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A virtual-reality system for interacting with three-dimensional models using a haptic device and a head-mounted display

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***Abstract*—Visualizing and simulating the real world by means of three-dimensional (3D) models is important in many fields, especially in science, technology, engineering and medicine (STEM). Exploiting the human senses, such as the sense of sight with head-mounted displays (HMDs) and the sense of touch with haptic devices, has helped in creating immersive virtual-reality (VR) experiences. However, HMDs and haptics have seldom been combined, and recently the technology has been advancing rapidly in both areas. The objective of this research was to develop a VR system which combines both a consumer-level HMD and a mid-level haptic device using a game-development platform. A proof-of-concept system was developed using the Oculus Rift HMD and the Phantom Premium 1.5 High Force haptic device. The system was implemented using the Unity 3D game engine and was tested with two 3D human anatomical models, a heart and part of a skull. The technical performance of the system was evaluated, and a small preliminary user evaluation was performed. Particular challenges and limitations of currently available hardware and software are also discussed.**

Keywords—virtual reality; 3D models; haptics; head-mounted display; anatomy; learning; evaluation

INTRODUCTION

Replicating the real world by means of three-dimensional (3D) models is important in many fields, and especially in science, technology, engineering and medicine (STEM). Interacting with these models in a realistic way is made possible with the emergence of various systems and displays which use one or more of our senses to immerse us in a virtual reality (VR) experience. Visual head-mounted displays (HMDs) take advantage of the sense of sight while haptic (force-feedback) devices allow users to interact with 3D models through the sense of touch. Several works have combined two or more elements of the human sensory system into one interface to obtain a “multi-modal virtual reality system” (e.g., [1]–[4]), but very little has been done so far to combine recent consumer-level HMDs with haptic devices.

In this paper we present a prototype system which combines a consumer-level HMD (the Oculus Rift) and a mid-level haptic device (the Phantom Premium 1.5 High Force) using a game-development platform (the Unity 3D game engine), to offer users the ability to touch, feel and manipulate 3D models by means of a haptic device while being immersed in the virtual world using an HMD. The technical performance of the system is discussed and a small preliminary user evaluation is presented.

HEAD-MOUNTED DISPLAYS

Early HMDs [5]–[7] were all helmet-mounted, but in 1963 Hugo Gernsback demonstrated a mock-up of a small HMD consisting of strap-on goggles [8]. Sutherland [9] presented the first HMD to use computer-generated graphics for the display. Subsequent developments have led to military and aerospace applications, to many engineering and scientific applications, and to use in the medical field. Over the past few years, HMDs have also been investigated for their use as consumer electronics products by being integrated into sports and gaming applications.

Consumer-level HMDs are affordable not only for gaming purposes but also for other cost-sensitive applications like teaching and learning. Typical devices have a weight of around 400 g and use an OLED display with a field of view from 96 to 110 degrees. High frame rates are needed in order to quickly change the displayed image and avoid simulator sickness when users move their heads. This requires a high-performance graphics card to redraw the VR scene twice for every frame, once for each eye. For a frame rate of 120 fps, the graphics card has to draw 240 frames every second, which is 4 times as fast as a typical 60-Hz computer monitor. To satisfy the frame-rate requirement, high-end graphics cards are required, but having the best graphics card does not guarantee that the system’s performance will be as good as desired for complex scenes. On the other hand, a system can still run, albeit perhaps slowly, even with a less powerful graphics card.

HAPTIC DISPLAYS

The term *haptics* has its origin in the Greek verb ἅπτω (hapto) meaning “to touch” (among other meanings) [10]. The sense of touch can be divided into tactile perception, provided by skin receptors responsible for sensing pressure, vibration, surface roughness, texture, shape, temperature and pain; and kinaesthetic perception, provided by receptors in the muscles and joints. Tactile haptic devices exploit the skin receptors while force-feedback haptic devices exploit mainly the kinaesthetic receptors. Force-feedback devices are the focus in

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this paper. They are mainly used in simulators, including surgical simulators; in teleoperator systems; for data visualization; and recently for gaming.

