The Delta Haptic Device

Sébastien Grange, François Conti, Patrick Helmer, Patrice Rouiller, Charles Baur

Institut de Systèmes Robotiques

Ecole Polytechnique Fédérale de Lausanne

1015 Lausanne, Switzerland

Human Computer Interaction (HCI) has seen tremendous changes in the past decades. The dramatic increase in computing power and understanding of human communication channels has had a significant impact on traditional HCI fields such as virtual reality and computer vision. At the same time, new interaction paradigms have been developed. The need for a more interactive experience in interacting with machines encourages the development of force-feedback devices, which exploit the often under-estimated human sense of touch. This paper presents an innovative haptic solution combining state-of-the-art parallel mechanics with dedicated control electronics, which can be coupled with a virtual reality engine. It opens the door to a wide range of applications including advanced simulations, user-friendly teleoperation and nanomanipulation.

INTRODUCTION

Recently, as computers have become an indispensable tool in most households, Human-Computer Interaction (HCI) has been the object of a growing research interest. The increase in computing power makes possible today what was thought unrealistic yesterday, and people are now expecting to interact with their home appliances in a way that makes the USS Enterprise computer system from Star Trek look primitive. Thus, the need for better paradigms than the traditional screen-mouse-keyboard one is driving the research effort in HCI.

At the same time, new tools need to be developed to allow more meaningful interaction with popular technologies, in particular Virtual Reality (VR). Traditionally, VR addressed the human sense of vision. In order to make VR simulations more realistic, a wider range of human senses should be involved. The sense of touch appears to be an excellent candidate. The amount of information that can be conveyed through the haptic sense is surprisingly high and justifies the recent excitement about force-feedback interfaces.

At the Virtual Reality and Active Interfaces (VRAI) group, we have developed an innovative force-feedback system which meets the high standards required for industrial applications by combining high strength, high stiffness and high sensitivity. This system is based on the Delta robotic structure, which provides three translational Degrees-Of-Freedom (DOFs). A dedicated mechanical wrist plug-in provides 3 rotational DOFs. All of the DOFs are fully active and generate forces and torques that are way beyond the performances of currently available

devices on the market. Dedicated electronics and signal processing provide the high-quality control (refresh rate > 1kHz) required for credible force rendering.

Our haptic device can be integrated into numerous common HCI applications and advanced control interfaces, such as simulations, teleoperation and nanomanipulation. The impact of adding haptic information to these known systems is significant. It provides a better understanding of the environment being interacted with, and allows a more intuitive, thus faster and more efficient, manipulation. The end results are shorter task completion times, a steeper learning curve for the user, as well as a significant decrease in misinterpretations and manipulation errors.

The Delta Haptic Device (DHD) is currently used as a platform for further haptic developments. Dedicated haptic tools are being developed, and the integration of the device into a complete HCI architecture involving VR and reality sensing (active vision, …) is in progress. A spin-off company dealing with its commercialization is currently in the creation stage.

RESEARCH ON HAPTIC DEVICES

Haptic vs. non-haptic HCI devices

The most common HCI devices such as keyboards, mice and other pointers offer a passive, one-way interaction with the computer. The force from the user is used to move the device to a desired position. Thus, the human control-loop needs to be closed through a high-level sense, usually vision or hearing. These senses require interpretation and leave little attention to perform other tasks.

It is far more intuitive, though, to close one part of the human control-loop locally (i.e. directly at the user's hand), by exploiting the user's lower-level sense of touch. This gives him the opportunity to perform high-level tasks in parallel and concentrate on strategic decisions. The haptic channel then becomes bi-directional and the user gets to use the forces generated by the device as a straightforward, intuitive source of information.

The complexity of such force-feedback systems has a dramatic influence on their price and target market, and much of the recent work on haptic devices has not left the research labs. Over the last few years, 2 DOFs force-feedback gaming joysticks have become quite popular in

the low-end mass market, but their performance is rather limited.

