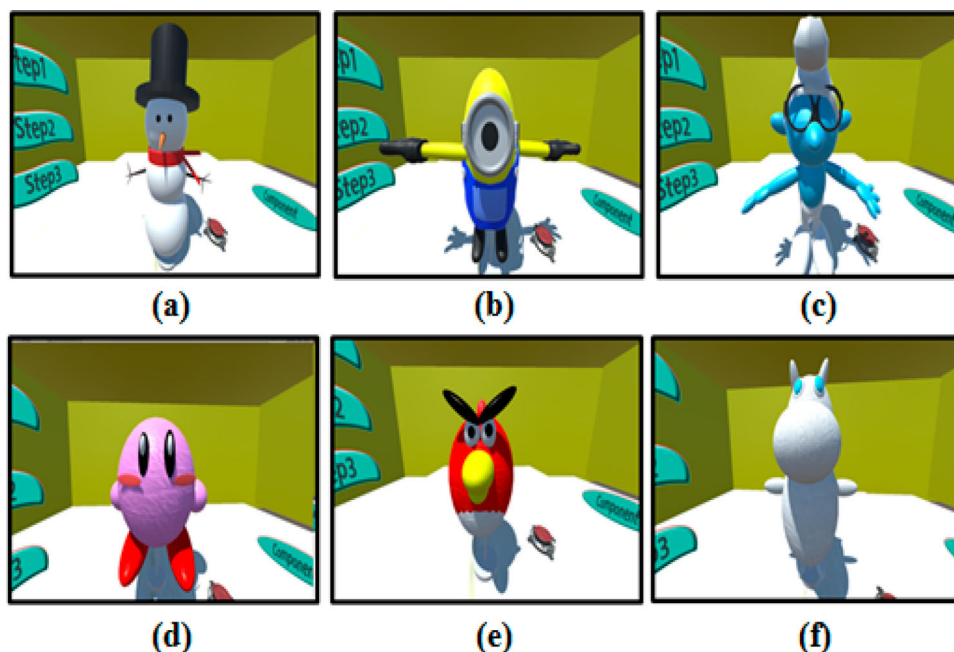


Figure 11. The figure models created at three levels: (a) and (d) for beginner; (b) and (e) for intermediate; and (c) and (f) for advanced. Figure models with tessellation: (d), (e), and (f). Images generated by the authors using their self-developed software VFMC: Virtual Figure Model Crafting, which was implemented with Unity engine, a copyright licence free game.

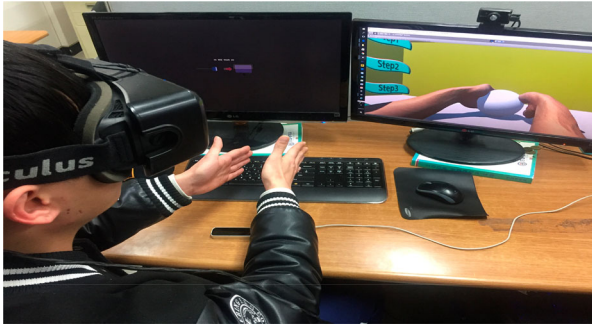


Figure 12. User study image.

Table 6. Questions relating to immersion.

| Immersion | |
|-----------|--|
| Q1 | Was the procedure of producing the figure appropriate? |
| Q2 | How interesting did you find the production process? |
| Q3 | How dizzy did you feel during the experience? |
| Q4 | Did the experience allow you to craft various figures? |
| Q5 | How immersive was the experience? |

Table 7. Questions relating to interaction.

| Interaction | |
|-------------|---|
| Q1 | Was the overall interface laid out in an appropriate manner? |
| Q2 | Was it convenient to use the interface? |
| Q3 | Did the Figures deform instantly while using the Leap Motion interface? |
| Q4 | Were the Leap Motion gestures provided during the figure production process recognized appropriately? |
| Q5 | Overall, were the interaction methods appropriate? |

the efficiency of the interaction. In the survey given to the users, the questions relating to immersion are presented in Table 6, and the questions relating to interaction are presented in Table 7. The questions are evaluated with a 5-point Likert scale (i.e. a minimum of 1 and a maximum of 5).

Analysis and discussion

All participants performed all three levels for the figure models in the VFMC. Then, the participants responded to the questionnaire described in Tables 6 and 7. The scores ranged from 1 to 5. The results of the evaluation

Table 8. The user study results.

| | Immersion | | Interaction | |
|---------|-----------|----------|-------------|----------|
| | m | σ | m | σ |
| Q1 | 4.3 | 0.44 | 4.3 | 0.53 |
| Q2 | 3.9 | 0.83 | 4.0 | 0.72 |
| Q3 | 4.0 | 0.93 | 4.2 | 0.66 |
| Q4 | 4.0 | 0.62 | 4.0 | 0.78 |
| Q5 | 4.1 | 0.61 | 4.2 | 0.66 |
| Average | 4.2 | 0.53 | 4.3 | 0.60 |

presented in Table 8 and Figure 13 are reported with respect to the mean (m) and the standard deviation (σ).

The survey results showed relatively high scores in m and low σ about Q1 and Q5, which might convey the findings that the FMC process was quite acceptable, and the VR HMD delivered immersive user experiences. On the contrary, Q2 had lower scores than the other questions. This could result from the process focusing on the fidelity rather than entertainment perspectives such as gaming elements. However, $\sigma = 0.83$ indicates that an individual deviation also exists. Similarly, the survey results for interaction were reviewed. The total average for the interaction questions was slightly higher than that for immersion. Q1, Q3 and Q5 had slightly higher scores than Q2 and Q4. Q1 relates to the interface layout: it is considered that the results originate from the VR perspective because the HMD VR provides an expansive working space that allows more convenient access to facilities. Q3 regarding deformation can respond to the interaction and it exhibits a relatively high score. This finding might convey that our customized algorithm works appropriately.

