


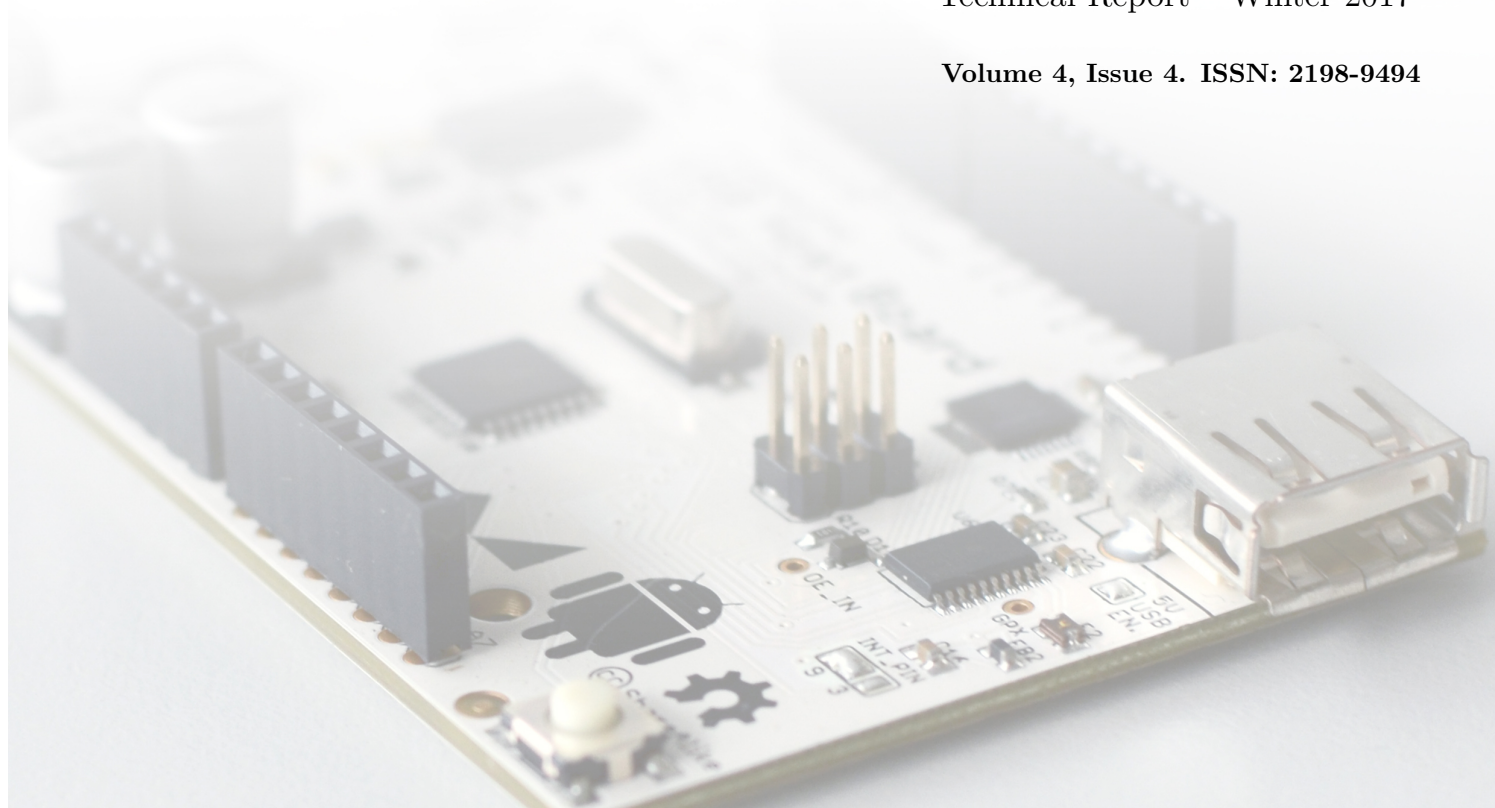
Gerold Hoelzl and Matthias Kranz (Editors)



# Touching the Void - Haptic Feedback & Brain Computer Interfaces

Advances in Embedded Interactive Systems  
Technical Report – Winter 2017

**Volume 4, Issue 4. ISSN: 2198-9494**



Gerold Hoelzl and Matthias Kranz

January 2017

## Contents

<b>Preface</b>	<b>4</b>
<b>Air Flow for Haptic Feedback.</b> <i>Shahin Doulati Heidari</i>	<b>5</b>
<b>Application Areas for Haptic Feedback Interaction.</b> <i>Iuliia Semenova</i>	<b>16</b>
<b>Overview of medical applications of Brain-Computer-Interfaces.</b> <i>Daniel Muenzhuber</i>	<b>28</b>
<b>Magnetic Field for Haptic Feedback.</b> <i>Daria Ivanova</i>	<b>34</b>
<b>Survey on Technologies for Contact Haptic Feedback.</b> <i>Ankit Sharma</i>	<b>44</b>
<b>Copyright Notes</b>	<b>56</b>

## Preface

Touching the void and inducing Haptic Feedback, even using Brain Computer Interfaces are an upcoming epoch of highly flexible and adaptable HCI methodologies. This report investigates into multiple facets and technologies that can be used to give haptic feedback to projected user interfaces and finally evaluates its usefulness for future application scenarios.

This technical report gives an overview of recent developments and results in the area of haptic feedback for non touchable objects. The topics comprise a number of areas, communication, object modelling and forming, technologies to get haptic feedback of various kind.

During the summer term in 2017, the Embedded Interactive Systems Laboratory at the University of Passau encouraged students to conduct research on the general topic of “Touching the Void - Haptic Feedback & Brain Computer Interfaces”. Each student analyzed a number of scientific publications and summarized the findings in a paper.

Thus, each chapter within this technical report depicts a survey of specific aspects of a topic in the area of Touching the Void - Haptic Feedback & Brain Computer Interfaces . The students’ backgrounds lie in Computer Science, Interactive Technologies, Mobile and Embedded Systems, and Internet Computing. This mixture of disciplines results in a highly post-disciplinary set of viewpoints. Therefore, this technical report is aimed at providing insights into various aspects of current topics in Human-Computer Interaction.

Passau, January 2017

The Editors

Gerold Hoelzl and Matthias Kranz

# Air Flow for Haptic Feedback

Shahin Doulati Heidari  
Universität Passau  
Lehrstuhl für Informatik mit Schwerpunkt Eingebettete Systeme  
Innstr. 43  
94032 Passau, Germany  
doulat01@stud.uni-passau.de

## ABSTRACT

This paper introduce the idea and necessity of using Air-Flow for Haptic Feedback. 3 Different approaches for using the air-flow as a medium to getting haptic feedback in virtual world will be discussed. At first there is an introduction to this rather new technology and the importance of having such feedback, then we move to example parts which we study 3 different technologies in this field based on multiple different papers published by other researchers. Each technology will be discussed in details with possible applications and also the limitations of them, at the end we conclude the whole idea of using the air-flow for haptic feedback in virtual world and a short anticipation of future of this technology.

## Keywords

Haptic Feedback, Air-Flow, Augmented Reality, Virtual Reality

## 1. INTRODUCTION

One missing piece in emerging computer-augmented world is the absence of physical feeling of virtual objects. Despite significant progress in developing tactile feedback technologies, in order to feel virtual objects, users have to either touch interactive surfaces or physical objects equipped with haptic devices or wear tactile feedback devices in the form of haptic gloves, belts, vests, etc [7]. Although these approaches can offer rich tactile sensations, requiring users to wear physical devices can impede natural user interaction and limit the overall range of applications that employ tactile feedback[8, 2]. Haptic rendering technologies are becoming a strategic component of the new Human-Computer Interfaces (HCI)[10]. Haptic interfaces stimulate users through tactile and kinesthetic channels to improve the interaction and immersion in teleoperated tasks or virtual environments. Haptic technologies demonstrated their value in different application fields. The use of haptic feedback for robotic teleoperated minimally invasive surgery can significantly enhance a surgeon's accuracy, dexterity and visual-

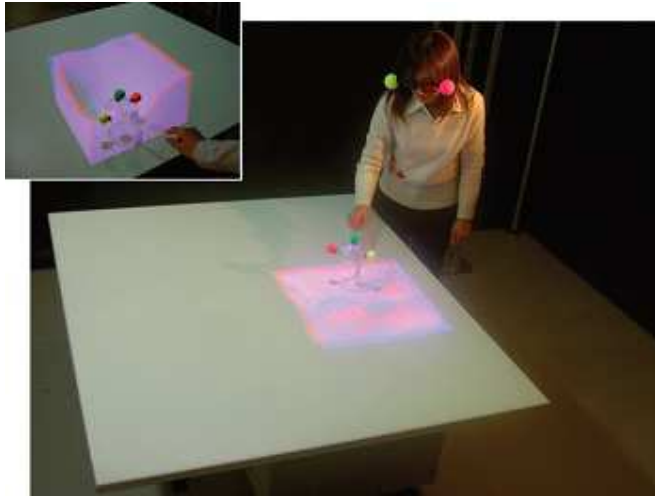
ization. Haptic based Virtual Reality (VR) approaches have increased both speed and accuracy of human-computer interactions for the edition and the assembly of 3D Computer Aided Design (CAD) models. In the field of rehabilitation, haptics plays an important role for the training of sensory motor skills and to alleviate the motor system impairments. In education, games, and entertainment several studies have shown the role of haptics to improve the learning and the interactivity though the physical interaction with the content. Despite the key role of haptic feedback in enhancing human computer interactions; the use of haptic devices in everyday and industrial applications is still limited. This is due to the intrusiveness and the limit of some performance factors of existing haptic devices. For example, haptic interfaces based on articulated robotic structures like exoskeletons, or cable systems adopt devices that must be physically connected to the user through mechanical systems. These systems are often intrusive, limiting the comfort and the transparency of interaction.[10, 3] Many VR systems tether the user by wires or heavy body devices, such as head-mounted displays. Among the many components of the VR interface, force feedback is one of the hardest technologies to untether. This is unfortunate because force feedback is the key to making VR systems more realistic and acceptable; it allows the user to fuse the physical sensation of touch with the sensation of vision to make the virtual objects come to life.[9] Conventional wisdom suggests that users must physically contact the interface device to receive the feedback force. The majority of current force feedback devices use rigid arms, wire-loaded handles or gloves. Any technique like these will disturb the user's free movement and raise the level of annoyance. Compared to tools used in daily life, existing VR systems leave a lot to be desired. The goal is to eliminate anything that restrains the user. A tool will not become part of daily life if it's seen as an encumbrance. Hence, the key goal is the fully untethered system.

## 2. AIR-FLOW HAPTIC FEEDBACK EXAMPLES

In this section 3 different examples of using air flow as a medium for getting feedback in virtual world is demonstrated. These examples are the work of other researcher and each of them will be discussed in detail. The experiment steps, applications and limitations of each example also will be studied. The order of the examples are based on the year that the paper was published.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, to republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

*Advances in Embedded Interactive Systems* '16 Passau, Germany  
Copyright 2016 ACM X-XXXXX-XX-X/XX/XX ...\$15.00.



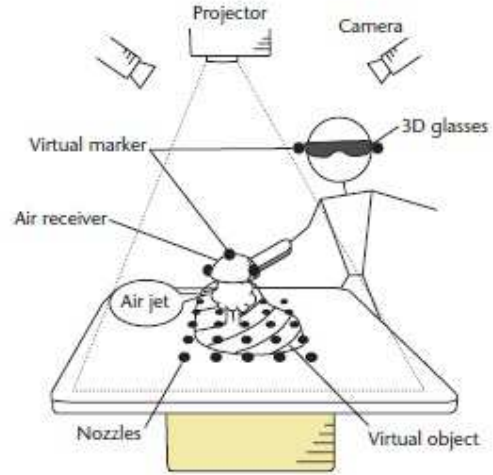
**Figure 1: Untethered VR System with air jet based force feedback**

## 2.1 Air Jet Driven Force Feedback in Virtual Reality

This system controls the air jet according to the position and orientation of the air receiver, which is held by the user. The air released from a jet impacts the air receiver, and the user perceives the air pressure as force. By using the air receiver, the air doesn't touch the body directly, which means the user feels pressure, not the wind itself. When the air receiver touches the virtual object, air is released from the nozzle and impacts the air receiver. The user receives the force upon touching a virtual object and feels as if his or her hand is touching it (Figure 1). The air receiver is a shallow cup-like surface attached to a lightweight stick, such as a simple paddle. Because the receiver is handheld, it's easy to start and stop using it. By using a shallow cuplike surface rather than a plane, it is found that the force provided by the air flow increases, and the size and direction of force doesn't change greatly even if the air jet hits the receiver slightly off center. The air receiver is mounted at the end of a stick so that the force applied to the air receiver is amplified according to the principle of leverage. The low air pressure of the prototype makes it ineffective to hold the air receiver directly in the hand. Because the feedback force is created by air, this interface does not constrain users with armor wire-based devices. The air receiver places no undue force on the user, which means it is safe. Using these ideas about air jets, an untethered VR system with force feedback was implemented (Figure 2). Three main design goals for the system were set: It should express the feel of touching three-dimensional objects, be tether free, and provide a realistic touching experience. To achieve these goals, three major technologies are combined: a force feedback interface that uses arrayed air jets, a wire-free display and sensing system, and the deformable computer graphics objects that mimic the feel produced by air jets.[9, 5]

### 2.1.1 System architecture

The system employs multiple air jets arranged in a matrix and detects the position and orientation of the air receiver.



