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Haptic Cues for Effective Learning in 3D Maze Navigation

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***Abstract*—Navigation in 3D virtual environment is a popular task in modern 3D applications. The main information is visual, which leads to an incomplete acknowledgement of the virtual environment, since other senses are impaired, such as touch or hearing. Haptic devices provides kinesthetic information which may improve the navigation capabilities of humans in virtual environments, however 3D haptic applications use intensive low level programming languages. This paper presents a 3D maze haptic navigation based on kinesthetic perception of the walls of the maze, wherein the walls surface have different properties, thus a learning haptic process enables better navigation skills after few trials. Experimental results done with a test users group, is realized with Novint as the haptic device and Panda3D as the haptic rendering system. Results with and without haptic cues indicates a successful learning curve to navigate with haptic cues. The haptic cues used are surface texture, viscosity, elasticity, shape recognition and external force. The results highlight the importance of haptic cues as navigation reference to improve the performance of the users.**

***Index Terms*—Haptic applications, virtual navigation, 3D applications.**

I. Introduction

The 3D virtual environments impact is growing in such diverse fields from psychology and neuroscience [2], to rehabilitation [3] to manufacturing [1], to medicine with perspective on minimal invasive surgery [5] and games [4]. Some tasks, such as navigation, are common to 3D applications, and are essential part of the application even when they are not the main goal of the application. Navigation can be defined [7] as the process whereby people determine where they are, where everything else is and how to get to particular objects or places. Navigation tasks usually requires spatial knowledge of virtual environments and the self location within the virtual world, because the visual information alone is insufficient to integrate a conceptual map of the 3D virtual world; for instance visual navigation aids are compared in [8] while [2] explores how a 3D human actor guides the user through the 3D environment, however better results are obtained [9] with haptic sound and kinesthetic coupling using visual and haptic cues to enhance the interaction and perception.

A. Motivation

The above paragraph indicates that to achieve a better perception and interaction capabilities on 3D environments, visual aids and the human kinesthetic channel blend into a data fusion to improve the information the user receives to achieve better abstraction of the 3D world so as to improve the performance during navigation tasks. The question is, if somehow a dynamical kinesthetic interaction is established, as we humans do when navigate in a cluttered environment, can we learn better patters to navigate effectively? This question has been explored previously in a static rather than dynamic kinesthetic coupling, the fundamental question is then, what else can we obtain from dynamic kinesthetic coupling? At first sight, it seems that an evident positive answer can be obtained, however is there any theoretical framework that provides a fundamental support for this intuitive positive question?

B. Contribution and organization

In this paper, we explore an experimental setup with theoretical support to provide a some insight. To this end, we explore visual aids and guided cues of haptic sensations to allow a learning process on user such that the user identifies useful clues on line to achieve the goal. In this way, a learning haptic process is implemented for better navigation skills after few trials. Experimental results suggest that data fusion allows the creation of mental maps to improve navigation skills on the labyrinth.

II. Haptic Model and How to Convey Rich Dynamic Kinesthetic Coupling

In order to provide the user with realistic force feedback, the haptic engine must allow the haptic rendering of complex virtual objects properties leading to the need of two kinds of objects properties: dynamic properties (eg. stiffness, elasticity) and surface properties (eg. texture, roughness). The most important issues of a new paradigm [5] for haptic rendering both object properties is presented in this document.

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A. Orthogonal decomposition haptic rendering algorithm

The first step in the orthogonal decomposition algorithm is to obtain the dynamic equation of the haptic device. The haptic device is modeled as a chained linked robot:

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau + \tau_h \tag{1}$$

$$\tau_h = J^T F_h \tag{2}$$

where $q, \dot{q} \in \mathbf{R}^n$ are vectors that represents the joints positions and velocities, n is the number of degrees of freedom (DOF), $H(q) \in \mathbf{R}^{n\times n}$ denotes a symmetric positive defined inertia matrix of the haptic device with $H(q) = H(q)^T$ positive defined, $C(q,\dot{q}) \in \mathbf{R}^{n\times n}$ is the Coriolis forces matrix with $\frac{1}{2}\dot{H}(q) - C(q,\dot{q})$ an antisymmetric matrix, $g(q) \in \mathbf{R}^n$ is the gravitational force vector, $\tau \in \mathbf{R}^n$ stands for the torque input, $J \in \mathbf{R}^n$ is the haptic device's analytic Jacobian, $F_h \in \mathbf{R}^3$ is the human input force, $\tau_h \in \mathbf{R}^n$ represents the torques input due to F_h, this is presented in Fig. 1.

