The DigiHaptic, a New Three Degrees of Freedom Multi-finger Haptic Device

Géry Casiez[1], Patricia Plénacoste[1], Christophe Chaillou[1], and Betty Semail[2]

[1] Laboratoire d'Informatique Fondamentale de Lille
Université des Sciences et Technologies de Lille,
59655 Villeneuve d'Ascq, France
{gery.casiez, patricia.plenacoste, christophe.chaillou}@lifl.fr
[2] Laboratoire d'Electrotechnique et d'Electronique de Puissance
Université des Sciences et Technologies de Lille,
59655 Villeneuve d'Ascq, France
{betty.semail}@polytech-lille.fr

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Abstract. This article presents the technical principles and a set of applications for a new ground-based three degrees of freedom haptic device. The DigiHaptic can be used in isometric or isotonic mode with force feedback. It is a new and original approach to object manipulation in virtual worlds using degrees of freedom decoupling. The process which led us to create the DigiHaptic was based on a changed perspective regarding object manipulation in virtual reality, which required reconsideration of the interaction between the user and virtual reality. Leading edge research has now moved beyond the mere imitation of reality and its everyday gestures and is progressing on to the mapping of virtual worlds using reference marks in Cartesian co-ordinates.

1 Introduction

Virtual reality can be defined as the user's real-time multimodal interaction with a computer generated world. This interaction is mediated by several sensory channels, initially by the visual and auditory ones and more recently the haptic channel has been added thanks to technical improvements.

Haptic feedback for virtual reality simulations groups the touch- and force-feedback modalities [1]. Touch feedback simulates virtual object surface mechanical smoothness, slippage, temperature and contact geometry. Force-feedback opposes the user's motion and is intended to convey information on virtual object hardness, weight and inertia. Haptic feedback (either tactile, force, or in combination) increases the realism of the simulation in the application domain of virtual environments.

The last ten years have seen the development of devices with more than two degree of freedom (DOF) that can be divided in two categories: ground-based and man-based. Ground-based devices are located on a surface (ground, desk, table...) whereas man-based devices consist of portable devices intended to be fixed to the user. These two categories can be divided into two subcategories: isotonic and isometric devices.

- The isotonic devices issue commands in terms of position: a position of the object being handled corresponds to a position of the device.
- The isometric devices issue commands in terms of force: a force proportional to the displacement of the device is exerted on the user and this force corresponds to a displacement speed of the object being handled.

The best known examples of ground-based isotonic devices are the computer mouse for the two dimensional environments and the stylus based device like Sensable's PHANTOM [2] for the three dimensional (3D) environments. The latter is a small, desk-grounded robot that permits simulation of single fingertip contact with virtual objects through the thimble or stylus. The SpaceMouse [3] and the SpaceBall [4] from 3DConnexion are commercial ground-based isometric devices. The SPIDAR-8 [5], a ground-based multi-finger isotonic device, can be used for both hands operations. It is mainly used to grasp objects with unidirectional force feedback.

A Man-based isotonic device-like the CyberGrasp, from Immersion Corporation, is an exoskeletal device that fits over a 22 DOF CyberGlove, providing force feedback. The CyberGrasp [6] is used in conjunction with a position tracker to measure the position and orientation of the forearm in 3D space. Another example is the Rutgers Master II [7] which has an actuator platform mounted on the palm that gives force feedback to four fingers. Position tracking is done by the Polhmeus Fastrak.

Currently haptic research is concentrated on reproducing everyday gestures and feelings leading to complex and expensive mechanical devices designed for restricted narrow area applications. For instance, the PHANTOM was designed to manipulate 3D objects like in the real world whereas the CyberGrasp is used to grasp objects in 3D. These isotonic devices are intuitive to use and force-feedback can be provided, however the significant amount of physical displacements can tire the user. Isometric devices are less tiring but no force-feedback can be rendered and DOF coupling is usually noted.

This article describes our device, the DigiHaptic [8], shown in fig. 1. Section 2 details the principles of operation of the DigiHaptic including the device design, design motivations, hardware and control algorithm. Section 3 relates examples of its application.

2 Principles of Operation

The principles of operation are discussed in four subsections. First the device design and its motivations are presented, next the hardware and control algorithm involved are discussed.

2.1 Device Design

Our device is a ground-based device intended to reduce user fatigue while providing efficient force-feedback. The device comprises three levers associated to the thumb, forefinger and ring finger according to figure 1.

The user puts his hand on the higher part of the device in an ergonomic way and can handle the three levers simultaneously. Each lever has 120° of freedom and 20mm of radius. This is a compromise between finger's and lever's freedom (i.e. the more the lever's radius, the less possible lever angle displacement). Maximum force was calibrated to be 2N. This appears to be sufficient to render stiff walls at fingertips.