In the high-end market, however, quite a few systems with up to 6 DOFs and improved performances are available. They split into several types of haptic devices, such as joysticks, pen-based devices, master arms, motion platforms, as well as hand and arm exoskeletons. A more complete list of devices is available at [21].

Haptic devices characteristics

The overall performance of such haptic systems is closely related to how convincingly the human sense of touch can be tricked. There are many functional components in a generic haptic device, which contribute to the overall system performance. The following summarizes what is admitted to be the minimum requirements for an optimal haptic device (referred to as "ideal").

- the *mechanical system* should have low inertia, high stiffness with low friction (force threshold) and no backlash (mechanically induced force discontinuity).

- the force *actuators* should enable back-drivability, offer a high dynamic range (ratio between the force threshold and the maximum output force ideally < 1-5% [10]), a sufficient maximum force (application dependant), a sufficient force output resolution (ideally < 0.01N [11] and < 0.003Nm [12]) and a sufficient force and torque precision (ideally < +-5% [13] for force and < +-10% for torque [14], not critical).

- the *position sensors* need to have a good position sensing resolution (ideally < 25μm [12], very dependant on control loop), and a sufficient precision (ideally < +-0.1 mm [15] and < +-1° [16], not critical).

- *force sensors* should be added as close as possible to the human user. When well tuned, they greatly improve the overall system performance.

- the *local control loop* must have a high frequency (10 to 20 times the force bandwidth [17] of the global control loop), to ensure (1) that vibrations are kept under a sensable level (higher than the maximum human sensitivity, which is between 40Hz and 400Hz [18], ideally > 1kHz) and (2) that control stability is achieved at the desired contact stiffness with the hardest virtual object.

- the *global force interaction* low-frequency loop, typically linked to a graphical environment, needs to be as high as possible (ideally > 20-30Hz [19]). A great effort has to be done in terms of simplification of the interaction with the huge amount of graphical information.

The design of a haptic device must take all of the above criterion into account. The use of transmission gears with high ratios is often problematic and leads to the choice of powerful motors (ideally to a direct drive transmission). If the cinematic structure of the device is a stack of single-degree-of-freedom linear or rotational stages (serial structure), inertia will become a critical issue.

Parallel cinematic structures are therefore preferred, as they allow fixing the motors off the mobile components of the structure. The price for using such configurations is the reduction of the workspace and the coupled geometrical and dynamical models, which make them complex to design and handle in real-time. As an example, for a 6 DOFs fully parallel structure, the translational 3D workspace where the entire three angular strokes are possible is drastically reduced.

DEVICE DESCRIPTION

Mechanics

The force feedback system we developed is based on the patented Delta structure [3] as presented in fig. 1. It is a parallel, articulated structure that provides three translational DOFs, and meets most of the requirements defined above for haptic devices. Its parallel architecture ensures a very small inertia, which is a critical element in rendering reality-like forces. One of its most interesting features is its geometric configuration (three double-bar parallelograms), which forces the nacelle to always be in a plane parallel to the base plane of the device. This makes it very easy to add a mechanical wrist onto the device, giving the haptic device as many as 6 active DOFs.
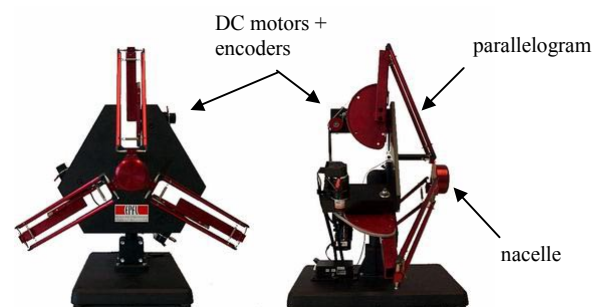

Figure 1 – Delta Haptic Device

As a consequence, the Delta structure decouples the translations from the rotations provided by the wrist. As it is much easier for a human user to first position a tool, then only choose its orientation, this decoupling makes the structure particularly suitable for a haptic use.

