PREVISE

A Human-Scale Virtual Environment with Haptic Feedback

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Abstract: This paper presents a human-scale multi-modal virtual environment. User interacts with virtual worlds using a large-scale bimanual haptic interface called the SPIDAR-H. This interface is used to track user's hands movements and to display various aspects of force feedback associated mainly with contact, weight, and inertia. In order to increase the accuracy of the system, a calibration method is proposed. A large-scale virtual reality application was developed to evaluate the effect of haptic sensation in human performance in tasks involving manual interaction with dynamic virtual objects. The user reaches for and grasps a flying ball. Stereoscopic viewing and auditory feedback are provided to improve user's immersion

1 INTRODUCTION

Virtual Reality (VR) is a computer-generated immersive environment with which users have real-time interactions that may involve visual feedback, 3D sound, haptic feedback, and even smell and taste (Burdea, 1996 ; Richard, 1999 ; Bohm, 1992 ; Chapin, 1992 ; Burdea, 1993 ; Sundgren, 1992 ; Papin, 2003). By providing both multi-modal interaction techniques and multi-sensorial immersion, VR presents an exciting medium for the study of human behavior and performance. However, large-scale multi-modal Virtual Environments (including haptic feedback) are few (Richard, 1996 ; Bouguila, 2000).

Among the many interaction techniques developed so far, the virtual hand metaphor is the most suited for interaction with moving virtual objects (Bowman, 2004). In this context tactual feedback is an important source of information.

Therefore, we developed a human-scale Virtual Environment (VE) based on the SPIDAR-H haptic interface. In order to increase the accuracy of the system, a calibration method is proposed. A large-scale virtual reality application was developed to evaluate the effect of haptic feedback on human performance in tasks involving manual interaction with dynamic virtual objects. In the next section, we describe the multi-modal human-scale virtual environment. Then we describe the proposed calibration method. Finally, the virtual ball catching application is described.

2 HUMAN-SCALE VE

2.1 Description

Our multi-modal VE is based on the SPIDAR interface (Figure 1). In this system, a total of 8 motors for both hands are placed as surrounding the user (Sato, 2001). Motors set up near the screen and behind the user; drive the strings (strings between hands and motors) attachments. One end of string attachment is wrapped around a pulley driven by a DC motor and the other is connected to the user's hand.

By controlling the tension and length of each string attachment, the SPIDAR-H generates an appropriate force using four string attachments connected to a hand attachment. Because it is a string-based system, it has a transparent property so that the user can easily see the virtual world. It also provides a space where the user can freely move around. The string attachments are soft, so there is no risk of the user hurting himself if he would get entangled in the strings. This human-scale haptic

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device allows the user to manipulate virtual objects and to naturally convey object physical properties to the user's body. Stereoscopic images are displayed on a retro-projected large screen (2m x 2,5m) and viewed using polarized glasses. A 5.1 immersive sound system is used for simulation realism, auditory feedback and sensorial immersion. Olfactory information can be provided using a battery of olfactory displays.

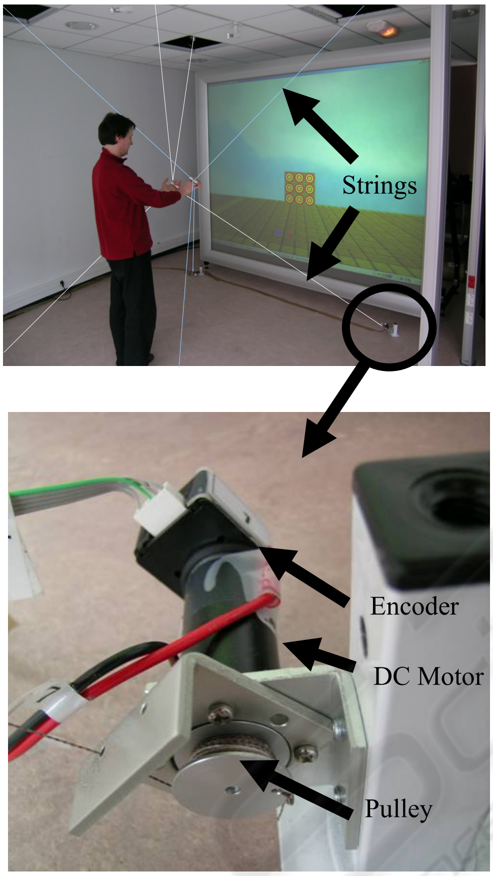


Figure 1: Framework of the SPIDAR-H

2.2 VE Workspace

Workspace is a well-know concept in robotics. The workspace of a robot is the minimum space that contains all the reachable positions of the end-effector. In the case of the SPIDAR-H, the workspace is also an important concept. This workspace is divided in two spaces:

Reachable space : as defined by Tarrin and al. in (Tarin, 2003) "The reachable space gather every points users can reach with hands"

Haptic space: gather every point where the system can produce a force in any direction.