**Figure 2: System configuration**

The system tracks the receiver and makes the virtual wand's object in the virtual space move accordingly.[9, 4] The system checks if the wand touches a virtual object. If the wand contacts an object, the system releases air from the appropriate nozzle. While the receiver remains in contact with the virtual surface, the system continues to release air from the nozzle. If the air receiver is moved across the object's surface, the system activates the next nozzle under the receiver. The system can thus express the existence of a 3D object. Because the user is holding the receiver, he or she feels the impact of the air at the position and height of the calculated contact point. The user feels as if he or she is touching the object's surface and so perceives one position on the object's surface (S-1 Figure 3). When the receiver is lifted above the surface, the air flow is cut (S-2 Figure 3). If the surface is inclined and the receiver is moved horizontally so that the separation between the receiver and surface is increased, the air flow is again cut (S3 Figure 3). By lowering the receiver to touch the surface again, air releases (S4 Figure 3). This means that the user can feel that the surface is inclined. Because this implementation uses only vertical air jets, it's not possible to feel the objects' sides, but corners and edges are recreated to some extent. When the user runs the paddle across the top surface of the object, the system releases air as long as the paddle is on the surface. When the paddle passes a corner, the system stops the last air jet, and the user feels a sudden drop in resistance from the surface. Adding horizontal force would dramatically improve the expressiveness of the system. Realizing a multidirectional air jet array is an important technical issue. The implemented system uses 100 air jet nozzles arranged in a 10 x 10 array embedded in a table (Figure 4). The nozzles are arranged at regular intervals. All nozzles are connected to the same air compressor with flexible tubes. The air flow through each nozzle is controlled independently by an electric valve placed between each nozzle and the air compressor. For simplicity, the strength of each air jet is constant. Only one valve corresponding to the position of the receiver opens

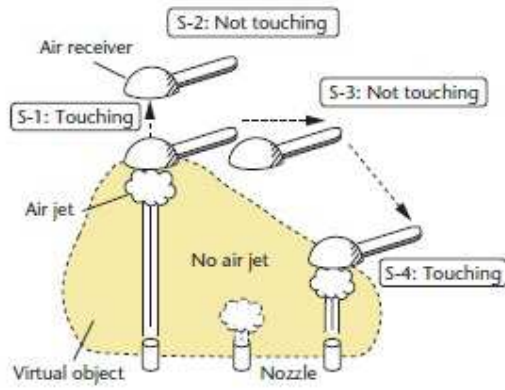


Figure 3: Expression of a virtual object



Figure 4: Implemented systems 100 air-jet nozzles.

at a time to reduce pressure loss. The nozzle pitch is set to 4 cm. This pitch is determined with a pilot experiment in which we measured, using a 10-cm diameter air receiver, the load received by the receiver while changing the distance from the center line of the nozzle (Figure 5). The load is relatively stable if the offset is less than 4 cm, but rapidly decreases with larger distances. Taking the resolution of position tracking into account, the nozzle pitch is determined. The effective height range of this force feedback system is approximately 30 cm above the air jet array. Beyond 30 cm, the air flow is too weak to provide a reliable sensation. Because of its simple construction, the output of one compressor is passed to multiple nozzles, which means it's easy to expand the effective area of the system by increasing the number of nozzles. Because there is no connection between the nozzles and the air receiver, the system could be built with multiple air receivers, allowing users to touch objects with both hands.

### 2.1.2 Display and sensing

To realize the wire-free display, a projection-based stereo display system is employed. In this system, stereo images are projected onto the top surface of the table. By detecting the positions of the user's eyes, the system provides the user with the view of the 3D virtual object that corresponds to

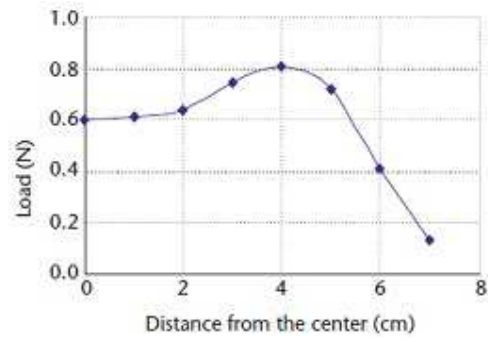


Figure 5: Loading on the air receiver versus distance from its center. The vertical distance from the nozzle is 20 cm.

his or her perspective. The black air jet holes on the top surface of the table are covered with simple white flaps so that the stereo images projected on the table don't degrade. The flaps open with the released air and close again when the air stops. The system uses anaglyphs because they are easier and less expensive to implement. The anaglyph stereo images are projected onto a horizontal white screen that is 140 cm wide, 110 cm long, and 70 cm high. This screen size and height is used so that users with heights ranging from 150 to 175 cm can get a full view of the virtual objects from anywhere around the screen. As with the wire-free position-sensing method, an optical position-tracking system is employed. The system uses two cameras to capture the visual markers and computes the marker's 3D coordinates. By using the position of three markers attached to the paddle, the system computes its orientation as well as position. By detecting the position of the two visual markers attached to both sides of the user's 3D glasses, the system knows the positions of the user's eyes, which is necessary to reproduce the stereo image from the user's viewpoint. This VR system is comfortable because the user is not encumbered by wires or arm devices. The user simply puts on the 3D glasses and holds the paddle.

### 2.1.3 Users and Applications

During the 40-hour Siggraph 2004 Emerging Technologies exhibit demonstration of the system, more than 2,300 people experienced the Air Jet Interface. The untethered attribute of this interface helped make this amount of tests possible. It required little time for people to take turns because the next person could simply take his or her place, wearing the eyeglasses and holding the paddle. The users reported that they enjoyed the feedback provided by the air jets and the deformable surfaces and that the system was comfortable to operate. Using this interface is not limited to tabletop applications. Imagine this system being installed in large areas or buildings to enrich the user's experience and establish interaction over extended distances. Multiple users could participate in the same game, and could enjoy interacting with virtual objects while walking along a hall. Because each air jet can be controlled independently corresponding to the users' action near the nozzles, this interface method has the significant advantage of scalability. It is also expected that this device will be effective in expressing lively



entities. After using the system for several months, the team felt confident that the interface's soft but quick reaction can be an advantage to express lively objects, such as frolicking animals or bouncing balls. Because the system uses air to generate force feedback, it's safe to use and can support quick reactions. Designing such objects is one of the key issues we are investigating.

#### 2.1.4 Personal Thought about this device

Although this technology gives us a great resolution and feedback for the respective applications but the size of the device is still a big problem, because it can not be used in normal daily life applications, but for the purpose of the academic or even industrial use this device seems suitable.

## 2.2 A Novel Wearable Device to Present Localized Sensation of Wind

Previous works on wind display systems have been proposed to increase the quality of an immersive sensation in virtual environments. Most of the methods display wind by ground-fixed wind fans around the user. Moon proposed a "windcube" which has an array of fans to evaluate the best placement of fans. Sawada proposed a communication system that has an input and output wind system. To decrease the number of fans, a system that can display wind at every angle using only two fans was proposed by Kulkarni. However, these systems have three problems. The first problem is the limited workspace because of the fixed fans, which mean that the simulated wind cannot be displayed if the user moves. The second problem is the distance between the source of the wind and the user. A strong wind source would be necessary for a user far away, increasing cost and energy. The last problem is localization of wind. When there is a large distance between the wind source and the user, the display area of the wind grows, and wind cannot be expressed to local areas of the skin. Cardin proposed a system called head-mounted wind, which had eight large fans. This is similar to this technology concept we are discussing, but the device was heavy and the presentation area was large. In this study, wind device is proposed to solve the three problems. The purpose is to manufacture a more compact, light weight, and practically wearable device, which can display wind closer and more localized to the skin. There are two main issues for the wearable wind device. One is where the wind should be displayed. The other is how to make the device compact while retaining sufficient power and response time.[6]

#### 2.2.1 System configuration

System configuration, driving circuit, and experiment setup are shown in Fig. 6, Fig. 7, and Fig. 8. The Position of the wind source can be adjusted freely. An analog signal from DA board (PCI-3523A, Interface Corp.) is amplified by a transistor (2SC1815, Toshiba Corp.) and supplied to small fans 15mm in diameter (F1019AP-01YV, SICOH Corp.).

#### 2.2.2 Air speed calibration

First, The fans are calibrated using an air speedometer (ANEMOMASTER6115, Nihondenko Corp.). The range of input voltage was 0 – 5.0 V and the distance from the small fan to the air speedometer was 15mm. Room temperature was 27 degrees and humidity was 38–46%. The result is shown in Fig. 9. The longitudinal axis indicates wind velocity and

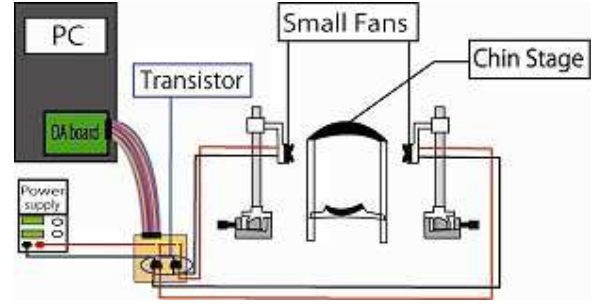


Figure 6: System configuration for the measurement of wind sensitivity at various locations

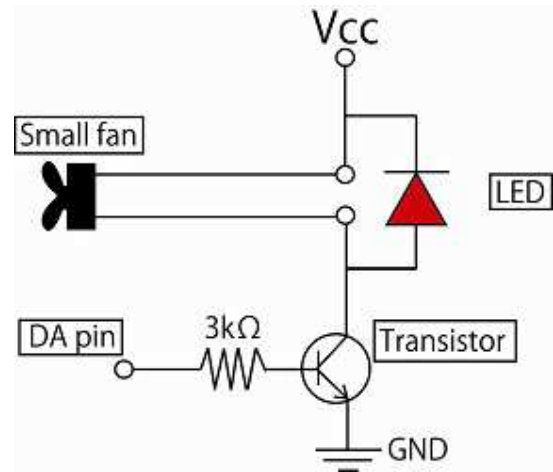
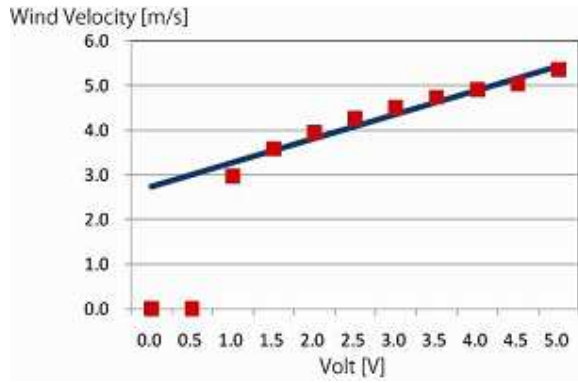


Figure 7: Fan driving circuit



Figure 8: Experiment setup: Small fan is attached on a motion stage. Air speedometer was used for calibration.



