Integration of Binocular Stereopsis and Haptic Sensation in Virtual Environment

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Abstract

The paper aims to present a new human-scale haptic device for virtual environment named Scaleable-SPIDAR (Space Interface Device for Artificial Reality), which can provides different aspects of force feedback sensations, associated mainly with weight, contact and inertia, to both hands within a cave-like space. Tensioned string techniques are used to generate such haptic sensations, while keeping the space transparent and unbulky. The device is scaleable so as to enclose different cave-like working space. Scaleable-SPIDAR is coupled with a large screen where a computer generated virtual world is displayed. The used approach is shown to be simple, safe and sufficiently accurate for human-scale virtual environment.

Keywords: Human-Scale, Virtual Environment, Force Feedback.

1. Introduction

The use of high quality computer-generated imagery, auditory and interactive scenes have recently been applied to many cave-like virtual environment. Accurate simulations and graphical display of these virtual environments are being used to impart users with realistic experiences. As well as, to provide a more comprehensive understanding of specific problems. However, visual and auditory cues alone do not allow the user to clearly perceive and understand physical interactions such as contact, pressure and weight. The importance of such sensory modality in virtual workspace had already been showed in many researches. To create an immersible human-scale virtual environment, the ability to interact physically with virtual environment , as well as the full and direct use of both hands are indispensable to control over objects and to develop a physical skill. However, to provide such capability of perception and action in a human-scale virtual environment, usually some mechanical equipment attached to a stationary ground as well as to the operator's body are required [7]. This direct contact between hard equipment and operator, limits the range of movement and may occlude the graphical display. As well, the weight and the bulk of the mechanical attachments are clearly perceived by the operator, figure 1.

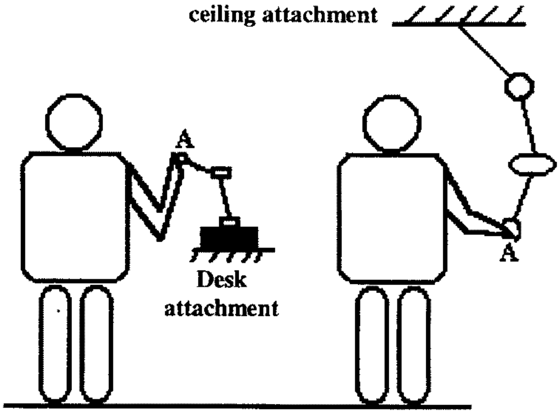

Figure 1: Typical mechanical attachment

Although GROPE-project [1] may be the most famous human-scale virtual environment system with force display. Yet, most of the current haptic devices are designed for desktop usage and display force feedback to only one hand. Unlike video and audio, force information is very difficult to send through air. To form a 3D force at a certain point, say point *A*, lead a "hard" mechanical device from a "force source" to point *A* may be the only "simple" and precise way. If *A* is moveable, then the force display device will become much more complicated in structure compared with video and audio display. Particularly, when the virtual environment workspace becomes larger, that is the point *A* may go far away from the force source, the haptic device structural strength needs to be enhanced to keep the precision. This enhancement usually makes the whole system bulky, heavy and expensive, as well limits the user's moving freedom. On the other hand, the machinery based forces displays are usually low dynamic performance. In a mechanical system, the dynamic performance is mainly decided by system's weight and moment of inertia. As the haptic devices in human-scale virtual environment are heavy, they would have lower dynamic performance than the ones in a relatively small system, desktop devices. Unfortunately, the task in large working space tends to need higher moving speed and bigger acceleration. How to balance precision and dynamic performance? while improving both of them are the key points to realize usable and accurate force display in human-scale virtual environment.

We propose a new approach, based on tensioned string techniques, to display force feedback sensation on both operator's hands in a large space. While allowing smooth movement and keeping the space transparent.

In the next sections, we explain the features of Scaleable-SPIDAR. A trial system was developed and tested through experiments. Additionally, an application was developed to evaluate the profitability of our device. In the last section, the remaining problems are discussed.

