IT potentialen hos haptik: Känsel ger tillgänglighet för människor med funktionshinder

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THE IT POTENTIAL OF HAPTICS

Touch access for people with disabilities

LICENTIATE THESIS

Abstract

Today, computers are important tools for blind people, but they are mostly used as text machines. The wide adoption of the Internet as an information channel has led to a minor revolution for people with visual disabilities by giving them access to information that was previously inaccessible. Graphical interfaces like Windows have made computers more accessible and easier to use for the majority of people. Unfortunately, the graphical interface is an obstacle rather than an improvement for people with visual disabilities.

Certec has been working on touch interfaces – haptic interfaces – since 1995, exploring the possibilities they can offer people with different kinds of disabilities. With a haptic computer interface, a blind person can play haptic computer games, learn mathematics by tracing touchable mathematical curves, and gain better access to graphical user interfaces like Windows.

This thesis attempts to condense experience and ideas that have resulted from our work, which began with the PHANToM (from SensAble Technologies Inc.) and now includes force feedback joysticks, the FEELit mouse (from Immersion Corp.), as well as other haptic devices. The differences between the 3D-haptics provided by the PHANToM and the 2D-haptics provided by the FEELit mouse are analyzed.

It is established that our early work on the PHANToM generated useful fundamental knowledge and a "head start in our thinking" which were of great use when we had the opportunity to try the FEELit mouse.

Three concept studies in the area of haptic Windows access are presented:

- FEELit Desktop from Immersion combined with synthetic speech and Braille for general Windows access
- Radial haptic menus to maximize the use of a small haptic devices
- A set of virtual haptic tools to be used as aids for searching disordered virtual objects like icons on the desktop.

A prototype of the FEELit mouse and pre-release software were used to implement test programs and to carry out a limited case study with two blind users. All of the concepts were considered to be useworthy as soon as the "teething troubles" and instabilities of the early implementations have been eliminated. The testers were very enthusiastic about the concept of haptics as a means of gaining better access to Windows in general and they had many ideas about possible uses for this kind of technology.

The results clearly justify further research, testing, and refinement of the use of haptics for computer access.

This licentiate thesis is based on the following papers:

The sense of touch provides new computer interaction techniques for disabled people
C. Sjöström, K. Rassmus-Gröhn
Article published in Technology & Disability (IOS Press)
Volume 10, Number 1, 1999

Using a Force Feedback Device to Present Graphical Information to People with Visual Disabilities
K. Rassmus-Gröhn, C. Sjöström
Short paper presented at the Second Swedish Symposium on Multimodal Communication, Lund, Sweden, Oct 1998

The Phantasticon – The PHANToM for blind people
C. Sjöström
Article presented at the Second PHANToM Users Group, Dedham MA, Oct 1997

To Use the Sense of Touch to Control a Computer and the World around You
C. Sjöström, B. Jönsson
Article presented at the AAATE conference, Thessaloniki, Greece, Sep 1997

KEYWORDS
Haptic, IT, Access methods, Disability, Windows, Blind, Mobile Impairment

Preface

One week before I finished this thesis I was on a weekend trip to London with my friends. Among other things we went to the Design Museum which was totally unknown for me up till then. The museum had put up an exhibition called "Design: Process, Progress, Practice". The exhibition was very inspiring and it talked directly to me as an engineer working in the field of design and rehabilitation engineering research. The following is part of the introduction to an essay collection published by the museum in connection to the exhibition:

When the Design Museum in London first opened its doors in 1989, it did so in both geographical and intellectual isolation. Now, ten years later, both the landscape and the mindscape have changed fundamentally. The quayside where the museum is situated is now in the most desireable parts of London, and design itself has become highest intellectual fashion. More important however is that the social environment also has changed over the years. Design is no longer only making things look esthetically pleasing. As we move into the 21st century we think that design must also take environmental and social responsibilities.

Later in the book I read these words in an essay by Richard Seymour:

Design is making things better. For people.

That is what I try to do in my daily work and in this thesis. I work with design for usability and useworthiness. I hope that the work presented here can make things a little bit better, that is why I want to be a designing engineer and researcher.

First of all I want to thank my life companion Marika Östman for supporting me during uncountable hours in front of the computer. You were of great help both directly and indirectly!

Special thanks to Bodil Jönsson, my guide and supervisor in the land of rehabilitation engineering research and to Kirre Rassmus-Gröhn, my workmate in the haptics group who has also become a very good personal friend.

My special technical thanks goes to Chris Hasser and Immersion Corp. who provided the prototype FEELit mouse and helped us in many different ways. And to Thomas Massie and SensAble Technologies Inc. for invaluable help and a wonderful spirit. I hope that you guys can stand being in the same paragraph, even though I know you are competitors on the haptic arena.

Thanks also to Ulf Larsson and Karin Jönsson at HADAR, as well as my test users Knut Thorstensson and Joakim Nordell. These people's knowledge about and experience of visual impairment has of course been very important.

Anna-Karin Batcheller has been of great help in making the text in the report much better. Karin Rehman made the layout. Thank you both!

Financial support for my work has been provided by KFB, the Swedish Transport and Communications Research Board. KFB is a central government authority whose task is to plan, initiate, coordinate and support overall research, development and demonstration projects. My project is supported within the Telematics Program that aims to ascertain the effects of the increased use of telematics, both for the individual and for society.

Contents

Introduction

Haptic computer interfaces are creating new ways of interacting with computers. Sound and graphics will be accompanied by virtual touch. Soon we will be able to *feel* our way around the computer desktop.

Certec has been working on touch interfaces – haptic interfaces – since 1995, exploring the possibilities they can offer people with different kinds of disabilities. With a haptic computer interface, a blind person can play haptic computer games, learn mathematics by tracing touchable mathematical curves, and gain better access to graphical user interfaces like Windows.

Fig.1. Marie, one of our first PHANToM testers.

HAPTIC TECHNOLOGY

Haptics is the science of applying touch sensation and control to interaction with computer applications. According to Merriam-Webster Online the word derives from the Greek *haptesthai,* meaning to touch. Haptic interfaces allow the user to touch and manipulate *virtual* objects, with the true "feeling" of the physical properties of those objects.

Psychophysicists define the tactile sense as a combination of touch, kinesthesis, and proprioception. Haptic is the term used to describe the dynamic combination of proprioception and touch.

In combination with a visual display, haptic technology can be used to train people for tasks requiring hand-eye coordination, such as surgery or maneuvers in hostile environments. It can also be used for games in which you both feel and see what is happening on the screen. For example, you might play squash with another networked computer user somewhere else in the world. Both of you can see the moving ball and, using the haptic device, position and swing your squash rackets and feel the impact of the ball.

Certec's haptics research began with the PHANToM, a research grade 3D haptic interface from SensAble Technologies Inc. We developed a set of programs for the PHANToM which demonstrated how haptic technology could be used by persons with visual disabilities. One of the first ideas we had was to create a haptic Windows system that would compensate for at least some of the obstacles faced by people who are blind when using a graphical user interface.

WINDOWS FOR PEOPLE WHO ARE BLIND

Windows has undoubtedly been a revolution for computer users. Its spatial graphical paradigm with menus, buttons, and icons unburdens the user from memorizing commands and reading long sections of text on the screen. Windows is designed to be explored: when you see it you will understand it. A sighted user can remember that the Start-button is in the lower left-hand corner or place an icon in a certain location on the desktop and quickly find it using a cognitive map of the desktop. Another feature of graphical user interfaces is that they allow a user to manipulate objects directly. For example, one can move a file from one folder to another by dragging the icon from one window to a second window.

The drawback is that Windows makes the computer harder to use for a blind person. The structure of the computer system is represented by pictures, and if you cannot see the pictures it is very hard to grasp this underlying structure and it becomes hard to use the computer at all. Nevertheless, despite the fact that they are unable to take advantage of all the benefits that Windows offers a sighted user, many blind users prefer Windows to older computer systems.

Most blind computer users use a screen reader that gives them access to text on the screen via either synthetic speech or a Braille display. With a haptic interface, it is possible to access at least some of the graphical interface elements, and that in turn will enable users with visual disabilities to benefit more from their computer system.