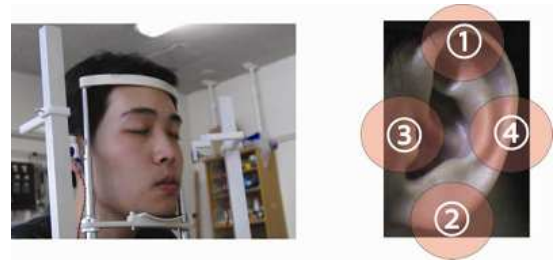


**Figure 9: Relationship between input voltage and wind velocity**

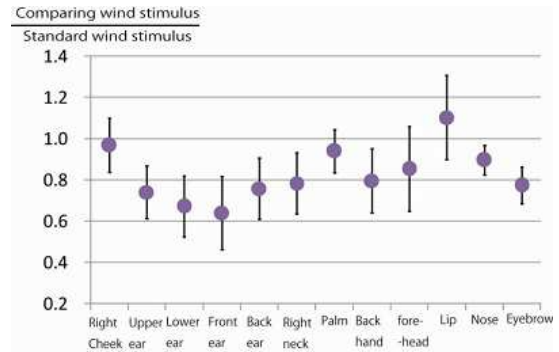
the abscissa axis indicates the voltage. The relation between voltage and wind velocity was nonlinear because the transistor has a diode feature between the base and the emitter. The line in Fig. 9 is a straight-line approximation. The formula is  $y=0.54x + 2.73$

### 2.2.3 Experiment

To measure the wind sensitivity at various locations, An experiment is conducted using a method of adjustment. The participants were three males (22–23 years). Their heads were fixed on the chin stage and they listened to white noise by earphone to avoid perception from the sound of rotating fans (Fig. 10). They compared two wind stimuli, standard wind stimulus and comparison wind stimulus. The cheek was selected as a standard wind stimulus area. The standard wind stimulus was applied to the left cheek and the comparison wind stimulus was applied to the nose, ear, forehead, lip, eyebrow, palm and backhand. These are the body parts that are exposed to air while wearing clothes. Participants adjusted the amplitude of the comparison wind stimulus so that the same amount of wind sensation could be felt as the standard wind stimulus. In this experiment, the display area of the ear was divided into four areas, because the complicated structure of the ear might influence the result (Fig. 10. Right). The initial condition of the comparison wind stimulus was either strong (4.0 V) or weak (1.0V). The standard wind stimulus was fixed to 2.0V, 2.5V, or 3.0 V, selected at random. The sequence of areas was selected at random too. Two small fans ran for 1 sec alternately. The distance between the fan and skin was 15mm. The room temperature was 20 degrees and humidity was 38–40%. The experiment was performed three times on each area, and the results were averaged. The results are shown in Fig. 11. The longitudinal axis indicates the ratio of the standard wind stimulus to the comparison wind stimulus. The abscissa axis indicates each part. Fig. 11 clearly shows that the most sensitive area to wind stimulus was the front of the ear, while all other parts of the ear exhibited similar results. It was concluded that the area around the ear would be the most effective area for wind display. The system configuration is shown in Fig. 12. The participants were four males (22–23 years). They fixed their chin on the chin stage and evaluated a two-point wind stimulus. The target of the first source of wind stimulus was the front of the ear, which is



**Figure 10: Left: experiment setup Right: four area of ear 1-upper 2-lower 3-front 4-back**



**Figure 11: Result of two-point threshold experiment**

the most sensitive area. The second source of wind stimulus was placed to extend the distance between the two wind sources. The first wind stimulus was applied to the front of the ear for 1 sec. Then, another wind stimulus was applied for 1 sec. Participants were asked to compare the two wind stimuli and answer whether the air was from the same or a different point. The driving frequency was fixed at 400 Hz. The distance between the points started from 9 mm because of the diameter of the hose pipe. The distance from the ear to the source of wind was 40mm – 140mm. Room temperatures was 27 degrees and humidity was 30 – 32 %. The experiment was done twice at each distance. The result is shown in Fig. 13. The longitudinal axis indicates the distance between each source of wind and the abscissa axis indicates the distance from the source of wind to the ear. As a general trend, the two-point wind threshold of all participants increased in proportion to the distance between the ear and source of wind. However, the threshold decreased at some points. This seemed to be due to the shape of the ears. Participants commented that they could easily perceive when the air hit the upper or interior parts of the ear.

### 2.2.4 Application

Summarizing the points so far, it was obtained three important points for manufacturing a wearable wind device. First, the most sensitive area to wind is around the ear. Second, audio speakers with a slit and tube attachment were able to display local wind with fast response. Third, spatial resolution of wind perception around the ear is notably high. In this section, An application system is being described. One problem is that because of the high spatial resolution

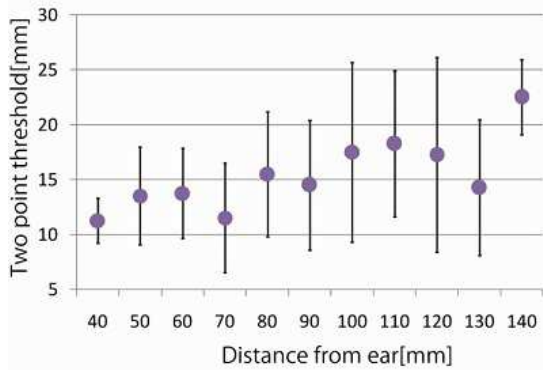


Figure 12: Result of two-point threshold experiment

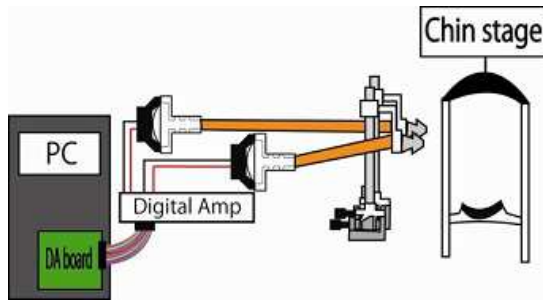


Figure 13: System configuration of the measurement of two-point threshold

of perception around the ear, numerous wind sources are necessary, which may lead to a quite heavy system. In this application example, Light weight and fast response for the wind device is the priority. This prototype device is shown in Fig. 14. The audio speakers were replaced with lighter ones (LF040P1-S, Lead sound Corp.). Air tubes are extended to the ears, and the weight of the total system is about 700g. it is confirmed that this device could apply local wind to the ears by activating an audio speaker. By replaying a wind sound with the speaker, the device can present natural wind and sound simultaneously. There are two specialized applications of this device. The first application is “a sensation of something passing the ear within kissing distance”. The immersive sensation would be increased by applying wind with visual contents such as a bullet or punch passing by. Tactile apparent motion is being used to present moving sensations. In this application, a 200msec wind sound was prepared. If something passes from front to back, at first the front side speaker is actuated for 100msec and after that the back side speaker is actuated for 100msec. The scenario is a marital quarrel. A woman angrily throws a slipper, and local strong wind is applied to the ear at the moment the slipper passes by. The second application is “wind augmentation by motion”. For example, humans feel wind by swinging their heads and jumping. The wind is augmented by this system. In this application, an acceleration sensor is used to acquire real-time user motion.

### 2.2.5 Personal Thought about this device

This technology has potential to become a mainstream



Figure 14: prototype device: Helmet has four speakers and air tube extends to ear

tool specially for gaming devices as it can have good representation of the battle scene and so forth; yet still the problem is that the user have to wear an external device and in a long run, as we can see from experience, people tend to not like wearing any external device other than the controller in gaming devices.

## 2.3 AIREAL: Interactive Tactile Experiences in Free Air

AIREAL is a novel haptic technology that delivers effective and expressive tactile sensations in free air, without requiring the user to wear a physical device. Combined with interactive computers graphics, AIREAL enables users to feel virtual 3D objects, experience free air textures and receive haptic feedback on gestures performed in free space. AIREAL relies on air vortex generation directed by an actuated flexible nozzle to provide effective tactile feedback with a 75 degrees field of view, and within an 8.5cm resolution at 1 meter. AIREAL is a scalable, inexpensive and practical free air haptic technology that can be used in a broad range of applications, including gaming, mobile applications, and gesture interaction among many others. This section reports the details of the AIREAL design and control, experimental evaluations of the device’s performance, as well as an exploration of the application space of free air haptic displays. Although we vortices are used, it is believed that the results reported are generalizable and will inform the design of haptic displays based on alternative principles of free air tactile actuation.[8]

### 2.3.1 Physics of Air Vortices

An air vortex is a ring of air that typically has a toroidal shape and is capable of traveling at high speeds over large distances. Unlike laminar airflow which quickly disperses, a vortex is capable of keeping its shape and form.[8] A vortex forms when air is quickly ejected out of a circular aperture. Air molecules at the center of the aperture move faster than the air molecules at the edge of the aperture due to the drag between the air molecules and the aperture’s surface. As the air leaves the aperture, this difference in speed causes the air to rotate around the aperture, accumulating air molecules into a ring. When the ring becomes too large, it pinches off from the aperture using its rotating motion to carry itself through space. This rotating motion minimizes the energy lost due to friction and allows the vortex to remain stable. The stroke ratio characterizes the stability of the vortex as



**Figure 15: Top: a fully assembled AIREAL device. Bottom: an exploded view showing speakers, the pan and tilt motors as well as the 3D printed enclosure, flexible nozzle and gimbal structures.**

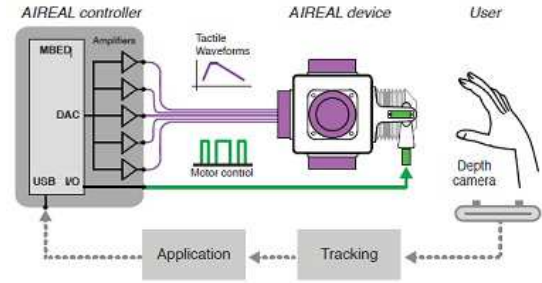
it leaves the aperture. If it is greater than a theoretically defined threshold value, called the formation number, a large turbulent wake will be created behind the vortex, resulting in lost vortex energy. A typical value for the formation number falls between 3.6 and 4.5 for various vortex systems.

### 2.3.2 Vortex Generator

The AIREAL vortex generator is shown in Figure 15 and is comprised of a cubic enclosure (8x8x8 cm), flexible nozzle (4 cm in length) and a pan and tilt gimbal structure that is used to actuate the nozzle. All components except for the actuators and motors are 3D printed on an Objet™ printer using a mixture of hard and soft UV-cured photopolymers and resins. Five 2-inch 15W Whisper™ subwoofers were used as actuators, mounted around the enclosure with the flexible nozzle facing outward into the environment (Figure 15). The actuators contain a flexible diaphragm that, when displaced, pushes a volume of air. The displacement rate of the speaker cones determines the flow rate of the air going in and out of the device. The total weight of the AIREAL device is 1278g.

### 2.3.3 AIREAL Implementation

The AIREAL signal generator is an Mbed microcontroller control board based on the LPC17168 ARM Cortex M3 microprocessor which generates low-amplitude pulse waveforms using a digital-to-analog converter. The amplitudes and frequency of pulses are dynamically controlled from a host PC using a simple protocol over serial interface. The waveforms are smoothed using a low-pass filter and amplified using a TI3001D1 single-channel 15 W D-class differen-



**Figure 16: The overall AIREAL system diagram.**

tial sound amplifier. There are five amplifiers implemented on the control board with the total output current limited to 8A with a maximum power consumption of 60 W. The control pulse frequency varies between 1 and 30 Hz. The motors controlling the motion of the flexible nozzle are driven directly from the digital control pins of the microcontroller. The board is powered with a 12 V DC power source. The amount of displacement of a speaker's cone is directly related to the amount of current passing through the speaker. At 12V and 1.1A, the speakers produced the largest displacement at 8 mm (i.e. -4 mm to +4 mm), in line with manufacturer specifications of the speakers. Driving the speakers with higher current yielded no further increase in displacement. The 3D printed pan and tilt mechanism controls the flexible nozzle, which allows the vortex to be directed to a specific location in physical space (Figure 16). To direct the vortex to a 3D location, the AIREAL device is combined with depth sensors to allow real-time tracking of a user's hand and body as well as physical objects in the environment. AIREAL is primarily comprised of two depth-sensing configurations: (1) a local configuration, where a small depth sensor (PMD Camboard Nano) is mounted directly to a base plate rigidly connected to the AIREAL device; (2) a global configuration, where a large depth sensor (Microsoft Kinect) instruments the user's physical environment. The on-board sensor enables the direct ad-hoc interaction with AIREAL device allowing for a simple and quick setup at the cost of a smaller tracking volume, i.e., 2 meter distance from the sensor. In contrast, the large environmental sensor allows tracking over larger distances and simplifies connecting multiple AIREAL devices to cover larger volumes of space. In order for vortices to be accurately directed to a 3D location, the AIREAL device must be calibrated to the depth sensor. This requires that the 3D position of the AIREAL device be known with respect to the depth sensor. For the local configuration, A known baseline (7.2 cm) is being used between the rigidly mounted depth sensor and the AIREAL device. An initial manual calibration process uses a line laser mounted inside the flexible nozzle to estimate the position and orientation of the AIREAL device in relation to the depth camera. For the global configuration, A manual calibration is followed process using the Procrustes transformation to extract a 3D rigid transform between the AIREAL device and the depth sensor. Each AIREAL device was manually instrumented with a small calibration rig composed of infrared markers. The markers were detected by depth cameras and used to find 3D correspondences with locations on a known 3D model of the AIREAL device. This

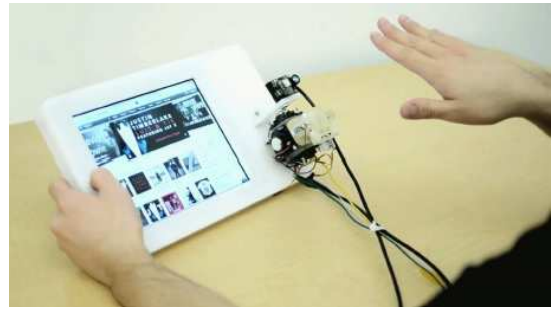


**Figure 17: Haptic projection: a projected butterfly is collocated with free air tactile sensations.**

calibration procedure is found sufficient for the applications. A key challenge of controlling air vortices in 3D space is to ensure that the movement of the servomotors controlling the flexible nozzle does not hinder vortex creation. For example, if the flexible nozzle is moving too quickly, air resistance may prevent the vortex from forming correctly at the tip of the nozzle, leading to irregularities in the vortex's movement. To ensure stable vortex creation, a 5 ms delay was introduced, i.e., an estimated pinch-off time measured in earlier latency tests, for each cycle in the pulse signal. This technique greatly improved the directionality control of our device and allowed for accurate continuous free air sensations to be directed at a specific location in the environment.

