HAPTICS AS A MULTIMEDIA DATASTREAM
INTRODUCTION TO HAPTICS AND HAPTICS FOR HUMAN COMPUTER INTERACTION

Seminararbeit

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List of Abbreviations

HCI	human computer interaction
VR	Virtual Reality
CAD	computer aided design
DOF	degree of freedom
UI	user interface
RTP	Real-Time Transfer Protocol
AV	audio/video
I/O	input/output

Abstract

So far, computing makes limited use of human senses of perception. With high definition audio and video, the limits of what can be achieved with visual and acoustic perception have largely been reached. Recent research suggests that realism of simulations and fluidity of interaction can be significantly improved using haptic devices, recording forces exerted by humans for input, displaying forces to allow the user to actually feel virtual objects, and interactive devices. This seminar paper gives an introduction to haptics in computing, presenting the history of haptic devices, design techniques, classes and applications of haptic devices, and further specializes on haptics for human computer interaction.

1 Introduction to Haptics

1.1 Overview

"Computer: Essentially intended for solving problems, unfortunately mostly the problem itself." (Proverb)

The integration of computing into everyday life is a key process which will, in the end, determine which systems, products and applications will prevail in practice. The transition from command line to the Windows operating system has been a huge leap allowing people to use a vast amount of the computer's potential without actually knowing how it works internally. This focus on ease of use is a key factor for the immense prevalence of the MS Windows operating system. However, it turns out that the full potential of this approach has not yet been exhausted, as we can see in the still remaining proverbs and rail against "stupid technics".

The silver bullet to make the society use the entire potential of IT is to change the way humans interact with computers from a technical oriented to an application oriented activity stream. Technical oriented means that the interaction takes place via a technically easy-to-implement interface used for many greatly varying applications: Users move the mouse and perform a click to choose between options of a menu, move around the viewing perspective in a VR simulation, aim and shoot an arrow in a game and so forth. This decreases fluidity of interaction due to the non-intuitive or non-real-world-compliant action trigger. It would be much better to interact with the objects the computer displays right in the way we interact with physical objects. This is called application oriented interaction.

1.2 Historical Evolution

Basic haptic devices are in use since many years. Back in 1997, Nintendo released the "Rumble Pak", which triggered a vibration when e.g. the avatar impacted a wall in a racing game. A similar feature known for a long time is the mobile phone's vibrating alert for incoming calls. However, there is much potential left for creating devices that do not display just a single homogeneous stimulation, but spatial force patterns.

Figure 1 shows the basic evolution of haptic devices.

- Stage 1: These devices – as just described – provide a very basic, uniform actuation. They have been in use for a long time.


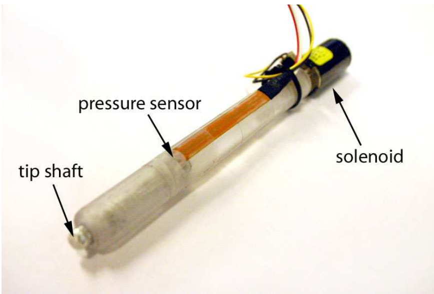

Figure 1: Evolution of haptic devices. Left: Nintendo Rumble Pak attached to video game controller (en.wikipedia.org). Right: Haptic Pen [7]

- Stage 2 devices give haptic enhancement to known interaction methods. Examples of these are the Haptic Pen [7] or vibration capable mice. However, this restricts the ways of interaction the devices are capable of, and reduces the achievable level of realism. For example, vibration capable mice can display forces, but the haptic and visual feedback is provided at different spatial locations. The sense of temperature is not addressed in Stage 2 devices.
- Stage 3 is the final goal: Fully tactile interactive devices using large actuator arrays. They allow users to handle virtual objects just as if they were real, and they are not bound to previously known interaction methods. There are hardly any Stage 3 devices available yet.

The theoretical background for haptic devices has been studied for many years. The field of psychophysics was known a long time before computers were invented. This field is presented in detail in section 2.1 - The Human Factors.

1.3 Classes of Haptic Devices

Since the sense of touch applies to a wide part of the human body, the variety of haptic devices is greater than the variety of visual or acoustic devices. They can be classified as follows; it is also possible that there are further criteria not yet identified.