THE POTENTIAL OF IT

Information Technology and its applications have already given people with different disabilities many new opportunities. IT can actually wipe away a major part of the handicap that is often assumed to be inescapable for a disabled person. With e-mail for example, I can communicate with my friends and colleagues without thinking about whether or not they can see. As long as we use plain text we can communicate on almost exactly the same terms. With better IT and better IT accessibility it will be possible to extend the area where people can interact regardless of disability. Haptic user interfaces are an important IT potential that will probably become better known and more widely used in the near future.

Another potential area to be explored is haptic robot control. Certec has been working for many years on robots to help physically disabled people, and this is still an important part of our work. One of the problems faced by a disabled user is how to control the robot. It must be done with precision, accuracy, and without taking a long time. It is important to enable a user to move a robotic hand freely in order to reach areas that he cannot reach on his own. When it comes to this kind of free control a haptic interface like the PHANToM can be a great help. It gives a natural conversion between the movements of the hand and the movements of the robot, and it also gives feedback so that you can feel what is happening. Many robotics experts say that force feedback is essential to good robot control in these cases. An extra feature of using virtual touch for the feedback is that it becomes possible to use personalized settings to control the size of movements and the force exerted to the finger.

Background

Fundamentals of virtual haptics

In order to explain the fundamentals of virtual haptics I will start by describing the operation of the PHANToM. I have chosen this approach because the PHANToM was the first haptic interface we used and because it has a very transparent and straightforward design.

With the PHANToM, the user puts one finger in a thimble connected to a metal arm. By moving his finger around, the user can feel virtual three-dimensional objects that are programmed into a computer. Moreover, he can control the computer in the same way as if the PHANToM were a mouse or a joystick.

When activated, the PHANToM coacts with the computer to interpret the user's finger position in three-dimensional space and to apply an appropriate and variable resisting force. Three sensors track the position of the user's fingertip and this position is read by the computer. In the software, the position is compared to the boundaries of all objects in the haptic scene. If the user is not close to an object, the calculated force is zero, but if the fingertip is in contact with an object, the computer calculates a force that pushes the finger back to the surface of the object. The actual force that can be felt is provided by three DC-motors.

This process is carried out 1000 times per second. The high frequency and the high resolution of the encoders enable a user to feel almost any shape with a great deal of realism [Massie, 96].

Fig.2. The PHANToM and a close-up of two motors

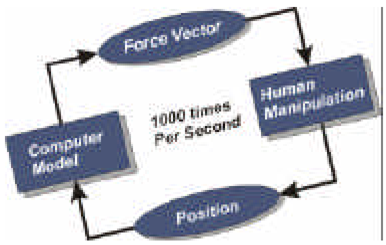


Fig.3. The control loop

Point interaction haptics

The basic method for calculating forces for the interface is based on point interaction. This means that the user is modeled as a single (infinitesimal) point in the virtual world. This is obviously a simplification but it is still a very common method since it makes the computations simpler while it still affords a very good haptic illusion.

The simplest version of point interaction starts by measuring how far into the object the user point is located. The force is then calculated as a constant (the stiffness) times the distance. This is repeated for each object in the virtual world and the force applied to the user is the sum of the force of each object.

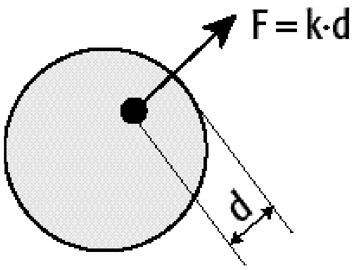


Fig.4. Simple point interaction

The next step for refining the algorithms is to introduce a velocity term (the damping of the virtual material). Now the force for each object is calculated as:

$$F = k_1 \cdot d + k_2 \cdot v$$

The velocity term ensures that objects that feel hard when tapping them on the surface.

Many other enhancements are included in the programs that are in use today. Most of them are built into software developer kits, so the ordinary programmer does not have to bother about all the details. Instead, he can build the virtual world by adding primitive objects or effects to a "scene" and by giving the objects different properties.

One of the big problems with point interaction is that the objects exert no force at all if the user does not touch them. This means that one can come very close to an object and still feel nothing. This is no big problem if the haptic interface is used in combination with graphics. However, if no graphics are available it can be a real problem since searching a virtual world becomes unnecessarily complicated. See "Rules of thumb for point interaction haptics" for a more detailed discussion of this problem.

Existing haptic displays

At Certec, our work has involved the PHANToM, the FEELit mouse, and two different force feedback joysticks. The following is a very brief description of those devices as well as some other devices that are in use today.

THE PHANToM

The PHANToM is a high-end force feedback device from SensAble Technologies. It has 3 full degrees of freedom and is available in several different models. The PHANTOM device is the result of work carried out at MIT and it is unique in that it allows the user to feel the properties of virtual 3D objects with much higher fidelity and at a much lower cost than previous force feedback devices.

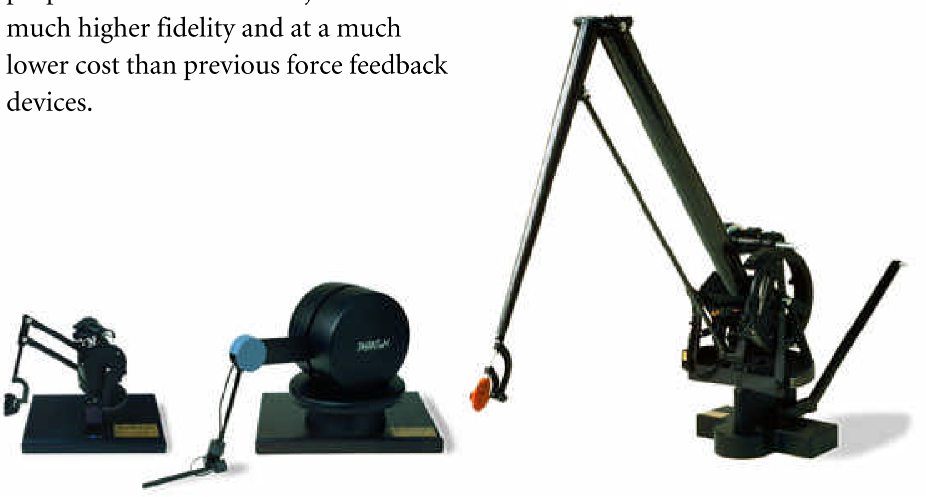


Fig. 5.The PHANToM: version 1.0, 1.5 and 3.0. SensAble Technologies Inc.

Specifications for the PHANToM 1.0:
Nominal position resolution: 0.03 mm
Workspace: 13 x 18 x 25 cm
Maximum exertable force: 8.5 N
Interface: PCI or ISA interface card
Approx. price: 18,700 USD
http://www.sensable.com/

THE FEELit MOUSE/WINGMAN FORCE FEEDBACK MOUSE

The FEELit mouse is a 2D haptic device intended as a mass-market product, and as such it must be inexpensive. It has a smaller work area than the other devices and can only exert a fraction of the force that can be felt with many other devices. Immersion justified force feedback for the mass market by emphasizing benefits like increased targeting speed in Windows and better ergonomical factors. But the mouse now being introduced by Logitech is mainly marketed as a device that gives an added dimension to strategy games, etc.

Fig.6. (left) The FEELit Mouse. Prototype from Immersion Corp./ Logitech.

Fig.7. (right) Logitech Wingman Force Feedback Mouse, the commercial version of the FEELit mouse

Specifications for the FEELit mouse
Workspace: 1,9 x 2,5 cm
Maximum exertable force: 1 N
Interface: Serial
Approx. price: 100 USD
Wingman Force Feedback mouse comes with a USB interface
http://www.immersion.com/
http://www.feeltheweb.com/
http://www.force-feedback.com/

PENCAT/PRO

PenCAT/Pro is a 2D haptic device with a pen manipulandum. The PenCAT/Pro is aimed at 3D designers, artists and CAD users, but the first models (called pantographs) where designed to be used in a haptic user interface for people who are blind. Haptech also has software called TouchDesktop that adds haptic interaction to Windows. The PenCAT/Pro is not yet available to the end user.