2. Concept of Scaleable-SPIDAR

The device is derived from the original desktop SPIDAR device, which was introduced late in 1990 by Makoto sato *et al* [3]. As shown in figure 2, Scaleable-SPIDAR is delimited by a cubic frame that enclose a cave-like space, where the operator can move around to perform large scale movements. The experimental prototype is 27m^3 size (3m x 3m x 3m). Within this space, different aspect of force feedback sensations associated mainly with weight, contact and inertia can be displayed to the operator's hands by means of tensioned strings. The front side of the device holds a large screen, where a computer-generated virtual world is projected. Providing such a combination of haptic and visual feedback cues is indispensable to lets the operator's eyes and hands work in concert to explore and manipulate objects populating the virtual environment.

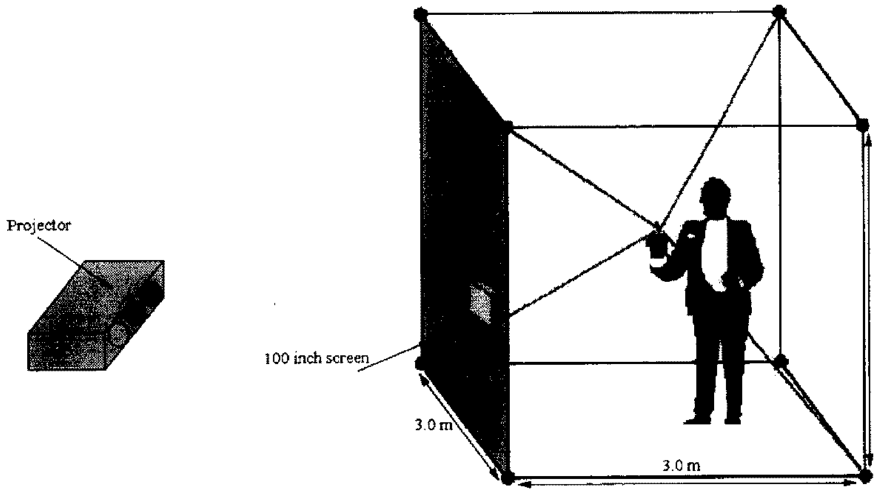

Figure 2: Overview of Scaleable-SPIDAR

The device uses tensioned string techniques to track hands position as well as to provide haptic feedback sensations. The approach consists mainly on applying appropriate tensions to the four strings supporting each fingering worn by the operator. The force feedback felt on the operator's hand is the same as the resultant force of tension from strings at the center of the fingering, next subsection gives more detail about forces and position computation. In order to control the tension and length of each string, one extremity is connected to the fingering and the other end is wounded around a pulley, which is driven by a DC motor. By controlling the power applied to the motor, the system can create appropriate tension all the time. A rotary encoder is attached to the DC motor to detect the string's length variation, Figure 3-b. The set of DC motor, pulley and encoder controlling each string is fixed on the frame.

2.1 Force Control

Scaleable-SPIDAR uses the resultant force of tension from strings to provide force display. As the fingering is suspended by four strings, giving certain tensions to each of them by the means of motors, the resultant force occurs at the position of the fingering, where transmitted to and felt by the operator's hand.

Let the resultant force be $\vec{f}$ and unit vector of the tension be $\vec{u}_i$ *(i=0,1,2,3)*, figure 3-a, the resultant force is :

$$\vec{f} = \sum_{i=0}^{3} a_i \vec{u}_i \qquad (a_i > 0)$$

where a_i represents the tension value of each string. By controlling all of the a_i the resultant force of any magnitude in any direction can be composed [5].