- **grounded vs. ungrounded device:** This refers to whether the device has a physical connection with the ground the user's body is bound to, e.g. a table or the floor. In general, grounded devices produce more realistic effects, whereas ungrounded devices are handier, less power consuming and suitable for mobile applications.
- **modality of tactile perception:** The somatosensory system comprises the senses of touch (which is commonly used synonymously), temperature and nociception (pain). Most currently available haptic devices are limited to the sense of touch. Furthermore, temperature lacks precision, making it the second choice for adding senses of perception to human-computer interfaces. Meanwhile, technology has advanced far enough to also simulate rapid changes of temperature on small-volume devices, although only few devices are available which make full use of this potential yet. There is sometimes even interest of users to feel pain when interacting with computers, e.g. in a game giving a small pain stimulus when the actor gets hit by an opponent. This is because of the human body, which reacts to stress situations by dumping adrenaline, followed by sense of pleasure when the situation is successfully mastered.
- **area of effect:** Most currently available haptic devices apply to the hands and forearms, while there is a growing percentage of wearable devices typically exerted to the upper body. There are a number of reasons for this: Firstly, the hands have some of the densest populations of tactile sensory cells (Figure 2). Secondly, the hands form the part of the body most involved in physical perception (computer → human) as well as manipulation (human → computer) of objects, making them most relevant for real-time haptic interactive applications. Last but not least, unlike most other parts of the body, the hands are not covered by clothing, making the devices practical to handle. This is in contrast to e.g. a haptic shirt which needs to be dressed and undressed frequently since it is not permeable to water in order to protect inner electronics, and therefore uncomfortable to wear for an extended period of time.

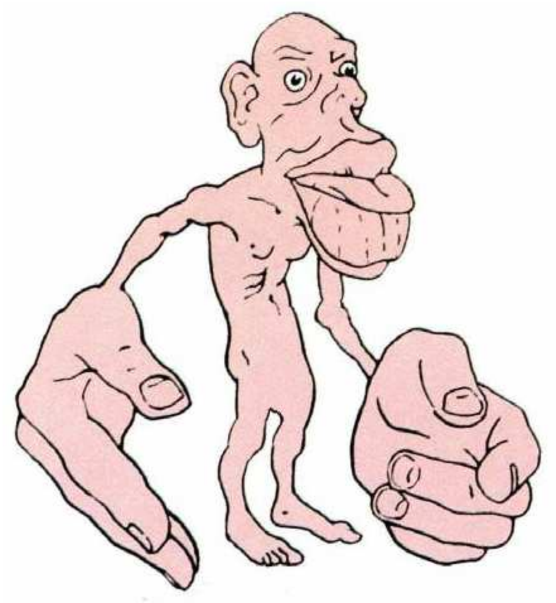

Figure 2: Human body parts, proportional in size to tactile receptor density [20]

- **symbolic vs. realistic effect:** This is a crucial issue in the design of haptic devices. Realistic effect means that the device imitates the real-world effect as lifelike as possible, whereas a symbolic effect has some properties in common with the effect it represents in order to trigger the same psychological association, but differs from it for example in scale. Symbolic effects are often more than sufficient since the human mind generates the perceived reality by agglomerating such psychological associations. In many cases, realistic effect is neither achievable nor desired. For example, when playing a sports game, nobody would want to sweat after 30 minutes, but rather feel miniature representatives of the real forces.
- **input vs. display vs. interactive device:** Haptic input devices use physical activities with parts of the human body, as well as posture of several body parts relative to each other, as a source of input. Haptic display devices – as the name implies – display haptic information to the user. Finally, interactive devices have both input and display functionality, which operate concurrently to generate a realistic interactive experience.
- **stand-alone vs. peripheral device:** In some cases, the device is not directly attached to a computer but to a network, so it can be shared among many computers. In this case, UDP is the recommended communication protocol [17].

In some cases, these criteria correlate. For instance, ungrounded devices have inherent limits of the strength of realistic gravity sensation they can produce, as we will see in section 2.1 – The Human Factors.

1.3.1 Pen

Devices held like a pen form today's most popular class of haptic hardware. The pen is small and handy, moreover already one of the most widespread tools, making the devices easy and familiar in use.

