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Dual quaternion based virtual hand interaction modeling

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Abstract Virtual hands play key roles in three-dimensional interaction in various virtual reality applications. However, their visual realism has seldom been seriously discussed in the community of human computer interaction, not to mention the challenging balance between their visual/motion realism and real-time performance. In this paper, a novel approach for virtual hand interaction modeling based on dual quaternion is proposed. Specifically, dual quaternion blending (DQB) is introduced as pseudo muscular layer of our virtual hand model instead of traditional linear blending (LB) and quaternion blending (QB) due to its advantages in muscular deformation. A framework for virtual hand interaction is proposed which supports both gesture interactions and 3D manipulations. Experimental results show that our proposed virtual hand interaction model is suitable for most virtual reality applications and achieves good visual/motion realism while maintains real-time performance.

Keywords virtual reality, virtual hand interaction, dual quaternion, gesture interaction, 3D manipulation

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1 Introduction

Virtual reality (VR) provides users an artificial environment created with digital technology. By immersing users in a virtual environment, it is revolutionizing the way of interacting with computers. As established, the creation of intuitive and natural user interfaces forms the main theme of virtual reality activities.

User interactions within a virtual environment can be divided, in general, into two categories: interactions with the system and interactions with virtual objects consisting of the virtual scene. For interactions with the system, multi-modal input and output dominates the VR interfaces, including stereo view, stereo sound, voice input, gesture recognition, and even haptic interactions. For interactions with virtual 3D objects, besides realistic visual feedback of virtual objects, their motion and behavior should also be realistically simulated.

Many often, interactions within a virtual world involve the human hand. In fact, dataglove provides the possibility of tracking the user's finger motions. It has been used as a main kind of VR input devices. In

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this context, a virtual hand is used as an avatar of the user's hand. Specifically, for interactions with the system, hand gestures are usually preferred as command inputs; for interactions with virtual 3D objects, a virtual hand is often a necessity for manipulation tasks. As a result, the modeling of the virtual hand, including shape modeling and kinematics modeling, is fundamental and important for 3D interactions, and is required by a wide range of virtual reality applications [1].

However, most virtual hand models used in VR applications, especially in engineering applications, are constructed by modeling each joint as a separate polygon mesh and combining several such joints into a finger, mainly for the sake of easy kinematics control at the expense of visual realism. Even the commercial software package VirtualHand SDK/Studio, a complete development solution for adding hand-motion capture, hand-interaction and force feedback to simulation applications, adopts such a simple hand model [2]. Indeed, unified representational schemes (e.g. a NURBS surface or a complex triangular mesh representing the whole hand) already exist for human hand modeling in the field of three-dimensional computer animation, and deformation techniques are developed to model the constrained finger motion [3]. But in the domain of human computer interaction, the visual realism of a virtual hand is seldom discussed, with even much less attention being paid on the challenging balance between the visual/motion realism and the real time performance of the virtual hand model.

We think the realism of the virtual hand model, including both visual realism and motion realism, is valuabe to enhance the immersion of virtual environments, with real-time performance yet-another critical issue that must be simultaneously addressed. In this paper, we propose a novel approach to the modeling of a realistic virtual hand for both gesture interactions and manipulation tasks, which simulates natural anatomy in its appearance and motion. Our main contribution lies in that we introduce dual quaternion blending (DQB) in place of the traditional linear blending (LB) and quaternion blending (QB) as the pseudo muscle layer of the virtual hand to achieve the balance between visual/motion realism and real time performance of the virtual hand. We also introduce a virtual hand interaction framework which is capable of supporting two types of mainstream virtual hand interactions: gesture interactions and 3D manipulations.

The rest of the paper is organized as follows. Section 2 briefly reviews related works. Section 3 proposes our virtual hand interaction framework. Section 4 presents our virtual hand interaction model for both gesture interactions and manipulation tasks from geometry and kinematics perspectives. Section 5 shows experimental results. Section 6 concludes the paper.

2 Related works

The related work on human hand modeling can be classified into two main categories according to the application domain: hand modeling for realistic visual effects in computer animation and hand modeling for interaction tasks in three-dimensional interaction. In general, virtual hand modeling adopts methods of modeling in virtual reality, which are surveyed in [4]. In the following, we survey much more related works from the perspectives of 3D computer animation and 3D interaction.