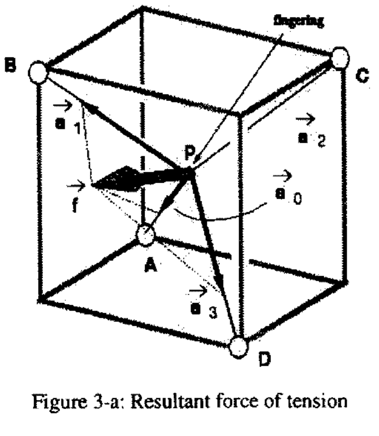

Figure 3-a: Resultant force of tension

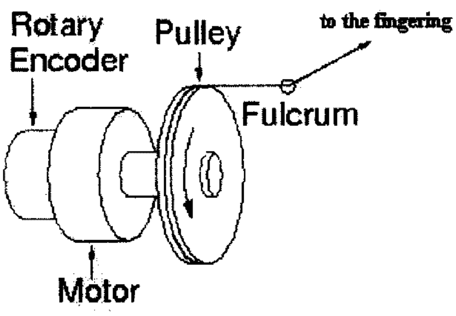

Figure 3-b: Motor and rotary encoder

2.2 Position Measurement

Let the coordinates of the fingering position be *P(x,y,z)*, which represent in the same time the hand position, and the length of the i^{th} string be l_i *(i=0, ..., 3)*. To simplify the problem, let the four actuators (motor, pulley, encoder) A_i be on four vertexes of the frame, which are not adjacent to each other, as shown by figure 4 [2]. Then *P(x,y,z)* must satisfy the following equations (Eqs).

$$(x+a)^2+(y+a)^2+(z+a)^2=l_0^2 \quad (1)$$
$$(x-a)^2+(y-a)^2+(z+a)^2=l_1^2 \quad (2)$$
$$(x-a)^2+(y+a)^2+(z-a)^2=l_2^2 \quad (3)$$
$$(x+a)^2+(y-a)^2+(z-a)^2=l_3^2 \quad (4)$$

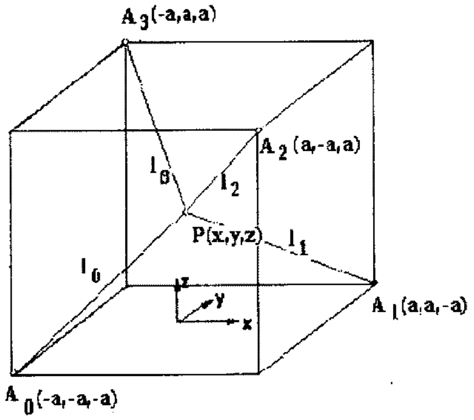

Figure 4: Position measurement

After differences between the respective adjacent two equations among equation (1)-(4) and solve the simultaneous equations, we can obtain the position of a fingering (hand) as the following equation (5):

$$\begin{cases} x=\dfrac{(l_0^2-l_1^2-l_2^2+l_3^2)}{8a} \\ y=\dfrac{(l_0^2-l_1^2+l_2^2-l_3^2)}{8a} \\ z=\dfrac{(l_0^2+l_1^2-l_2^2-l_3^2)}{8a} \end{cases} \quad (5)$$

3. Experimental Prototype

The experimental prototype provides two fingerings to be worn by the operator on both hands, Figure 7-b. The fingerings are made of light plastic material and the size can fit to any operator. As well, this small device leaves the hand free and easy to put on and off. Although the operator can wear the fingering on any finger, middle finger is most recommended. The bottom of this finger is close to the center of hand, and the force feedback applied on this position is felt as being applied to the whole palm.

Figure 7-b: The fingering

To provide the appropriate tensions and lengths of the strings, a personal computer (PC) is used to control an 8-bits D/A , A/D converter and a VME bus, which control respectively the currents entering the motors and detect the changes occurred on each rotary encoder. The PC is connected to a graphics workstation that provides a real-time video image of the virtual world. The apparatus of the prototype is shown by Figure 7-a.

Figure 7-a: Apparatus of the Scaleable-SPIDAR

3.1 Performance of Scaleable-SPIDAR

Position Measurement Range: the coordinates origin are set to the center of the framework. The position measurement ranges of all x, y and z in[-1.50m, +1.50m].

Static Position Measurement Error: the absolute static position measurement errors are less than 1.5cm inside the position measurement range.

Force Feedback Range: within the force displayable sphere[7], force sensation range is from 0.005*N* (minimum) to 30*N* (maximum) for all directions.

System Bandwidths:

- Video: 10 ~ 15 Hz
- Audio: 22 kHz (stereo)
- Position measurement and force display: > 1200 Hz (depends also on hardware installation)

Comparison With Other Haptic Devices: the next tabular shows the performance of Scaleable-SPIDAR compared with two other well-known force display devices, PHANToM [4] and Haptic-Master[6].

