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Audiovisual Guidance for Simulated One Point Force Exertion Tasks

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Abstract

This paper describes a novel guidance method for force exertion tasks with one contact point haptic interface using visual and auditory cues in a virtual environment. To teach how to exert force accurately, the proposed method displays a pre-recorded example force magnitude curve which user tries to follow. Orientation of manipulation can be presented as a visual cue or as an auditory cue through a mapping from 3D environment to a 2D plane to provide auditory guidance from the user's perspective. The proposed method was evaluated in a case of palpation of the aorta and proved to guide users to exert force more accurately than the traditional position-tracking approach.

CR Categories and Subject Descriptors: I.3.6 [Methodology and Techniques]: Interaction techniques; H.5.2 [User Interfaces]: Haptic I/O; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism – Virtual reality.

Keywords: Audiovisual display, haptics, VR interaction techniques, VR-based surgical training.

1 Introduction

In surgical training, manual skills are hard to gain. The trend so far in Virtual Reality research is teaching manual skills to medical residents using real-time physics-based interaction modeling and haptic user interfaces [Burdea et al. 1999; Nakao et al. 2003; Berkley et al. 2004]. This study aims to facilitate skill-transfer of manual skills in surgery with a guidance method for force exertion. Conventional simulators, such as [Nakao et al. 2003], allow user to feel realistic reaction forces through a haptic device, thus providing a safe environment for surgical training. Yet, a skilful surgeon is still needed to teach the surgical procedure by observing and correcting resident's trials in a similar way as when using cadavers. Studies concerned with transfer of motor-skills have offered a new approach to mediate manual skills directly through a computer system by recording and replaying teacher's manipulation data [Teo et al. 2002; Saga et al. 2005]. According to Shaffer et al. [1999], the medical field requires explanation of manipulation.

The authors pursue to develop a system for surgical skill-transfer that facilitates teaching of several residents indirectly by using recorded simulation. Initial target is palpation of the aorta which is needed before open-heart surgery. The task requires subtle manipulation and diagnosis of stiffness level of different areas of the aorta. This study focuses on a guidance method for following of an example force exertion task in palpation. The task consists of following the example in terms of

- magnitude of exerted force in relation to time
- orientation of exerted force

Since timing can play an important role when learning manipulation from recorded simulation, the guidance method has to minimize the latency of user's manipulation to the example shown. Combination of two modalities (visual and auditory) for the two aspects of manipulation (magnitude of force and orientation of manipulation) could give non-obstructive guidance without overloading the user with too much visual information.

2 Related Work

2.1 Visual Approach

Just Follow Me (JFM) [Yang and Kim 2002] is a purely graphical technique for tracking of movements. A "ghost" metaphor is used to display an example motions and postures, which the user tries to follow in real-time or in slow-motion. JFM may not apply well to circumstances where the example should be shown in a dynamic Virtual Environment (VE) which is manipulated by the user. Using transparent target organs, the ghost example can be made visible, but subtle differences between the example and the user's manipulation are hard to be perceived in real-time.

To indicate location information, a graphical approach is usually chosen. Vertex coloring technique is a flexible and effective method to display areas on a deformable surface mesh [Hong et al. 2005].

2.2 Audio Approach

Jovanov et al. [1999] summarized sonification techniques that could be used in biomedical applications: *audio gages*, *mimetic audio interfaces*, *audio widgets*, *musical instrument interfaces*, and *orchestra presentation*. The most basic sonification technique, the Beat Interference Method (see [Jovanov et al. 1999]), presents the difference between two positions as pitch difference of two musical note triads. As pointed out by Jovanov et al. [1999], to use the Beat Interference Method in user interfaces has to be applied so that representation of different coordinates becomes more intuitive. Two-dimensional musical mapping that presents sonified data directly has been used as an audio interface for people with normal or impaired vision in shape detection [Alty and Rigas 1998] and in diagrams for the blind [Bennett 2002]. Similar approach has been applied to ease motor skill acquisition in surgical training in the context of approaching anatomical landmarks with surgical instruments in a VE [Müller-Tomfelde

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2004]. Distance between the landmarks and the instrument was presented to the user as audio signals. Audio guidance for other aspects of manipulation in three-dimensional space, such as the use of force, has not been thoroughly studied.