Haptic devices differ as to number of DOFs; maximum force and torque; workspace size; software interface; price; and many other factors. Comparing such devices by plotting the position resolution, maximum force, and number of DOFs against price shows that the price generally increases for a finer position resolution, for a higher maximum force and for a larger number of DOFs. Initial selection of a haptic device to meet the requirements of a specific application can be done based on the characteristics mentioned above, but some important characteristics are often not specified by manufacturers, such as the force resolution, stiffness and frequency response. In any case, testing devices from different manufacturers is generally required to finally decide which one is best suited for a given application. The testing process is itself challenging because these devices are expensive and manufacturers often have their own device-dependent application program interfaces (APIs).

Combination of Haptics and HMD

Introduction

As mentioned earlier, the main objective of this research was to develop a proof-of-concept system which combines both HMD and haptics. We tested our prototype with anatomical models as a simple preliminary test case. In the following sections we cover the system components, configuration and implementation.

Hardware and game engine

A Phantom Premium 1.5 High Force haptic device was selected for this project because it is in the middle of the range in terms of performance and price as discussed above, and because it is compatible with the Unity game engine that we adopted for developing the system. This device includes a stylus with a switch and provides 6 DOFs both in position sensing and in force feedback.

The Oculus Rift Development Kit 2 (DK2) was used as the HMD for this project. It has a resolution of 1920×1080 (960×1080 per eye), a maximum refresh rate of 75 Hz and a head-position tracker. We used the Oculus SDK for Windows version 0.8.0.0-beta with its corresponding engine integration version 0.1.3.0-beta.

Unity [11] is one of the most popular game development platforms on the market today, and it became freely accessible in 2015. We selected Unity for being compatible with both the Oculus HMD and our haptic device.

3D models

We used anatomical models [12] which were simplified using a quadric-based edge-collapse strategy in MeshLab [13] to reduce the numbers of polygons by ~70%. The need for this simplification will be seen below.

Configuration and implementation

The system was implemented in C# under the Unity 3D game engine. We used the OVRPlayerController “prefab” in Unity to navigate in the virtual environment using a keyboard and a mouse. For haptics we implemented a controller class responsible for initializing the haptic interaction and for workspace update. Four managers were also implemented to take care of the haptic interaction along with scene and structure management, such as resetting the scene, rotating the model and fading a given structure. A HapticDevice class was implemented to define the haptic device workspace and mode.

The system starts with a main screen where the user has the option of selecting one of the three available scenes (Fig. 1): (a) a sample scene with three simple 3D models; (b) a heart scene with a 3D model of a human heart and a 2D illustrative poster; and (c) a skull scene with a 3D model of part of a human skull and a 2D illustrative poster. Each of these scenes represents a room where the 3D model is placed on a table with a colour palette on the left side and a 2D illustration of the corresponding anatomy on the right side of the scene. The 2D illustration helps in identifying the different structures of the 3D anatomical model and learning their names. By wearing the HMD, the user becomes immersed in the scene and is able to interact with the 3D model using the haptic device. The scene is designed so that the user will turn their head from side to side and benefit from the HMD’s wide field of view.

When an object is added to the scene, we attach a HapticProperties script to it in order to define the material and object properties needed for haptic interaction such as stiffness, damping, friction and mass. To enable haptic interaction, the object must be tagged as “Touchable”. In the current scene we made touchable the 3D model, the colour palette, the walls, the floor, and the refresh and home buttons. The user can