Fig.8. PenCAT/Pro from Haptic Technologies Inc.

Specifications:
Nominal position resolution: 0.002 mm
Workspace: 10 x 1o cm
Maximum exertable force: 3 N
Interface: RS232 serial cable
Approx. price: 1000 USD
http://www.haptech.com/

THE MOOSE

The Moose was designed by Brent Gillespie and Sile O'Modhrain at CCRMA at Stanford University.

The Moose is designed to work as a haptic mouse with a medium size workspace (about 4x4 cm). It is intended for people with visual impairments. The manipulandum is coupled to two linear voice coil motors through two perpendicularly oriented flexures. This setup makes it easier to write programs for the device, since there is no need to convert coordinates between cylindrical and ordinary coordinate systems as with most of the other devices. This is still a pure research interface and it is not commercially available.

Fig.9. The Moose.
CCRMA Stanford University

Specifications
Nominal position resolution: 0.0017
Workspace: 3.8 x 3.8 cm
Maximum exertable force: 6 N
Interface: IO card

http://www-csli.stanford.edu/arch/
http://www ccrma.stanford.edu/~sile/moose.html

THE VIRTUAL REALITY MOUSE

The Virtual Reality Mouse (VRM) is a 2D haptic device with a standard 3-button mouse as the manipulandum. The VRM was constructed in 1995 as a haptic mouse mainly intended for people with visual disabilities. There are programs for the VRM that enable a user to feel objects on the Windows work area. Software for Windows 3.x and Windows 95 is available.

Fig.10. The Virtual Reality Mouse. Control Advancement Inc.

Specifications
Workspace: 8.9 x 6.7 cm
Maximum exertable force: 9.1 N
Interface: ISA-card

http://www.synapseadaptive.com/controladv/virtual%20reality%20mouse.htm

FORCE FEEDBACK JOYSTICKS

These devices are intended as pure gaming devices with a home user price tag. However it is possible to make special programs for force feedback joysticks that can be both educational and fun for blind children [Johansson, Linde 1998].

Fig.11. Microsoft SideWinder Force Feedback Pro. Microsoft, Logitech and many others

http://www.force-feedback.com/
http://www.microsoft.com/sidewinder/devices/FFBpro/

CYBERGRASP

The CyberGrasp Haptic Interface for the whole hand is constructed as a force-reflecting exoskeleton that fits over a CyberGlove and adds resistive force feedback to each finger. The grasp forces are exerted via a network of tendons that are routed to the fingers and can be programmed to prevent the user's fingers from penetrating or crushing a virtual object. There are five actuators, one for each finger.

With this device it is possible to get the sensation of grasping an object instead of touching it. Thus, unlike the other devices, CyberGrasp does not use single point interaction. The technology is impressive, but it still does not give a realistic sense of grasping and it is not possible to represent as many different shapes as one might wish.

Fig.12. CyberGrasp. Virtual Technologies Inc.

Specifications:
Maximum exertable force: 12 N per finger
Interface: RS-232 or Ethernet
Approx. price (April 1998): 45,000 USD

http://www.virtex.com/

OTHER HAPTIC DEVICES

There are many other haptic interfaces in use in laboratories around the world. An overview of some of them can be found in the photo gallery of the "Haptics Community Web Page":

http://haptic.mech.nwu.edu/intro/gallery/

Virtual Interaction

To understand why virtual haptics can be useful it is necessary to understand that virtual haptics is not only a virtual representation of a real object. An apple will always feel more real when one touches it in real life. The potential of virtual haptics lies in the possibilities that come with the fact that all the normal laws of physics must be programmed into the virtual world. If they are not programmed they will not exist!

Consider this list of property pairs that can be represented using virtual haptics:

Static objects	⇔	Dynamic objects
Real things	⇔	Abstract things
Bigger scale	⇔	Smaller scale
Controlled movements	⇔	Free movements
Controlling	⇔	Sensing and touching

Material properties are variable: it is possible to change the stiffness, damping, friction, attraction, density, etc. at any time.

Static/dynamic objects

refers to the fact that objects in a virtual world can be fixed in one position or they can be moveable. If you want gravitation you add it to your dynamic model. If you want your objects to be levitating you can set the gravitation to zero.

Real/abstract things

refers to the fact that the objects in a virtual world can be representations of real objects or something purely imaginary.

Bigger/smaller scale

refers to the fact that it is possible to change the scale or size of the virtual objects at any time. It is also possible to represent a real object virtually on a larger or smaller scale.

Controlled/free movements

refers to the fact that it is possible to let the user move around freely in the virtual world, but it is also possible to guide the user or to restrict his movements to a predefined path.

Controlling or sensing

describes what the user can do in a virtual environment. He can move around just to feel what is there, but he can also use the environment as a means of controlling and giving commands to the computer (or to a device that is connected to the computer).

Moreover, it is possible to change material properties at any time. One of my favorites is a haptic sculpting program from SensAble which enables a user to sculpt things in virtual clay. Since the clay is virtual it is possible adapt its properties to suit each manipulation situation. For example, if you want to knead something, the clay should be quite soft but you can also choose to make the clay very hard if that is what you want.

The possibilities that come with virtual haptics can be compared to the advantages of using a drawing program instead of pen and paper: with virtual technology it is possible to try something and then undo it if the result is not satisfactory. One can make different versions of an environment without changing the original. It is possible to share information across digital networks etc. Virtual haptics can be very useful even if the representation does not feel very realistic.

Point interaction haptics vs. ordinary touch

The most important and obvious difference between point interaction virtual haptics and real touch is that in the first case the user has to sense the environment through a single point while in the latter case it is possible to use the whole hand. One can compare virtual point interaction to sensing and touching objects in real life with a tool (for example a screwdriver) or with a finger in a metal thimble.

Structures and other surface properties cannot be felt directly. However, it is possible to simulate structures rather well when the user is moving. Movement is used in all kinds of touching, even in the real world, but in virtual point interaction haptics, movement is even more important because without movement the information transfer is limited to a single force vector.

Another aspect of virtual touch is that the serial nature of the information flow makes it harder to reduce to the raw input information to something that is useful. Becoming aware of objects in the virtual environment and making a mental picture of them requires a cognitive process. It is also possible that this serial information must be handled at a higher level of consciousness than the corresponding information obtained through real touch.

Computer access and its relevance to people who are blind

Computer access and the wide adoption of the Internet as an information channel have led to a minor revolution for people with visual disabilities. The net provides access to information from the media, from public and private organizations, etc. – the kind of information that used to be inaccessible to people with visual disabilities. Accessible computers with an Internet connection have created a new way of communicating with the rest of the world. Shopping is only one of the many things that are so much easier to do on the Internet than in real life for a person who is blind.

As mentioned above, most blind computer users use a screen reader that gives them access to text on the screen via either synthetic speech or a Braille display. People with partial visual disabilities use a bigger monitor and/or an enlargement program. Any text that is available in digital form can be read by a blind person with a computer and the necessary peripherals. This is done in real time and, in addition to being much more flexible, it saves space compared to books with Braille text on paper. But, at present, that is about as good as it gets for computer users with visual impairments.

Nowadays there is a strong emphasis on documents with graphics, and increasingly so on the Internet. These graphics are completely inaccessible to blind websurfers. However, it is possible to define an alternative text in the HTML-document, explaining what the picture shows, but these texts are sometimes omitted because of a lack of awareness about the benefit for blind users.

TWO GROUPS OF USERS

Even though most blind computer users have the same kind of adaptive tools (synthetic speech and Braille displays) there is a difference in the way they are used. The first group, also the biggest according to professionals at HADAR [Jönsson, Larsson 1999], use a pure linear text translation of Windows and navigate mainly with the keyboard buttons. This approach gives a poor understanding of the spatial dimension of Windows. It is a one-dimensional version of Windows that fits very well into the limitations set by today's adaptive devices, but it does not mirror the whole truth of what is shown on the screen.

This kind of user will keep his hands on the keyboard or the Braille display all the time. The mouse is not used at all.