In the field of 3D computer animation, it is an important research topic to model the human hand as realistic as possible for the purpose of convincing visual effects. For instances, Moccozet et al. [5] implemented a multi-layer deformation model, using DFFD (Dirichlet Free-Form Deformation) as the intermediate layer between the skeleton and the skin. The DFFD based hand animation allows to combine the simulation of the muscles behavior with the hand lines behavior. Albrecht et al. [6] constructed a reference hand model for hand animation by scanning a plaster cast of a human hand. The model is of high quality but at a very high cost. In [7], an image-based modeling method was proposed to construct a virtual hand surface from a single canonically pose palm image and extract the principal creases on the palmar surface with tensor voting. Though the reconstructed hand mesh is realistic in appearance as image-based modeling and rendering is employed, the method fails to work on the whole human hand since it only adopts one image of the human hand as input. In [8], an interesting approach to geometric model completion via interactive sketches is proposed, which can be used to support interactive geometry modeling of virtual hands.

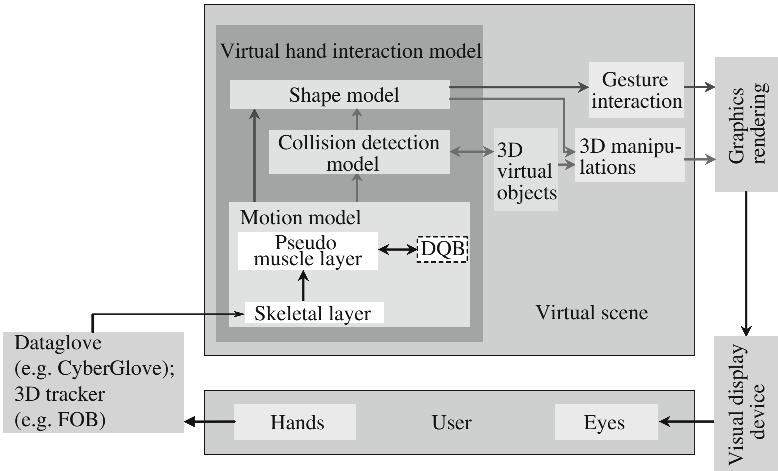


Figure 1 Framework of virtual hand interaction.

In the field of 3D interaction, however, things are a bit different. More efforts were put on modeling the human hand to fulfill various interaction tasks. To simulate virtual grasping, Li [9] introduced a novel shape matching algorithm to identify candidate grasps for a new object. They used a database of predefined hand poses to identify an ideal grasping pose. Their algorithm returns a set of suitable hand poses among which the user has to choose the best matching one. Ciocarlie et al. [10] proposed an approach to building analytical contact models for soft fingers, which captured frictional effects such as coupling between tangential force and frictional torque. However, the high computational burden makes its application for interactive virtual environments difficult. In [11], a 4-layer flexible virtual hand model was proposed for virtual hand haptic interaction. The skin layer, kinematics layer, collision detection layer and haptic layer are integrated into a virtual hand to simulate the natural anatomy of the human hand in its appearance and motion, and more important, to reflect the area contact feature of force feedback datagloves. More recently, Jacobs et al. [12] developed a soft hand model for precise and robust finger-based manipulation tasks. The hand model is capable of adapting its stiffness of soft part dynamically. While robust grasping of 3D virtual objects can be achieved in real-time, the downside of the model lies in the lack of visual realism since it is built with very simple geometries.

Very often, linear blending (LB) is applied to the skeletal structure of the virtual hand to drive its skin deformation due to its simplicity and high efficiency in computation. However, linear blend skinning is also notorious for its failures, such as the collapsing-joints artifacts and the opposite effect of candy wrapper. To partly overcome these artifacts and opposite effects, Kavan et al. [13] proposed the spherical blend skinning. Later, they further introduced dual quaternion skinning to human body deformation and solves the artifacts of linear blend skinning at minimal additional cost [14,15].

3 Framework of virtual hand interaction

We propose a framework for virtual hand interaction (Figure 1). In the interaction loops, the user sends instructions via a virtual hand to the virtual scene and the virtual scene gives visual feedbacks to the user.