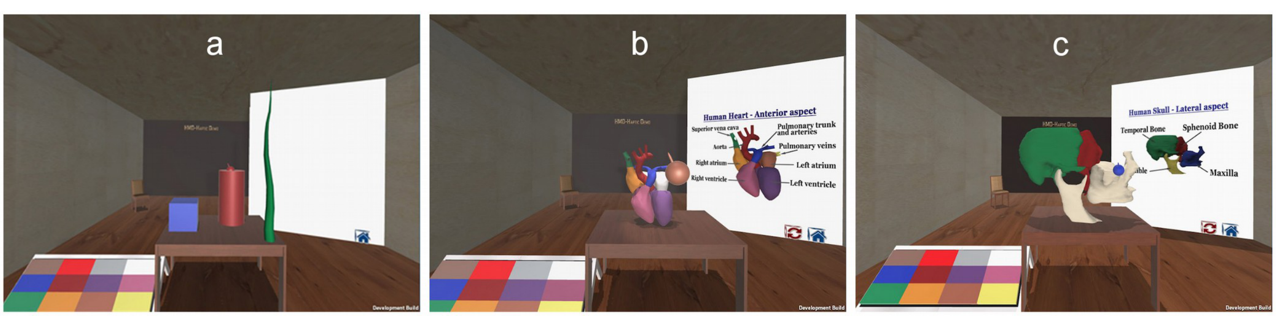

Fig. 1. The three scenes of the system, each having a colour palette on the left side of the room to colour the model; a table with the 3D model in the middle; and a 2D anatomical illustration to the right, with a Reset icon and a Home icon at the bottom. (a) Sample scene with three simple 3D objects. (b) Scene with a 3D model of a human heart. (c) Scene with a 3D model of part of a human skull.

disassemble the model and colour each structure by selecting a colour from the palette using the haptic virtual pointer.

User interaction

During the system development phase we tried various combinations of mouse buttons, keyboard keys, gamepad controller and the stylus switch for the user interaction. In the final version, the user selects a scene from the main screen by looking at it, thus targeting it using the Oculus HMD, and then clicking on the stylus button. Once inside a given scene, the haptic device is manipulated using the dominant hand to touch the 3D objects.

The haptic tooltip is simulated in the scene by a 6 DOF virtual pointer. When the user clicks on the stylus button, the colour of the pointer changes from cyan to green and its shape becomes a cube instead of a sphere. When the user touches an object with the virtual tool and clicks the stylus button, the selected object can be rotated and moved around the scene by moving the stylus in the desired direction. To move around the scene in the left, right, forward and backward directions, we use the keyboard's arrow keys or the gamepad controller. Left-right motion is defined by the gamepad controller joystick or the Oculus HMD tracker, which follows the user's head to define the direction of view.

SYSTEM EVALUATION

This section presents a preliminary technical-performance evaluation of the current version of our system and also includes a small evaluation of user responses.

System performance

To obtain a good VR experience, a frame rate of 75 frames per second (fps) or more is desired. One PC used to test our system had an Intel Core 2 Extreme X9650 3.00-GHz CPU, 4 GB of RAM, and an NVIDIA GeForce GTX TITAN graphics card. For models with 3,500-4,000 triangles or less, the frame rate was 70-75 fps. Increasing the number of triangles to 5,000-6,000 lowered the frame rate to 50 fps. Complex models such as the skull, with 35,013 triangles, were clearly not a good fit for the system using that PC and graphics card. For the simplified skull with 10,521 triangles, the frame rate was around 30-35 fps. The heart model, on the other hand, has fewer triangles to start with and, after simplifying it from 11,812 to 3,543 triangles, the frame rate was 75 fps when starting the system and 65 fps when interacting with the heart using the haptic device.

We ran another set of tests after migrating the system to a more powerful PC configured with an Intel Core i7-6700K 4.00-GHz CPU, 24 GB of RAM, and an NVIDIA GeForce GTX 960 graphics card. Even though the graphics card of this PC was less powerful than the other, the resulting frame rate was good, ranging from 60 to 75 fps when interacting with the 3D models.

User evaluation

After achieving these acceptable results on the new system, we recruited five undergraduate students, who had previously taken or were taking a first-year visceral-anatomy course, to conduct a preliminary user evaluation. The study was approved by the Institutional Review Board of McGill University (study number A04-E31-14A). We presented the system components using a fixed set of instructions. The participant started by interacting with the simple geometric 3D models shown in Fig. 1a to get used to the system. They were then directed to the heart scene where they had to do three timed tasks: (1) colour the heart model according to a 2D illustration on the right side of the scene (Fig. 1b); (2) interact with the heart by selecting a structure and moving it closer to their eyes, rotating it and then placing it back; and (3) moving around the scene using the gamepad controller. After completing the timed tasks, they were presented with a user-evaluation questionnaire. Following this, the participant was provided with the option of trying the skull scene (Fig. 1c), a more complex scene with a higher number of triangles that might cause simulation sickness related to a variable frame rate.