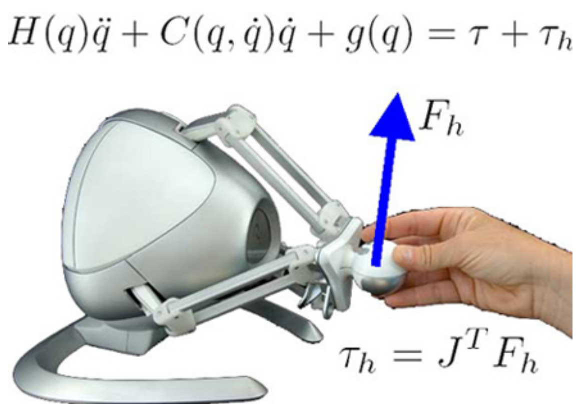

Fig. 1. Dynamic coupling of haptic device and human operator.

B. Joint manifolds

The virtual object's dynamic properties are generated by two manifolds defined as an implicit functions of the joint variables or generalized coordinates q as follows:

$$V_o = \{q \in \mathbf{R}^n \mid \varphi(q) = 0\} \tag{3}$$

$$V_{psi} = \{q \in \mathbf{R}^n \mid \psi(q) = 0\} \tag{4}$$

with $\varphi(q) : V_o \rightarrow \mathbf{R}$ called object manifold and $\psi(q) : V_{psi} \rightarrow \mathbf{R}^n$ called psi manifold.

It is possible to define $\varphi(q), \psi(q)$ such that the matrices:

$$P = \frac{J_\varphi^T J_\varphi}{J_\varphi J_\varphi^T} \tag{5}$$

$$Q = \begin{bmatrix} J_{\psi_1} \\ J_{\psi_2} \\ \vdots \\ J_{\psi_n} \end{bmatrix} \tag{6}$$

where

$$J_\varphi = \left[\frac{\partial}{\partial q_1}\varphi(q), \ldots, \frac{\partial}{\partial q}\varphi(q)\right] \tag{7}$$

$$J_{\psi_i} = \left[\frac{\partial}{\partial q_1}\psi_i(q), \ldots, \frac{\partial}{\partial q}\psi_i(q)\right] \tag{8}$$

the following properties are fulfilled:

P1 : $rang[P] = 1$
P2 : $rang[Q] = n - 1$
P3 : $Q = I - P$
P4 : $P^T = P$
P5 : $PP = P$
P6 : $Q^T = Q$
P7 : $QQ = Q$
P8 : $PQ = 0$
P9 : $J_\varphi Q = 0$

where $I \in \mathbf{R}^{n\times n}$ is the identity matrix. This matrices allows the orthogonal decomposition of a vector with respect to manifold defined by $\varphi(q) - a_0 = 0$ where a_0 is a constant scalar. The matrices P and Q allows the orthogonal decomposition [6] of any vector in $\mathbf{R}^n$ as follows: given a vector $v \in \mathbf{R}^n$ and given that P y Q expands all the space $\mathbf{R}^n$ and projects v onto the normal and tangent spaces to $\varphi(q) - a_0 = 0$ respectively, the orthogonal decomposition of v is done as follows:

$$v = Pv + Qv \tag{9}$$

where Pv and Qv is the normal and tangent components of v respectively.

The pseudoinverse of J_φ is defined:

$$J_{\varphi *}^T = \frac{J_\varphi^T}{J_\varphi J_\varphi^T} \tag{10}$$

C. Orthogonal decomposition of human torque

Given the properties (P1,...,P9) any given vector τ_h in $\mathbf{R}^n$ applied over the end effector of a robot or haptic device could be decomposed as follows:

$$\tau_h = P\tau_h + Q\tau_h = J_\varphi^T \lambda + Q\zeta \tag{11}$$

where $\lambda = \frac{J_\varphi}{J_\varphi J_\varphi^T \tau_h}$ represents the magnitude of τ_h in the normal direction of $\varphi(q)$ and $\zeta = Q\tau_h$ represents the tangent component of τ_h referenced to $\varphi(q)$ as is shown in Fig. 2. This principle is known as orthogonal decomposition and was proposed by Arimoto [6], this principle was applied only during interaction with infinitely rigid objects and in this work we extend the results to nonlinear deformable and cutting objects.