As illustrated in Figure 1, our proposed virtual hand interaction model consists of 3 layers, namely, kinematics layer (motion model), collision detection layer (collision detection model), and skin layer (shape model). The 3 layers are integrated into a sophisticated virtual hand interaction model to facilitate two kinds of virtual hand interactions: gesture interactions and 3D manipulations. In an interaction cycle, the user′s hand motion data are captured by a 3D tracker and a dataglove and used to drive the skeleton structure of the kinematics layer of the virtual hand. While the kinematic transformations are directly transferred to the collision detection layer, the skin layers deformation is either directly driven by the

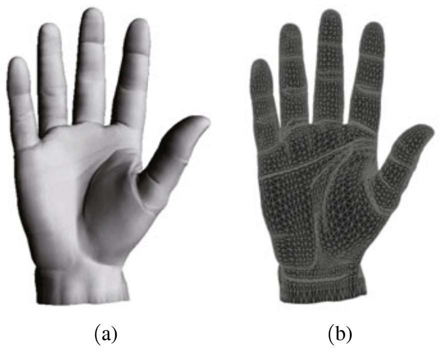


Figure 2 Appearance model of our virtual hand. (a) Coloring map; (b) grid map.

kinematic transformations or constrained by whether there are contacts between the collision detection model and other virtual objects in the scene, depending on the virtual hand interaction tasks are whether gesture interactions or 3D manipulations.

4 Virtual hand interaction modeling

4.1 Appearance modeling

The complexity of the hand structure makes its shape modeling a complicated and tedious process. Many modeling techniques, from polygonal modeling, parametric surface modeling to implicit modeling, have been proposed for modeling geometry of the human hand. Some of the previous studies focus only on the kinematic modeling of human hands. They model virtual hands with simple geometries such as cylinders and spheres losing sight of the visual realism. Accordingly, it is hard to simulate virtual grasping precisely. Our target is to build a virtual hand performing well in appearance, as well as in motion flexibility. The development of subdivision surfaces seems to help alleviate the heavy burden of lots of user input, since they not only have the adaptability of the polygon mesh topology, but also have the advantages of spline surfaces like local continuity and geometrical invariability [16]. We apply the method of subdivision surfaces to our hand shape modeling. To facilitate rendering and motion control, we construct the geometry of the virtual hand with triangular mesh, based on the knowledge of the hand shape and its anatomic structure [17]. Besides, the balance between the amount of triangles and the visual appearance is also taken into account.

With skinning algorithm, we bind the geometry model to the inner skeleton and set weights for every vertex to describe how the skeletons influence them. Thus the skin layer will deform and move along with the skeletal layer. Figure 2 shows the appearance of the virtual hand we set up.

4.2 Collision detection modeling

For 3D manipulation tasks, real-time collision detection is used to automatically identify whether there are interferences between the virtual hand and virtual objects. In general, collision detection requires a significant computational overhead, especially when involving deformable models. However, collision detection should be computationally efficient since real-time feedback is fundamental for 3D interactions.

To some extent, visual realism is of more interest, rather than accuracy, for virtual hand operations. We think that collision detection between virtual hand and virtual objects is a more qualitative issue rather than a quantitative one as far as 3D interaction is concerned. Realizing this, we build simplified structures for the palm and each joint of the virtual hand, and use these simplified geometries as the collision detection model. In order to prevent the penetration of virtual hand into virtual objects, the simplified structure are a bit larger than their corresponding geometries. We use OpenCCD, a continuous collision detection API as the collision detection engine between the collision detection model of the virtual hand and virtual objects in the scene [18].

Figure 3 Anatomical structure of hand and the simplified skeletal structure. (a) Human hand skeleton; (b) simplified hand skeleton; (c) simplified hand skeleton embedded in hand geometry; (d) hand geometry with vertex binding.

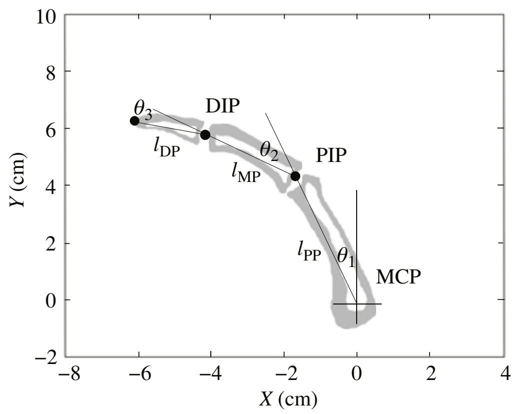


Figure 4 Joints and the local coordinate system.