The Phantom haptic series form some of the best-known devices which are currently available commercially. It is made up of a stylus connected to a grounded base with force output and 6 DOF (degree of freedom) positional sensing. These properties open it up to a wide range of applications, as we will see at various places in this work (e.g. 1.4.2, 2.2, 2.4).

Figure 3: Sensable Phantom haptic device [3]

First stylus devices apply simple haptic effects like vibration or simple force pattern output at a place of the stylus which is in contact with the finger pad. Many pens measure the force the user's hand presses it into the writing surface with in order to e.g. paint lines of varying thickness.

There is a variety of what can be done with pens. It also allows for migrating to haptic devices via a smooth transition from known interfaces, which is an important factor for the successful introduction of a new device type. However, since most interaction techniques with physical objects are not based on stylus tools, this may be a transitional state until people have gotten used to more advanced classes of haptic devices allowing for more natural interaction with virtual objects.

1.3.2 Glove-like

Inherent by the approach, they produce more realistic effects than for example devices worn like a ring. However, they impede the simultaneous interaction with real objects since they cover the entire hand. Therefore, they will probably remain restricted to special applications.

1.3.3 Attachments to Fingers

Like styluses, attachments to fingers are easy and comfortable to handle, making them one of the most popular class of haptic devices. They can for example be used to display gravity sensation (see 2.1), determine properties of contact between the finger and other objects (like force angle, force direction), and make the hand feel remote objects captured with a camera (see 2.5.2).

1.3.4 Shirt / Wearable

Those devices are designed to generate as realistic effects as possible. Therefore, their applications are VR and gaming. One example of a wearable haptic device is the HugMe interpersonal communication system [8]. The system uses a 2.5D camera (2D RGB image and a depth channel, which is a grey-scale bitmap) to track image and depth information of a person. This information is used to detect collisions between the communicating persons, which are then rendered to a haptic jacket making the persons feel each other. Further, the authors plan to install heaters inside the jacket to transmit the warmth of touch.

1.4 Transmission of Haptic Media Data

1.4.1 Amount of Data

This is a fundamental issue for communication protocol design. The recommended sampling frequencies vary greatly for different senses of perception. Psychophysical studies recommend an update rate of 1 kHz for haptic devices [12].

Sense	Recommended Stimulus Update Frequency	Data per sample	Total bandwidth
Audio	44 kHz	16 bit	0.67 MBit/sec
Video	30 Hz	40 kByte[1]	9.375 MBit/sec
Haptic	1 kHz [12]	1 kByte[2]	7.8 MBit/sec

Table 1: Exemplary bandwidth requirements for different senses of perception

[1] With compression
[2] This value can vary depending on the device class. E.g. for the three-dimensional force applied to a stylus device, we would need to save 3x the force magnitude. According to the JNDs measured in section 2.1, we could use a nonlinear force strength coding. Thereby, we should be able to do plenty with 1kByte per sample.

1.4.2 Lossy Compression of Haptic Data

Like other multimedia applications, haptics generate large amounts of data. Therefore, we need to study haptic data compression and evaluate the perceptual impact of the loss of compression. There already exist a variety of haptic data compression techniques, which can be divided into two main categories:

- Statistical approaches focus on the statistical properties of the haptic signal.
- Perception-based approaches use limitations of the human haptic perception to compress the haptic data in a similar way to jpeg or mp3 techniques.

Previous haptic compression techniques store data only when the force exceeds a certain threshold. Researchers have proposed several approaches using JND (just noticeable difference, i.e. the “minimum difference between two stimuli that is necessary in order for the difference to be reliably perceived” [9]), which are able to reduce the amount of data by up to 90% without impairing immersiveness of haptic perception. However, these studies focus on interaction with stationary rigid objects, and research has shown that these thresholds vary depending on the velocity of the human hand [16]. The authors utilize the Phantom haptic device the test study subjects maintained at a given velocity, while applying opposed and aid forces. They found increasing AFTs (absolute force threshold, i.e. smallest amount of stimulus energy necessary to produce a sensation) for increasing velocities at which the subjects move the shaft of the Phantom device. Force thresholds for opposed forces were slightly greater than those for aid forces.

