An Innovation of Interaction Method Based on Force Feedback in HMD System

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Abstract. With the development and wide application of virtual reality technology, the emerging virtual reality system brings better visual experience. In the field of scientific visualization, immersive visual experience and well-designed interactive method can enhance user experience. Since traditional 2D input devices such as mouse and keyboard cannot support direct 3D manipulation, they cannot be applied to virtual reality visualization. Moreover, basic VR interactive devices like controllers also have some problems such as low operation precision and the lack of sensory simulation and real-time feedback operation. In order to solve these problems, we propose a virtual reality interactive method based on force feedback to deal with the complex interactive operation of scientific data in 3D space. We also reported a user testing which compared our approach with traditional VR controllers in same tasks demonstrates that the proposed approach has higher accuracy and better user experience.

1. Introduction

Recently, with the rapid development of virtual reality (VR) technology, its excellent visual expression and interactivity have been widely used in many fields [1, 2] including scientific visualization [3]. Scientific visualization needs to expound the data content through the operation of visual data, so how to design a high-precision and simple interaction method is one of the main problems in scientific visualization.

The traditional visualization operation is performed on a 2D display, which is complicated and inaccurate [4]. In order to simplify the operation of manipulating object in 3D space via 2D input devices, Guo et al. [5-6] used real-time multi-channel instructions based on the multi-touch interactive display. However, this method still requires mapping the input to the data space and can’t support free rotation without the widget.

To solve above problems, VR has been introduced into scientific visualization [3]. VR technology can combine user operation and data space without constructing the mapping of user operations into data space. Currently, the six-degree-of-freedom (6-DOF) operation [7] used by the controller is of great simplicity in the VR system. The lack of user guidance and DOF-constraints during the operation results in the unstable operation precision and difficulty of processing complex data.

For scientific visualization, the existed interaction methods have some disadvantages such as low precision and complicated operation. We propose a virtual visualization interaction method based on 6-DOF force feedback stylus, which supports high-precision 7-DOF interaction. Our user testing in this paper compared our method with traditional VR controllers demonstrates that our approach is suitable for most scientific visualization operations and has significant improvements in accuracy and user experience.
2. Related Work

Human-computer interaction (HCI) is an important part of scientific visualization. Scientists need to achieve a deep understanding of visual data through a series of necessary HCI.

2D input device interaction is a widely used HCI method. By mapping a 2D operation into 3D data, 3D data interaction has been performed, which is represented by a mouse-and-keyboard interaction [4]. In order to guide the operator better, touch is introduced into HCI as an important aesthetic sense [5]. Guo et al. [6] introduced a multi-touch display that allows for more than 10 touch inputs and supports structured single object operation with simple and precise operation.

VR technology brings an immersive experience to scientific visualization, and also introduces a new interactive mode [7]. VR interaction uses VR devices to integrate the operating space into the data space. In VR, the interaction allows the operator to directly interact the visual data in three dimensions, and make simple 6-DOF operations with the aid of the VR controller.

Force feedback interaction is widely used in teleoperation, medical simulation and virtual assembly. And it is a high-precision immersive virtual interaction method [8-10]. Sal et al. [11] first proposed a force interaction simulation which follows the Hooke's law to simulate the feedback force. Ruspini et al. [12] used the interference value between Haptic interface point and virtual objects to calculate the surface feedback force of the object. But the drawback was the surface of the object is difficult to define. Song et al. [13] designed the virtual widget proxy method which did not define the surface of the object, instead, they proposed that simulated the interference amount in the form of virtual proxy, which is very helpful for our work. Fortmeier et al. [9, 10] used the 6-DOF force feedback device to expand the operational dimension of the force feedback interaction, but was limited by the application scenario, and the interaction mode was monotonous, users still needs to watch the tradition screen for 3d operation.

To solve the above problems, we innovatively add the force feedback interaction to the virtual reality visualization, and design a new VR visualization interaction method. We use a 6-DOF force feedback stylus and add a DOF-constraint. Compared with the traditional force feedback interaction, our method significantly improves the operating space and the operation accuracy at the same time.

3. Proposed Approach

Our approach implements the necessary interactions of force feedback for scientific visualization in virtual Reality Head-mounted display (HMD) environment.

The experiment used the following equipment and development platform:

- Development platform: Unity3D, OpenHaptics api.
- Force feedback device: Sensable Phantom Omni.
- VR device: HTC VIVE Head-mounted display and controller kit.