4.3 Kinematic modeling

The human hand is a complex structure with extra articulation that enables us to grasp, hold, and operate a wide variety of objects. The kinematic system of human hand is composed of bones, ligaments, muscles, tendons and other soft parts. There are 27 bones and 22 joints, in which 8 bones belong to the wrist, 5 bones belong to the palm and 14 bones compose 5 fingers (Figure 3(a)). The mathematical definition of relative motion between human hand segments is a complex task. This is due to the peculiar shape of the kinematic elements forming cartilagineous and synovial joints [17]. For this reason, in the development of mathematical models, a common approach is the replacement of such joints with those simplified ones (Figure 3(b)). In our simplified skeletal structure, 20 bones are retained out of 27 and every 3 bones constitute a finger. The rest of 5 bones belong to palm, connecting the fingers and the wrist.

We couple the simplified skeletal layer with the skin layer and bind every vertex to its related bones (Figure 3 (c) and (d)).

The motion model is based on forward kinematics, that is to say, the children objects are driven by their parent objects. We build a node tree of the virtual hand, in which the palm is the root node with each joint a pivot point. The three bones of a finger are linked one by one from the palm root end to the fingertip. As a consequence, the movement of the end knuckle is the combined effects of the three joints.

Taking the index finger for example, to establish a local coordinate system (Figure 4), we make the finger move in the XY plane and set the metacarpophalangeal joint (MCP) as the origin of local coordinate of the finger. It is the Y-axis's positive direction from the origin to the distal interphalangeal joint (DIP). The lengths of bones constituting a finger are denoted as l_{PP}, l_{MP} and l_{DP} respectively as shown in Figure 4. The values of θ_1, θ_2 and θ_3 represent the stretching or bending degrees of each joint. Thus the

Table 1 Simplified movement of each joint of the virtual hand

Tag	Degree of freedom	Amount	In total	Mode of motion
TDIP	1	1	1	bend, stretch
TPIP	1	1	1	bend, stretch
DIP	1	4	4	bend, stretch
PIP	1	4	4	bend, stretch
MCP	2	4	8	bend, stretch, adduction, abduction

position of the fingertip can be written as

$$\begin{aligned} x &= l_{\mathrm{DP}} \times \sin(\theta_1+\theta_2+\theta_3) + l_{\mathrm{MP}} \times \sin(\theta_1+\theta_2) + l_{\mathrm{PP}} \times \sin\theta_1, \\ y &= l_{\mathrm{DP}} \times \cos(\theta_1+\theta_2+\theta_3) + l_{\mathrm{MP}} \times \cos(\theta_1+\theta_2) + l_{\mathrm{PP}} \times \cos\theta_1. \end{aligned} \tag{1}$$

Additionally, we adjust the degrees of freedom of each joint as shown in Table 1, in which TDIP stands for the thumb end joint, TPIP for the thumb interphalangeal joint, DIP for the rest four finger end joints, PIP for the rest interphalangeal joints, and MCP for the rest four root joints. The thumb is a special case since the movement of its root joint is very complex. In this paper, we only take the motion of its interphalangeal joint and end joint into consideration. Furthermore, neither is the cyclovergence movement our focus.

4.4 Dual quaternion blending as pseudo muscle layer of virtual hand

Linear blend skinning is a popular solution for skeletally deformable models nowadays. But it demands experienced animators to set the weights and it cannot eliminate some artifacts like muscle bulging. Besides, the hot study of quaternion deformation has trouble with rotation centers and cannot solve the artifacts of collapsing. Fortunately, dual quaternions offer a very simple yet efficient deformation method. It was firstly introduced into the study of mechanics by A. Kotelnikov et al. at the turn of the 20th century [19,20]. According to [14,15,21,22], dual quaternion is a powerful mathematical tool for the spatial analysis of rigid body motions. It is capable of representing the motion of 3D objects including rotation and transformation while keeping the shape, and maintaining the distances and angles between points on the object. Inspired by their observations, we embed dual quaternion blending (DQB) between the skin layer and the skeletal structure of virtual hand, serving as the pseudo muscle layer so that the skeleton can drive the hand skin to move and transform like a real hand, and hence, to achieve the balance between the real-time performance as well as the visual/motion realism of the virtual hand interaction.