The other group of users use the mouse in some special cases. Most of the work is still done with the hands on the keyboard, but sometimes these users find the mouse useful even though they cannot see the pointer. This maneuver requires a different setting of the screen reader so that it displays whatever the mouse is pointing at. It may also be helpful to have a mouse tracker that indicates the cursor position by giving different tones.

These users are aware of the spatial dimension of windows and they are usually able to think in terms of left/right and up/down in a computer environment. Most likely, these are the users who will be the first to embrace haptic technology in Windows environments.

Previous and ongoing research – various approaches

There are many interesting research projects around the world dealing with access to graphical user interfaces. Historically, most of the research has focused on access methods using sound and other non-haptic means of interaction. However, haptic computer access is gaining ground and is now available in a more than one flavor. A short review of some of the research projects in this field is given below.

ON THE RESEARCH LEVEL – WITH HAPTICS

The Adaptive Technology Research Centre at the University of Toronto is running a project aimed at developing software applications that make it possible to deliver curriculum that can be touched, manipulated, and heard via the Internet or an intranet [Treviranus, Petty 1999]. According to information provided by the Centre, software tools, as well as exemplary curriculum modules will be developed in the project.

Immersion Corporation – the developers of the FEELit Mouse – also has an ambitious research approach that includes the use of haptic interfaces for people with visual disabilities. Papers from L B Rosenberg [Rosenberg 1997] and others at Immersion focus on the use of force feedback sensation to enhance user interaction with standard graphic user interface paradigms and force feedback in medical simulation. The intended users are computer users in general, but Immersion is also working on special adaptations for people who are blind.

J. P. Fritz and K. E. Barner have been working on a Haptic Visualization System for People with Visual Impairments at the Department of Electrical and Computer Engineering at the University of Delaware [Fritz, Barner 1999] since the early days of the PHANToM. The project has involved many different kinds of data visualization methods using haptic technology. The main focus of the project is thus not on haptic user interfaces but on another *very* important use of virtual haptics for people with visual disabilities.

C Ramstein is one of the pioneers in haptic user interfaces for people with visual impairments [Ramstein et al 1996]. His work involves multimodal interfaces in several ways. The haptic information is combined with both hearing and Braille technology. Ramstein is now the head of Haptic Technologies Inc. who manufacture and sell the PenCAT/MouseCAT and TouchDesktop systems.

BT Labs is investigating the use of a haptic display used in conjunction with VRML, the emerging standard for display of 3D graphics on the WWW [Hardwick, Furner, Rush 1998]. The work is based on experience gained from developing a browser capable of driving a force feedback probe from a VRML file. The purpose of this work is to identify potential solutions to the problem of access for visually disabled people before the methods of 3D presentation of images become immutable. The work at BT Labs is done in cooperation with the Department of Psychology at the University of Hertfordshire, UK [Colwell, Petrie et al 1997].

ON THE RESEARCH LEVEL – WITHOUT HAPTICS

E. D. Mynatt has been working with the transformation of graphical user interfaces into auditory interfaces for blind users in many different projects [Mynatt 1997]. Her papers discuss major interface design issues for access systems, and she has made an abstraction of graphical user interfaces that is eminently useful also in haptic interface work.

My work is closely related to all the projects mentioned above. At Certec, we have been interested in haptics as a way to get access to graphical user interfaces for many years, and we have also been looking into haptic maps, games, mathematics etc. I think that what is proposed in this thesis can be compatible and enhancing to any haptic user interface, regardless of what hardware or software base is used.

Designing haptics for IT potentials

Design is concerned with the interaction between needs, ideas, visualization, form, the environment, financing, planning, production, user trials, end use, and the utilization of experience. Design involves both the process – an iterative and partly non-sequential interplay between the individual and the evolving artifact – and the results of the design process and their effect on the individual during the use phase. Rehabilitation Engineering Research has a great deal in common with, and can be seen as a subset of, design research [Jönsson, Anderberg 1999]. Its focus is on design for *usability and useworthiness* in a (re)habilitation context [Eftring 1999].

The design process

Design requires reflection-in-action. It does not remove people, objects, or events from their context in order to study them separately. Donald Schön's *The reflective Practitioner* from 1983 is an important milestone in the evolution of design as a science [Schön 1983]. In the book, he analyzes structures for reflection-in-action and the fact that design problems seldom are defined by the surrounding world. Moreover, it is usually not possible to work from a technical specification. Instead, problem descriptions must be constructed from the situation in question, preferably using technology as a language.

My work has developed in accordance with this method. By creating computer programs for testing the three-dimensional PHANToM and its useworthiness to people who are blind, I gained experience of haptic interfaces. I put this experience to use when working with 2D haptics and, in a difficult situation with only one FEELit mouse prototype available, I had to rely on my experience as a reflective practitioner since I had to be a test user as well as designer.

I have made not insignificant progress, and the circle of stake-holders has been extended by cooperating with people who are blind and deaf (Mogård Folk High School and Resource Center, Finspång, Sweden), people with mobility impairment (Furuboda Folk High School and Resource Center, Åhus, Sweden) and practicing hand surgeons (Sahlgrenska University Hospital, Göteborg) who are interested in restoring or improving their patients' sense of touch.

Outline of my complete work

The work presented in this thesis can be summed up as follows:

First, I attempt to structure the experience we have gained from using the PHANToM. This section includes an analysis of the difference between real and artificial touch, and how this difference can be used in a constructive way. Next, I list a number of rules of thumb that we have established with regard to point interaction haptics. I also analyze the differences between the 3D-haptics provided by the PHANToM and the 2D-haptics provided by the FEELit mouse, and what this difference means for different applications, the user, and the possibility of transferring ideas from one environment to another. I value the results from these analyzes just as highly as the more direct results in the form of technical implementations.

I conclude the first section with a set of thoughts and ideas about virtual haptics use especially for people with visual disabilities.

In the second section, I use the knowledge gained, applying it to the FEELit mouse. I have not yet had the possibility to test all the ideas mentioned, but I have made programs and carried out tests on a few of them. In the tests, I used a prototype of the FEELit mouse and pre-release software to:

1. Combine FEELit Desktop with synthetic speech for general Windows access
2. Develop “radial haptic menus”
3. Construct a set of virtual haptic tools that can be used as aids for searching disordered virtual objects like icons on the desktop.

Of these, the first is an example of direct translation from graphics to haptics. FEELit Desktop from Immersion is a program that makes a direct translation of many graphical interface objects to corresponding haptic objects. My work has been to try to determine how well FEELit Desktop can compensate for things that are not made accessible by the speech synthesizer.

The other two tests are examples of what can be accomplished when haptics is used more on its own terms. The radial menus are menus where the choices are indicated as rays pointing out from a center instead being arranged in a column as in ordinary linear menus. There are several reasons why it is likely that this kind of menu works better in a haptic environment, especially when using a device with a small workspace.

The search tools are intended to help the user when he is exploring an unknown environment, for example the Windows desktop on somebody else’s computer. I propose three different search tools but, so far, I have only had time to implement the first one:

- A “cross” that makes it possible to feel when you line up with an object horizontally or vertically.
- A “magnet” that pulls the user towards the nearest object.

- A “ball” that makes it possible to feel objects at a distance but with less detail.

With these tools it is possible to feel objects without touching them directly.

I have carried out a limited case study of the usability and usefulness of these tools involving two blind computer users. Unfortunately, because we only had one FEELit mouse, these tests are very limited in both time and depth.

What the PHANToM and other devices taught us

We have been using the PHANToM and other haptic devices since 1995, but until now we have not written a comprehensive summary of what we have learned during this time. The following is an outline of the knowledge we have acquired through our experience with the PHANToM which I hope will prove useful to anyone who is working in the field of haptic interfaces for people with visual disabilities.

NAVIGATION WITH VIRTUAL TOUCH

One of the interesting things about haptics in computer interfaces is the navigation possibilities it creates. Our “Memory House” project was a test of how well virtual haptics support navigation in an unknown environment. This and many other informal tests have given us a good basis for understanding haptic navigation in a virtual world. We have found that the following factors influence how well a person is able to manage when using this kind of navigation:

- Movement is vital – the movements must be of appropriate magnitude and speed. This also influences the choice of interaction tool (the manipulandum). Finger movements often provide a better haptic image than hand movements.