This procedure permits the orthogonal decomposition of the human torque in the normal and tangent direction of the manifold $\varphi(q)$ in joint space.

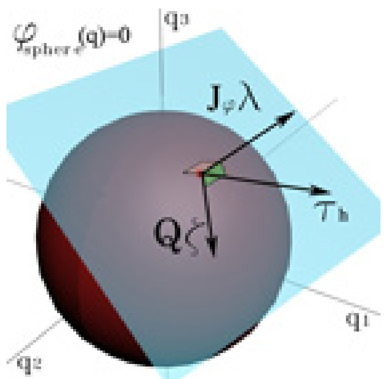

Fig. 2. Orthogonal decomposition of $\tau_h \in \mathbf{R}^3$ over a surface represented by a virtual sphere represented by $\varphi_{sphere}(q) = q_1^2 + q_2^2 + q_3^2 - r^2 = 0$ using equation(11).

III. Application Development

We now introduce the experimental setup designed to prove this paradigm. In this sense, first, the analysis of all components are presented. The analysis of the application platform is based on three programming layers, each one provides control over specific component, being: *i)* the haptic device; *ii)* the 3D engine, and *iii)* the communication between both layers.

A. Programming layers

Developing 3D haptic virtual environments requires low level programming language to generate the haptic engines that solves the differential equation model at every time sampling, validates the stable behavior and establishes the communication between the user application and the haptic device driver. In this programming layer the haptic effects and complex force calculations are done, based on the model presented in Section 2, see Fig. 3. In this way, the user can perceive a dynamical kinesthetic coupling, which in turn provides a rich perception on the contact surface and in this way, the user can build mental maps to discriminate the right road map to navigate in it. Notice that this is a memory-based haptic approach.

Fig. 3. Programming layer levels

B. The haptic engine

The haptic engine is a low level programming layer that computes the solution at each time, that is the kinematics of the whole virtual world, including contact force. In this way, the solution is ready to establish a communication between the haptic device and the PC. This engine also provides the mathematical computation required to update the haptic device proxy at the given position and velocity, based on the physic-based model of the interaction between the virtual objects and the proxy of the real haptic display.

This layer has a heavy-duty computational load and must be update at high rates, around 1000 Hz, because of we human perception of forces and shapes [10]. The haptic device used in this work is the Novint model from Falcon [11]. This devices has 3 degrees of freedom (DOF) of motion along x, y, z orthogonal cartesian axis, which provides energy to actuate the virtual world, so the haptic rendering algorithm depends on the solution of the model of Section 2 at every instant. The Novint haptic robot has 4 buttons in its handler which can be used to interact with the application, see Fig. 1.

The haptic engine takes advantage of the software development kit (SDK) provided by Novint company to generate a software library, in this way we create our own haptic effects, along with physic models for virtual objects and complex vector and matrix calculations. Finally, we obtain the displacement and velocity of the haptic device during contact to virtual objects and update all elements of the virtual world.

C. Orthogonal decomposition algorithm

The haptic rendering force is done using a complex algorithm based on the orthogonal decomposition [5] presented in previous section, this algorithm enables the rendering of nonlinear dynamic properties for the virtual objects along with complex surface, in this way, the haptic device display the forces coming from this interaction and the human operator perceives its surface properties like textures and tangent friction, so that the human operator can discriminate from one another and in this way, the human operator can classify the road map according to successful/failure trials. In this way, haptic memory is built over mental haptic maps in the human operator, so that haptic memory indicates him/her a better choice to navigate next time.

The question remains, how can we human operators achieve this? in this paper we surmise that rich haptic stimulation is required so that the human operator can discriminate different successful paths. Evidently, dynamic coupling can be an option, rather than penalty-based static kinesthetic coupling. So, anyway, we need a way to provide the dynamic kinesthetic coupling between the virtual world and the real human perception system. One way to achieve this is to model the whole nonlinear dynamics behavior of the haptic device together with nonlinear dynamical haptic virtual world.

According to the virtual object dynamic properties, the two manifolds 3 and 4 are reinterpreted for haptic rendering purpose. The manifold $\varphi(q)$ represents the virtual object contour when $\varphi(q) = 0$, through it, we simply assign a dynamic behavior to the dynamical model based-on $\varphi(q)$. The goal of the algorithm is to decompose the closed-loop dynamics of the haptic device together with dynamic model of the virtual world,modeled in their orthogonal coupled dynamics so as to a control may guarantee that the real human operator behaves stably. To this, it is necessary that the haptic display and rendering algorithm be realistic such that the human operator reacts normally and he/her produces an stable behavior.