1.4.3 Protocol Design

In order to allow integrated haptic computing in a heterogeneous environment of device manufacturers and capabilities of users’ equipment, there should be a single protocol as many haptic devices are compatible with as possible. Because of the great variety of haptic devices, which have – in contrast to visual and acoustic display – even several fundamental design approaches, this is a challenging issue. The major design requirements of such an abstract protocol are

- **flexibility:** Since we cannot know all possible future applications, it is important to design the protocol for simple and clean extensibility (compare IPv6).

- **network delay management:** This varies depending on the application. When the haptic signal is going to be replayed many times after transmission (e.g. video download), a higher protocol overhead can be accepted to gain lossless transmission. On the other hand, when the signal becomes useless when it does not arrive in time, the user will prefer an error prone playback over no playback.
- **synchronization with visual and acoustic devices (teleconferencing):** The Real-Time Transfer Protocol (RTP) is suitable, as it is designed for time synchronization of multiple data streams.

As the bandwidth requirements of haptic data are in the same dimensions as of other multimedia applications, the practical choice of the protocol is similar.

1.5 Applications of Haptic Computing Devices

The physical sensations generated by haptic devices can be used to enhance existing interaction with graphical user interfaces as well as to improve accessibility of computer systems to users with visual, hearing or motor disabilities.

1.5.1 Virtual Reality

The goal of virtual reality is to generate a best-possible approximate of the real-world. This field of application is open to a wide range of users. Some popular examples of virtual reality are teleconferencing and gaming. Human touch, e.g. handshake or comforting hug is fundamental to emotional development between persons. One proposal for a realization of this approach is the HugMe interpersonal haptic communication system [8] described in 1.3.4.

1.5.2 Decision Support, e-Learning

Haptic devices can be used to underline other senses of perception. For instance, the interaction with computer application tools can be improved using a haptic device [1].

1.5.3 Visually Impaired

In order to assist visually impaired persons, haptic devices can e.g. generate Braille dynamically [13] or translate the image recorded by a camera to the haptic sense of perception, e.g. the Fingersight system [5].

1.5.4 User Authentication

In everyday life, we have a large number of reflexive operations which we can complete fluently without additional concentration necessary. Haptic devices for user authentication utilize the uniqueness of every human being, which is also present in the intra-muscular coordination generating this automation of operations. The textbook example of this application is a pen measuring the push strength the operator presses it into the writing surface with while writing.

1.5.5 Medical Technology

Haptic devices for medical technology can be divided into two groups based on the target audience:

- **devices for patients:** Haptic devices can for example assist rehabilitation of damages to the nervous system.
- **devices for surgeons:** A glove, for instance, can record the motion of the hand and fingers, transmitting them in a weakened magnitude to the operating devices, in order to allow more fine grained operations. The operating device may also be small-sized and have multiple centers of rotation, allowing for intuitive operations at places where the human hand cannot go.

2 Haptics for Human Computer Interaction

In order to further increase fluidity in interaction between human and computer, the interaction channels need to be broadened. Currently, haptic devices are mostly used in special applications such as medical technology, which are characterized by small production quantities, high unit costs and frequent redevelopment of products. Thus, opening up haptic technology to a wider range of users will foster investment in research which will again lead to further advances in both mass and special applications of haptic technology.

2.1 The Human Factors

Background knowledge of how humans perceive environmental impact is crucial to design and evaluation of haptic devices. Basically, there are two kinds of perception:

- **external perception:** Provides information from the environment. This expression is often used synonymously to common perception, which is the integral of both types.

- **proprioception:** Provides information from and via own body parts. For example, the gravity of an object is sensed by the deformation of the finger pads (external perception) and the weight propagating from the fingers to the hand, the hand to the arm etc. (proprioception).

To demonstrate in which situations external perception and proprioception play a role to what extent, Minamizawa, Kajimoto, Kawakami and Tachi [2] present a wearable, ungrounded ring-like display that generates gravity sensation of virtual objects. This is achieved by vertical stress and shearing stress on the finger pads which is also caused by the weight of real objects.