- It is important to use the right amount of force. In this case, too, it is important to move the right part of the body. Since the finger/hand/arm do not have the same strength and precision they do not provide the same experience.

- Motor skills are as important as the sense of touch. This follows from the points listed above but, in addition, practicing motor skills can lead to improvements in the sense of touch.

- It is important to be systematic and to use tactics when exploring a virtual space.

- By practicing and concentrating a user can significantly improve his ability/experience. It is interesting to note that practicing in a virtual haptic environment should create optimal conditions for conditioning. This follows from the fact that conditioning requires consistent, evaluating feedback and, in a haptic environment, the feedback is provided through the same channel as the rest of the exchange of information. This type of practice is thus different from other types of practice because haptics allows the flow of information to take place via the same channel both to and from the user.

- It is entirely possible to compare a total haptic experience with previous memories of touching, sensing and also seeing. (This may not apply to all users who tested the PHANToM, but at least a number of the test users had this experience.)

DIFFERENCES IN HAPTIC ABILITY

In the course of the PHANToM user tests we noted that the ability to handle virtual touch varies considerably between individuals. One might think that because a person is blind she will automatically be better at using her sense of touch, but we found no such connection. In particular, we noted that there are major differences in blind children in terms of their ability to use virtual haptics.

The reasons for this difference have not been established, but we have distinguished some important parameters. Our findings are based on an analysis of touch and virtual touch similar to the one I described above, as well as on an analysis of our tests involving the Memory House [Sjöström 1997]. To date, we have identified the following parameters:

- Motor skills
- Ability to concentrate
- Ability to interpret tactile sensations

In addition, it is reasonable to assume that differences in the tactile system of receptors and nerves affect the ability to perceive virtual tactile sensations.

It is important for designers of haptic interfaces to be aware of this difference. We found that the effect of the differences in haptic ability is much greater than the effect of, for example, differences in visual acuity in ordinary (sighted) computer users.

The ability to concentrate and, to some extent, motor skills vary not only between users but also over time for the same user, who may thus find that his haptic ability varies from day to day. Consequently, in order to achieve the best possible haptic experience, it is important not to disturb the user's concentration or motor function unnecessarily.

Finally, we would again like to emphasize the importance of practice. A person becomes better at using haptics after practicing for a while, presumably because of improvements in all three characteristics mentioned above.

RULES OF THUMB FOR POINT INTERACTION HAPTICS

- Provide well defined and easy-to-find reference points in the environment. This is necessary to facilitate navigation.

- With pure one-point haptics it is easy to miss an object even if one is really close to it. It is thus important to compensate for this when designing haptic software by using, for example, an enlarged interaction point, magnetic objects, or different surface characteristics.

- It can be just as difficult to determine that an object does not exist as it is to find an object. It is always easier to move along some kind of "path" to the location where the object is located or where there is no object. Such a path can also be designed as a virtual tool that follows the user. It is also useful to tell the user what to expect in order to speed up the search in an unknown environment.

- Although it is not necessary for the haptics to be true to life, it may be helpful (and sometimes essential) to help the user follow the outline of the object. For example, it is easy to make a thin touchable hose easier to find by giving it the appropriate attractive force. Without such a force it is almost impossible to feel the hose in 3D.

- In order to make objects easy to find they must capture the user's movement in some way. One way is to make them, for example, large or long. Alternatively, something else must guide the movement, for example, an attractive force or a path as described above.

- Sharp edges and corners that can be felt from the "outside" are much more difficult to feel and understand than rounded shapes. The user almost always loses contact with the object when moving past a corner, thereby disturbing the cognitive process that translates the impressions received into an inner picture. Moreover, it is difficult to determine the size of the angle; many users believe that the angle is more acute than it really is. This also means that a direct translation of VRML models is not satisfactory in a haptic environment for people who are blind. It is at least necessary to even out the edges, and/or use normal interpolation to minimize the problem of sharp edges.

- When going through a thin wall or past an edge, the finger often accelerates a great deal. Consequently, the next wall or edge cannot be very close since there is a risk that the finger will go through that as well (sometimes without the user noticing). It may thus be better to indicate the center of each area rather than the borders between the areas. The problem becomes apparent when one wishes to represent menus and coordinate systems.

- The feeling is not the same when moving in different directions even if the haptic characteristics of the program are the same. This is because the joints and muscles involved are not the same.

- When an object is moving very slowly, it is not possible to sense that motion. The motion will not become noticeable until the object has moved a certain distance. This can be compared to when an escalator's handrail is moving just a little bit too fast in relation to the escalator. You will not notice that this is the case until your hand is a bit ahead of yourself. This effect can for example be used to provide a sensation of jumping between different planes without using too much space in the vertical direction [Miller, Zeleznik 1998]. (See picture).

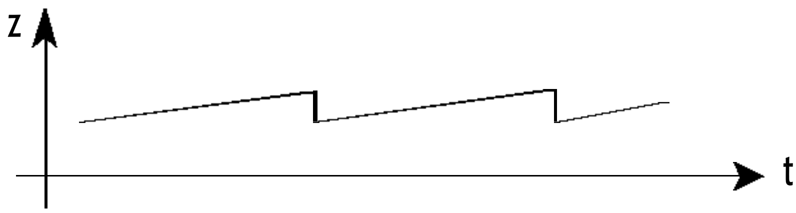


Fig.13. Slow versus fast movements, only the vertical steps are noticed by the user.

MANIPULANDUM DESIGN

The manipulandum is the tool that the user grasps in his hand. In the PHANToM, the manipulandum is a stylus or a thimble. In the FEELit mouse, it is the mouse-body itself. The choice of manipulandum can affect the haptic sensation a great deal since the force distribution to the user and the movements are different in different manipulandi.

Examples of manipulandi

Manipulandi that are in common use today include:

- A thimble
- A pen
- A joystick handle
- A mouse

The form and surface of the manipulandum have an effect on how the force is applied to the user, the kind of movements used, and the feeling of being in contact with the virtual object. For example, a thimble with sandpaper on the inside causes many people to use less force when grabbing a virtual object because they get the sensation that the objects are less slippery [von der Heyde 1998]. This is true even if the friction in the computer model is the same as when using a thimble without sandpaper.

Different manipulandi versus workspace size

Many of the blind users who have tested the FEELit mouse complain about two things: it is too weak and the workspace is too small. They say that they have to be very careful since the virtual objects are so small. My suggestion is that if it is impossible to provide a larger workspace, a smaller manipulandum would make the device easier to use.

Research and design experience supports this view. In an experiment studying the dexterity of the test subjects when manipulating an object in the hand, Zhai found that they were able to position the object more accurately when grasping it with their fingertips rather than the whole hand [Zhai, Milgram 1998]. Cutkosky and Howe have presented a human grasp classification comprising two general classifications: power and precision [Cutkosky, Howe 1998]. Precision grasps involve the fingertips, while power grasps involve the whole finger and the palm. This is also in line with our experience of using different manipulandi with the PHANToM.

A computer mouse forces the user into a power grasp for what is essentially a precision task since the mouse must be grasped with the whole hand. This is not experienced as a big problem for a sighted user since he can compensate with vision, but for a blind user it can degrade performance significantly.

Manipulandum design is crucial to a user's acceptance of a haptic device and to his performance when using it. A manipulandum for a small workspace haptic interface must accommodate some form of fingertip grasp. This grasp could use one, two, three, or more fingers. It must allow the user to move throughout the workspace with precision and speed while minimizing awkward postures. It must ensure that the sensitive portions of the finger pad remain in contact with it. It must encourage a grasp that is not just precise, but robust to disturbance forces. And finally, it must allow the user to activate the buttons similar to the mouse buttons without degrading manipulation precision.

Our tests show that PHANToM users work differently when they are using the pen-shaped stylus instead of the thimble. It can be argued that with the thimble a user may believe that feeling is the same as in real life, which is not true. With the stylus it is obvious to the user that what can be felt virtually is not completely the same as what he can feel with his hand. However, many users feel that they perform better with the thimble, which is probably because the thimble encourages finger movements while the stylus requires hand movements. This transition from finger movements to hand movements also amounts to a slight transition from precision to power.