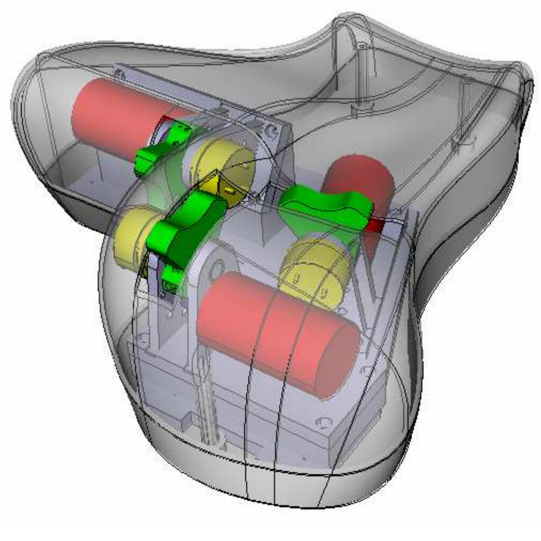

Fig. 1. The DigiHaptic with the three motors, levers and potentiometers that can be seen through the upper shell in transparency.

2.2 Design Motivations

Grounded multi-finger devices are a new research area. One existing multi-finger device is The Claw [9] that was proposed to play doom-like games. It replaces the keyboard in providing keys to fingers in an ergonomic way. The way the keys are placed on the device is isomorphic to the keyboard. Nevertheless there is no force feedback.

While designing our device, we were searching for a cheap three degrees of freedom solution with force feedback. We also wanted to keep the advantages of non-tiring, low bulk isometric devices, while avoiding the direction coupling usually found on them. So the idea was to separate the three degrees of freedom. This in turn reduces the mechanical complexity but we expect it to increase the learning time for coordinating the three levers.

The realization is done with three effectors that can be handled simultaneously or separately but always independently. These kind of effectors can only be used with fingertips which are the most sensitive part of the hand to feel force feedback [10].

One intuitive solution would be to use the thumb, fore-finger and middle finger. Nevertheless the ring finger was chosen [Fig 2] instead of the middle finger, because there are common muscular groups between the fore-finger and middle finger [11][12]. Further the use of fingers has the advantage that there is a reduction of the maximal force required to render a range from low stiffness to stiff walls using a low power motor to reduce the bulk.

We tried to preserve the natural position of the fingers, proposing actions that were within the range of primary movements of the fingers. Empirical observation showed a good comprehension of the relationship between the finger movements and the handling of the virtual object.

The design was chosen to keep the hand at rest compared to the PHANTOM that requires the operator to keep the forearm raised and to manipulate each DOF according to the human hand's degrees of freedom.

One application where these advantages can be utilized is in CAD software, where 3D manipulation is usually done by keeping control of the main directions which are the x,y and z axes. The Space Mouse has been used for this purpose but combines the degrees of freedom. Our device makes this easier by providing combined or separate handling of each DOF.

2.3 The Hardware

Although less compact than pulse-width-modulation (PWM) amplifiers and demanding more heat dissipation, linear amplifiers provide a faithful translation from input voltage to motor torque without the "scratchy" feeling and high frequency auditory noise associated with PWM amplifiers. The binding between the motor and the lever consists of a stainless-steel ca-

Fig. 2. Picture that shows the way to put the hand on the DigiHaptic.

ble [Fig. 3] between the motor pulley and the lever (cable drive is low inertia, low friction, high bandwidth, and is easily backdriven by the user). Motion of the lever was sensed directly by a potentiometer with 13 bit conversion; it measures angle in theoretical increments of 0.02° (0.06° in practical because of measure noise) at 1000 Hz.

The sensor was used to measure the lever angle and determine the torque to be return to the motor. A potentiometer was chosen in order to read the absolute displacement of the lever. This ensures no calibration before starting and no loss of information in time.

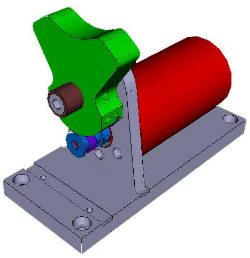

Fig. 3. A lever actuated by a DC motor through cable transmission. Iron brush bearings reduce friction.

2.4 The Control Algorithm

A QNX RTOS PC at 350MHz controls the device in real time at 1000Hz through a Servotogo [13] analog digital card. Impedance control is used (i.e. position as input and force as output) Fig.4.

The computer running the virtual environment is used with an ethernet connection to the QNX computer by UDP/IP protocol (possible loss of data is not of much importance). The QNX control algorithm is divided into two threads. The first one reads lever angular position and calculates velocities which are both sent to the virtual environment after filtering. The lever inertia and low viscous frictions are compensated by issuing commands. Forces are rendered on the lever according to its mechanical characteristics. The second one waits for input forces from the virtual environment. The advantage is that variable input force frequency is not a problem: the system always outputs the last force received and no instabilities can arise.

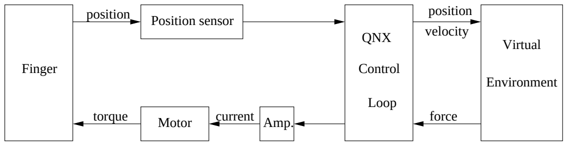

Fig. 4. The general control scheme.

2.5 Modes of use

The DigiHaptic is a force feedback device although tactile feedback up to 100Hz can be rendered. It's also possible to superimpose vibration over force. Our device can be used in isotonic or isometric mode.