### 2.3.4 Applications - Haptic Projection with AIREAL

If virtual objects can emit haptic sensations on the human body, they can create richer and more enjoyable user experiences and significantly increase the realism of virtual objects. There is a long history of bringing virtual objects into the real world, including augmented reality[1], using handheld projectors to display dynamic virtual images both on the physical world and on the human body[11], and designing augmented computing environments that allow seamless manipulation of virtual objects in physical space. However, enhancing virtual images with tactile feedback has been a difficult challenge in designing computer-augmented environments. AIREAL offers an ad-hoc and lightweight approach that makes it easy for users to see and feel projected images. With AIREAL, the human body acts as an interactive display surface enriched by free air tactile sensations. An AIREAL device is calibrated with an overhead projector and depth camera system to enhance projected images with free air haptic sensations (Figure 17). Virtual images were dynamically projected on the user's hand that was simultaneously tracked using a depth camera. A classic distance transform metric was used to extract the local maximums in the depth image of the user's hand, providing its location in 3D space. Figure 17 demonstrates an example interaction where virtual images projected on a user's body are collocated with free air haptics. A projected 3D butterfly is displayed hovering on the user's hand. AIREAL tracks the motion of the user's hand and arm and adjusts the direction of vortices to preserve the collocation of virtual and haptic stimuli. A 100 mVpp, 6 Hz tactile stimulus is used to match vortices to the movement of the butterfly's wings. The vortex latency measurements were used to calculate when to send out a vortex towards the user's body.



**Figure 18: Persistent haptic spaces provide gestural feedback as a user performs swipe gestures to scroll images.**

The system used the distance between the AIREAL device and the user's hand as well as the speed and position of the virtual butterfly to compute the ideal emission time of a vortex. Although this helped to alleviate some of the vortex latency, the latency inherent in all projector-camera systems still contributed to the vortices falling slightly behind the virtual butterfly during rapid movement of the user's body. Nevertheless, the early user feedback indicated that the interaction provided compelling physical sensations of the virtual butterfly. As one user described it, "it feels natural, it feels like a butterfly should feel."

### 2.3.5 Applications - Augmenting Gestures with AIREAL

Free air gestural input can be a powerful complement to traditional mouse, keyboard and touch screen interfaces and has recently become very popular in gaming, home and location-based entertainment. Providing efficient tactile feedback to free air gestures in 3D space can significantly improve performance and enjoyment of such interactions. AIREAL can provide tactile feedback to 3D gestures without requiring any instrumentation of the user. A scaled down version of the AIREAL device instrumented with a PMD Camboard Nano is used to track a user's hand motion in relation to an iPad tablet computer encased in an acrylic case. The AIREAL device was attached to the front and right side of the device (Figure 18). A series of invisible 3D virtual buttons were placed around the tablet to enable interaction with an iTunes on-line store interface. Virtual 3D buttons were accompanied with tactile feedback and together they created persistent interactive haptic spaces around the mobile device. For example, left and right swipe buttons were virtually positioned on the sides of the tablet device and a selection button was virtually positioned in front of the tablet device. When the user's hand intersects the virtual 3D button, a vortex is emitted to signal that the user has selected a virtual button. To implement and validate these interactions, GlovePIE was used to map 3D gestures to mouse events on the tablet. This application of AIREAL demonstrates many interesting possibilities in designing effective 3D gestural interfaces for graphical applications. Being able to interact with virtual elements and receive physical feedback in much the same way as we interact with real physical objects, e.g., real buttons that provide physical feedback, could provide more natural spatial interfaces in future applications. One user described his experiences as "... a burst of air is hitting your hand, like something is hitting me."





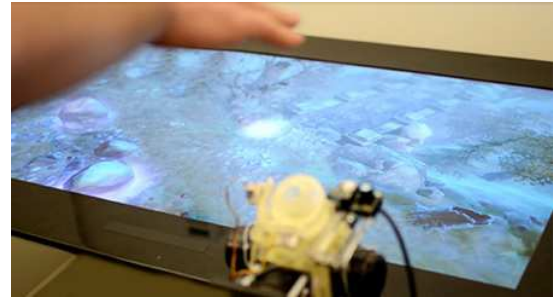
**Figure 19:** Continuous free air tactile sensations around the user. The user who is playing a game can feel virtual seagulls fly continuously around him.

### 2.3.6 Applications - Making Continuous Free Air Experiences

Creating immersive experiences that surround the user is one of the most important goals in designing home and location-based entertainment environments. Audio has often been used in combination with on-screen visuals to create immersive user experiences. Similarly, free air haptics can be used to surround a user with continuous haptic experiences. In combination with AIREAL, conventional displays, such as a computer monitor, TV or movie screen, can bring virtual elements such as virtual characters from the screen into the real world. By combining multiple AIREAL devices that coordinate with each other, the users can physically feel virtual characters moving around them (Figure 19). To simulate this experience, three AIREAL devices were placed around the user who was facing a desktop monitor (Figure 19). All AIREAL devices were calibrated to a single depth camera's coordinate system using manual calibration techniques. The user's head was also tracked using a standard Haar classification technique. To demonstrate continuous haptic motions, an exemplary game was created where virtual seagulls were attempting to steal food from the user's virtual character. To create an experience of a seagull flying around the user, the virtual position of a seagull was translated into the physical environment, and the AIREAL device closest to the location of the seagull was activated. The seagull's physical position is projected on the user's head, providing a location of where to direct a vortex. As the seagull circles around the user's virtual character, vortices are emitted continuously to simulate the seagulls moving around the user in the real world. This simple yet powerful interaction provides the user with an intuitive and natural way to physically feel the actions taking place in the virtual world, e.g., there is a seagull flying nearby. As one user commented, "it feels like the wake of the bird is hitting you as it flies by."

### 2.3.7 Applications - Feeling Varying Textures in the Air

Real world objects often have a high degree of surface variance that produces distinct and prominent tactile texture sensations. For example, stones can feel rough, sand can feel gritty and water feels smooth. Simulating tactile textures using a variety of haptic devices have been an active and important area of research. AIREAL can be used



**Figure 20:** The user can feel textures of the virtual terrain.

to create free air tactile sensations of 3D objects with different textures. For example, users can move their hands over a virtual 3D object with a smooth surface, followed by a virtual 3D object with a rough surface and feel completely distinct free air sensations (Figure 20). To create free air tactile textures, a set of free air tactile stimuli with distinct tactile sensations varying in amplitude and pulse frequency was designed. These tactile stimuli were mapped into the initial set of visual textures, including sand, stones, grass, water and metal ridges. These signals were designed using JND(Just Noticeable Difference) values collected from the perceptual experiments as well as informal pilot studies where users were asked to feel a series of distinct free air sensations and characterize their tactile perception. Adjectives such as "bursty" and "slippery" provided by the users was used to define a texture space of free air tactile sensations that we mapped into a 3D game. Figure 20 shows a virtual game environment that created containing multiple distinct terrains. A Microsoft PixelSense tabletop computer was used with an AIREAL device placed in front of it and oriented upward towards the user's hand. Four signals varying in amplitude (0.1 mVpp to 3.3 Vpp) and pulse frequency (1 Hz – 30 Hz) were mapped to textures of grass, a stone bridge, wooden rooftop and water. A lookup table was created to map signals to virtual 3D objects associated with a free air sensation. To play the game, a user gestured with their dominant hand to control the location of a virtual character moving around the environment. A "virtual joystick" metaphor was implemented for character navigation: moving the hand away from the initial start position defined the direction that the character followed. To deactivate, the user simply moved their hand away from the depth sensor. Hand tracking procedure described in previous applications was used to track the user's hand. This allowed users to freely gesture and move their character through the environment, passing over terrains mapped to free air textures identified previously. For example, going from the grass to a bridge would switch from smooth, low amplitude vortices to a more pronounced "bumpy" one.

### 2.3.8 Applications - Moving Further Into the Real World

The examples presented above demonstrate that the AIREAL approach can provide rich free air tactile sensations that open new and exciting applications in interactive computer graphics. However, the applications of free air haptics are much broader and new and exciting opportunities for inter-



**Figure 21: Free air haptics can be expanded into the real world with projected virtual imagery on physical objects.**

action exist with free air tactile feedback devices. Figure 21 shows one example where a virtual butterfly rests on a plant. As the butterfly moves its wings, the plant's leaf moves in response. If a user decides to touch the butterfly, the user can initiate the experience by simply stretching a hand and touching the butterfly projection. In other speculative examples, real world explosions can cause shocks and vibrations that move surrounding objects. We can imagine a future use of AIREAL where the free air sensations are not just directed to the user, but to peripheral objects in the environment where an explosion in a movie causes a piece of paper to fly off the desk, or plants in the background to shake their leaves. With AIREAL, objects in our physical environments can truly come to life.

#### 2.3.9 Limitations

The AIREAL technology enables the design of new and exciting interactions and free air haptic experiences. However, there is a limitations of the current device. The AIREAL device produces an audible sound. This is mainly caused by the speakers, which produce a low frequency physical "knock" when driven by a high amplitude, low frequency signal.

#### 2.3.10 Personal thought about this device

In my opinion in all the devices that came till now for using the air flow as a media for getting feedback from virtual world, this device (AIREAL) is the most applicable and usable in daily life one. not only it is accurate in resolution, but also it doesn't require the user to wear an external device and also not too heavy or big so it cannot be moved. i think in future with advancing in technology if we could generate powerful air-vortex using even smaller speakers (or an other device) this technology can be even part of the next-generation mobile phones and the usage of it will become mainstream.

### 3. PERSONAL OPINION ABOUT USING AIR-FLOW FOR HAPTIC FEEDBACK

Using the air-flow seems to be a good idea for getting feedback in virtual world as it is rather cheap to build the device compare to other technologies which use sonic-waves or electromagnetic, and also the technology itself is not very complicated so people can improve it more often. I think that in near future with improving this technology, so the

device become really compact and also become more accurate, it is expected that game and movie production companies will use this technology to give the users a new and exciting experience for presenting their media, which is a vital part of their business. but of course for mainstreaming this technology a lot of investment and advertising should be done as it is always a hard job to convince the users try new and unexplored technologies.

### 4. CONCLUSIONS

This paper studied the necessity of having haptic feedback in softwares, games and other fields in virtual world and demonstrated multiple examples of works done by other researchers in this field. Although this approaches and the whole idea of this technology is rather new but significant improvement is being observed and it is shown that using this technology and devices can actually have a big impact on user experience and even performance of the respective applications. But it seems that there is still one problem with this devices and it is the size of the Air-Vortex Generator which is expected in near future it will be resolved such that this technology could be usable even on the mobile devices.

### 5. REFERENCES

- [1] R. Azuma, Y. Baillet, R. Behringer, S. Feiner, S. Julier, and B. MacIntyre. Recent advances in augmented reality. *IEEE Comput. Graph. Appl.*, 21(6):34–47, Nov. 2001.
- [2] G. Hoelzl. A personalised body motion sensitive training system based on auditive feedback. In T. Phan, A. Montanari, and P. Zerfos, editors, *Proceedings of the 1<sup>st</sup> Annual International ICST Conference on Mobile Computing, Applications, and Services (MobiCASE09)*, volume 35 of *Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering*, San Diego, California, USA, October 26-29 2009. ICST, Springer. ISBN: 978-3-642-12606-2.
- [3] G. Hoelzl, A. Ferscha, P. Halbmayer, and W. Pereira. Goal oriented smart watches for cyber physical superorganisms. In *Workshop on Collective Wearables: The Superorgansim of Massive Collective Wearables, at 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp 2014)*, Seattle, USA, September, pages 1071 – 1076, September 2014.
- [4] G. Hoelzl, P. Halbmayer, H. Rogner, C. Xue, and A. Ferscha. On the utilization of smart gadgets for energy aware sensitive behavior. In *The 8th International Conference on Digital Society, ICDS 2014, March 23 - 27, Barcelona, Spain*, pages 192 – 198, March 2014.
- [5] G. Hoelzl, M. Kurz, and A. Ferscha. Goal processing and semantic matchmaking in opportunistic activity and context recognition systems. In *The 9th International Conference on Autonomic and Autonomous Systems (ICAS2013)*, March 24 - 29, Lisbon, Portugal, **Best Paper Award**, pages 33–39, March 2013.
- [6] Y. Kojima, Y. Hashimoto, and H. Kajimoto. A novel wearable device to present localized sensation of wind.