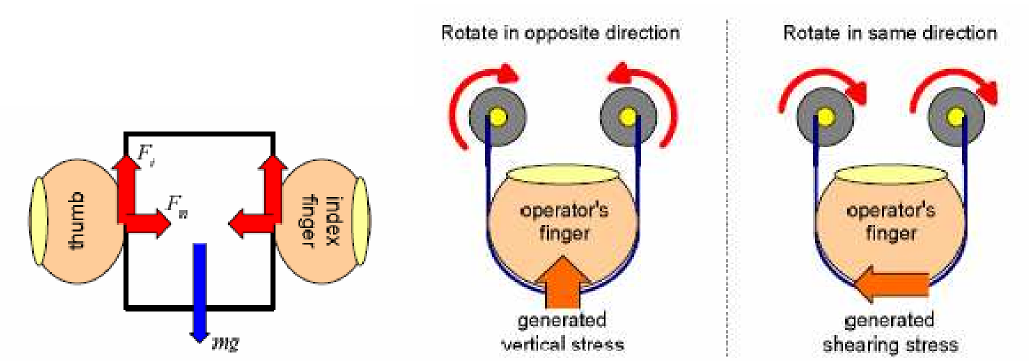

Figure 4: 1. Vertical stress F_n and shearing stress F_t when grasping an object, 2. Simulation of gravity by generating vertical stress and shearing stress on finger pad [2]

Those two forces applying to the fingertips (see Figure 4), in combination with the proprioceptive sensation on the arm and the finger, make up the gravity sensation of the object. The authors conducted several psychophysical experiments, namely (1) the correlation between the generated shearing range on the finger pads and the perceived weight, as an improvement also with vertical stress, (2) the grip force exerted to real and virtual objects when their weight counterbalance was abruptly removed, and finally (3) the limitations of the device. The findings were (1) a concave increase with an upper limit of the presentable weight, as proprioception becomes more important with increasing weight (more intra-muscular activity), (2) almost identical increase of grip force in real and virtual objects (40g for 300g weight), and (3) deformation of finger pads without proprioception produces a reliable gravity sensation for small weights (< ca. 400g). The last observation confirms our thesis that already a symbolic effect triggers a psychological association which enables the benefits of broader interaction.

Further findings of the literature are

- Humans collect less information on objects when slipping the hand over them at higher speed (e.g. surfaces perceived as smoother) [19].

- The JND for forces applied to the moving hand (0.16-0.2 m/s) is between 30% and 50%. It is (independently thereof) greater for decrementing and aid forces [9].
- The human body can (on average) distinguish 2.8 different levels of surface stiffness, 2.9 of force magnitude [6]. The human's ability to identify the absolute value of a parameter in isolation is limited.
- Matching of a haptic stimulus with visual has a higher JND than vice versa [14].
- Increasing compliance (softness) of an object decreases compliance JND [15].
- The logarithm of the perceived magnitude of vibration of a mobile device is linearly proportional to the amplitude [11].

2.2 Haptic Input

This section describes approaches on how activities with parts of the human body most significant to tactile perception, especially the hands, can be utilized as an input source. The focus lies on these parts of the body since they are thus relevant for real-time haptic interaction. Extending this field of input will greatly enhance the user's reality experience since these parts of the body are most of all involved in physically exploring and manipulating objects. Besides the already existing devices (for instance [3]), literature has proposed several approaches, of which some are outlined in this work.

Iwamoto and Shinoda [4] present a tactile device measuring the vibrations along fingers in 2 DOF. The goal is to estimate properties about the source of the vibrations, such as location of contact, direction of applied force etc., in a similar way to seismology. The inherent advantage of this approach is that the tactile perception of the finger pad is not disturbed (in contrast to force-sensing pads attached to the fingertip). The device additionally utilizes the estimation of the location of contact to assign "virtual buttons" located around the finger. In these experiments, it was yet possible to identify whether the tapping took place on the distal or middle phalanx.

Applications like Adobe Photoshop provide tools to modify the document currently in workspace, e.g. an "insert label" tool. Before the tool is applied, the user sets parameters like e.g. font size and color. Smyth and Kirkpatrick [1] propose a haptic alternative to the tool palette called Pokespace, which is based on the Sensable Phantom haptic device [3]. The authors suggest that the precision of the mouse movements required and the exclusive reliance on visual feedback prevent those operations from becoming secondary to the user. Pokespace renders forces when the user moves the cursor around in the workspace with the Phantom device. These forces attract – in a gravity fashion similar to a desktop window docking function – the cursor to certain points of the workspace, where the user can adjust tool parameters. Unfortunately, statistical analysis of the test studies found no significant improvement of performance using the Pokespace haptic tool interface. However, Pokespace suggests a promising approach to using multimodal interaction to increase performance of HCI.