The wrist that was developed to provide the 3 rotational DOFs is based on the PARAMAT [20] structure, as illustrated in fig. 2. It is simply mounted onto the Delta nacelle.
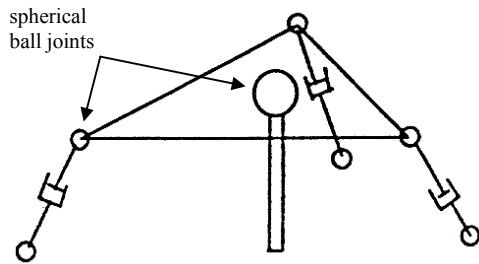
spherical
ball joints

Figure 2 – PARAMAT structure

Control

The haptic system controller includes a micro-controller board driven by a standard PC. A software library has been written to provide a straightforward access to the device encoders and to apply force commands. The link between the PC and the board was first established through the PC parallel port, but was then moved to a PCI I/O board for ease-of-use and portability reasons.

Also, a 6 DOFs force sensor has been embedded into the nacelle.

Figure 3 – Delta Haptic System

The Delta Haptic Device and its controller are presented in fig. 3.

Since the system can render important forces, a robust security layer had to be implemented to prevent any erroneous forces from being sent to the device, which could result in a hazardous situation for the user. A DSP controller was implemented into the Delta Controller and enforces the following safety rules (see figure 4):

- *check speed velocity* of the nacelle. If the speed goes beyond a given threshold, the controller cuts the power to the device motors and electromagnetic brakes are applied.

- *check structure position limits*. If the nacelle is set to an extreme position nearing the structure singularities, power to the motors is cut.

- *check PC Watchdog*. If the PC stops or fails to update the force at a minimum rate of 100Hz, the DSP controller cuts the power to the motors.

The Delta controller is monitored by its own watchdog. In case of a software glitch or malfunction of the controller board, the system shuts down and the brakes are automatically activated.
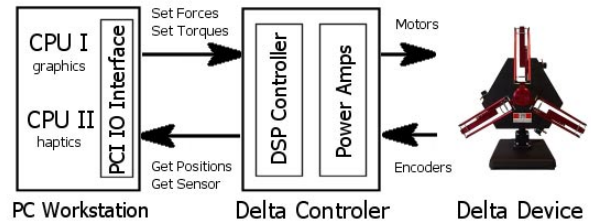

Figure 4 – control system overview

Virtual Reality

Over the last ten years, VR has encountered dramatic improvements, mostly due to the increase in computing power, leading to a new generation of graphic cards. As a consequence, richer and more realistic virtual environments can be rendered in real-time, with increasingly more complex physics modeling built in the virtual system behavior. Moreover, pseudo-real-time kernels make it possible to run complex simulations at a high refresh rate (> 25Hz) on off-the-shelf PC hardware.

We developed a proprietary 3D graphics engine that allows fast, complex simulations of flexible structures [7].

System integration

The 3D graphics engine can be coupled with the Delta Haptic System as well as other external sources of data. The VR world acts as a representation and field of action buffer between the user environment and the environment being interacted with (whether real or virtual). This buffer makes it possible to eliminate artifacts and unwanted effects such as update delay, relative precisions, … and to optimize the interaction between the system components (typically the bandwidth).

It is important to emphasize that in the context of haptic manipulation, VR is *not* a static representation of the environment. Multiple sources of data can be integrated to allow real-time update of the system, either on a global scale (describing the relations between objects in the environment) or/and on a local basis (describing each object properties). Dedicated techniques [6], [8] as well as classical approach (such as finite elements systems) have been implemented for this purpose, and this architecture is the center of further developments of the system.

PERFORMANCE AND APPLICATIONS

Performances

Table I shows some of the relevant technical specifications of the Delta Haptic System.