![Figure 1. Feedback force flow chart.](image)

3.1 Calculation and optimization of feedback force

In the process of haptic simulation (Figure. 1), the feedback force that user feels is usually defined \( F_{\text{user}} = F_t + F_n + F_f \). As shown in Figure 2, \( F_f \) is the Coulomb friction force, \( F_t \) is the material friction force, and \( F_n \) is the ordinary feedback force. Considered that \( F_f \) and \( F_t \) have a little influence on the experimental objectives of this study, we assume that the virtual experimental scenario is an ideal environment, so the feedback force is redefined as \( F_{\text{user}} = F_n \).
User feels the feedback force through a stylus handle (Figure 3). This part is called Haptic Interface Point (HIP), and the posture and position of the HIP are mapped to an agent in the virtual scene, called HIP proxy. Shen et al. [10] used the God-object method to calculate common feedback force. That means, they defined an additional proxy object God-object that would always stay on the surface of the model to avoid the phenomenon of penetration, and to fundamentally solve the ambiguity problem of feedback (Figure 4). This paper is based on the Hookean physics model, and uses the feedback force calculation model to calculate the common feedback force $F_n$. The formula is as follows:

$$ F_n = k \Delta x $$

$\Delta x$ is the depth of the HIP proxy penetration model, $k$ is the hardness of the object, the experimental object is the ideal rigid body, and $k$ is taken as 1. Considering the influence of the inertial force $F_i$ in this experimental scenario, we correct the $F_{user} = F_n + F_i$. In this experimental scenario, $F_i$ is considered as an instantaneous impact force, so $F_i = \varphi m v (\varphi > 0.01)$. $m$ is the mass of the object being manipulated, $\varphi$ is a hyper-parameter, generally taking 0.01.

Finally, our feedback force calculation formula is as follows:

$$ F_{user} = k \Delta x + \varphi m v $$

(1)

3.2 Design Goals

According to the interaction characteristics of the force feedback pen and the VR environment, we follow the following methods to design a better interaction to manipulate the 3D object. We design our method to:

- G1: support all 3D operations of 7-DOF,
- G2: expand easily,
- G3: provide constrained manipulation and free manipulation,
- G4: design complex interactions without affecting the usability of basic interactions,
- G5: make sure easy to switch different types of interactions,
- G6: build a clear and intuitive way of operating,
- G7: be more efficient than the common VR controller while dealing with complex problems.

Next, we will introduce the devices and methods designed for operating 3D models in the VR environment, and implement the above experimental goals one by one.

3.3 Interactions Design for 3D Model Manipulation

Firstly, press the second button to call the UI interface for selecting and switch the type of operation. Because of the use of virtual button switching mode of operation, so the operation could be easily expanded. In VR environment, the user can obtain the rigid body collision feedback force by
manipulating the virtual stylus to touch the operation object, and press the first button to directly operate the object (Figure. 6). The user can feel the feedback force during the translation and rotation.

(a)Transform  (b)Rotation  (c)6-DOF operation  (d) Scaling operation

**Figure 6.** Different types of interaction diagrams

3.4 **Interactions Design for VR Controller**

The HTC Vive handle controller can not only interact with the buttons on the handle, but also track the position and orientation of the handle. The handle controller is shown in Figure 7.

4. **User Study**

It turns out that input devices are highly dependent on the applications and the tasks. In order to verify the user's feeling of the method when dealing with 3D objects in VR better, we compare our methods with standard VR controllers. The method of this paper is evaluated based on the user's performance and preferences, especially for the goal (G6, G7).

4.1 **Participants**

| Task            | Description                        |
|-----------------|-------------------------------------|
| Translation     | Translate the 3D model to match the target |
| Rotation(x/y/z) | Rotate the 3D model to match the target. |
| Multiaxial rotation | Rotate the 3D model to match the target. |
| Scaling         | Scale the 3D model to match the target. |

We invited 12 students (6 males, 6 females) to participate in user testing studies. Six of them have the experience of computer graphics or using 3D design software. Six of them had used VR devices. Their age ranges from 18 to 27 ($\mu = 23.58$, $\sigma = 2.5$. $\mu$ is the average, $\sigma$ is the standard deviation).

4.2 **Tasks Setting**

According to the characteristics of basic interactive operation in VR environment, this study sets up 4 groups of basic operational tasks and one integrated operational task composed of basic operational tasks. We tested three interaction modes: translation, rotation and scaling, as shown in Table 1.