Haptic device	*work space (cm)*	*position resolution (mm)*	*peak force (kgf)*	*inertia (gf)*
Haptic Master	40x40x40	0.4	2.1	220
PHANToM	20x27x38	0.03	0.87	75
Scaleable-SPIDAR	300x300x300	15	3.0	50

4. Experiments and Application

In this section, the implementation of a haptic feedback experience with Scaleable-SPIDAR and an evaluation application are described.

4.1 Experiments

An investigation is carried to state the feasibility and the effect of the Scaleable-SPIDAR's force feedback on an interactive task. As "Space-Pointing" movements are considered as basic operations in any virtual reality applications and they are expected to be performed accurately within the minimum of time, a pushing button task was simulated to study how perfectly the operator can perform this task with and without force feedback. The operator is provided with a virtual flat wall, where five hemisphere shaped buttons are fixed on it; one of them is lighted red and the others are green. A graphical representation of the hand is displayed to give visual feedback cues. The apparatus of the setting is presented in figure 8. The operator is asked to move his hand on the top of the red button and push it to a certain deep. If he succeed, an audible bell is displayed and the red button changes to green while the next green button is lighted up to red. The order is the same as writing the letter "Z". The times spent from a button was lighted up to red until it is successfully pushed are recorded as "Task Times" (TTs) under the following conditions:

- *Condition 1: Visual Feedback Cues Only:* in this condition, the operator is only able to get visual feedback cues, force feedback information is not available; hence, operator's hand can pass through the buttons and the wall.
- *Condition 2: Visual and Force Feedback Cues:* in this case the operator can feel force feedback when his hand comes into contact with the wall or any of the button. The spherical shape of the buttons and the flatness of the wall are haptically perceived.
- *Condition 3: Force Feedback Cues Only:* after the operator has remembered the buttons' positions in his mind, the hand's visual feedback cues are disabled; thus the operator can not "see" the position of his hand in the simulated scene. That is he do not know whether his hand is moving close to the button or not, but only "feel" force feedback reactions when the hand runs over the virtual wall or the buttons.

Figure 8:Space-pointing task

Four right-handed subjects participated in the experiment, including two of the authors. None of them reported any haptic deficiencies. Although it was not necessary for the experiment, all subjects were familiar with haptic devices and virtual environment. Each subject was told about the three different conditions and the task to be performed. There was three different sessions of trials for all subject. In each session the red button should be pushed successfully 40 times. Before any session a short time of practice was given.

4.1.1 Results

TTs' means and variances are presented in figure 9 under the different conditions. When force feedback is available together with visual information. The "push button" task can be performed faster and only cost about 65% of the time needed for the "visual feedback only" condition. At the mean while, after plenty of practice even with the "force feedback only" condition, the user can still finish the "push button" task faster than the "visual feedback only" condition. This is because after practices, and by trials the operator has remembered the space positions of the buttons and can quickly move his hand toward the red button since the order is fixed and previously known.

It was found also, that in condition 1 80% of the TTs is devoted exclusively to push the button, whereas only 20% of the TTs is needed for positioning the hand in front of the red button. Nearly the opposite situation is present for trials done under condition 3, where 30% of the TTs is devoted exclusively for the pushing task and the other 70% of times are used to localize the targeted button. Also, as it can be seen from figure 9 that, the TTs variance are smaller when force feedback is available.

The difference of time spending in both condition 1 and 3 is significant. In the former one subjects have mainly a lack of depth perception, but good navigational performance. The later condition shows better capability of manipulation and interaction with objects, although the navigation is slow. The combined influence of visual and haptic modalities has a clear effect on the subject's performance in the second condition.