TABLE I : system specs

Property	Value
workspace	cylinder Ø360mm x 200mm +/- 20° for each rotation
force	25N
torque	0.2 Nm
resolution	< 0.1 mm (translation) < 0.04° (rotation)

As mentioned earlier, various software and hardware parameters influence the overall quality of the force rendering. The most important ones are evaluated below for the DHD.

- *the inertia of the DHD structure* is low, thanks to its mechanical configuration and material. Having the three motors fixed to its static base takes a big part of the credit for it. Backlash is also avoided through elastic preconstraints, preventing vibrations during control of the force/position.

- *the force range* is directly related to the motors size. The DHD can output a continuous force ranging from 0 to 25 N. Typically, users only map 20% of the full force capacity, the remaining being reserved for gravity compensation of the nacelle and its extensions. The major drawback of having bigger motors is the increase of mass and inertia, which is not critical in the case of a parallel structure like the DHD (since the motors are fixed, only the motor rotors do have an impact on inertia).

- *the 6 DOFs force sensor* added into the nacelle can measure forces and torques applied by the user; this data is then integrated in the control loop. The decrease in friction and inertia that resulted makes a significant difference from the user perspective.

- *the refresh rate* constitutes one of the highest challenges with haptic rendering. Our control architecture guarantees a data refresh rate above 1kHz. Our software applications run two asynchronous loops, ideally on two different CPUs, processing graphics and haptic rendering separately [9]. Unlike ours, currently available commercial libraries (Ghost, SensAble Technologies) offer such high refresh rates for static and non-deformable objects only.

Compared to other haptic devices on the market, the DHD offers, through a simple mechanical structure, high quality force-rendering with a large range of forces. This platform is dedicated in particular to research and industrial applications. By contract, other devices are usually designed for desktop application. They are more compact and easier to transport, but do not support custom extension modules (wrist, tool, gripper…)

Applications

Many HCI applications can potentially benefit from new interaction modalities. These either increase the awareness and understanding the human being has of the environment, or allow actions that would otherwise be impossible. The tactile modality can act as both an output to the human and an input to whatever environment or system it is used to interact with. The following examples illustrate how we used the DHD in order to make HCI more efficient and user-friendly.
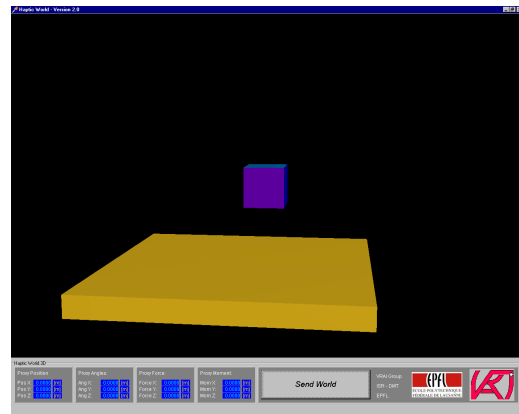

Figure 5 – virtual simulation

The first application that was implemented as a test bench for the device consisted in a VR simulation. The six DOFs of a virtual cube are mapped with the six DOFs of the DHD nacelle. The cube can then come in contact with a virtual plane, allowing the user to "feel" not only the contact impact and force, but also the torque imposed on the cube (fig.5). More complicated simulations have been developed, such as [4] and [6].

Another application that demonstrates the strong potential of the DHD in enhancing HCI is teleoperation. In the KoalaDriver demo [2], a DHD was used as an input device to rate-control the motion of a mobile robot (fig. 6). Infrared range sensors on the robot are mapped onto a virtual envelope that constrains the nacelle movement to the directions that are safe for the robot. When an obstacle is encountered, the system renders a force opposing the user command to go towards the danger. This simple scheme allowed novice users (schoolchildren) to safely navigate the robot in a complex maze without any collision, an operation that is very difficult with traditional teleoperation interfaces.
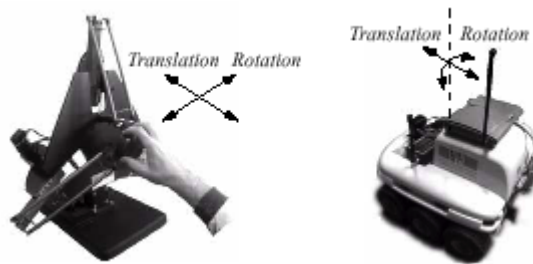
Figure 6 - KoalaDriver