2.3 Haptic Approach

Haptic guidance methods are based on playback of movements of a haptic device. For example, Teo et al. [2002] used motion guidance to teach writing of Chinese characters and gave a push at the beginning of each stroke to ensure right order of the strokes. Haptic Video [Saga et al. 2005] enables pro-active touch for manual skill training but does not allow the user to follow example manipulation freely. In the current study, total control on haptic manipulation should be given to the user. The guidance should be provided by another modality than haptic. Unlike the haptic modality, the visual modality is capable of displaying the differences between the example and the user's manipulation and future states of past simulation at the same time. Thus, real-time feedback on the success of the user's force exertion can be shown.

2.4 Multimodal Approach

The Virtual Haptic Back project [Williams et al. 2004] demonstrated how palpation of back can be trained using haptic playback of pre-recorded examples and multimodal feedback. The benefits of using different modalities were not clearly explained, though. Lécuyer et al. [2002] compared the use of various sensory cues that were activated on collision in the VE using a 2-screen workbench for an insertion task. Design of multimodal applications must consider information overflow to each sensory channel and the overall cognitive load. As mentioned in discussion by Loftin [2003], a solid theory on human multi-sensory perception has not yet been discovered. Studies so far have reported only individual observations. For example, one has to take into account the *detectable musical mapping* [Alty and Rigas 1998] for allocation of musical features, such as pitch and rhythm, to translate of distinguishable messages to the user.

3 Methodology

3.1 Division of Two Modalities

The traditional method to display force in a 3D VE is a reaction force vector that points away from the contact point. Length of the vector is related to magnitude of the exerted force so that both magnitude of force and orientation can be expressed. Using the traditional method, only one state of the example can be perceived. In addition, display of differences in force exertion between two manipulations is not exact because of the changing viewpoint.

In the case of palpation, the area for touching does not have to be accurate. Magnitude of force is a more critical factor. Yet, some feedback has to be given about the contact point, and visual feedback facilitates the user's reaction to changing visual cues.

Audio signal serving as a continuous aural force curve would require pauses between individual force exertion tasks so that the user could hear an example before acting. Force curve as a visual cue is suitable for presenting continuous use of force. Force curve can also display difference of the example and the user's manipulation accurately in real-time in an intuitive manner.

3.2 Visual Presentation Design

The proposed visual design is presented in Figure 1. To display continuous example manipulation and its future states, two curves representing magnitude of force are shown on the screen. Both the future and the past manipulation can be seen, in addition to the present state. This allows the user anticipate future motions and get immediate feedback of force exertion task. Contact area is highlighted by vertex coloring. Colored part of the target area was considered the most intuitive means to display the contact point in the example manipulation. In a deformable model, the area stays colored even if the 3D model is being manipulated. The contact area is stored in the recorded example and shown in the interactive simulation. Visible size of the force curve is parameterized by maximum width and height. Scaling of force curve by the example manipulation's greatest value of force magnitude is automatically computed.

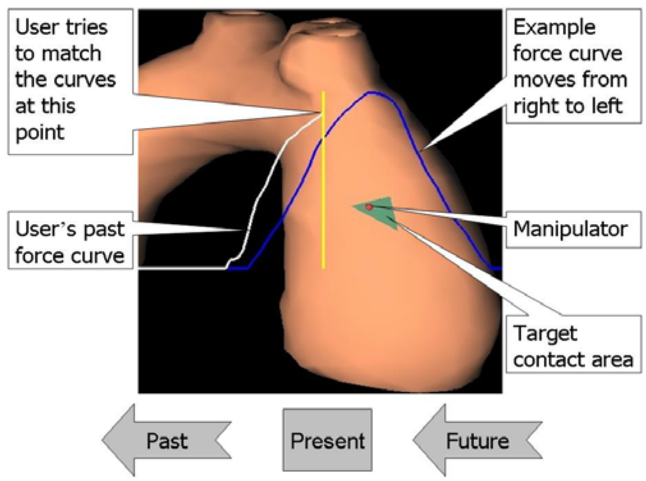

Figure 1: Visualization of magnitude of force and contact area. Blue color represents the example force exertion.