I would argue that full hand manipulation via a mouse or a pen not only requires more power, it also requires a larger workspace to preserve a reasonable level of precision.

With this in mind, I have come to the conclusion that one very important objective with regard to haptics in computer interfaces is to find an optimal manipulandum for a haptic device with a fairly small workspace. The manipulandum should encourage finger grasp and movement as much as possible in order to maximize manipulation speed and precision. Moreover, the device as a whole must provide good palm support and the workspace should be reachable almost without lifting the palm from the support.

What is the optimal size of the workspace?

In order to establish the optimal workspace size, I decided to make a simple experiment. I put a pencil tip in a rubber fixture (a self-adhesive rubber foot), which I taped to my index finger. With my hand resting on a sheet of paper, I moved my finger around in a way that felt natural. This simple test gave the following picture:

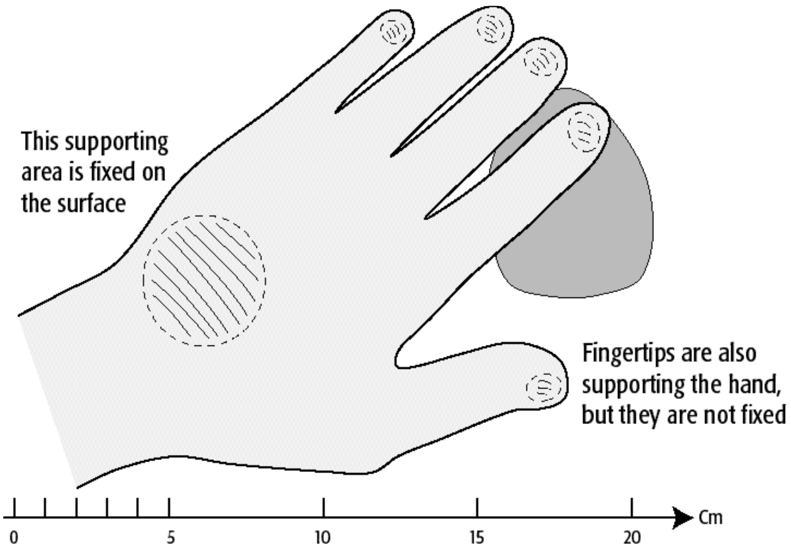


Fig.14. Hand with index finger movements marked

According to my theory, the optimal workspace for my left hand is about 7 x 6 cm. The picture also shows that a rather large support area is needed. The distance from the fixed support area of my palm to the fingertip is about 20 cm. One must also keep in mind that all the fingers support each other in a precision task, which means that it must be possible for all the fingers to rest on the supporting surface without disturbing the interaction.

I hypothesize that a small workspace 2D force feedback interface can be useful to a blind computer user. Further, I hypothesize that using a manipulandum that allows for a precision fingertip grasp rather than a full hand grasp will enhance manipulation and sensing performance.

- Haptic devices that use finger grasp and encourage finger movements enhance manipulation precision and performance.
- A haptic device with a workspace size fitted to what can be reached using (almost only) finger movements maximizes manipulation speed.
- A haptic device with the properties mentioned above is close to being the optimal device for a haptics supported windows system for people with visual disabilities.

HAPTICS IN 2 AND 3 DIMENSIONS

As we have seen there are some obvious differences between the PHANToM and the FEELit mouse. The most important difference is probably that the PHANToM is a 3D-device while the FEELit mouse is a 2D-device. Nevertheless, most of our first PHANToM programs where more or less 2-dimensional. Our three first programs were called “Paint with your fingers”, “Mathematical curves and surfaces” and “Submarines”.

“Paint with your fingers” is a painting program with structures associated with each color in the palette. The user is painting on a virtual plane, which only involves 2 dimensions. The third dimension is used to give the user a sensation of moving across a rough surface.

“Mathematical curves and surfaces” is a program that can display 2- or 3-dimensional graphs haptically. The program uses different modes for 2D and 3D. In the 2D-mode, the user can feel the function graph as a groove or a ridge on a virtual plane.

”Submarines” is a PHANToM variant of the well-known battleship game. The player can feel 10x10 squares in a coordinate system. In the game, your finger is a helicopter which is hunting submarines with depth charge bombs. If you lay your finger on the ”water surface” you can feel the smooth waves moving up and down. The waves on the surface feel different in order to indicate the state of each square. The four states are:

- Not yet bombed – calm waves
- Bombed, but missed – no waves (flat)
- Bombed, hit part of a submarine – vibrations
- Bombed, hit entire submarine – small, rapid waves

All of these programs thus have 2D properties when it comes to navigation and they use the third dimension to provide additional information of different kinds. Does this mean that it would be possible to create this type of program for a 2D-device? It is possible and often quite effective to simulate the third dimension using so called “bump mapping”. This is a technique which has been borrowed from the 3D-graphics world. The idea is to map different normals to a flat surface, thereby simulating the bending of the surface without really bending it. When used in haptics this means that when moving across a surface the user can feel the tangential forces in the same way as if she were moving across a structured surface. But the normal force is kept constant, so it is possible to do this kind of 3D-simulation with a 2D haptic device. Bump mapping has been proven to work with the PHANToM by the TouchLab at MIT among others. They have also showed that the illusions are even more convincing if one adds graphics which fool the user into believing that he is moving in the third dimension as well.

Fig. 15. Cross-section of a bump on a plane with interaction point positions and forces using real 3D haptics.

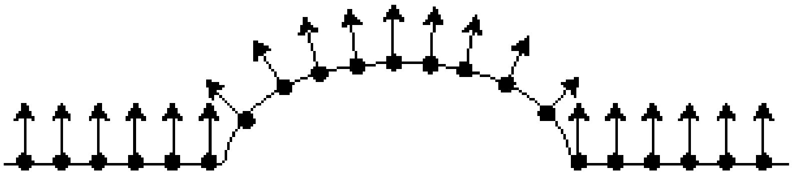
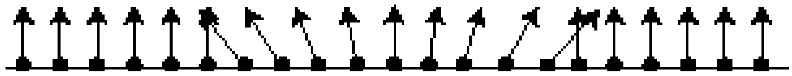


Fig.16. Cross-section of a similar bump with haptic bump mapping. This can be done with a 2D haptic device.



Given this, it seems as if it would be easy to convert, for example, “Submarines” from the PHANToM to the FEELit mouse or a force feedback joystick, and this was one of the things I intended to do for this thesis.

At first I found that it was quite easy to make a program that showed a haptic grid. I decided to use two linear, perpendicular springs to pull the user towards the center of each square in the coordinate system. This kind of grid worked quite well, but the problems came when I tried to add the moving waves to the grid. I tried to add the force from the waves to the other forces in the system as well as to make the whole grid move like waves. Neither of these approaches worked. Either the wave information became very subtle and to hard to detect among the other forces or, when I turned up the wave force and amplitude, they disturbed the sensation from the grid to such an extent that it became impossible to navigate in the system.

What I wanted here was a way to give the user information about the type of square she is currently in. I wanted to give that information in a consistent way that is easy to understand and I wanted to do it with haptics because that was one of the really good features of the original “Submarines” game. The reason behind the problems I ran into is that almost all of the information bandwidth in the two dimensions available is needed for navigation. When one tries to add more information on the same channel everything becomes jumbled and the information disappears in the noise of the summed forces.

The bottom line here is that what may seem to be a 2D-task could benefit greatly from getting extra information in a third dimension. However, it is not necessary for this third dimension to allow a great deal of movement. For example, with the exception of the 3D-part of “Mathematical curves and surfaces”, our three first programs would work very well with a third dimension of only 10 mm. With such a setup, it is possible use two dimensions for navigation and the third for added information. In my opinion this is especially interesting for a blind user since she has to get so much more of the information via haptics, and since haptic information bandwidth is generally considered to be much lower than visual bandwidth [Fritz, Barner 1999].

This is also true for most situations where you want to make a haptic representation of a graphical user interface. The Windows system can be viewed perfectly with only two dimensions, but a third axis can obviously add a great deal of extra information, and this will probably increase the overall bandwidth. What I want is a haptic interface that allows movements of say 80 mm in two dimensions and about 10 mm along the third axis. I have not had the opportunity to test such a device yet. Nevertheless, I do not think that it would be too far-fetched to call such a device a 2,5D haptic device.