Users quickly learned and began interacting with the system components. They were able to understand the system in less than 5.5 minutes and practised with the sample scene for less than 5 minutes. The individual task times for the heart scene are low, which demonstrates that the system is user friendly and easy to learn and use. All but one user spent more than 4.5 minutes interacting with the optional skull scene, signifying that they found the system interesting and engaging.

All five participants gave positive feedback based on their experiences interacting with the system. Participants agreed that the system is useful and easy to use and could be useful as a study tool. They also found that it was easy to navigate through the scenes, and that the tasks were clear and easy to understand. Overall, participants were satisfied with the ease of use and the amount of time for completing the tasks. The haptic component was found to be easy to use and easy to learn, and to provide a realistic interaction with the 3D models. As for the HMD component, users mostly agreed that it was easy to perform the tasks while wearing the HMD and that the field of view provided a good virtual-reality experience. However, only one user felt that the HMD's resolution was good enough. Three users felt dizzy after the experiment, which might be related to the amount of time spent interacting with the system while wearing the Oculus HMD; the three users who felt dizzy spent around 15 to 18 minutes each, while the other two spent around 12 and 14 minutes respectively. One of the three also said they had a headache. We did not attempt to quantify the severity of dizziness or headache.

In the free-text part of the questionnaire, users provided the following written comments and recommendations: (1) the first participant mentioned dizziness ('Felt a little bit dizzy after the task. But overall very helpful and a great experience'); (2) the second participant asked for better resolution and easier rotation in all directions; (3) the third participant suggested adding collision detection between the structures to make the 3D models more realistic, and asked for forcing a slower movement to avoid dizziness while navigating in the scenes; (4) the fourth participant asked for higher resolution and a more comfortable HMD which is 'lighter or easier to wear, especially for people with glasses'; and (5) the fifth participant suggested not having the images so much 'in the face', which causes dizziness and headache.

In addition to the written comments, one of the participants mentioned the difficulty of finding the haptic pointer in the scene sometimes. Two other participants also mentioned the difficulty of finding the gamepad controller and the haptic stylus while wearing the HMD as it blocks the user's vision.

Even once the user has found the gamepad, interaction with it is still challenging. With the eyes covered by the HMD, the dominant hand is used to manipulate the haptic device and the user is left with the non-dominant hand for using the gamepad controller and/or the keyboard without any visual feedback.

Overall, the data are consistent among the five participants and provide a preliminary indication that the combination of both HMD and haptics can be helpful for interacting with 3D models. However, a more in-depth user evaluation should be conducted to demonstrate the usability and usefulness of such a system for specific applications and as a study tool.

Conclusion

This paper presents a demonstration of the feasibility of combining HMD and haptics in one system.

For many STEM applications, like surgical training for example, more complex features such as material deformation and cutting are required. It is not clear whether the Unity game engine is the best choice for such simulations. It may be worth considering another real-time simulation framework such as SOFA [14], which has an emphasis on medical simulation.

A more in-depth study should be conducted to evaluate the usability of this system, addressing many issues such as (1) the position of the haptic device, in front of the screen or on the side of the user's dominant hand; and (2) the user interaction, to make better use of the gamepad controller, the keyboard and the mouse. More sophisticated input devices (e.g., a 6-DOF mouse, a motion-sensing game controller, or a second haptic device) could also be used to make better use of the non-dominant hand. Devices like haptic gloves or the Leap Motion hand-and-finger motion sensor [15] are also worth considering.

Most haptic devices require a "sit still" setup and the power of the HMD's head tracking might be better exploited by using a portable haptic device like the Haplet [16].

With the emergence of increasingly powerful computer processors and graphics cards designed specifically for virtual environments, as well as techniques like retinal projection and eye tracking, the resulting VR experience is coming closer to the real-world setting. This can be very useful for education and training purposes. However, the technology behind HMDs and haptics is still under rapid development, with new prototypes, devices and systems emerging or planned for the near future. Further advances are still required in order to provide a fully immersive VR experience.

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