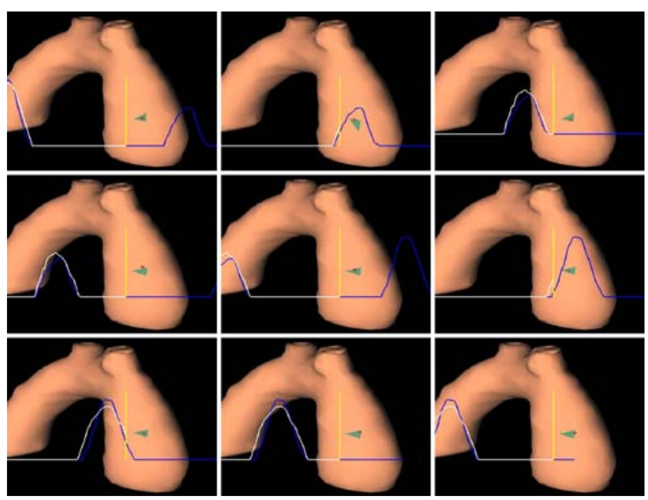

Figure 2: Screen captures at 1sec interval presenting motion

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of the force curves (from top left to bottom right).

A moving force curve displays the example time series of magnitude of force, which is followed at a point near contact area by the user. Figure 2 illustrates the motion of the force curves. The motion allows presentation of examples with indefinite duration. Display is updated at 25Hz, which was considered adequate for human inability to detect differences at over 30Hz.

3.3 Auditory Presentation Algorithm

Auditory cues are simplified from the 3D environment to 2D. In this design, the sonification is set to match the orientation of the screen. In order to avoid too complex cues, auditory feedback is simplified to two axes, left–right and up–down. The sonification method presented here falls into *orchestra presentation* category of Jovanov et al. [1999]. Relation of the audible sound and the reaction force is defined as

$$X = A - Sk(F_{0x} - F_{1x}), \quad Y = B - Sk(F_{0y} - F_{1y}) \qquad (1)$$

Where F_0 is the example's recorded force, F_1 the user's force, S a constant factor for scaling of the frequency to musical scale and k a chosen factor for scaling the sound audible in relation to the force value. S is defined in musical theory as twelfth root of 2 and it represents the relation of each successive half-step in the musical scale. A and B are base frequencies for the X and Y axes.

4 Experiment

4.1 Hypotheses

Two hypotheses were defined: In a force exertion task, in which magnitude of force and orientation of manipulation should be followed by the user,

- presentation of future states of the example as a force curve improves timing and accuracy.
- sonification of orientation improves force exertion by letting the user to focus on the magnitude of force without reducing accuracy of orientation.

4.2 Conditions and Platform

Medical Virtual reality simulation Library [Kuroda et al. 2005] is a collection of Finite Element Method –based simulation functions for fast creation of new simulations for palpation, cutting, retraction and extraction of deformable organs. MVL was running on a Xeon 3.2GHz dual processor with 4GB RAM. PHANToM Desktop was used as the haptic interface. Example manipulation was recorded and rendered to visible playback.

Three conditions, shown in Figure 3, were implemented: position-tracking + reaction force vector (C1), force curve + visible orientation (C2) and force curve + sonified orientation (C3). C3 represented the proposed method. Force feedback was present in all the conditions.

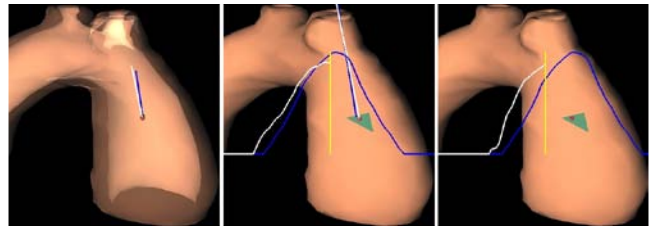

Figure 3: Conditions from left to right: position-tracking + reaction force vector (C1), force curve + orientation line (C2) and force curve + sonified orientation (C3).

C1 represents the previous position-tracking method that is used for example in JFM [Yang and Kim 2002]. Position-tracking was implemented with two manipulators: one for the example and one for the user. Reaction force vectors were visualized for both manipulators. The aorta model was made transparent so that the user would see the example manipulator even if it went inside the aorta during a single force exertion task. C1 represented the traditional position-tracking method. C2 consisted of the visual curve and orientation line. C2 was designed to show differences between visual and auditory representation of orientation. C3 presented the proposed method. Sound A = 440Hz (musical A4 note) for X axis and B = 880Hz (musical A5 note) for Y axis in (1). Force vectors F_0 and F_1 were normalized, then multiplied by the scaling factor k = 2.0. Synthesized 100ms 'beep' sounds were made distinguishable by setting their beat into relation of 2:1. The Y axis was played first.