To this end, consider the following control law

$$\begin{aligned} \tau_1 &= C(q,\dot{q})\dot{q} + g(q) - PH(q)J_{\varphi *}\dot{J}_{\varphi}\dot{q} - QH(q)\dot{Q}\dot{q} \\ &\quad - J_{\varphi}^T\lambda_d - Q\zeta_d \qquad (12) \\ P &= \frac{J_{\varphi}^T J_{\varphi}}{J_{\varphi}J_{\varphi}^T} \qquad (13) \end{aligned}$$

where $J_{\varphi} \in \Re^n$ and $Q \in \Re^{n\times n}$ are the jacobian matrices of functions $\varphi(q)$ and $\psi(q)$, respectively, while $J_{\varphi *}$ is the pseudo inverse of J_{φ}. Substituting (12) in (1) the closed-loop equation is

$$\begin{aligned} \ddot{\varphi}(q) &= M_{\varphi}(\lambda - \lambda_d) \qquad (14) \\ \ddot{\psi}(q) &= M_{\psi}(\zeta - \zeta_d) \qquad (15) \end{aligned}$$

with

$$\begin{aligned} M_{\varphi} &= J_{\varphi}H(q)^{-1}J_{\varphi}^T) \qquad (16) \\ M_{\psi} &= QH(q)^{-1}Q \qquad (17) \end{aligned}$$

The variables $\varphi, \dot{\varphi}, \ddot{\varphi}$ represents the virtual objects position, velocity and acceleration of the deformation, respectively. The variable $\psi, \dot{\psi}, \ddot{\psi}$ stands for the tangent position, velocity and acceleration respect to the virtual object surface, while λ_d, ζ_d are a key variable used to induce, through the haptic display (in this case, the Novint robot), the virtual object dynamics to the human operator [5]. In this way the haptic rendering algorithm displays the updated virtual world and the haptic display transmits the force contact vector to the hand of the human operator at fast rate. This algorithm enables perception of nonlinear virtual dynamics so as to the human operator can discriminate among different walls while navigating in the "3D Maze Navigation" world.

D. The application engine

The application engine is the highest programming level layer, which provides the application graphics like 3D virtual objects, labels and text on screen, texture mapping, the managing of the graphics attributes, the generation of sounds, the control of interruption to map properly input/output addresses of peripherals mouse and keyboard, the application window managing and any other high level peripheral. This layer works at low rates from 30 to 100 Hz without affecting the human perception (remember that the visual refresh of human perception is below this rate, so humans do not lose information above this rate). The application engine used in this work is based on the free graphic programming tool Panda3D [12], which allows, when properly programmed, an stable haptic rendering, see Fig. 4. Since Panda3D is a library of subroutines

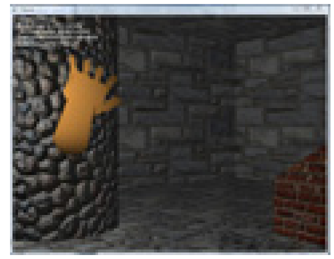

Fig. 4. Panda3D screenshoot.

for 3D rendering and game development, written in C++, based on Python bindings under Disney Studios guidelines, now an open-source engine supported by the Entertainment Technology Center at Carnegie Mellon University, it is platform independent and exportable under current open source C++ based simulators. For this paper, the Panda3D engine for Windows is used, then the data interchange is essential in haptic applications because the simultaneously generation of visual and kinesthetic stimulation provides the user with redundant information. A simple example is when the user sees the virtual 3D wall and Panda recreates, through the haptic rendering engine, the contact force with the wall which is displayed via the haptic device, in this case the the Novint haptic interface.

E. The interoperability layer

When the Novint does not change its orientation, the rendering could lead to change in the orientation of the scenario so this transformation must be consider such that the haptic device provides the correct force feedback onto the human operator, depending on the virtual contact world state. This communication could be achieved by data sharing via internet like [13].

In this work, a dynamic linked library (DLL) was programmed in order to establish the communication between the haptic engine and the visual engine. This DLL gives the visual engine the position and velocities of the haptic device, obtained by the haptic engine. In the other hand the DLL gets the state of the 3D environment and the haptic rendering setup and takes this data to the haptic engine so a consistent rendering of forces could be achieved. This DLL was programmed in Visual C++ using Novint Falcon SDK, and it is used in Panda3D through Python programming language.