Objects can be translated or rotated. Translations are done according to the width of the screen with the thumb, the height of the screen with the ring finger and the depth of the screen with the forefinger. This corresponds to applying a Cartesian coordinate system in the virtual world. Rotations are done around the x,y and z axis with the corresponding levers.

In isotonic mode, the virtual operating range is limited to a cube of about 10 cm of side due to the limited freedom of each lever. On each lever due to hand morphology constraints (male and female) a user can use up to 60° over 120°.

In isometric mode, springs are simulated on each lever so as to always bring back the lever to a neutral position set at equal distances of the lever boundaries. The spring stiffness can be configurated. If the stiffness is high then the levers don't perceptivily move (isometric mode). If the stiffness is low to average then a force proportionnal to the lever's position is generated thus we can speak of elastic mode in the sense of Zhai [14].

3 Example of Applications

Each lever can be configured depending on the application. This section presents examples of applications in which the DigiHaptic has been empirically tested.

3.1 Pointer Manipulation

The way of manipulating a pointer as an ergotic gesture [15] depends on the workspace configuration. If it is restricted to a restricted operating range then absolute isotonic devices such as the PHANTOM or the DigiHaptic can be used to manipulate the pointer. For virtual worlds with infinite operating range, isotonic relative devices (like the mouse - not suitable for 3D) or isometric devices can be used.

Fig. 5 presents an application with a restricted operating range that consists of manipulating a pointer through a trajectory without leaving it. Different trajectories are proposed from simple one to more difficult and the DigiHaptic has been empirically tested in isometric and elastic modes. In this application, the operating range is too high to use the isotonic mode. Empirical experiments show that simultaneous manipulation of two DOF is not a problem whereas simultaneous manipulation of three DOF requires learning time.

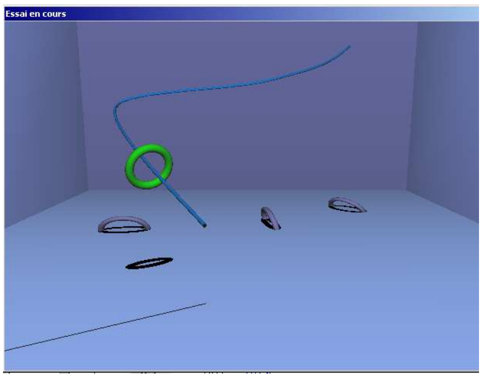

Fig. 5. Pointer manipulation in elastic mode.

3.2 Pointer Manipulation with Force Feedback

In the previous application, no force feedback could be rendered. A different virtual environment [Fig. 6] is operated with SPORE [16]. SPORE is a physical engine able to render objects, properties and forces according to physical equations and uses either penalty based method or "god-object" for collision detection. Thus the user can operate ergotic and epistemic gestures [15]. The DigiHaptic was connected to SPORE using the isotonic mode with force feedback. The environment is composed of a fabric held by four bricks. There is also an upper brick and the probe can be seen below it. Stiff force feedback is rendered on bricks and soft feedback on the fabric giving a realistic sensation of the virtual world.

During collision detection, forces calculated by the virtual environment are projected on the x,y,z axes and each projection is sent on the corresponding lever.

The device operating range is calibrated to correspond to the virtual operating range. For virtual large workspaces, isometric devices have to be used but the question of force rendering posed through pseudo-haptic feedback is possible [17].

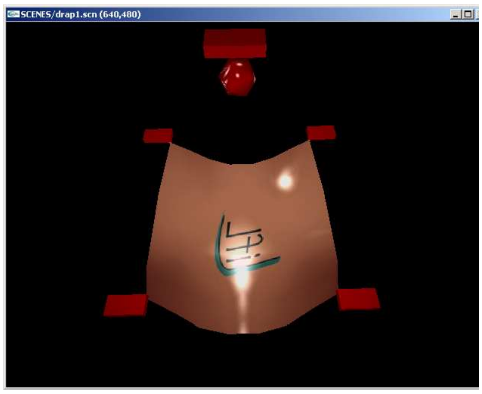

Fig. 6. Pointer manipulation in isotonic mode with force feedback.

4 Conclusion

A new haptic device called the DigiHaptic is discussed in this article. Its originality lies in having three end effectors which can be handled at the same time with force feedback. Its use with a large set of applications from doom-like games to CAD software can be imagined.

Evaluation will be carried out to measure the time required to learn how to use the DigiHaptic, in particular the time needed to integrate the manual and cognitive use of the tracing paper which is the reference mark. The first empirical experiments were encouraging because they showed that users are able to use the device after a short training period without difficulties or cognitive conflicts. Further the force vector projection on each lever in isotonic mode does not disturb the user in finger motivity and cognitive behavior. This positive reaction to decoupled degrees of freedom is in accordance with the way players in doom-like games use the keyboard to move the character. (The keyboard can be assumed to be a decoupled degrees of freedom isometric device in these games.)

Comparison with other isotonic and isometric devices will be carried out to compare their performance and limits according to the application described in subsection 3.1. The DigiHaptic will also be evaluated in object manipulation situations.

Finally force feedback in elastic mode is under development.

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