12 subjects were divided into 3 groups, 4 subjects in each. To see possible learning effects between groups, the conditions were introduced to Group A in the order C1, C2 and C3, to Group B in the order C2, C3 and C1, and to Group C in the order C1, C3 and C2. Every task consisted of 4 individual palpative manipulations so that the method can be evaluated in continuous manipulation. There were eight series resulting in 32 tasks per condition. In total, number of recorded force exertion tasks was 96 for each subject. Data was evaluated by calculating mean error for force magnitude so that at any moment, if the subject's force magnitude differed from the example, the error became greater. Orientation was only compared when force was present in both data and calculated as average error per a single task. Timing error was added whenever there one of the data contained force and the other one did not. Accuracy of the timing error was about 10ms.

5 Results and Discussion

Results of the experiment are summarized in Table 1 and average ratings in post-trial questionnaires in Table 2. The results are compared against the hypotheses in the following subchapters.

Table 1. Results of a force exertion task experiment in three conditions. Mean errors of 24 4-task series performed by each of the 12 subjects were calculated. (LSD=Least Significant Difference, p<0.05)

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	Mean magnitude error (N)	**Mean timing error (sec)**	**Mean orientation error (degree)**
C1	0.46	0.98	6.4
C2	0.40	0.63	7.5
C3	0.37	0.67	7.8
LSD	0.05	0.12	1.4

Table 2. Results of a questionnaire. The subjects were asked to rate their understanding of magnitude of force and orientation of the example manipulation on the scale of 1-5 after each condition.

	Magnitude of force	**Orientation**
C1	3.71	4.20
C2	4.08	3.63
C3	4.17	2.17

5.1 Timing and Magnitude of Force

Mean error for magnitude of force was clearly lower in C2 and C3 than in C1. The mean error in C1 was higher than in C2 and C3: 0.46N, since the force curve displayed the difference between manipulations more accurately. Post-condition questionnaires revealed that subjects rated the understanding of magnitude of force as 3.71 in C1, 4.1 in C2 and 4.2 in C3. The reaction force vector in C1 was easy to understand and seemingly accurate, but it made mean error in magnitude of force higher than the force curve in C2 and C3.

Timing errors were higher in C1 and about the same in C2 and C3: 0.98, 0.63 and 0.67sec. The first hypothesis was supported: presentation of future states of the example as a force curve improves timing and accuracy of magnitude force.

5.2 Sonification of Orientation

Mean error in orientation varied between all the conditions only by 1.4 degrees, which was within normal variation in the results. The questionnaire results revealed that orientation was considered easier to understand in C1 with average of 4.20, whereas in C2 the average was 3.63 and in C3 only 2.17. In general, the subjects understood how the sonification worked, but in the experiment, reaction to changing orientation during a single force exertion task was difficult. Reaction was rapid when only one axis was sonified. Group C, to which C3 was given first, the mean orientation error was only 7.1 degrees. These results suggest that orientation was difficult to follow more accurately than at 7 degrees mean error in general. Orientation in the examples did not vary enough to make clearly distinguishable difference between all conditions.

The second hypothesis was only partially supported. Sonification was successful in a way that it did not reduce accuracy of orientation. Yet, it did not help the user to focus better on the force curve so that the magnitude of force would have been followed more accurately. The results suggest that it was equally difficult to monitor three aspects of manipulation (force curve, contact area and orientation) when orientation was auditory or visual information. Even though sonification did not improve results compared to the purely visual approach, the merit of sonification lies in its ability to let the user focus on the most important factor. Sonification is suitable for the least significant and not dynamic factor of manipulation as background cues.

6 Conclusion

The proposed method provides audiovisual guidance for force exertion tasks by a visual force curve and sonified orientation. The method was evaluated in a simulated palpation of the aorta task. Presentation of future states of the example manipulation as a force curve improved timing and accuracy of force level in force exertion tasks. Sonification of orientation resulted in equally accurate force exertion as with the purely visual approach. Yet, the sonification was hard to be reacted on when the orientation suddenly changed. Sonification is suitable for static factors of manipulation to be presented as background information. Future research will be concerned with methods for more dynamic factors of manipulation, such as orientation during stroking.

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