IV. 3D Environment Navigation

During navigation users has three spatial knowledge: landmarks, route and survey knowledge [14]. In unfamiliar environments people first learn about landmarks, which are distinctive environmental features, the second information is obtained by route knowledge, this developed from a first person perspective. Finally the survey knowledge ”is developed from a third person perspective (e.g., through maps) or by extensive traveling in an environment and describes relationships among locations allowing users to assess where certain objects are located with respect to others in the environment” [8]. This work is centered in the survey knowledge enhanced by the haptic feedback stimulation, so in order to just evaluate this knowledge, the other two must be inhibited.

V. HAPTIC MAZE: A PROPOSAL FOR BENCHMARKING TESTS

We developed an application to test the influence of haptic cues during navigation in 3D virtual environments under 3D maze or labyrinth environment. The maze consists of five rooms with haptic cues and a dummy room without haptic cues, each room with four branches, the first branch is the entrance to the room, the other three are exits, see Fig. 5. Each room has one haptic cues, which is different from the other haptic cues of other rooms, as follows

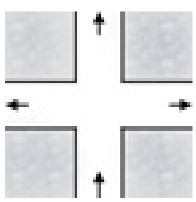

Fig. 5. Room configuration in the haptic maze.

1 Textured walls: the walls, floor and ceiling of the room has different texture type than the other rooms.
2 Environmental viscosity: navigation along the room presents a linear opposition, when viscous friction such as $F = -bv$ where v is the displacement velocity and b is the viscous friction coefficient.
3 Elastic contacts: the walls, floor and ceiling of the room, may be assigned a different type of stiffness, so different contact forces are perceived according to the restitution Joule law.
4 Hide objects: in this room a non visible virtual object is haptic render, so the user perceive a virtual sphere interfering the navigation.
5 External force: in this room a fluctuating force in just one direction is applied all over the room.

The maze has only one correct exit combination for each room, eg. Room A = right, Room B = left, Room C = straight, etc. The correct route trough the maze is defined before the experiment begins and is changed for each user. The maze objective is to pass all over the rooms using the correct route according to succesful/failure trials.

In order to inhibit an objective landmark recognition by the user, all rooms has the same form and dimension with same walls textured graphics and same spatial distribution. In order to inhibit the route acknowledge of the user, the rooms are presented in random order so the correct route is not in the same order all the time, see Fig. V. To achieve 3D immersion a headtracking device was develop using infrared camera an infrared LEDs glasses [15]. This device enables the rotation of the camera depending on the movement of the user head respect to the screen.

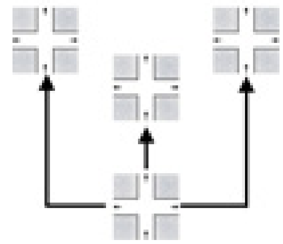

Fig. 6. Room sequence in the haptic maze.

VI. EXPERIMENT SETUP

To establish the influence of the haptic cues in 3D virtual navigation, the 3D virtual maze application has the following directions:

1 The objective of the user is to find the correct route along the rooms.
2 The rooms are labeled such that the user identifies them on screen. During trials with haptic cues enabled the labels are hidden so that the unique reference is the kinesthetic stimulus.
3 Once the user has passed all the rooms, the score of each room is presented showing in which room the branch taken was correct or wrong.
4 The experiment ends when the user takes all the correct branches.
5 The haptic cues are enable and disable according to the testing group of people.
6 The haptic rendering of walls, floor and ceiling is always enabled but the texture rendering is enable in the haptic cues enable modality.
7 The first room does not contain present haptic cues and is used to learn the navigation issues of the application.

The experimental results shows that during the 3D navigation with haptic cues enabled takes more time for the users to accomplish the maze objective, but in other hand the haptic cues helps in the generation of a mental map of the virtual environment as is presented in the following section.

VII. Experimental Results

The 3D haptic navigation was tested in a group of 16 persons of different ages between 14-35 years old, with different 3D virtual environments backgrounds. To establish the influence of the haptic cues in 3D virtual navigation the group was divided in a group of 8 persons used the maze application with haptic cues enabled and 8 persons used the maze application without any haptic cue. The experimental results show that the users navigating without haptic cues realized the task with average of 30% less time than the persons experimenting the haptic cues, this due to the time used for cues recognition and interpretation. The same tests with the same configuration were applied for each user after a short time, and the experimental data shows that 75% of the persons that experiment the haptic cues needed less time to accomplish the task compared to 25% of the persons without haptic cues. This is a relevant information obtained from the experiments and it is established in the following sentence:

Kinesthetic information retrieved by users during 3D virtual environments navigation established a stronger and durable mental abstraction of the virtual world than just memory acknowledge. This result shows that although in the first case the task is realized in minor time, the haptic cues provides an important information for mental abstraction that remains longer in users memory, we call this fact *haptic learning*.