The global workspace is defined by the intersection of these two spaces. The figures 2.a and 2.b show the workspace of the reachable space; the volume is mixed up with the frame of the SPIDAR. The figures 2.c and d. show the haptic space. In (Tarin, 2003), the authors consider that the manipulation space is defined by the intersection of right and left hand workspace, i.e. the intersection of the four spaces described on figure 2. This hypothesis is only true when the two hand attachments are linked together (for position and orientation for example as in SPIDAR-G (Kim, 2002)). In the following, hands are not linked; we differentiate the spaces for right and left hand.

Note that the haptic space is described by a tetrahedron. This shape is a theoretical workspace, in practice; the real workspace is smaller than this shape. Besides, the faces of the tetrahedron are not included in the workspace. It seems natural that when the hand attachment is located on the face, a force can not be produced in any direction outside of the space. To generalize, when the hand attachment is close to the centre of the tetrahedron, the SPIDAR-H is more efficient (it can produce an important force in any direction).

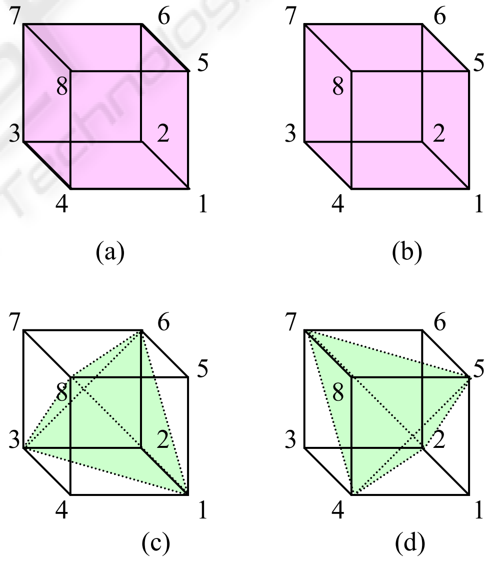


Figure 2: reachable and haptic space of the SPIDAR-H. (a. right hand reachable space, b. left hand reachable space, c. right hand haptic space and d. left hand haptic space)

In the following, we consider that the workspace is approximately defined by the space described by figures 2.c. and 2.d.

2.3 Position measurement

Let the coordinates of the hand attachment position be *P(x,y,z)*, which represent in the same time the hand position, and the length of the i^{th} string be *li (i=0, ..., 3)*. To simplify the problem, let the four actuators (motor, pulley, encoder) *Ai* be on four not adjacent vertexes of the cubic frame, as shown on figure 3. Then *P(x,y,z)* must satisfy the following equations (1-4).

$$l_0{}^2 = (x+a)^2 + (y+a)^2 + (z+a)^2 \quad (1)$$

$$l_1{}^2 = (x-a)^2 + (y-a)^2 + (z+a)^2 \quad (2)$$

$$l_2{}^2 = (x-a)^2 + (y+a)^2 + (z-a)^2 \quad (3)$$

$$l_3{}^2 = (x+a)^2 + (y-a)^2 + (z-a)^2 \quad (4)$$

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

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

The coordinates origin is set to the centre of the framework. The position measurement range of all x, y, and z in [-1.25m, +1.25m]. The absolute static position measurement error is less than 1.5cm inside the position measurement range.

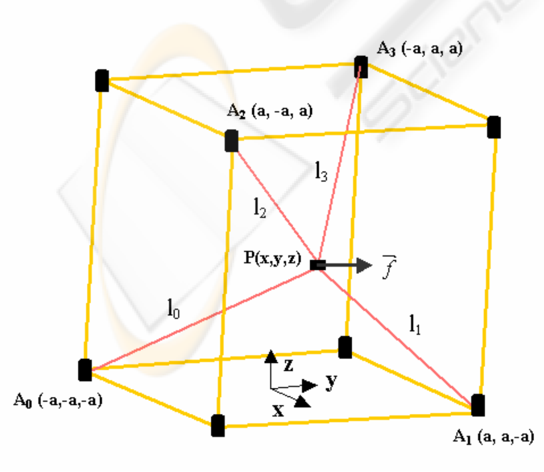


Figure 3: Position measurement and resultant force

2.4 Force control

SPIDAR-H uses the resultant force of tension from strings to provide force display. As the hand attachment is suspended by four strings, giving certain tensions to each of them by the mean of motors, the resultant force occurs at the position of the hand attachment, 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*), the resultant force is :

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

Where a_i represents the tension value of each string attachment. By controlling all of the a_i ,a resultant force in any direction can be composed.