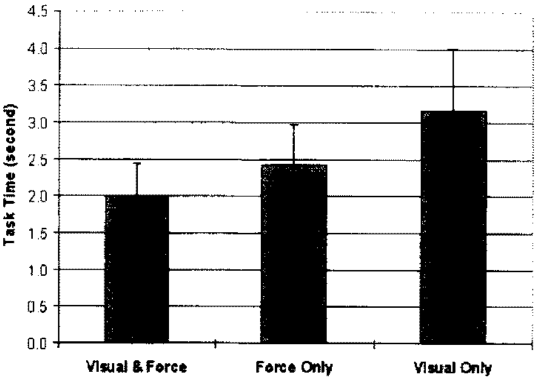

Figure 9:Mean task-time of different conditions

As conclusion, Scaleable-SPIDAR's force feedback system is shown to be able to improve the interaction with objects. Such haptic capability and enhancement is not only desirable but could be indispensable for dexterous manipulation.

4.2 Application:

Scaleable-SPIDAR is used to simulate the experience of the basketball's free throw shot, which is considered a skillful action that requires large space to play and where the haptic sensation of the ball is crucial to shoot a hoop. Being inside the playing space, the operator face a large screen where a 3D basketball's playground, backboard and a ball are displayed. As well, a graphic representation of the player's hands to give a visual feedback cues, figure 10.

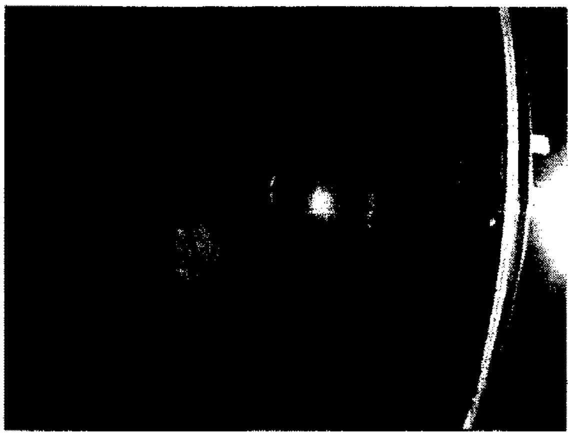

Figure 10: Virtual basketball

In order to control the ball and perceive haptically its weight and shape, the player has to wear the two fingering on both hands. As the player start moving inside the frame the system tracks the hands' position, and when they come into contact with the virtual ball appropriate forces are displayed, such as its weight. If the player doesn't hold tight enough or open her/his hands, the ball will fall down and bounds on the floor. After making a shot, the ball begins a free falling movement determined by the hand's velocity and orientation while freeing the ball. If the ball doesn't go through the hoop, it may rebound from the backboard, basket's ring or objects surrounding the playground. The virtual ball is designed $40cm$ in diameter and weights $300g$.

To show the force feedback effectiveness in such skillful operation, we asked two users to play this game, while recording the distance between their hands. Two session was organized, one with force feedback, that is the user can fell haptically the spherical shape of the ball as well as its weight. And a second session, where only visual feedback cue is provided. The results of this experiment is shown by figure 11a,b. The horizontal axes show the time and the vertical show the distances between the two hands. Time spent for each trial is devised into three parts. Part A where the user is trying to catch the ball. Part B is when the ball is hold by the user. During this part the user start first by ensuring the fact of holding a ball (B1), this part is still characterized by some vibrations due to user's behavior as well as software optimization. Then the user brings his attention to the backboard and aim the hoop (B2) and finish this part by throwing the ball toward the basket (B3). At last in part C the hands become free again.

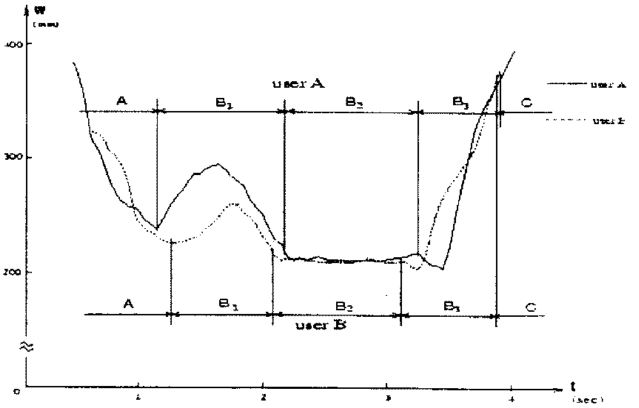

Figure 11-a: With force feedback

The part to which we are interested is B2, where there is a direct and full contact between the virtual ball and user's hands. As the figures 9a-b show, the distance between the two hands is more stable when force feedback is displayed. In this case the user unintentionally does not think about the ball, instead he is concerned about the game and his skills to shoot a hoop. Without force feedback, the user can not easily keep his hands in right distance to hold the ball. The only thing he can do while holding a ball, is to keep looking whether or not his hands are deep inside the ball.