We require users to locate and orient models according to translucent target models to achieve the high accuracy standards as quickly as possible. (displacement<0.1, angle differ per axes<2°, scaling differ<0.1). We also gave the instruction for each task in the VR experimental scenario to guide users to perform the corresponding interactions. Then we calculated whether the target model matched the
desired position, and if so, the task would automatically stop. Participants were allowed to abandon the task.

4.3 Experimental Design

We used a repeated-measures design for the independent tasks with two input devices (force feedback stylus and VR controller). Each user should use two devices to complete the test, half of the user first tested the VR controller, and half first tested our method.

Before the start of each device experiment, users were introduced to how to operate the input device. In basic tasks, users need to manipulate the object to match the target. And we recorded the time of the user's operation and the number of operation times. The actual experimental scenario is shown in Figure 8.

Eventually, when all tasks were done, users were asked to fill in their overall feelings and task evaluations on a seven-point Likert scale. In addition, this study collected previous user experience related to experimental operations and communicates with each user to provide advice and inspiration for future work.

5. Results

5.1 User Study Data

![Figure 9. Average time-consuming comparison of tasks. t1, t2, t3, t4 for translation task. r1, r2 for rotation task. m-r1, m-r2 for Multiaxial rotation task. Com for integration task.](image)

|        | Our Method | VR Controller |
|--------|------------|---------------|
|        | Total(s)   | Experienced(s) Non-experienced |
|       |            |               |
| Our method | 48.53       | 4.37          | 70.6 |
| VR Controller | 42.36       | 7.84          | 60.0 |

This paper describes the results of user testing from three perspectives, including the difficulty of learning interactive methods, the results of each task and the overall preferences of users. In this section, we will conduct specific analysis and discussion in conjunction with experimental data.

In the actual experiment, we find that whether the user have VR device interaction experience or not has obvious influence on the experiment, as shown in Table 2. In general, our method is slightly longer for the user who does not have experience in interacting with VR devices, but the learning time shortens significantly for experienced users. The experiment confirm that we have reached target(G7).

As shown in Figure 9, the results of each task show that our approach is compared to the standard VR controller: not only the scaling and pannig operation are significantly more efficient, but also the rotation is slightly better than using the VR handle. In the integration task, our method takes less time and fewer operation times than the traditional method (Figure. 10).

Users were asked to fill in the 7-point Likert scale after completing the experiment, and the device preference was scored for each operation task. At the same time, we also collected user preferences for learning difficulty and interactivity.
Figure 10. Integration task Result. The time and times of operations per user in the integration task.

Figure 11. The user scores each tasks of each device. AVG is the average score for all tasks.

Figure 11 is a score of the user's evaluation of each operation. In general, users think that it is easier to complete the interaction with our method. But in rotation tasks, users think that the VR controller is easier to operate. For complex integration tasks, users clearly consider that our method is better (G7).

In preference score of each device for users (our method:6.75, VR handle:6.49), which proves our method have achieved the goal of learning easily. Moreover, 83.3 percent of the user think the force feedback is very helpful in 3D space interaction.

5.2 Discuss
For scaling and translation tasks, our method more efficient and better user experience obviously. For rotation tasks, sometimes the user's operation deviates from the expectation due to the limitation of the rotation of the stylus. More than that, because of the influence of feedback force, the user's tiredness of holding the pen for a long time leads to a decrease in the satisfaction of some users (4 ×). But most users think that it makes the interactive feedback more realistic (8 ×). For integration tasks, users are more willing to choose our method as well as DOF-constraint operations, which makes them to complete tasks more easily and accurately. When using the VR controller, some users feel tried because of the large movement (3 ×).

6. Conclusion
In this paper, force feedback device is added to virtual reality, and proposed a VR visualization interaction method based on 6-DOF force feedback stylus. This method supports immersive interaction of 3D visualization data in virtual space(G1), whether it is 7-DOF direct interaction or DOF-constraint interaction (G3, G5). This method also uses expandable virtual UI interface to provide a variety of Switching modes of operation (G2, G4), as well as supporting natural walking to obtain a free view. The results of the user testing show that the interaction method of this paper is easy to learn, conforms to the natural interaction logic, and the operation is smooth (G6). Aiming at the problem of dealing with complex integration tasks, the accuracy and interaction experience is significantly better than the VR controller interaction (G7). In the future, we hope to address the issues raised in section 5.2 and design better DOF- constraint operations for VR interactions that give feedback.
Acknowledgment
This research was supported by Zhejiang Provincial Science and Technology Program in China.

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