Dual quaternions can represent rotations with arbitrary axes. As is well established, any directions can be the rotation axis for rotation of dual quaternions, which is a fundamental solution to the selection of the rotation center and the coordinate system. Chasle's theorem states that any rigid transformation, that can be described by a screw motion and the geometric interpolation of dual quaternion relating to screw motion, is a rotation and translation about the same axis [23]. For every unit dual quaternion, it can be expressed as

$$\hat{\boldsymbol{q}} = \cos\frac{\hat{\theta}}{2} + \hat{\boldsymbol{s}}\sin\frac{\hat{\theta}}{2}, \tag{2}$$

where $\hat{\boldsymbol{s}}$ is a unit dual vector with zero scalar part, and there are $\hat{\theta} = \theta_0 + \varepsilon\theta_\varepsilon$ and $\hat{\boldsymbol{s}} = \boldsymbol{s}_0 + \varepsilon\boldsymbol{s}_\varepsilon$. Angle $\theta_0/2$ is the angle of rotation and $\boldsymbol{s}_0$ represents the direction of the axis of rotation. $\theta_\varepsilon/2$ is the amount of translation along vector $\boldsymbol{s}_0$ and $\boldsymbol{s}_\varepsilon = \boldsymbol{r}\times\boldsymbol{s}_0$, where $\boldsymbol{r}$ is a vector pointing from the origin to an arbitrary point on the axis (since $(\boldsymbol{r}+c\boldsymbol{s}_0)\times\boldsymbol{s}_0 = \boldsymbol{r}\times\boldsymbol{s}_0$).

Denote the skinning unit dual quaternions of the vertices as $\hat{q}_1,\ldots,\hat{q}_p$, where p is the number of related joints, and the weights of each dual quaternion as $w=(w_1,\ldots,w_p)$, the dual quaternion blending equation is:

$$\mathrm{DQB}(w,\hat{q}_1,\ldots,\hat{q}_p) = \frac{w_1\hat{q}_1+\cdots+w_p\hat{q}_p}{\|w_1\hat{q}_1+\cdots+w_p\hat{q}_p\|}. \tag{3}$$

In order to accelerate the computation, we calculate and store the unit dual quaternion of each joint before skinning so that we just need to read out the data needed to avoid repeated calculations. The following steps show the dual quaternion blending for virtual hand skin deformation.

1) Calculate the dual quaternion of each joint $\hat{q}_1, \ldots, \hat{q}_n$, where n is the number of all joints. There are 20 joints in our simplified virtual hand, in which the 5 joints of palm and the root joint of thumb are invariable and initialized as unit dual quaternions. As a result, there remain 14 joints which are movable.

2) Traverse the mesh vertices of the virtual hand. The process terminates until all the vertices are processed.

3) Read out the dual quaternions and weights related to the current vertex v.

4) Calculate the DQB as follows:

$$\hat{b} = w_1\hat{q}_1 + \cdots + w_p\hat{q}_p. \tag{4}$$

Then normalize $\hat{b}$ (let b_0 be the real part, and b_ε be the dual part). Rewrite b_0 as the sum of scalar part a_0 and vector part d_0. And b_ε is the sum of scalar part a_ε and vector part d_ε.

5) Set the vertex v' and normal v'_n of the deforming virtual hand as follows respectively:

$$v' = v + 2d_0 \times (d_0 \times v + a_0 v) + 2(a_0 d_\varepsilon - a_\varepsilon d_0 + d_0 \times d_\varepsilon), \tag{5}$$

$$v'_n = v_n + 2d_0 \times (d_0 \times v_n + a_0 v_n). \tag{6}$$

6) Jump to step 2).

Note that the results of DQB must be normalized since only the normalized results can eliminate the opposite effects of candy wrapper and collapsing.

4.5 Virtual hand interactions

Looking back to the interaction framework we proposed in Figure 1, there are two kinds of tasks supported by virtual hand interactions, i.e. gesture interaction and direct 3D manipulation.

Gestures are natural interaction styles both in our daily life and computer generated synthesized virtual worlds. A gesture is often defined as a physical movement of the hands with the intent to convey information and/or meaning. Gesture interaction in a virtual world is characterized by WYSIWYG (What-You-See-Is-What-You-Get) principle and its enabling technologies include robust hand/finger tracking, realistic virtual hand deformation, etc. For the gesture interactions, the user's hand motions are tracked via a dataglove and a 3D tracker, and the hand motion data are transmitted to our virtual hand model, which in turn is rendered into hand gestures and visually presented to the user. This forms one of the interaction loop.