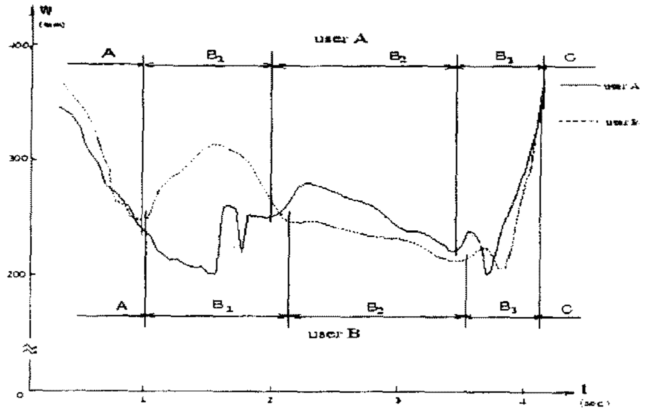

Figure 11-b: Without force feedback

Other results of this interactive experience showed that, with force feedback sensation the player improve considerably his performance of scoring up to 60% better than throwing the ball without force feedback. Haptic sensation is revealed to be indispensable to show the real skills while manipulating virtual object.

5. Discussion and Conclusion

Tensioned strings techniques are used to realize force feedback on both hands in a large space. Although the approach makes the human scale device very light and easy to use as well as safe, it also has some problems. Mainly, the strings may interfere with each other if the operator try to turn around her/himself or cross deeply his hands. Actually, this backdraw is inevitable for any system using direct contact attachment with the operator to generate force feedback. Another problem, that was partially improved by [2] but still remain, occurs when the operator moves her/his hands with a very high speed. This kind of movement makes the string no longer strait and cause a length miscalculation, which affect the precision of hands' position.

The concept of the Scaleable-SPIDAR is new and unique and it offers possible application in a wide variety of fields. Its main features, are the ability to display different aspects of force feedback within different size cave-like space without visual disturbance; As well, the device is not bulky, and easy to use; Another distinguishing characteristic of Scaleable-SPIDAR, is that the operator does not think in terms of manipulating an input device, instead he has a full and direct use of his hands.

Recently we are investigating the use of scaleable-SPIDAR in a visual-less virtual environment, that is to explore what can be accomplished within an "invisible" but audible and tangible virtual environment. Such system has a great deal of interest in building new computer interfaces for blind persons.

6. REFERENCES

[1] F.P. Brooks, M.O.Young, J.J.Batter and P.J.Kilpatrick (1990)" Project GROPE- Haptic Display for Scientific Visualization" Computer Graphics, Proc. ACM SIGGRAPH'90, Vol.24, No4, pp. 177-185.

[2] Y. Cai, M. Ishii, and M. Sato, "Position Measurement Improvement on a force Display Device Using Tensioned Strings". IEICE TRANS. INF. &SYST. Vol. E77-D, N°6 June 1996.

[3] Y. Hirata, M.Sato and H.Kawarada, ``A Measuring Method of Finger Position in Virtual Work Space" Forma, Vol.6, No.2, pp.171-179(1991)

[4] http://www.sensable.com/product.htm

[5] Ishii and M.Sato, 1994a, "A 3D Spacial Interface Device Using Tensioned Strings," Presence-Teleoperators and Virtual environments, Vol. 3. No 1, MIT Press, Cambridge, Ma, pp 81-86

[6] H. Iwata: ``Artificial Reality with Force-Feedback: Development of Desktop Virtual Space with Compact Master Manipulator," (Computer Graphics), 24(4), 165-170(1990)

[7] Salisbury, J. and M. Srinivasan, 1992, "Virtual Environment Technology for Training (VETT)" BBN Report No 7661, VETREC, MIT, Cambridge, MA.

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