2.5 Calibration method

As the workspace, calibration is also a well-known concept in robotics. Calibration is a technique that computes all the parameters of a robot, for example the length of the links between two axes. On real robots, this technique generally requires an external measurement device that provide the absolute position of the end-effector (coordinate measurement machinery, theodolites). Unlike robots, the SPIDAR-H can be calibrated without external system according to the following hypothesis:

- The parameters to calibrate are the position of each motor.
- The exact length of each string is known at any time.
- The strings are long enough to reach any motor.
- The junction of the string is considered as a point.

In order to complete the calibration, it is necessary to set the position and orientation of the original frame. We have no warranty that the motors are placed exactly on the corner of the cube, so, taking the cube as original frame may be a wrong hypothesis. Let's define a new frame independent from the cube. The origin of the frame is located on motor 4. Concerning the orientation of the frame, we arbitrary fixed the following relationship:

- the v axis is given by the vector [motor4 – motor2],
- the plan v-w passes though motor 7.

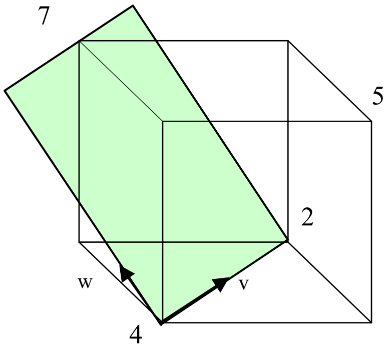


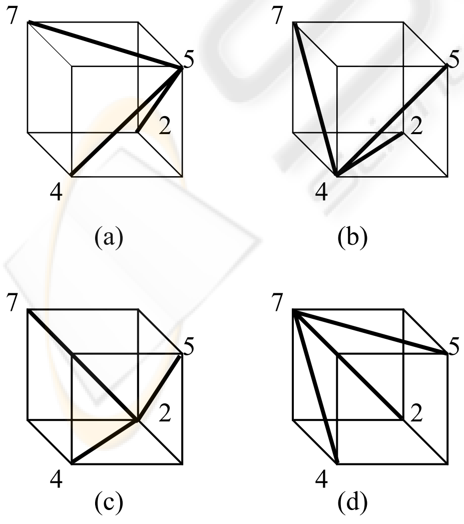
Figure 4: position and orientation of the original frame

The figure 4 illustrates the position and orientation of the frame. According to the previous relationships, the position of each motor can be defined by:

$$Motor4:\begin{bmatrix}0\\0\\0\end{bmatrix}\qquad Motor2:\begin{bmatrix}0\\v_2\\0\end{bmatrix}$$

$$Motor7:\begin{bmatrix}0\\v_7\\w_7\end{bmatrix}\qquad Motor5:\begin{bmatrix}u_5\\v_5\\w_5\end{bmatrix}$$

The first phase of calibration consists in positioning the end-effector of the SPIDAR-H at some positions called “exciting positions”. Figure 5 shows the 4 exciting positions.



(a) (b)

(c) (d)

Figure 5: exciting positions

Each position produces 3 data: the length of the three strings:

- Position A_2 (a) gives l_{45}, l_{25} and l_{57},
- Position A_0 (b) gives l_{42}, l_{47} and l_{45},
- Position A_1 (c) gives l_{42}, l_{25} and l_{27},
- Position A_3 (d) gives l_{47}, l_{27} and l_{57}.

Where l_{ij} is the distance between motor i and motor j. These lengths provide the six equations of the following system where v_2, v_7, w_7, u_5, v_5 and w_5 are the six parameters to calibrate.

$$\begin{cases} {l_{42}}^2 = {v_2}^2 \\ {l_{47}}^2 = {v_7}^2 + {w_7}^2 \\ {l_{45}}^2 = {u_5}^2 + {v_5}^2 + {w_5}^2 \\ {l_{27}}^2 = (y_7 - v_2)^2 + {w_7}^2 \\ {l_{25}}^2 = {u_5}^2 + (v_5 - v_2)^2 + {w_5}^2 \\ {l_{75}}^2 = {u_5}^2 + (v_7 - v_5)^2 + (w_7 - w_5)^2 \end{cases}$$