CONDENSED IDEAS

I conclude this section with a set of ideas about virtual haptics use especially for people with visual disabilities. This is an attempt to formalize and extract a number of condensed thoughts from the above material.

1. One can maximize the usefulness of virtual haptics by taking it one step further instead of just trying to mimic the real world.
2. A haptic user interface must have the same general "look and feel" as the corresponding graphical user interface, but it should not merely be a haptic reproduction of the graphical image.
3. It is possible to create a haptic user interface which works very much like the corresponding graphical user interface, but which has some interface elements that are optimized for haptics.
4. It is possible to compensate for the difficulties of searching in a disordered virtual environment by giving the user a virtual search tool as a complement to point interaction.
5. A finger grasp is better for sensing details and controlling with more confidence. A finger grasp may thus be better than a mouse for a haptic windows system.
6. It is not necessary to have three full degrees of freedom to make a haptic Windows system, but having only two degrees of freedom can be limiting. 2,5D hardware may be the best option in this case.

In the next part of the thesis I will apply the knowledge I have gained to the FEELit mouse. It is beyond the scope of this thesis to test all of these ideas, but I will continue working on this in the future.

Windows specifics

One key feature in Windows is that it is made to be explorable: when you see it you will understand it. Windows has a spatial graphical paradigm with menus, buttons and icons, which unburdens the user from memorizing commands and reading long sections of text on the screen.

Alan Holst [Holst 1999] describes two alternative philosophies about Windows access:

According to the first philosophy you do not have to know what the screen looks like to be able to work in Windows. In this view, the user has to memorize a large set of options to achieve a given effect.

Using speech alone as the access method often works this way, and Holst finds that this does not give enough feedback for him to be an effective improviser. It only works as long as nothing unusual happens.

The other way of looking at Windows access is the view that you need *a good cognitive map* of the screen to be an effective Windows user. Tactile interfaces enable the user to build a cognitive map (see also Sjöström 1997) and they make the screen more concrete. Holst finds that a tactile interface enables him to improvise and be more creative.

Mynatt has been working on making graphical user interfaces accessible to blind people through the use of sound [Mynatt 1997]. She has determined five objectives for screen alternative interface design:

- Access to functionality. The screen alternative should at least give the user access to the same functions as those presented by the graphical user interface.
- Iconic representation of interface objects. The screen alternative has to be able to recognize and present the same information as is communicated by the visual appearance of the interface objects such as the picture size and color.
- Direct manipulation. The user should be able to manipulate each object in the same manner as in the graphical user interface case.
- Spatial arrangement. The spatial arrangement of the graphical objects also conveys information and helps the user in structuring and working with many tasks at once. The screen alternative should also offer this functionality.
- Constant or persistent presentation. Visual information is not time dependent in the same way as audio is. The visual information exists in physical space and can be obtained and reviewed at any time; this is not the case for audio information. The screen alternative should offer this kind of temporal independence.

Haptics in computer interfaces

With the above mentioned objectives in mind and our previous knowledge from using the PHANToM, I decided to concentrate on three different themes for this thesis:

1. Combining FEELit Desktop from Immersion with synthetic speech for general Windows access
2. Developing "radial haptic menus"
3. Constructing a set of virtual haptic tools that can be used as aids for searching disordered virtual objects like icons on the desktop.

Of these, the first is an example of direct translation from graphics to haptics. The other two themes are examples of what can be done when using haptics more on its own terms.

haptics as a direct translation – FEELit Desktop

FEELit Desktop is a program that makes a direct translation of many graphical interface objects into corresponding haptic objects. The FEELit-Desktop exists today and it a serious attempt to make a major part of Windows touchable. Almost all objects in the user interface produce something that is touchable. FEELit Desktop uses Microsoft Active Accessibility [MSAA], which means that many objects in application programs become touchable in the same way as the system objects. If one combines FEELit Desktop with speech and/or Braille output the result is a possible solution that will help a blind user to discover, manipulate and understand the spatial dimension of Windows. My work in this case has been to try to find out how well FEELit Desktop can compensate for things that are not made accessible by the speech synthesizer. In this context, interesting aspects are support for:

- Direct manipulation of objects
- Communication of spatial properties
- Free exploration of the interface

These properties are central (and widely accepted) properties of graphical user interfaces, which ensure many people find them easier to use than a text based interface (e.g. MS-DOS). It is a very challenging thought that the visual interfaces which created so many opportunities for sighted people, but so many drawbacks for blind people, could now be complemented with haptics. Perhaps this is the breakthrough for graphical/haptical user interfaces.

However, I do not think that a direct translation of a system that was originally optimized for visual use is the best way of implementing haptics. Consequently, I am trying to create a haptic interface which is very similar to Windows but which goes a little bit further in using haptics as haptics and not merely as a replacement for graphics.

haptics on its own terms – radial haptic menus

Radial menus are menus where each choice is indicated as a ray pointing out from the center instead of having the choices arranged in a column as ordinary linear menus. A radial menu can be likened to pie or a clock. I have been using a radial menu with 12 choices in each menu and that makes it very easy to use a clock-analogy (e.g. “copy is at three o’clock”).

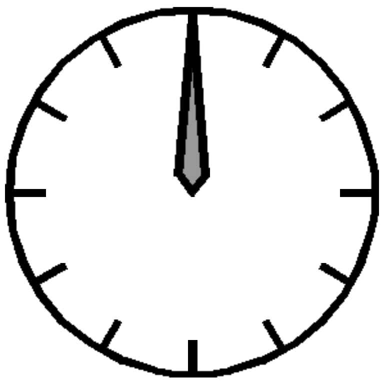


Fig.17. Clock metaphor of a haptic radial menu

There is a virtual spring that pulls the user to a line from the center of the clock to each menu choice. There is also a small virtual spring that pulls the user towards the center. My hypothesis is that radial haptic menus can work better than linear haptic menus for three different reasons:

- It is possible to tell which choice is the active one by reading an angle instead of reading an absolute position.

- The user has a well-defined and easily accessible reference point in the center of the menu.
- It is easy for the user to adjust the menu to her own needs by moving the mouse in a circle at a greater or smaller distance from the center. Away from the center greater force and larger movements are required to get from one menu choice to another. Conversely, it is possible to change the active choice using only a small movement and almost no force at all when moving closer to the center. Needless to say, the navigation precision required increases as one moves closer to the center.

Moreover, radial menus are generally considered to be efficient because they allow the user to select from a number of possibilities without moving very far and the number of choices is relatively large.

I believe that "snap-to-centerlines" is a useful approach for creating haptic menus. I have tried thin walls etc. but they do not work very well. It's very easy to move across one menu item without noticing it even if the distance to the next wall is fairly large.

In the case of a radial menu I think that the snap-to-line idea is even better since it makes it easy to feel the angle of the current selection. If you create a wedge-shaped area with thin walls to the next selection it must be much harder to feel the direction you are moving in. And since the distances are very small in this type of menu I think that it is a very good idea to use direction as much as possible. It is also quite hard to remember/identify exact positions in a haptic environment; movement is absolutely necessary and that means that we want to use directions rather than positions as much as possible.

In any virtual environment it is important to provide good reference points for the user. My tests with "the Memory House" showed that the subjects who actively used reference points in the rooms performed much better than those who did not use reference points. The only well-defined natural reference points on a haptic display are the corners. The fact that radial menus have a well-defined reference point in the center is therefore of great importance.

To test radial menus I have made a special program that shows a fake menu system similar to a standard word processor. This program uses sampled words to indicate the imagined function of each menu choice.

HAPTICS ON ITS OWN TERMS – VIRTUAL HAPTIC SEARCH TOOLS

Menus can be very useful when the information is ordered and fits in a linear-hierarchical structure. The opposite is the case when objects are scattered over an area with no special pattern. For a blind person, locating an object with a point probe in a 2D space can be as hard as finding a needle in a haystack. Even if you get as close as 0.1 millimeter from the object you still do not feel anything at all until you touch it. This is a problem since it is necessary to be able to locate objects if one is to understand someone else's Windows desktop.