- pages 61–65, 2009.
- [7] I. Poupyrev and S. Maruyama. Tactile interfaces for small touch screens. pages 217–220, 2003.
  - [8] R. Sodhi, I. Poupyrev, M. Glisson, and A. Israr. Aired: Interactive tactile experiences in free air. *ACM Trans. Graph.*, 32(4):134:1–134:10, July 2013.
  - [9] Y. Suzuki and M. Kobayashi. Air jet driven force feedback in virtual reality. *IEEE Comput. Graph. Appl.*, 25(1):44–47, Jan. 2005.
  - [10] M. Y. Tsalamlal, P. Issartel, N. Ouarti, and M. Ammi. Hair: Haptic feedback with a mobile air jet. In *2014 IEEE International Conference on Robotics and Automation (ICRA)*, pages 2699–2706, May 2014.
  - [11] K. D. Willis, I. Poupyrev, S. E. Hudson, and M. Mahler. Sidebyside: Ad-hoc multi-user interaction with handheld projectors. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology*, UIST ’11, pages 431–440, 2011.



# Application Areas for Haptic Feedback Interaction

Iuliia Semenova  
Universität Passau  
Lehrstuhl für Informatik mit Schwerpunkt Eingebettete Systeme  
Innstr. 43  
94032 Passau, Germany  
semeno02@gw.uni-passau.de

## ABSTRACT

Haptic interaction is a new field of research that adds the sense of touch to virtual environments. This includes using touch as a feedback system to communicate information to the user and to simulate virtual objects. In this paper, I concentrate on the different application areas for haptic feedback interaction. Existing technologies and devices are reviewed and considered in terms of their application. At the end, several observations per area are provided and suggestions for future work are proposed.

## Keywords

Haptic Feedback, Robotics, Magnets, Ultrasound, Telemanipulator

## 1. INTRODUCTION

The word haptic, from the Greek: *ἅπτικός* (*haptikos*), means "pertaining to the sense of touch" and comes from the Greek verb *ἅπτεσθαι* (*haptesthai*), meaning "to contact" or "to touch". The international scientific vocabulary defines haptic as relating to or based on the sense of touch or characterized by a predilection for the sense of touch. Human haptics is defined as the human touch perception [40].

In the physical world we impose forces on ourselves whenever we touch anything. These forces and the position and motion of our hand and arms are transmitted to the brain as kinesthetic information [39]. This information along with cutaneous (touch) senses, force and motor capabilities are what allow us to touch and manipulate objects and relate them to the space around us.

Haptic interactions give the user the illusion that they are dealing with real, physical objects. Interactions to this extent of reality in this new field are motivation for research of this topic. There are several technologies that provide Haptic Feedback, such as Telemanipulators (remote manipulation systems), electric actuators, vibrations and for Non-Contact Haptic Feedback: magnetic force, ultrasound, air-jet and air-vortex. The last two approaches are known for

long operation distance but with very weak force strength and are quite limited in the possible areas of use. Moreover the systems based on air technologies is quite slow in reaction. Thus, I will consider only telemanipulators, magnetic force and ultrasound, as they are the most promising and popular in my opinion.

In this paper, I concentrate on the different application areas for haptic feedback interaction. The paper is organized as follows: Section 2 contains a review of most popular technologies: Remote manipulation systems, Magnetic forces and Ultrasound. In Section 3, I provide a brief survey of existing implementation of haptics in medicine, space exploration, touch less interfaces, virtual reality and touchable holograms. In Section 4, I discuss about cases where haptic feedback can be used and which technology in which case is most suitable. The paper closes with a conclusion and ideas for future work.

## 2. HAPTIC FEEDBACK TECHNOLOGIES

In this section will provide a brief overview of Haptic Feedback technologies, main characteristics and the basic inventions.

### 2.1 Remote manipulation systems

In the past, people used devices that would give them a sense of touch. Simple tongs, mechanical hands, and levers were used to control remote actions such as pouring hot liquids, or grabbing flasks. Designer Knoll, at Bell Labs in the 1960's was one of the first to demonstrate the touching of a virtual shape using a computer haptic interface [39]. Since then researchers have continued to work on robotic systems which are through electronic, hydraulic, or mechanical linkages, allows a hand-like mechanism to be controlled by a human operator, and robot - human interface technologies. These new interactive systems (telemanipulators) expand the abilities of humans, by increasing physical strength, by improving manual dexterity, by augmenting the senses, and most intriguingly, by projecting human users in to remote or virtual environments.

Standard remote manipulation systems usually is controlled by direct current (DC) motors that have sensors and encoders attached to them. The number of motors corresponds to the number of Degrees Of Freedom (DOF) a particular system has. DOF are the directions the user can move in. The encoders track the users motion or position along the x, y and z coordinates and the motors track the forces exerted on the user along the x, y and z axis. From the motors there is a cable that connects to an aluminum

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, to republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

Application Areas for Haptic Feedback Interaction '17 Passau, Germany  
Copyright 2016 ACM X-XXXXX-XX-X/XX/XX ...\$15.00.

linkage which connects to a passive gimbal which attaches to the thimble, stylus or any special tool. A gimbal is a device that permits a body freedom of motion in any direction or suspends it so that it will remain level at all times. In simple systems no torque is measured, only force applied to the point. Friction and inertia must be constant to limit distractions of the user [30]. Moreover, remote manipulation haptics systems must be able to interpret force and motion information, analyze and sense the forces applied by the user and then deliver the sensation back in real time.

### 2.1.1 Phantom

In 1993, J. K. Salisbury and Thomas Massie presented and commercialized the Personal Haptic Interface Mechanism - the Phantom. The Phantom haptic interface began the new field of research called computer haptics [39]. The Phantom tracks the motion of the user's finger tip and can actively exert an external force on the finger, creating compelling illusions of interaction with solid physical objects. A stylus can be substituted for the thimble and users can feel the tip of the stylus touch virtual surfaces. By stressing design principals of low mass, low friction, low backlash, high stiffness and good back drivability the system capable of presenting convincing sensations of contact, constrained motion, surface compliance, surface friction, texture and other mechanical attributes of virtual objects.

Nowadays there exist a lot of telerobotic systems with 1 - 7 DOF. The Phantom also has improved and expanded its lineup. Currently, the most popular are the The Phantom Omni and The Phantom Premium. This haptic devices have 6 DOF haptic feedback. In addition to force feedback along the x-, y- and z-axis, this 6 DOF haptic device simulates torque force feedback in three rotational degrees of freedom: yaw, pitch and roll. Geomagic Touch is a motorized device that applies force feedback on the user's hand, allowing them to feel virtual objects and producing true-to-life touch sensations as user manipulates on-screen 3D objects. A new handle design for the Phantom Premium enables attaching interchangeable end effectors that provide pinch functionality. Thus it provides 7 DOF positional sensing.

### 2.1.2 Sensors

Dexterous handling of small, delicate structures such as micro mechanisms, surgical scalpels needles and soft, compliant biological tissues requires precise sensing and modulation of manipulation forces in order to prevent unintended damage. Several innovations have been made in recent years to facilitate haptic feedback in micromanipulation, including piezoresistive strain gauges [4, 31] and optical Fiber Bragg Grating (FBG) sensors [43] for tool-tip force measurement in microsurgery devices, piezoelectric polyvinylidene-fluoride (PVDF) films [37] and MEMS-based capacitive sensor arrays [41], [16] for tactile sensing in robotic micromanipulation, and monolithic MEMS-based force-sensing manipulators [26], [6]. All of these innovations enable precise force measurement or contact localization suitable for micromanipulation, but several of them also entail problems with fabrication cost, mechanical robustness, signal fidelity and temporal hysteresis, packaging and assembly limitations, and a lack of functional versatility that make them unfit for general-purpose micromanipulation.

Advances in flexible electronics have enabled a new class of soft, elastic, skin-like sensors that promise to improve the

feasibility and flexibility of force and tactile sensing in micromanipulation. New sensor technologies such as stretchable conductors [42], single-walled carbon nanotubes, and conductive particle and liquid microchannel embedded elastomers [7, 27, 35], and elastomer-coated capacitive MEMS sensors [32] are mechanically robust and innately reduce peak forces in micromanipulation due to their compliance [29]. These soft sensors improve manipulation by conforming to object surfaces to increase contact friction, allowing stable grasps with smaller applied forces, and by enabling palpation to determine object geometry, mechanical properties [36], and an object's position within a microgripper [10].

### 2.1.3 Exoskeletons systems

Another way to receive haptic feedback is using so-called exoskeletons systems. It is a wearable devices that is powered by a system of electric motors, pneumatic, levers, hydraulics, or a combination of technologies that allow an operator to control a remotely-located robotic and literally feel the tele-manipulated objects.

Modern remote manipulation systems permit touch interactions between human users and remote virtual and physical environments with high-precision sensitivity and response.

## 2.2 Magnetic

Another approach to implementing haptic feedback is through magnetic forces. Magnets exert forces and torques on each other due to the complex rules of electromagnetism. The forces of attraction field of magnets are due to microscopic currents of electrically charged electrons orbiting nuclei and the intrinsic magnetism of fundamental particles (such as electrons) that make up the material. Both of these are modeled quite well as tiny loops of current called magnetic dipoles that produce their own magnetic field and are affected by external magnetic fields. The most elementary force between magnets, therefore, is the magnetic dipole-dipole interaction. If all of the magnetic dipoles that make up two magnets are known then the net force on both magnets can be determined by summing up all these interactions between the dipoles of the first magnet and that of the second.

Magnetic levitation haptic devices allow users to receive force-feedback by manipulating a handle that is levitated within a magnetic field. Users can translate and rotate the handle while feeling forces and torques from the virtual environment. Compared with traditional haptic devices that use motors, linkages, gears, belts, and bearings, magnetic levitation uses a direct electro-dynamic connection to the handle manipulated by the user. Some of the advantages of this approach are: no static friction, no mechanical backlash, high position resolution, simulation of a wide range of stiffness values, and mechanical simplicity. Magnetic haptics has been considered in relation to surgical training systems [8].

The basis of most modern systems with magnets haptic feedback is array of magnetic coils or magneto-rheological fluid, whose rheological properties may be rapidly varied by the application of a magnetic field.

## 2.3 Ultrasound

The method of using a focused ultrasound to stimulate receptors in the human body was investigated as an alternative that requires no physical contact. The method is

based on a nonlinear phenomenon of ultrasound: acoustic radiation pressure. The acoustic radiation pressure  $P[Pa]$  is described as:

$$P = \alpha E = \alpha \frac{I}{c} = \alpha \frac{p^2}{\rho c^2}$$

where  $E[J/m^3]$  is the energy density of the ultrasound,  $I[W/m^2]$  is the sound intensity,  $c[m/s]$  is the sound speed,  $p[Pa]$  is the RMS sound pressure of the ultrasound, and  $\rho[kg/m^3]$  is the density of the medium.  $\alpha$  is a constant ranging from 1 to 2 depending on the reflection coefficient  $R$  at object surface;  $\alpha = 1 + R$ . In case the object surface perfectly reflects the incident ultrasound  $\alpha = 2$ , while if it absorbs the entire incident ultrasound  $\alpha = 1$ . The acoustic radiation pressure acts in the same direction of the ultrasound propagation. That is, roughly saying, the ultrasound 'pushes' the object. Thus, the equation suggests that the spatial distribution of the pressure can be controlled by using wave field synthesis.

The use of focused ultrasound as a non-invasive method to stimulate neuroreceptor structures in various parts of the human body has been a topic of research since the early 1970s [13]. By stimulating neuroreceptors within the skin, it has been demonstrated that focused ultrasound is capable of inducing tactile, thermal, tickling, itching and pain sensations [14]. These tactile sensations are caused by a non-linear effect of focused ultrasound called acoustic radiation force. The radiation force induces a shear wave in the skin tissue, creating a displacement, which triggers the mechanoreceptors within the skin [15]. Should be noticed, that tactile sensations cannot be felt continuously unless it also changes continuously with time, as tactile receptors are mainly sensitive to changes skin deformation roughly between 200Hz and 300Hz. Thus, the ultrasound has to be modulated at a frequency which corresponds to the peak sensitivity of the tactile receptors.

In 2008, T. Iwamoto and al. proposed to combine the transducers in the arrays (tactile device) to produce tactile sensation with airborne ultrasound in 3D space [24]. At the beginning, the prototype was consisted of two dimensional phased arrays of 91 ultrasound transducers and could move a focal point only along  $Z$  axis. In 2009, it was upgraded and the prototype was consisted of 324 ultrasound transducers, which could move a focal point in three-dimensional [21]. Moreover, an interaction system was also added to track user's hand and provide tactile feedback according to the hand's position. The positions of hand are tracked by a special controller and fed into the application running on a PC. The controller provides the 3D coordinates of the fingertips and palm of the users' hands. Users could feel the pressure with their bare hands on 20cm above the device.

Currently, most research and development towards the ultrasound non-contact haptic feedback is based on this invention.

### 3. APPLICATION AREAS

Because the number of possible human activities is unlimited, it is impossible to describe all cases of haptic applications. As a matter of fact, applications of this technology have rapidly been extended to devices used in graphical user interfaces (GUIs), games and multimedia, scientific discovery and visualization, arts and model creation, vehicle in-

dustry and engineering, telerobotics and teleoperation, education and training, medical simulation and rehabilitation. Consider some of them.

#### 3.1 Medicine

Haptic interfaces for medical simulation may prove especially useful for training in minimally invasive procedures such as laparoscopy and interventional radiology, as well as for performing remote surgery. The incorporation of haptic technologies in medical software and simulations has grown, and various companies developed medical stations using haptic devices.