The three foundamental principles of direct 3D manipulation are continuous visibility of objects and actions of interest, rapid, reversible and incremental actions, pointing or other physical actions on objects of interest [24]. Realistic visual presentation and real time feedback are the keys to support continuous visibility of virtual hands and their actions. Refering to our virtual hand interaction framework, the virtual hand motion model, collision detection model and shape model are intergrated to form another direct 3D manipulation interaction loop. More issues such as real-time collision detection and virtual grasping heuristics must be addressed, besides the similar operations as hand/finger tracking and virtual hand deformation. However, the discussion of either real-time collision detection or physically based grasping heuristics is far beyond the scope of this paper. Interested readers can refer to [12,18] for more details on these topics.

5 Experimental results

The proposed virtual hand interaction model has been implemented on a desktop computer (Intel(R) Core(TM)2 Quad Q8300/ 2.5 GHz). And the statistic information of the virtual hand is listed in Table 2. In particular, the proposed dual quaternion blending (DQB) and the traditional quaternion blending (QB) are compared. In a more than 1000 frames gesture interaction sequence, the average running time of

Table 2 Statistics of the virtual hand model (8668 vertices, 20 bones, 18 degrees of freedom)

Bone ID	1	2	3	4	5	6	7	8	9	10
Number of vertices	4486	2998	1449	837	574	3354	1302	658	493	775
Bone ID	11	12	13	14	15	16	17	18	19	20
Number of vertices	1161	664	445	837	1310	732	543	661	1082	686

Table 3 Frame rate results

	LB	QB	DQB
Frame rate (fps)	29.36	28.49	27.81

(a)

(b)

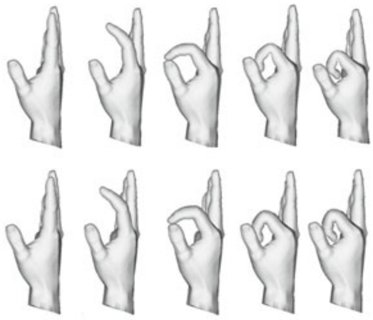
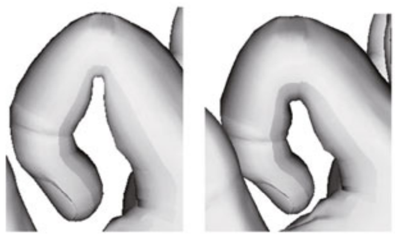


Figure 5 Gesture comparison results. (a) QB; (b) DQB.



(a) (b)

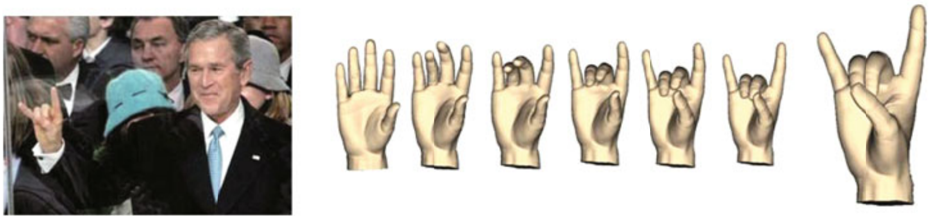
Figure 6 Zooming in effects. (a) QB; (b) DQB.

Figure 7 Examples of daily gestures.

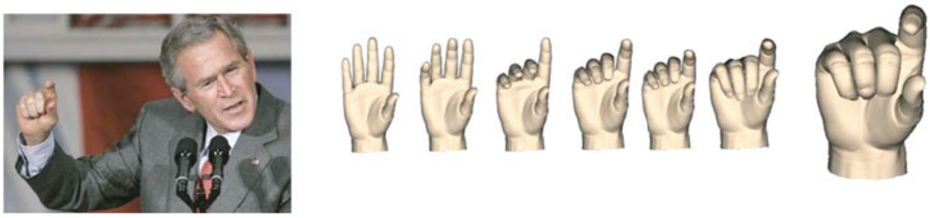
the DQB algorithm is just 2.4% longer than the QB algorithm, and the average frame rate is more than 27 frames/s. Table 3 shows the frame rates of linear blending, quaternion blending and dual quaternion blending. It is easy to conclude from these data that the proposed DQB virtual hand can be used in real-time circumstances and there is rare extra time cost to switch from the QB virtual hand.