We also carried out another user study to compare the usefulness of HMD VR and Non-VR in which the participants created figures both with HMD VR and with PC only. Questions shown in Table 9 are related to perspectives that could differentiate VR from conventional PC facilities. The results show that HMD VR achieves double the scores of non-VR as shown in Figure 14.

We also present the time to complete three figure models. The 23 participants were classified into three

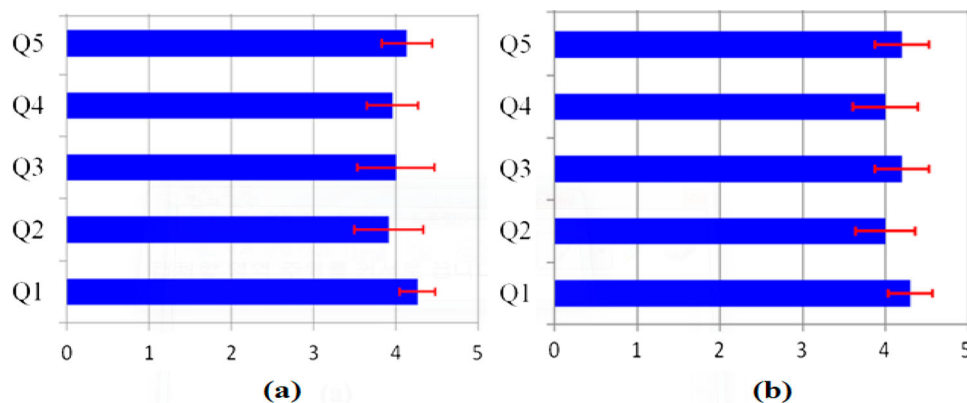
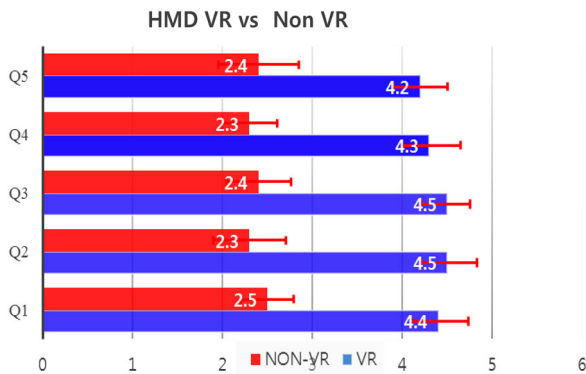


Figure 13. Results of the user study with mean and standard deviations for questions regarding (a) immersion and (b) interaction.

Table 9. Questions on HMD VR and non-VR.

| HMD VR vs. non-VR | |
|-------------------|--|
| Q1 | Can you feel the sense of space? |
| Q2 | Is your vision easy to manipulate? |
| Q3 | Do you feel the 3D sense of the figure? |
| Q4 | Does your figure make you feel realistic? |
| Q5 | Do you fall into content while experiencing? |

**Figure 14.** Results of the user study on HMD VR and non-VR.

groups. The novice group had six members, who took an average of 30 min to complete the model. The intermediate group had twelve members, who required 26 min to complete the model on average. Lastly, the advanced group had five members: these users had an elapsed time of 16 min on average. In addition, a few instances of motion sickness were reported from the novice group because they interacted with the VR interfaces for a longer period. We also report further suggestions to enhance FMC techniques. The participants wanted the VFMC to support diverse figure sets over diverse levels. The use of Leap Motion required time to become familiar with, which means that a user needs sufficient practice beforehand. Enabling more menus such as zoom in/out or moving camera control could be beneficial for creating a detailed figure model. In addition, various material properties could be considered such as elasticity, viscosity, and transformation for more advanced modelling and reflectance, translucency and scattering for improved high-fidelity rendering.

Conclusion

In this study, we developed the VFMC system that allows the user to handcraft virtual figures through the gesture input over a VR HMD. The proposed system can deliver immersive crafting experiences through overcoming the limitations of the previous handicraft content in 2D environments, and it can generate greater interest as the user can directly experience the process. The Raycast method was used to perform the deformation of figure materials and collision detection. The user can perform virtual figure model crafting using Leap Motion, an intuitive natural user interface (NUI), rather than traditional interfaces such as a keyboard and a

mouse. The gestures required during figure production were defined as Leap Motion lexicons. User evaluations were performed to verify the proposed techniques. The preliminary study results confirmed that the VFMC provided immersive and interactive crafting experiences in a virtual reality environment.

Actually, this study aims to build general handcrafting systems that can support the entire process of virtual figure model crafting. As noted earlier, we showed that the proposed system could be extended to support various application scenarios, such as psychotherapy. To this end, we note that it is important to carefully build a virtual figure modelling module and its service scenario with input from clinical psychologists about different conditions (e.g. social anxiety and depression). Furthermore, randomized clinical trials are required to evaluate effectiveness. Since our primary goal is to validate the feasibility of fully supporting the entire process of virtual figure model crafting, we leave building and evaluating its application scenarios, including psychotherapy, as part of future work.

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No potential conflict of interest was reported by the authors.

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