##### 3.1.1 Training

Medical procedures often involve the use of the tactile sense to manipulate organs or tissues by using special tools. Doctors require extensive preparation in order to perform them successfully; for example, research shows that a minimum of 750 operations are needed to acquire sufficient experience to perform medical procedures correctly [8]. Haptic devices have become an important training alternative and they have been considered to improve medical training because they let users interact with virtual environments by adding the sense of touch to the simulation. At the moment there are already created training systems in such areas: stitching, palpation, dental procedures, laparoscopy, orthopedics and biopsy.

##### *Stitching techniques*

Simulation of stitching procedures is one of the areas where haptic technology has been implemented to create learning simulators. Skin and organs have flexible features, so stitching simulators consider mainly rendering techniques of deformable objects. Additionally, haptic simulators combined with active learning environments can provide users with features such as deformation of the suture thread, knot tying, and interaction between tools, the needle and the environment. One of the work in the suture field is made by Ricardez et al. that was focused on generating an external suture environment named SutureHap [38]. SutureHap used NVIDIA PhysX physical engine, OpenGL to render the graphical environment, and 2 Phantom Omni devices. For haptic rendering, three blocks were developed. Collision detection and calculation of force feedback response between the cloth and the haptic cursor were performed by using the simplified model, used a algorithm based on the addition of multiple rays that are emanating from the center of the haptic avatar in different directions. The system is based on the elaboration of a suturing knot using a real technique, which was consulted among medical staff.

Another trainer system was created for all military anesthesiologists preparing for the introduction of peripheral nerve blocks [45]. The Energid RAS trainer includes innovative devices capable of generating haptic feedback during needle insertion, injection and palpation through Magnetorheological fluid (MRF) control and tactile display systems - controllable actuator arrays - enhanced with the development of modular software and algorithms, configurable procedures and scenarios, and integrated training modules. MR fluid is a type of controllable 'smart material' whose rheological properties may be rapidly varied by the application of a magnetic field. This interesting property has brought the possibility to use the MRF to develop haptic devices [3].

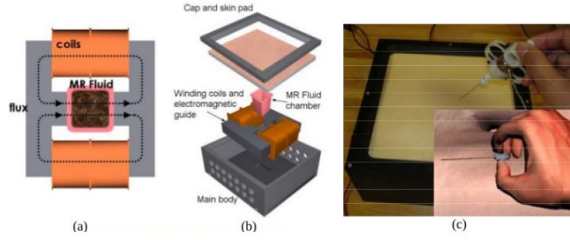


Figure 1: MR fluid-based needle insertion Haptic device; (a) An illustration of the flux flow, (b) the exploded system components, (c) the MR haptic device with a force sensor

The haptic system for needle insertion consists of an electromagnetic field winding and an MRF chamber (see **figure [1]**). By controlling the magnetic field strength inside of the MRF chamber, the viscosity of the MRF can be changed in such a way that the needle resistive force is created mimicking the actual muscle/tissue viscosity of the human body. Hence, the controllable haptic feedback is generated in the system. The performance of the MRF haptic system may be determined by the MRF (the base density and viscosity) and winding unit (the strength of magnetic field).

#### Palpation

Palpation is the process where surgeons analyze, via their fingers, tissues or organs to detect anomalies on the surface. Stiffness is essential in this medical procedure. Areas that are stiffer than other can be considered as potential tumors. Therefore, correct calculation of force feedback is necessary during the creation of virtual simulators with haptic devices. Energid's tactile palpation device aims to achieve high fidelity tactile feedback through a configurable platform [45]. Devices for tactile display systems are based on arrays of independently controllable actuator elements that are able to exert forces in normal direction to the user's skin surface. The main components in this system are a high-density pin array, a deformable skin layer to mimic virtual human model, a positioning system, and an actuator to reconfigure skin profiles by precisely controlling the pin array. The advantage of this design is that it can mimic touch sensing of virtual objects in a high resolution, high fidelity and high force level that conventional haptic systems lack.

#### Laparoscopy

There are several "minimally invasive surgery" (MIS) techniques that became gold standards in surgery with respect to traditional open surgery, especially in the case of: cholecystectomy, appendectomy, operations to heal gastroesophageal reflux disease etc. In these examples, the sensorial information available to surgeons is limited with respect to open surgery, as the visuo-motor coordination with tactile feedback is mediated through the camera mounted on laparoscope and surgical tools constrained within trocars. The learning curve of MIS techniques is significantly more shallow than the traditional open one, even for highly experienced surgeons. Haptic virtual-reality (VR) based simulators are a valuable resource to train operators and medical staff to a neat execution of these techniques, and to assure the correct usage and maintenance of the expensive technologies.

One of such training simulator is eLaparo4D, which was created by Gaudina et al. in 2013 [12]. They designed training exercises for medicine students in realistic scenarios of videolaparoscopic surgeries. The system is based on a node.js application server, which enables all the visualization, communications and administration. The user interface uses HTML5, which runs a Unity3D engine plugin. The meshes in the simulation were developed in Blender 3D [1]. Haptic feedback is provided by using three Phantom Omni, where the first two are used as tool handlers (grasper, hook or scissors) and the third one is used to move the camera within the virtual abdomen. By using three haptic devices, students would experience a realistic approach of the laparoscopic equipment.

#### Orthopedics

In Orthopedics, one specific surgery process for fractures on the human femur is the Less Invasive Stabilization System (LISS). LISS allows surgeons to insert a per cutaneous plate and fix it in the distal femur with screws to help bones recover from fractures. For this operation, Cecil et al. developed a virtual collaborative simulator for LISS training [5]. The simulator uses FEM approach to model deformations when surgical tools interact with the surfaces of the bone. The importance of this research was the implementation of the collaborative mode. Each user has their own virtual environment on their work station; the control of the simulation remains with a specific user until he grants permissions to another user, in a token-based approach. This simulator incorporates a Phantom Omni haptic device to interact with the environment and obtain force feedback from it.

#### Biopsy

A biopsy is a medical test commonly performed by a surgeon, interventional radiologist, or an interventional cardiologist involving extraction of sample cells or tissues for examination to determine the presence or extent of a disease. Training of this task can only be performed on live patients, where consequent risks may occur in patients. Therefore, the importance of creating systems that provide visual realism and controlled environments is emphasized. In this area, Ni et al. developed a virtual reality simulator for Ultrasound-Guided (UG) liver biopsy training [33]. The authors combined images obtained from computertomographie with ultrasound images to provide higher realism. In addition, the generated deformable model is able to simulate the breathing of a patient by changing controlled parameters. For haptic feedback, they used two haptic devices that are managed in independent routines, a Phantom Omni to simulate an ultrasonic scanning probe and a Phantom Premium to handle the virtual needle.

Additional to the previous medical areas, there have been simulators in other specific areas or tasks as dental procedures, ophthalmology, otorhinolaryngology, etc. Training virtual environments that incorporate haptic devices pose an important alternative to train and gain hand-operated skills.

#### 3.1.2 Surgery robots

Robotic surgical systems have greatly contributed to the advancement of minimally invasive endoscopic surgery. Robot-assisted minimally invasive surgery (RMIS) holds great

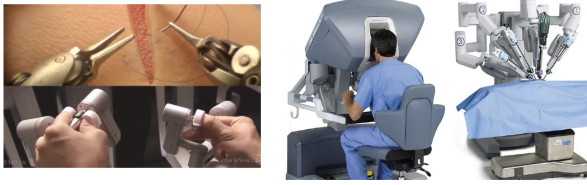


Figure 2: The da Vinci System. The instruments’ jointed-wrist design exceeds the natural range of motion of the human hand; motion scaling and tremor reduction further interpret and refine the surgeon’s hand movements

promise for improving the accuracy and dexterity of a surgeon while minimizing trauma to the patient. However, widespread clinical success with RMIS has been marginal. It is hypothesized that the lack of haptic (force and tactile) feedback presented to the surgeon is a limiting factor. Haptic feedback systems for RMIS are still under development and evaluation. Most provide only force feedback, with limited fidelity. The major challenge at this time is sensing forces applied to the patient. A few tactile feedback systems for RMIS have been created, but their practicality for clinical implementation needs to be shown.

The most popular robotic surgical system nowadays is the da Vinci Surgical System (VSS) designed to facilitate complex surgery using a minimally invasive approach, and is controlled by a surgeon from a console. VSS operate in hospitals worldwide, with an estimated 278,000 surgeries conducted in 2012.

The instruments provide seven degrees of freedom (three for translation, three for rotation, and one grasping), which is closer to what a human wrist can do than commonly used laparoscopic instruments (see **figure [2]**). And the three-dimensional stereoscopic display provides a detailed rendition of anatomic features, even in compact spaces [17, 28].

VSS doesn’t provide surgeons with haptic feedback yet, but utilizes sensory substitution to display the information through visual cues. Ideally, tactile feedback from the device would render the exact applied forces and tissue deflections resulting from the surgical procedure. Even though the haptic feedback is displayed visually (a form of tactile-visual sensory substitution), it can still augment a surgeon’s performance.

To provide haptic information to the surgeon without sacrificing the maneuverability and dexterity afforded by the RMIS system is a major technical challenge. Simultaneously, the robot components, particularly disposable instruments, must remain low cost and robust. The goal of tactile sensing in RMIS can be to detect local mechanical properties of tissue such as compliance, viscosity, and surface texture – all indications of the health of the tissue – or to obtain information that be used directly for feedback to a human operator, such as pressure distribution or deformation over a contact area [35]. Constraints in sensor design include cost, size, geometry (for example, to fit within a laparoscopic grasper), biocompatibility, and surface finish to allow grasping. Many sensors require some deformation of the sensor in order to measure distributed information; this necessitates flexible coverings, which also remove detailed, local information. In addition, data recording from tactile sensors is difficult because they often include many individual sensing elements.

Tactile displays attempt to create the perception that the surgeon’s fingertip is directly contacting the patient or surgical material such as suture. The most literal type of tactile display is an array of pins that are individually actuated (for example, [20, 25]), so that their position commands are easily mapped from data from an array-type tactile sensor. Making such arraytype displays for RMIS is very challenging due to size and weight constraints. The display must sit at the end of the master manipulator and not impede its maneuverability.

Such pin displays developed for MIS and RMIS are actuated using shape-memory alloys [18, 22], micromotors [34], and pneumatic systems [11], where the authors have developed a tactile display consisting of an array of small balloons that provide spatially distributed forces to the fingertip. The device was integrated with the The da Vinci System. The latter method allows the most lightweight display to be attached to the master manipulator, but requires infrastructure for air pressure, which can be noisy, and has limited resolution.

Research has been done to combine kinesthetic and tactile information for surgery, but one study demonstrates that the ability to maintain an appropriate force in the remote environment is necessary for the surgeon to take full advantage of the spatially distributed force information from the tactile sensor [9]. Graphical displays of tactile data can also be very compelling, especially for diagnosis applications. Most of the developed tactile sensors and displays have not been tested in RMIS systems. Due to the complexity of integrating distributed tactile information into RMIS, it may be useful in the future to consider clever ‘tactile illusions’ [44] and other display methods recently developed in the haptics research community.

The latest robot is created by Linda van den Bedem from Eindhoven University of Technology (TU/e). She has created a first surgical robot that provides tactile feedback, and its name is Surgeon’s Operating Force-feedback Interface Eindhoven (Sofie). Sofie is controlled via joysticks on a control panel, which become harder or easier to move, depending on how much pressure the robotic surgical instruments are exerting against the patients’ tissues. Such a system could be particularly useful for tasks such as making sutures, as it should give surgeons a better sense of how tightly they’re pulling the thread. TU/e has patented the force-feedback system, and van den Bedem is now looking into commercializing Sofie.

### 3.2 Space Exploration

On September 7, 2015 the real-time teleoperation experiment was conducted between the International Space Station (ISS) and the Earth [2]. This experiment allows for an astronaut crew in space to control, in real-time, robotic assets on Earth, using force feedback. The photo of the experiment is presented on **figure [3]**.

The Interact Robot (Interact Centaur) consists of a 4 drive 4 steer mobile platform, head system allowing to perceive the environment optical information, camera and 2 seven degrees of freedom robotic arms on the front of the rover allow the operator to perform very precise manipulation tasks. The arms can be ‘soft controlled’ to safely interact with humans or delicate structures. The arms are equipped with highly ‘force sensitive’ sensors and can flex and adapt in a similar manner to human arms during remote control. On-





Figure 3: Interactive robotics demonstration from on-board the ISS

board, the crew use a tablet PC and a small force reflective joystick letting him feel whenever the robot's arm met resistance. These tactile sensations were essential for the success of the experiment, which involved placing a metal peg into a round hole in a 'task board' that offered less than a sixth of a millimeter of clearance. The peg needed to be inserted 4 cm to make an electrical connection [2, 19].

The real challenge was achieving meaningful force feedback despite the distance more than 144 000 km the signals had to travel. The inevitable two-way time delay approaches 1 sec in length, but the team used sophisticated software based on a dedicated control method termed 'model mediated control' to help compensate for this lag. As the Space Station travels at 28 800 km/h, the time for each signal to reach its destination changes continuously, but the system automatically adjusts to varying time delays [2].