The system is solvable and provides the following parameters:

$$v_2 = l_{42}$$

$$v_7 = \frac{-{l_{27}}^2 + {l_{17}}^2 + {v_2}^2}{2v_2}$$

$$w_7 = \sqrt{{l_{17}}^2 - {v_7}^2}$$

$$v_5 = \frac{{l_{45}}^2 - {l_{25}}^2 + {v_2}^2}{2v_2}$$

$$w_5 = \frac{{l_{25}}^2 - {l_{75}}^2 + (v_7 - v_5)^2 - (v_5 - v_2)^2 + {w_7}^2}{2w_7}$$

$$u_7 = \sqrt{{l_{15}}^2 - {v_5}^2 - {w_5}^2}$$

Theses results prove that the SPIDAR-H can be calibrated without external system. The correctness of this demonstration was confirmed by simulations.

Note 1: if the position and orientation of any motor is known in an external frame, it becomes easy to transfer the position of each motor in this new external frame.
Note 2: if a high accuracy is needed, last square methods can be used (each length is measured at least two times: l_{45} is given by positions a. and b.).

3 VIRTUAL CATCH BALL

The virtual catch ball application was developed for human performance evaluation in tasks involving reaching and grasping movements towards flying virtual objects. Such experimental paradigm has been used in many studies (Bideau, 2003 ; Zaal, 2003 ; Richard, 1994). However, a few of these involve haptic feedback (Richard, 1998 ; Jeong, 2004). In our application, the user catches a flying ball using a data glove (NoDNA) integrated in the SPIDAR interface. The user could therefore feel the ball hitting his/her virtual hand. A user catching a virtual ball is shown on Figure 6. A snapshot of the ball catching environment is illustrated in Figure 7. The catch ball simulation was developed in C/C++. OpenGL Graphics Library (Woo, 1999) was used as well as some video games tools and tutorials (Astle, 2001).

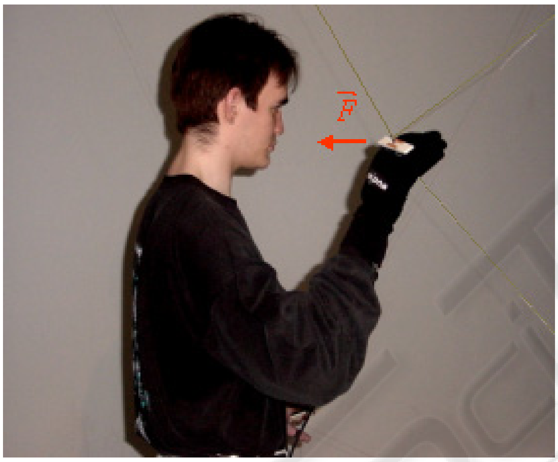


Figure 6: A user catching a virtual flying ball

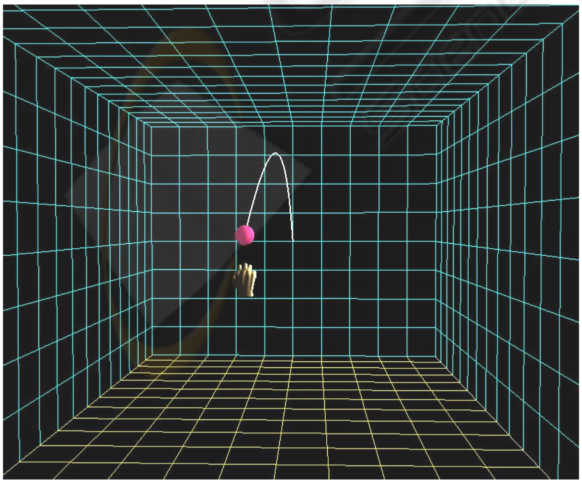


Figure 7: Snapshot of the ball catching world

4 CONCLUSION AND FUTURE WORK

We present a human-scale multi-modal virtual environment with haptic feedback. The user interacts with virtual worlds using a large-scale bimanual haptic interface called the SPIDAR-H. This interface is used to track user's hands movements and to display various aspects of force feedback associated mainly with contact, weight, and inertia. In order to increase the accuracy of the system, a calibration method is proposed. A virtual reality application was developed. The user reaches for and grasps a flying ball. Stereoscopic viewing and auditory feedback are provided to improve user's immersion.

In the near future, human performance evaluation involving ball catching tasks will be carried out. Moreover, the developed VE will serve as an experimental test-bed for the evaluation of different interaction techniques.

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