VIII. Conclusions

It is surmised that unknown haptic clues allows to build haptic mental models for better navigation skills in 3D virtual environments. We provided a theoretical framework to allow to establish the trade efforts for haptic interfaces for navigation. The main source of information is visual which is complemented with haptic feedback. The novelty is the way we allow to build haptic memory to discriminate contact states over time and command motor commands to achieve the goals. Experimental results based on 16 subjects, using Novint as the haptic device and Panda3D as the haptic rendering system. The haptic cues are mechanical properties of surface texture, viscosity, elasticity, shape recognition and normal force. The results highlight the importance of haptic cues as navigation reference to improve the performance of the users.

IX. Future Work

During the experiments presented in this work, landmarks acknowledge and route acknowledge during 3D navigation were inhibited.The survey acknowledge were provided by haptic cues, the cues used in the application provided the user of the application of a better abstraction of the virtual world, but Which acknowledge provides a more durable mental abstraction of the virtual world? A future work must deal about a comparative study between landmarks, route and haptic survey acknowledge in 3D navigation. An other possible work must be a comparative study between the different acknowledge provide for each haptic cue type.

References

[1] Mujber, T. S., Szecsi, T. and Hashmi, M. S. J. (2004), *Virtual Reality Applications in Manufacturing Process Simulation*, Journal of Materials Processing Technology 155-156, 18341838. Riva, G.,

[2] Botella, C., Legeron, P. and Optale, G., eds (2004), Cybertherapy - *Internet and VR as Assessment and Rehabilitation Tools for Clinical Psychology and Neuroscience*, Vol. 99 of Studies in Health Technology and Informatics, IOS Press, Amsterdam, The Netherlands.

[3] Patton, J.L.; Dawe, G.; Scharver, C.; Mussa-Ivaldi, F.A.; Kenyon, R., *Robotics and virtual reality: the development of a life-sized 3-D system for the rehabilitation of motor function*, Engineering in Medicine and Biology Society, 26th Annual International Conference of the IEEE", 2004

[4] http://home.novint.com

[5] Gabriel Seplveda,Vicente Parra, Omar Domnguez, Noninear Haptic *Rendering of Deformation and Cutting Based on Orthogonal* Decomposition, Journal Research in Computing Science, 2008,pp 51-61, vol. 35.

[6] Suguru Arimoto, Control Theory of Non-linear Mechanical Systems, Oxford Science Publications, 1996, First Edition

[7] Jul, S. and Furnas, G. W. (1997), *Navigation in Electronic Worlds*, SIGCHI Bulletin 29(4), 4449.

[8] Stefano Burigat and Luca Chittaro, *Navigation in 3D Virtual Environments: Effects of User Experience and Location-pointing Navigation Aids*, HCI Lab, Dept. of Math and Computer Science, University of Udine

[9] Frank A Biocca, Yasuhiro Inoue, Andy Lee, Heather Polinsky, and Arthur Tang, *Visual cues and virtual touch: Role of visual stimuli and intersensory integration in cross-modal haptic illusions and the sense of presence*, Proceedings of Presence 2002. Porto Portugal

[10] Mohsen Mahvash, Vincent Hayward,*Passivity-Based High-Fidelity Haptic Redndering Contact*,Journal ICRA , pp 14-19,2003

[11] http://home.novint.com/products/technical_specs.php

[12] Mike Goslin, Mark R. Mine, "The Panda3D Graphics Engine," Computer, vol. 37, no. 10, pp. 112-114, Oct., 2004

[13] Kenneth Waldron, et al,*Simulated medical learning environments on internet*, Journal of the American Medical Informatics Association, Vol 9,No 5, October 2002

[14] Siegel, A. and White, S. , *The Development of Spatial Representations of Large-scale Environments*, in H. Reese, ed., Advances in Child Development and Behavior, Vol. 10, Academic Press, New York, pp. 955.,1975

[15] Johnny Chung Lee, *Head Tracking for Virtual Reality Displays using Wii Remote*, Human-Computer Interaction Institute, Carnegie Mellon University.