5.1 Visual/motion effects of gesture interactions

To demonstrate the visual/motion effects of our DQB virtual hand applied in 3D interactions, we make contrast experiments on the DQB algorithm and the QB one by performing a series of same gesture interactions. It can be clearly seen from Figure 5 that the artifacts of the index finger become severer with increasing bending angle in the QB virtual hand, while our proposed DQB virtual hand preserves reasonably good shape. Figure 6 shows the zoom-ins of the index finger. Figure 7 shows 8 vivid daily gestures generated by our DQB virtual hand. From these different finger combinations, we can see that our DQB virtual hand is capable of producing realistic, natural hand gestures. Figure 8 shows 3 different gestures of former American President Bush and the corresponding simulated gestures with our DQB virtual hand. The left-most column shows the target gestures, the right-most column shows their simulated correspondences, and the middle columns present the gestures' deformation processes.



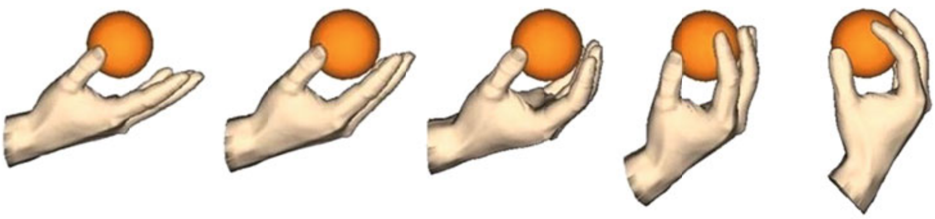
(a)



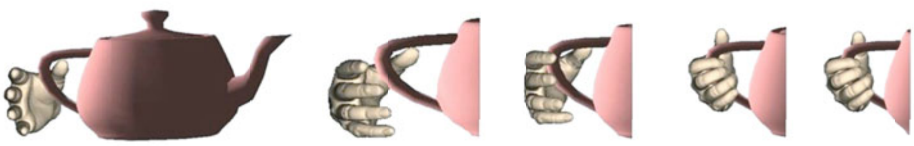
(b)

(c)

Figure 8 Simulated gestures of former American President Bush. (a) Target gesture 1 and simulated gesture sequence; (b) target gesture 2 and simulated gesture sequence; (c) target gesture 3 and simulated gesture sequence.



(a)



(b)

Figure 9 Virtual grasping sequences. (a) Virtual grasping of a ball; (b) virtual grasping of the Utah teapot.

5.2 Visual/motion effects of 3D manipulation tasks

3D manipulation is another important kind of interaction tasks in virtual world. Our proposed virtual hand interaction model is easy to be integrated to interact with virtual 3D objects. As the framework in Figure 1 shown, the virtual hand is driven by the dataglove/tracker combination, and during the interaction process real-time collision detection is performed between the virtual hand and virtual objects. By employing certain grasping heuristics, the virtual objects can be manipulated by the virtual hand in an intuitive and natural manner. Figure 9 shows two grasping sequences with our DQB virtual hand. One is the grasping of a virtual ball, and another is the grasping of the Utah teapot. The OpenCCD continuous collision detection package [18] and the physically-based grasping heuristics [12] together with a 5DT dataglove are employed to generate the two grasping sequences.

6 Conclusions

Virtual hands are used as avatars of human hands to extend users into virtual worlds so that they can interact with the virtual system or virtual objects. Virtual hand interactions play key roles in virtual environments, especially when gesture interactions and dexterous manipulation of virtual objects are concerned. In this paper, a novel virtual hand interaction model is proposed to address the challenging balance of its real-time performance and visual/motion realism for 3D interaction tasks. Qual quaternion blending is introduced as pseudo muscular layer of the virtual hand model in place of traditional linear blending and quaternion blending due to its advantages in eliminating the opposite effects of collapsing and candy wrapper. We also propose a virtual hand interaction framework to integrate the proposed virtual hand interaction model to support two mainstream 3D interaction activities: gesture interactions and 3D manipulations. Experimental results on artificial gestures, virtual grasping operations and simulations with real world gestures show that the proposed virtual hand interaction model achieves good visual/motion realism while maintains real-time performance, hence it is suitable for most virtual reality applications such as 3D navigation, virtual assembly, and whole body games, etc.

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