Another interesting input method is to observe the color of the fingernails to determine the forces which apply to the fingers [18]. This subject has been studied by various researchers. One main advantage of this technique, like in [4], is that we can predict what the finger pad perceives without covering it with a pad which would impair the original tactile perception. Due to complex histoid mechanics, a purely mathematical black-box model is used. The results of the study are that we can predict finger pad shearing forces with 0.5N rmse (root mean square error), normal forces with 1N rmse and posture angle with 10° rmse.

2.3 Haptic Display

There is a large variety of approaches on how to make the user actually feel objects displayed on graphical and acoustic interfaces. Typical examples are presented in 1.3. The approaches can be divided into two groups:

- **real world approximation:** As the title implies, these approaches aim to generate virtual duplicates of real objects. Therefore, they render forces which are approximates of the forces exerted by real objects to the human body. Typical applications are VR and Gaming.
- **virtual creation:** These approaches generate effects which do not exist in reality. Therefore, they may underline or extend other senses of perception, like for instance the Pokespace tool [1]. Examples are decision support and HCI, especially tools in computer applications which are made a virtual object which the user can feel.

A typical example of an early haptic display device is the Haptic Pen [7], which is used to operate stylus-based touch screen displays while providing haptic feedback. The pen uses a pressure sensor in combination with a solenoid which performs movements excited by an electric signal. The placement of the actuator in the pen allows the support of multiple users interacting with a large display at the same time, provide uniform feedback quality regardless of screen size, and provide tactile feedback also when the stylus is not in physical contact with the screen. Placing the actuator behind the touch surface would limit the display in scalability – therefore, this approach constitutes an alternative to the DM^2 actuation method [10]. The pen generates forces along the longitudinal axis of the pen, simulating the stiffness of a button being clicked. Therefore it supports several actions: Lift (lift up solenoid with certain strength), hop (lift and drop back solenoid) and buzz (vibration). In this basic setting, the device successfully simulates haptic feedback of the pressure of buttons. The authors of the paper plan to extend their approach to further elements of the GUI. Furthermore, the Haptic Pen is compatible with nearly any location discovery technology. For example, a six degree-of-freedom motion tracking system allows objects to be transformed into a surface which the user can feel via tactile display.

2.4 Real-Time Interaction

The final goal of research on haptics for human computer interaction is to synchronize haptic input (human → computer) and haptic display (computer → human) in real-time to generate a realistic experience of interaction with objects.

Mora and Lee [12] utilize the Sensable Phantom Omni Haptic device to simulate stirring a fluid in a bowl with a baton, including haptic feedback. This includes the deformable liquid surface and density, velocity and inertia of the fluid. The haptic information is integrated with visual feedback in real-time. Stiffness properties of the simulated fluid control elastic spring forces, making it repel the probe more at dense points. Furthermore, they introduce gesture recognition with the Phantom device, so special actions can be triggered in a more intuitive way.

The Ubi-Pen [13] is a stylus with an integrated compact tactile display module providing texture and vibration stimuli. As seen in Figure 5, there are several actuators boosted by a transducer made of piezoelectric ceramic material.