Our recent research efforts are aiming at interfacing the DHD with an AFM (Atomic Force Microscope) in order to achieve nanomanipulation [5]. The AFM seems well suited for this application, as its probe is both a sensing device, and can be used as a nano-actuator. By including the DHD in the AFM control loop, we are able to sense the curve of the sample being studied. Also, at a later stage, we hope to make difficult operations at a nanoscopic scale, such as carbon nanotubes manipulation, possible. By allowing geometric scaling and force scaling, the DHD can make such an operation much easier and faster than traditional tools currently used to build small systems.

FUTURE PROSPECTS

Future development

The DHD is currently being used as a base platform for the development of haptic extensions such as pointing devices and grippers. Its parallel structure and its large payload make it particularly well suited for such plug-n-play add-ons.

Also, integration of the Delta Haptic System into a complete HCI system is under research. The system will consist of three key elements: the haptic device, a virtual reality environment, and an environment-sensing system (using active vision). This architecture will allow us to close the interaction loop between humans and machines by assuring the VR world be as close a match as possible to the sensed environment, making HCI straightforward and explicit.

The medical domain has shown a strong interest in haptic interfaces. There are several applications with which our device could prove helpful. It can be used either as a tool for minimally invasive surgery or surgery simulation, as in [1]. Moreover, it can also act as an input device to the physician in order to manipulate specific tools with a generic interface, or to perform delicate interventions with the help of VR modeling. At the same time, the high force the DHD develops is perfectly suitable for patients reeducation and movement recovery training. Several collaborations with academic and industrial partners are developing to develop medical applications.

Partnerships & spin-off

Several partnerships are going on between the VRAI group and other labs (Stanford, NASA Ames, National University of Singapore). The DHD generated very enthusiastic responses from visitors and partners. As there is an undeniable market for such a technology, a spin-off is being created under the name ForceDimension (www.forcedimension.com).

CONCLUSION

We have developed an innovative haptic device called the Delta Haptic Device that combines a parallel mechanic structure with dedicated electronic and software. Our device has 6 degrees-of-freedom and its performance in terms of workspace and applicable force and torque are beyond currently available haptic devices. The device can interact with a high-level virtual reality engine.

This haptic solution has been integrated into different fields of applications such as simulation of virtual objects, teleoperation of mobile robots and nanomanipulation. These applications demonstrate both the important contribution the sense of touch has in building efficient human-computer interaction applications, and the versatility of the Delta Haptic Device.

Our research effort for the near future will lead to the development of plug-in haptic tools that will enhance the application range of the device. At the same time, the haptic device will be integrated in a generic human-computer interaction solution involving virtual reality and environment sensing in real-time.

Several partnerships are being conducted, and a spin-off company is currently being created that will deal with the commercialization of the Delta Haptic Device.

ACKNOWLEDGEMENT

REFERENCES

[1] Baur C., Guzzoni D., and Georg O., "VIRGY, A Virtual Reality Force Feedback Based Endoscopic Surgery Simulator", *Proc. Medicine Meets Virtual Reality 6*, San Diego, CA, January 28-31, 1998 pp 110-116.

[2] Fong, T., Conti, F., Grange, S., and Baur, C., "Novel Intefaces for Remote Driving: Gesture, Haptic and PDA", SPIE 4195-33, *SPIE Telemanipulator and Telepresence Technologies VII*, Boston, MA, November 2000

[3] Clavel R., "Conception d'un robot parallèle rapide à 4 degrés de liberté " Thèse EPFL n°925, EPFL, 1991.