This experience could be vital for future exploration missions beyond Earth orbit, where astronauts would be able to control robotic assets to maximize scientific operations on Mars, asteroids, and other exploration targets.

### 3.3 Touch less Interface

Currently, the touchscreen interfaces is widespread, replaces the use of physical buttons and used in household appliances, in vehicles, portable navigation systems, information stands and so on. However, there are many scenarios where it is not possible to have visual contact with the display, such as while driving or if the user is visually impaired. In these cases, mid-air haptic feedback can be used to guide the user to the location of an interface element. Recent advances in haptics and display technologies has meant that interaction designers can also provide users with tactile feedback in mid-air and allow the user to feel the geometry of an interface and localize on a specific item.

#### 3.3.1 Ultrahaptics

Ultrahaptics company was founded in 2013 and has focused on providing users haptic feedback in free space using ultrasound technology. In 2013, they have introduced 'UltraHaptics', a system designed to provide multi-point haptic feedback above an interactive surface. UltraHaptics employs focused ultrasound to project discrete points of haptic feedback through the display and directly on to users hands. It employs the principle of acoustic radiation force whereby a phased array of ultrasonic transducers is used to exert forces on a target in mid-air, it is based on the method described

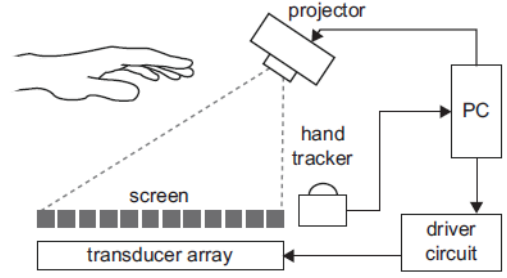


Figure 4: Overview of the UltraHaptics System

above in the 2nd section. The scheme is illustrated on **figure [4]**. It should be mentioned, that with the transducer array positioned behind, the display surface must allow ultrasound to pass through without affecting the focusing and with minimal attenuation. Finding a fitting projection material is not trivial, as it must efficiently permit ultrasound through while also appropriately reflecting incoming light. Through a series of experiments it has been discovered that perforated screens surfaces with 0.5mm holes sizes and 25% open space reduce the impact on any focusing algorithm while still creating a high performance projection surface.

The transducer array has 320 transducers arranged in a 16x20 grid formation. The transducer units are 10mm in diameter and positioned with no gap between them to minimize the array footprint. When haptic feedback is required, a phase delay and amplitude is calculated for each transducer to create an acoustic field forming the desired focal points. The output signal from the processors to the transducers is amplified from 5V to 15V. The visual content is projected onto the display surface from above. As controller for tracking hands position used Leap Motion, which provides the 3D coordinates of the fingertips and palm of the users' hands at up to 200 frames per second. Users can feel non-contact haptic feedback on 200mm above the transducer array. The **figure [4]** shows the example of using such system.

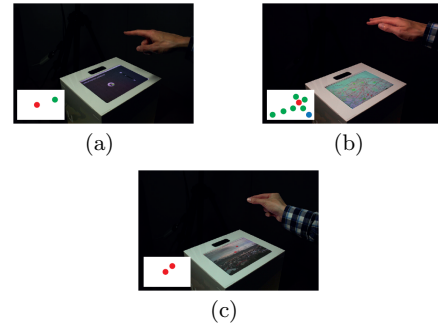


Figure 5: Applications using the UltraHaptics system. Inserts depict focal point locations with different colors representing different tactile properties. (a) pinch-to-zoom gesture in a photo application. (b) tactile information layer conveying population density. (c) jukebox application with focal points to guide the user to interface elements.

In 2015, Ultrahaptics has introduced a development platform that allows companies looking to evolve innovative con-

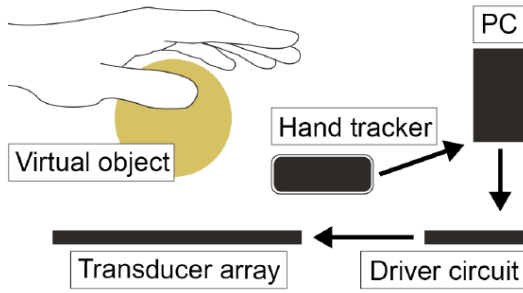


Figure 6: The setup of our system for generating three-dimensional haptic shapes

trol solutions a route to easily evaluate and appreciate the benefits of gesture controls enhanced by tactile feedback sensations. The UHDK5 TOUCH Development Kit provides a complete hardware and software package with an architecture that can readily be embedded in product designs, from prototypes right through to volume production. With its patented core technology, Ultrahaptics uses ultrasound to provide a unique touch sensation that can revolutionize the human-machine interface, enabling users to 'feel' virtual buttons, switches, dials and other objects in mid-air. They used a system consisting of an ultrasonic phased transducer array actuated by a driver circuit and a hand tracker together with a PC as shown in **figure [6]**.

In 2016, Ultrahaptics announced that it is supporting Jaguar Land Rover in the investigation of a mid-air touch system for its Predictive Infotainment Screen. Using the Ultrahaptics solution, the driver's hand can be located and tracked as it moves across the interactive field; the system locks on and creates a physical sensation to indicate connection. The user can feel virtual objects and control switches and buttons, giving the ability to control them in mid-air and receive feedback to confirm their action has been successfully completed. In January 2017, Ultrahaptics announced that its touch-free haptic feedback solution is integrated into a new concept car being exhibited into the automotive industry at CES 2017. Its touchless haptic technology enhances gesture control, providing a leading-edge human-machine interface (HMI) to Bosch's infotainment system. Gesture controls can be used to operate infotainment systems, such as in-car audio and connected-car applications, more intuitively. Ultrahaptics is engaged with the Bosch HMI Group across a variety of applications.

### 3.3.2 Finger Flux

FingerFlux is a haptic device generating near-surface force feedback for tabletops using attractive and repulsive magnetic force and vibration to guide the users when approaching the screen. Using array of electromagnet as force feedback actuator and magnets attached on the hand as force receiver, the device is able to generate repulsion, attraction, vibration, and directional feedback on and above the table surface. The feedback is perceivable in a volume near the surface up to a height of 35 mm.

For electromagnetic actuation, it is used the design of the Madgets table. A discrete grid of 19x12 electromagnets allows for synthesizing a 2D matrix of magnetic fields. Each magnet (19.5mm diameter, 34.5mm height) contains 3,500

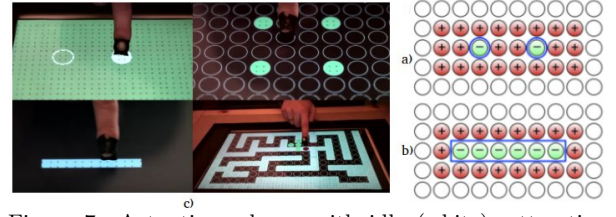


Figure 7: Actuation scheme with idle (white), attracting (green) and repelling electromagnetic fields (red). (a) Buttons (blue circles). (b) Slider (blue rectangle). (c) Examples of using.

turns of enameled copper around an iron core. The magnets are driven at 40 V DC and 255 mA. Strength and polarization of each electromagnet can be controlled individually from software. A backlit LCD panel on top of the array provides graphical output.

FingerFlux allows users to feel electromagnetic force fields when hovering above the surface. Using a single magnet with repelling magnetic field, a designer can model a haptic bump. This simple technique can be used to let users feel the table interface without looking or to emphasize the state of an on-screen object. For example, a strong repelling force can signify a UI element which is currently unavailable like an inactive button. When the polarization of an electromagnet is quickly reversed repeatedly, the user feels a vibration pattern when approaching the electromagnet. Those patterns could indicate a system event or warn users before they trigger critical operations.

Moreover, it can help to reduce drifting, by attracting the user's finger to each button's center. Repelling forces around the center increase this effect by pushing the finger away from the control's boundary. By arranging attracting and repelling magnets in lines, it is possible to create moderate physical constraints on the surface without using any physical widget, e.g., a virtual slider may use the actuation scheme (see **figure [7]**).

## 3.4 Touchable holograms

Researchers at the University of Tokyo are working on system that enable adding haptic feedback to holographic projections. Haptoclone is a revolutionary interactive system producing haptic and optical clone image in mid-air. The feedback allows the user to interact with a hologram and receive tactile responses as if the holographic object were real. The research uses ultrasound waves to create acoustic radiation pressure, which provides tactile feedback as users interact with the holographic object. Moreover two users apart from each other can touch each other with unaided eyes and bare hands.

This system has two workspaces apart from each other and the two workspace fields are virtually '*superimposed*' *optically* and *haptically*. The *lightfield* and *forcefield* of each workspace are cloned and forwarded to the other. A user in a workspace see the clone images of the objects existing in the other workspace. When a real object in a workspace is in contact with a clone image, the contact force is given to both the real object and original (real) object of the clone.



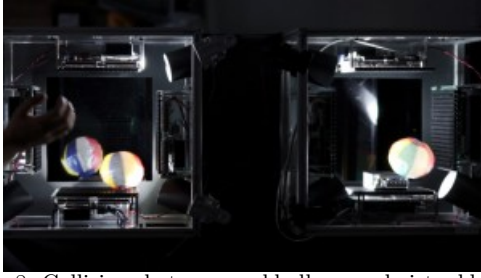


Figure 8: Collisions between real balloon and virtual balloon

Perfectly synchronized haptic-optical clone construction is achieved by using the key technologies:

- Aerial Imaging Plate (AIP) for copying optical light field, a pair of micro mirror arrays is aligned. The micro mirrors symmetrically reflect the light field coming from one side to the other. When using the two micro mirror arrays and align them as shown in **figure [9]**, the object at A is optically cloned to the position B and C. As the same way, human standing at C side is copied to the A side simultaneously. For this purpose commercially available mirror array named “Aerial Imaging Plate” were used.
- Airborne Ultrasound Tactile Display (AUTD) for copying haptic force field, it was used ultrasonic haptic holography technique [23]. By holographic synthesis of ultrasonic field, volumetric acoustic potential field can be reproduced and that cause radiation force to objects in the peer workspace. The ultrasonic phased arrays which surround each workspace can produce omni-directional and volumetric force and invoke haptic sensation to user skin. This system equips 1992 ultrasonic transducers in total. The shapes in the workspaces are measured by infrared depth sensor and represented as point clouds. The point clouds are exchanged each other over UDP/IP protocols. Each peer calculates the collisions between own point clouds and peer’s point clouds and reproduces reaction forces between real objects in the workspace and peer’s virtual objects.

The system concentrates ultrasound energy at the intersections of the real and clone objects, which creates pressure to the real objects. If the user use finger, he feels contact force from the 3D clone object by the ultrasonic radiation pressure. At the same time, the same forces are applied to the original real object (of the clone) in the other workspace.

For the moment, Haptoclone is limited due to it only being able to emit safe levels of radiation, meaning the tac-

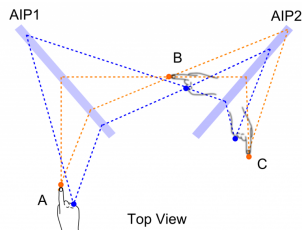


Figure 9: Passive Lightfield Forwarding

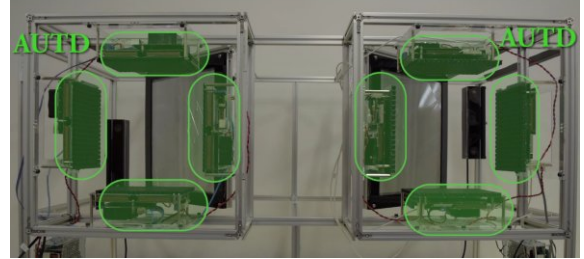
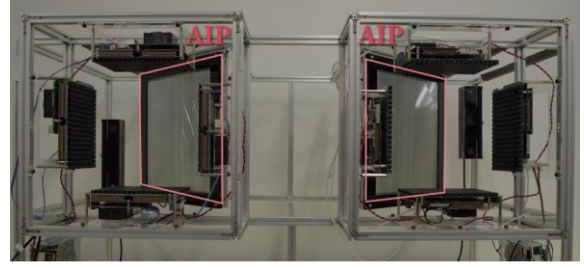


Figure 10: Construction: Aerial Imaging Plate (AIP) and Airborne Ultrasound Tactile Display (AUTD)

tile sensations are reduced to a light stroking rather than a handshake or a hug.

### 3.5 Virtual reality and gaming

Virtual and augmented reality technology has reached a sufficient level to make our brains believe that virtual objects are really right in front of us. Motion tracking technology and direct sensors can make our virtual hands exactly mimic our real ones. Allowing us to push and pull virtual objects. Talking about the ways we sense the world around us and virtual reality’s overall goal of replicating those experiences, it’s clear that our tactile senses are a crucial component to complete the illusion. However, to combine virtual reality (VR) and non contact haptic feedback technologies is not so easy, and nowadays for commercialized VR systems if user tries to touch the object, then he does not feel, other than air. This can be explained by the fact that it is difficult for the system to simultaneously monitor the position of the user’s hand in the space, to analyze how the user sees the virtual object, identify the exact moment, angle, speed, strength of the touch and to simulate tactile feedback. Nevertheless, there are currently taking place research and development to provide the user haptic feedback.