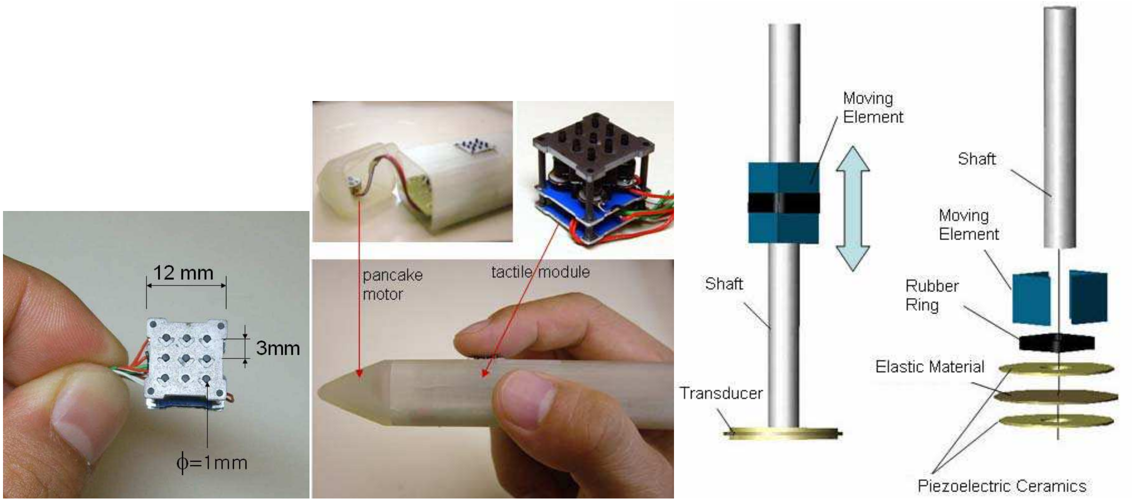

Figure 5: Ubi-Pen [13]

In addition, the pen contains a vibrating motor in its tip to provide a sense of contact with virtual objects displayed on the screen. The pen was successfully tested for providing Braille via the tactile display module; the click-like sensation decreased processing time in tasks highly involving buttons. One demonstrated application of the Ubi-Pen can load any grey-scale image, which is then transformed into tactile stimulation. In combination with location discovery technology, objects could be felt while moving around the Ubi-Pen in the air. Therefore, even haptic textures could be applied to a 3D model of an object in addition to the traditional textures, bump and normal maps.

2.5 Integration with Existing UI

2.5.1 Time Synchronization

So far, audio and video synchronization in real-time applications is based on an event-driven architecture: When the avatar in a game drops a glass, a sound of breaking glass is played back simultaneously with the 3D simulation; however in most implementations, the sound is always the same, regardless of e.g. sounds generated by splinters randomly impacting obstacles. However, more advances techniques could use 3D collision detection to generate haptic effects according to this unique situation. To best of my knowledge, there are no papers yet which statistically evaluate to which extent the realism of the sensation increases by applying this technique.

2.5.2 Spatial Integration

Level of realism and fluency of human computer interaction is currently limited, among others, by the separation of the location of inputs and outputs and further of the location of senses. The goal is to make the user not just feel objects, but also feel them where they are seen.

An example is the Haptic Pen described in 1.3.1, which allows – in combination with a motion tracking system – objects with known geometry to be transformed into a surface which the user can feel via tactile display. If we now further add 3D display, we can produce a very realistic integrated sensation of virtual objects.

As an example for possible integration with video devices, Stetten et al. [5] introduce the “Fingersight” system which extends the human hand’s inherent reach in which it can investigate and manipulate objects by skin contact. The original goal was to serve the visually impaired by transforming vision onto another sense of perception. A camera is placed on each finger’s distal phalanx. Each camera provides an image for real-time analysis, identifying objects of various complexities whose recognition is then displayed by a cell phone vibrator to each finger. The Fingersight system intends to allow remote control of objects like light switches, opening it up to a broad range of users.

As an outlook for the special case of VR / Gaming, we can propose 3D simulation not just by a camera in space defined by a stationary point and a look-at point, but an entire human model in space. The 3D engine performs collision detection with the other objects in space, translating collisions into haptic signals displayed on a wearable whole-body device.

3 Conclusions and Outlook

Even though theoretical background - especially in the field of psychophysics - has been studied for many years, there are to date hardly any examples of advanced haptic devices used in practice but in a few special applications mentioned before. This is the great surprise about haptic technology, since its improvement of interaction between user and computer has been shown already for some time by literature. However, the sluggish sales figures of high definition video hardware may encourage the electronic entertainment industry to shift their emphases in technology and product development.

Most today's papers only present early devices, and there is a huge unrealised potential lying in haptic technology. The slightness of today's progress is the exciting thing about the question of when haptic devices will become present in our everyday life. It remains to be seen which developments are going to take place over the next years.

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Eidesstattliche Erklärung

Hiermit versichere ich, die vorliegende Seminararbeit ohne Hilfe Dritter und nur mit den angegebenen Quellen und Hilfsmitteln angefertigt zu haben. Alle Stellen, die aus den Quellen entnommen wurden, sind als solche kenntlich gemacht worden. Diese Arbeit hat in gleicher oder ähnlicher Form noch keiner Prüfungsbehörde vorgelegen.

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