To help the user in cases like this I propose three virtual search tools that can be used as a complement to the standard point probe interaction:

- A "cross" that makes it possible to feel when you line up with an object horizontally or vertically.
- A "magnet" that pulls the user towards the nearest object.
- A "ball" that makes it possible to feel objects at a distance but with less detail.

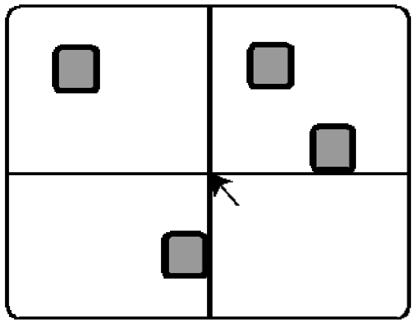


Fig. 18. The cross touching two objects at a simulated desktop

I have made a program to test the cross tool for finding objects in an unknown environment. The magnet and the ball have not been implemented yet.

With these tools it is possible to feel objects without touching them directly. It is similar to when a blind person uses a white cane to avoid running into things but, in this case, both the tools and the objects are virtual.

Since all of these tools distort the sensation it is important to make it easy to switch between the different tools and no tool at all. In my test program the user can turn the cross on and off by clicking the right mouse button. The test does not take the tools into the real Windows environment. It is a straightforward search task for testing purposes only.

A variant of the cross that could also be useful is a "half cross" – a vertical or horizontal bar. Both the cross and the bars reduce the 2D search task to a 1D task. The user can move along a line in order to feel if there are any objects. If a bar hits something, the user can move along the bar to feel what is there.

Locating objects is very important in all user interface work and, naturally, it is also important when the user is discovering a new or unfamiliar environment. Several things could be done to make it easier for a blind user to find objects. It is also important to help the user be certain that there is no object for her to feel. With clean point probe interaction it can be very hard to be sure that all the objects are gone. With the cross, the problem of determining when there are no objects at all is almost eliminated since it is very easy to scan the whole screen using a one dimensional movement.

User trials

Fig. 19. The FEELit mouse that was used in the user trials

In the user tests, I used a prototype FEELit Mouse on loan from Immersion Corporation. The FEELit mouse was used with standard PCs with Windows 98. I used the FEELit Desktop software provided with the mouse. This is a prerelease copy dated 981028. Later, I received newer software from Immersion, but it was not compatible with the mouse we had.

Two of the computers used were the test users' personal home computers so the users were very familiar with the equipment. Both computers where equipped with the Jaws for Windows screen reader. One of them had both speech synthesis and a Braille display, while the other one only had a Braille display.

For the radial menus and search tools I used software I had developed myself. The two programs were built with Feel Foundation Classes – FFC – from Immersion and Microsoft Visual C++.

OBSERVATIONS FROM USER TESTS

The two blind test users used the FEELit mouse and the software at home for 4 days. They tested the programs for several hours on their own. After the test session, I interviewed the testers to get their opinion about the setup. We also tested all the programs together both at the beginning and at the end of the test sessions.

The general impression was that the ideas behind both FEELit Desktop and the other two programs where highly appreciated, but the implementations must be refined before the software can be useful.

FEELit Desktop did give a better understanding of the spatial dimension in Windows for one of the testers. The other tester already had a spatial mental model of Windows, which did not change, but he valued the possibility of getting a sense of up, down, left and right since he thought that too many blind computer users do not get this opportunity. He stated that the FEELit Desktop system, if more complete, could be a good tool for teaching blind Windows beginners the fundamental layout and function of Windows.

Direct manipulation (drag-n-drop, etc.) was too difficult to perform with the FEELit. This was due to both the limited precision inherent in the small workspace and the lack of feedback which is partly caused by limitations in Microsoft Active Accessibility.

One of the testers said that a haptic desktop would help him to explore the environment more freely.

The radial menus worked very well for both of the testers. They were successful in handling the menus and they were also able to make good use of the clock metaphor. It is interesting to note that both testers thought that these menus worked well, but they where skeptical about introducing them in a Windows access systems. They both wanted the access system to be as transparent as possible and they want it to give them the same picture as a sighted person gets when looking at the monitor.

The cross search tool was especially well accepted by one of the testers. He found the cross very helpful when searching and asked if it was possible to use the cross when working in an explorer window. This was very encouraging since that is exactly the situation I had in mind when the idea of the cross came up. The other user was more uncertain about the cross. He talked more about magnetic objects as a way to guide the user. I take this as a proof of the fact that search tools can be useful and that there is a need for several different tools. Which tool is chosen will depend on the user's preferences and the situation.

Both users had minor problems with the small workspace of the FEELit mouse. Their spontaneous reaction was "This device requires tiny, tiny movements, can't it be made a little bit bigger?"

Both testers reported instability problems. It is apparent that this version of FEELit Desktop has compatibility problems with Jaws for Windows. While this is not a problem for ordinary users it is a very big problem for a blind user since all blind users use some kind of screen reader. However, one must also remember that the software and hardware used are prototypes, which have not gone through release testings.

To sum up, all of these techniques were considered to be useworthy as soon as the "teething problems" and instabilities have been eliminated. The testers were very enthusiastic about the concept of haptics as a way to get more access to Windows in general and they had many ideas about possible uses for this kind of technology.

A handful of the things that the testers asked for during the sessions were

- Haptic maps.
- Automatic conversion of graphics to haptics that will make even the pure graphics on the Internet accessible to blind users.
- Feel the layout of a MS Word document.
- Access to sound editing programs like for example Cool-Edit.
- Access to encyclopedias, etc. that contain mostly text but often use specialized graphics instead of standard Windows elements in the interface.

Results and Conclusions

The research we carried out on the PHANToM enabled us to achieve a head start in terms of our thinking which proved useful when the FEELit mouse was introduced. It proved possible to transfer knowledge, experience, and ideas generated by our previous research to the much simpler and cheaper platforms available today.

The transition from 3D-haptics to 2D-haptics can cause problems even if the task seems to be two dimensional. Even in a task where the navigation is purely two dimensional it can be fruitful (sometimes even necessary) to use a third dimension for information transfer. In a haptic Windows interface one can make use for a 3D haptic device were the third dimension has a relatively small working distance. I have chosen to call this kind of device a 2,5D haptic device.

The tests I have made of how well a graphical user interface translates to a haptic user interface show that the concept is very promising but the implementation of FEELit Desktop that was used in these tests is not good enough for blind computer users in general. To be useworthy the system must be more stable together with the major screen reading software, and it must also make a more complete translation of the system.

Virtual search tools are needed to provide a better overview of graphical user interfaces when a user cannot see. I find that there is a need for different search tools and it must also be possible to switch between the different tools and no tool at all in an easy way. In the long term, I hope that it will be possible to use these in conjunction with a system such as FEELit Desktop or to integrate them with the system.

Radial menus seem promising when it comes to making use of all the possibilities afforded by a haptic interface even when the workspace is small. It is doubtful whether radial menus are suitable for a haptic Windows system, but in specialized programs they may be advantageous.

While working on this thesis and carefully reviewing what I and others already have done, I have of course had lots of ideas for further research in this field. I am really looking forward to take up these ideas as soon as possible!

We will continue our search for the optimal haptic interface for a blind computer user. The experience we have gained from moving between 3D-haptics and 2D-haptics is important not at least for this search. The design of the interaction tool and the size of the workspace are important parameters requiring further research.

FEELit Desktop has great potential and as soon as it is stable when used with screen reader software we will carry out more extensive user trials involving 5–10 blind users. The FEELit Mouse will also be clinically tested at Sahlgrenska University Hospital in Göteborg. (People with spinal cord injuries will test and attempt to develop their sense of touch by performing meaningful tasks).

The search tools suggested in this thesis will be implemented and refined in collaboration with blind test users. Further tests with radial menus will be carried out to determine the best menu design and the cases where it is preferable to use a radial menu.

Advanced haptic interfaces like the PHANToM can create entirely new opportunities for people with motor disability. Controlling and interacting with personal assistive robots is a particularly interesting area.

Design is making things better. For people.

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