[4] Flückiger L., "A Robot Interface Using Virtual Reality and Automatic Kinematics Generator", *The 29th International Symposium on Robotics*, ISR 98 (Ed.), Birmingham, 1998.

[5] Kulik A., "Nanomanipulation of carbon nanotubes", CTI Projet n°4941.1, 1999.

[6] Conti F., "Déformation d'organes virtuels", Microengineering Semester Project Report, Swiss Federal Institute of Technology, Lausanne, Switzerland, February 1998.

[7] Conti F., "Deformation of virtual objects", MS thesis, Swiss Federal Institute of Technology, Lausanne, Switzerland, 1999.

[8] Grange S., "Vision-based sensor fusion for active interfaces", MS thesis, Swiss Federal Institute of Technology, Lausanne, Switzerland, 2000.

[9] Ruspini D., Kolarov K., Khatib O., "The Haptic Display of Complex Graphical Environments." *SIGGRAPH 97 Proceedings*, pp. 345-352, August 1997.

[10] Adelstein B. D., Rosen M. J., "Design and Implementation of a Force Reflecting Manipulandum for Manual Control Research", in Kazerooni H. (Ed.), *Advances in Robotics*, ASME, DSC-42, pp. 1-12, 1992.

[11] Srinivasan M. A., Chen J., "Human Performance in Controlling Normal Forces of Contact With Rigid Objects", in Kazerooni H., Colgate J. E., Adelstein B. D. (Eds.), *Advances in Robotics*, Mechatronics, and Haptic Interfaces, ASME, DSC-49, pp. 119-125, 1993.

[12] Rosenberg L. B., "How to Assess the Quality of Force-Feedback Systems", in Morgan K., Satava R., Sieburg H. B., Mattheus R., Christensen J. P. (Eds.), *Medicine Meets Virtual Reality - Interactive Technology and the New Paradigm for Healthcare*, IOS Press, Amsterdam, 1995.

[13] Tan H. Z., N. I. Durlach, Y. Shao, M. Wei, "Manual Resolution of Compliance When Work and Force Cues Are Minimized", in Kazerooni H., Colgate J. E., Adelstein B. D. (Eds.), *Advances in Robotics, Mechatronics, and Haptic Interfaces*, ASME, DSC-49, pp. 99-104, 1993.

[14] Jandura L., M. A. Srinivasan, "Experiments on Human Performance in Torque Discrimination and Control", in Radcliffe C. J. (Ed.), *Dynamic Systems and Control*, ASME, DSC-55, Vol.1, pp. 369-375, 1994.

[15] Tan H. Z., Pang X. D., Durlach N. I., "Manual Resolution of Length, Force, and Compliance", *Advances in Robotics*, ASME, Vol. 42, pp. 13-18, 1992.

[16] Tan H. Z., Srinivasan M. A., Eberman B., Cheng B., "Human Factors for the Design of Force Reflecting Haptic Interfaces", in Radcliffe C. J. (Ed.), *Dynamic Systems Control*, ASME, DSC-55, Vol. 1, pp. 353-359, 1994.

[17] Brooks T. L., "Telerobotic Response Requirements", *Proceedings IEEE International Conference on Systems, Man, and Cybernetics*, pp. 113-120, Los Angeles, CA, 1990.

[18] Shimoga K., "Finger Force and Touch Feedback Issues in Dexterous Telemanipulation", *Proceedings NASA-CIRSSE International Conference on Intelligent Robotic Systems for Space Exploration*, pp. 159-178, Greenbelt, MD, 1992.

[19] Shimoga K., "A Survey of Perceptual Feedback Issues in Dexterous Telemanipulation: Part I: Finger Touch Feedback", *Proceedings IEEE Virtual Reality Annual International Symposium*, pp. 263-270, Seattle, WA, 1993.

[20] Helmer P., "3D force-feedback wrist", MS thesis, Swiss Federal Institute of Technology, Lausanne, Switzerland, 2000.

[21] haptic community web page, Northwestern University, http://haptic.mech.northwestern.edu