#### 3.5.1 Haptic gloves

One of the products of the Glove Systems company is the CyberGrasp, - an innovative force feedback system for fingers and hand. It enables to reach into ‘virtual reality’ and grasp computer-generated or tele-manipulated objects. The CyberGrasp device is a force-reflecting exoskeleton that adds resistive force feedback to each finger (see in **figure [11]b**). With the CyberGrasp force feedback system, users are able to feel the size and shape of computer-generated 3D objects in a simulated virtual world. Grasp forces are produced by a network of tendons routed to the fingertips via the exoskeleton. There are five actuators, one for each finger, which can be individually programmed to prevent the user’s fingers from penetrating or crushing a virtual solid object.

Another company NeuroDigital Technologies, has presented

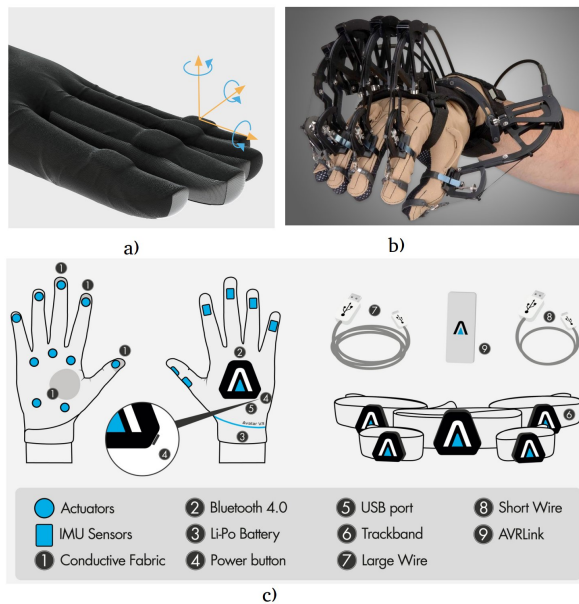


Figure 11: Haptic gloves. a,c) Avatar VR gloves; b) Cyber-Grasp gloves.

GloveOne prototype in 2015. Gloveone enables users to feel and touch any virtual object that they can see on the screen or in their VR headsets. Users can 'feel' its shape or weight, sense all of its physical features. It is all about translating 'touch sensations' into vibrations. There are 10 actuators distributed along the palm and fingertips of Gloveone, which vibrate independently at different frequencies and intensities, reproducing accurate touch sensations. The updated version of this gloves is Avatar VR. They have improved tracking systems. Now it is enable full finger tracking (see in **figure [11]a**), tracking entire arm and torso. Moreover, they provide almost immediate touch feedback by using vibrotactile actuators with a latency of just 20ms and low high speed communication technology: Bluetooth 4.0 LE with less than 8ms latency or cable connection with just 1ms delay. Thus, the total latency of our haptic gloves is under 28ms, giving user a highly realistic perception of touch. The scheme can be seen in **figure [11]c**.

The key words here are 'touch sensations', because haptic gloves doesn't really reproduce touch itself, but an approximative force that acts as a placeholder for touch-based interactions.

### 3.5.2 Haptic suits

The haptic exoskeleton concept can be extended to the entire body or to pneumatic suits. Modern haptic suits use neuromuscular stimulation similar to the technology used for therapy.

One of such suits is Teslasuit. The developers claim that it lets user to feel VR and touch partner over the Internet. The Teslasuit intends to use this technology to add full body touch, giving sensations of impacts, hot, cold, etc. At the same time it provides full body motion tracking, fulfilling several functions at the same time. The suit uses an "electro-tactile haptic feedback system" to really put user inside the playing games. It was demonstrated with a vir-

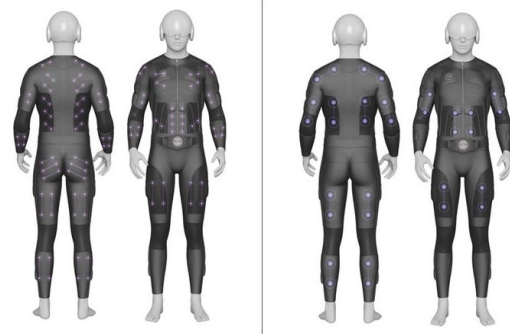


Figure 12: Tesla haptic suit Editions. Left: Prodigy, right: Pioneer.

tual paintball game. If user was shot in the game, he could see and feel where the paintball hit him. The suit comes in two editions with varying features as shown in. **figure [12]**. The Pioneer edition includes 16 channels of feedback, and the Prodigy edition includes 52 feedback channels with climate control to further immerse the user.

## 3.6 Others

Inaccessible objects (museums) Education and training Engineering

## 4. DISCUSSION

In realistic interactions with virtual or remote objects, haptics has achieved enormous interest as the core of realizing manual interaction with environment. Newest possibilities are opened up by introducing haptics to various disciplines involving virtual reality, medical training and surgery, and many other applications, where haptic rendering plays a key role in generating force feedback. Furthermore, it can be seen that for different applications some technologies are more suitable than others.

### 4.1 Technologies

Technologies that I have reviewed above are quite different, and they are used in different areas. Will try to compare them where possible, and to highlight the most significant differences. To begin with, the most stable and high-precision development is remote manipulation systems with sensors. Therefore, they are much more commonly used in such important and practical fields like medicine, space exploration than other technologies. However, as a rule, it is required a certain skill and training that the user can successfully work with these systems. In addition they are very bulky.

Regarding the magnetic technology, it is possible to say that they can be used in various fields. The strength of the action can be quite strong, the magnetic fields pass through many materials. However, interaction with such systems, there are required additional magnetic devices on hand, thus limiting its use. Talking about touchable holograms, it should be mentioned that ultrasonic is the only suitable technology for providing non-contact haptic interaction in similar with Haptoclone system. Magnetic feedback can be felt only through the magnets attached to the

users hands and can be provided by one side array of coils. If to create the box, like in Haptoclone (with 4 side arrays of coils), the magnetic field will be disturbed due to the superposition effect.

Speaking about Ultrasonic, it should be noted that this technology is the most appropriate for spontaneous use. The user is not required to put on additional sensors equipment. Users just can use bare hands to interact with a virtual object, or even use different objects (in case of Haptoclone). Of the major drawbacks, it is worth mentioning that the ultrasonic waves do not pass through all the materials. Therefore, the use of ultrasound to generate the feedback above display is only possible by using special material for display: perforated one or of a woven material. For portable devices like mobile phones, tablets it can be problematic.

## 4.2 Applications areas

### Medicine

Considering the medicine, may notice that almost only remote manipulation systems is used. Most of the training systems are based on Phantom devices. They are widespread and can be easily programmed under the required type of training system. This allows medical students to train more and with minimal risk, as they go to practice on live people after a lot of training in the virtual environment with haptic feedback. When thinking about training systems to palpation, it is worth mentioning that the use of magnetic fields and ultrasound is not suitable. Since these systems, due to their physical nature may not create sharp contours that need to palpate as the internal organs should be clearly distinguishable.

The appearance of such robots operating as da Vinci and Sofia, much improved accuracy and the possibility of operations. With these technologies, surgeons have the opportunity to operate even at a distance. To my knowledge, at least one such transcontinental operation was successfully performed. While the surgeon was in France, he was able to carry out the operation remotely in America with a delay of just 200 milliseconds.

For operation the surgeon uses manipulators that act as joysticks. Through manipulators Da Vinci translates all movements of the surgeon's hands (and fingers and wrist) in the precise movements of tiny instruments that are on the patient console. I think it will be useful to create a dual console model of the system da Vinci, for the training of young surgeons. At the same time the teacher and the student can see the same picture, each sitting behind his console. However, only the teacher will be able to directly control the process of operation. All the teachers movement will be transmitted on the student console, so student will be able to experience all the techniques and feel all movements for the particular surgery.

### Research in extreme environments

In addition to the use of telemanipulators and telerobotics in the medicine, there are many areas where they can be very useful. As mentioned earlier, for space research. Moreover, they can be used for the remote outside repair of the ISS, satellites and so on. Due to the tactile sensations there can be identified dents, cracks, which visually are not always visible. Also, the robots can be used for research under water at great depths. High accuracy can help to carry out manipulations without harming marine life.

### Virtual reality

As it become clear from section 3.4, one of the biggest limitations of current VR technology is the inability to convey a realistic and complete sense of touch. Developers, researchers, and companies from around the world presented experimental haptic technologies for VR. Haptic gloves and suits are most promising nowadays. Although they do not provide a true feeling, but nevertheless they help to plunge deeper into virtual reality. The probability of developing a system in which a person will not have to wear special equipment remains illusive. Nowadays this is only possible with Haptoclone system, but ultrasound is not as harmless to humans and to put a user in the box will not work.

### Multi-touch smart tables

Multi-touch tables have become common in public settings, with large displays appearing in railway stations, shopping malls, airports and other high foot traffic areas. These systems are able to dynamically change their interface allowing multiple users to interact at the same time and with very little instruction. This ability to 'walk-up and use' removes barriers to interaction and encourages spontaneous use.

Adding 3D haptic feedback in these tables is very important, especially for partially sighted and blind people. Since these tables will help them navigate in the space, creating a 'tactile map'. The prototypes of such tables based on magnetic and ultrasound technologies have already been developed, however they are not yet commercialized.

### Fascia in cars

Gesture recognition for in-car controls free the user from reaching from the limitations of physical buttons or small touchscreen interface. Touchscreens have already added vibrations to inform the user that they are engaged, and nowadays the industry is moving to mid-air controls. Drivers need to know their gesture has been received, without taking their eyes off the road. Such technologies as ultrahaptics adds touch to the mid-air. I believe such application is really very useful. Since the less driver is distracted by extraneous action, the more he focused on the road and the safer it is for him, for passengers and for all others. However, it is not a secret, that the voice control system and speech recognition are actively developed and implemented in different devices. Therefore it most likely that for controlling the machine, haptics will not be in demand, because many would agree that the voice control is easier.

### Interfaces for home appliances

Probably every housewife thought about the possibility of regulating stove and other appliances without direct contact. This is primarily due to the fact that in the process of cooking the hands are often stained, so to avoid contact with the buttons and switches would be convenient. Also it should be noted that in this case the application of ultrasound is preferable because the hands should remain bare.

## 5. CONCLUSIONS

In this work, it was presented a survey of different technologies and application areas that use haptic feedback. Currently, all the technologies are faced with limitations, so it seems to me that the work will go on optimizing existing solutions and the development of new algorithms to increase system performance. The most actively conducting research and development in providing haptic feedback in virtual reality and games.

## 6. REFERENCES

- [1] Blender foundation, blender. <http://www.blender.org/>, accessed Oct-15-2014.
- [2] E. E. S. Agency. Slam dunk for andreas in space controlling rover on ground. <http://www.esa.int/ESA>, September 2015.
- [3] N. S. Antonio Bicchi, Enzo Pasquale Scilingo and D. D. Rossi. Haptic interfaces based on magnetorheological fluids. *Interdepartmental Research Centre E. Piaggio*, 2007.
- [4] P. J. Berkelman, L. L. Whitcomb, R. H. Taylor, and P. Jensen. A miniature microsurgical instrument tip force sensor for enhanced force feedback during robot-assisted manipulation. *IEEE Transactions on Robotics and Automation*, 19(5):917–921, 2003.
- [5] J. Cecil, P. Ramanathan, V. Rahneshin, A. Prakash, and M. Pirela-Cruz. Collaborative virtual environments for orthopedic surgery. In *Automation Science and Engineering (CASE), 2013 IEEE International Conference on*, pages 133–137. IEEE, 2013.
- [6] H. K. Chu, J. K. Mills, and W. L. Cleghorn. Mems capacitive force sensor for use in microassembly. In *Advanced Intelligent Mechatronics, 2008. AIM 2008. IEEE/ASME International Conference on*, pages 797–802. IEEE, 2008.
- [7] D. P. Cotton, I. M. Graz, and S. P. Lacour. A multifunctional capacitive sensor for stretchable electronic skins. *IEEE Sensors Journal*, 9(12):2008–2009, 2009.
- [8] D. Escobar-Castillejos, J. Noguez, L. Neri, A. Magana, and B. Benes. A review of simulators with haptic devices for medical training. *Journal of medical systems*, 40(4):1–22, 2016.
- [9] C. W. C. Feller, R.L.; Lau. The effect of force feedback on remote palpation. *IEEE International Conference on Robotics and Automation*, pages 782–788, 2004.
- [10] Q. W. R. D. H. F. Frank L. Hammond III, Rebecca K. Kramer and R. J. Wood. Soft tactile sensor arrays for force feedback in micromanipulation. *IEEE SENSORS JOURNAL*, 14(5), May 2014.
- [11] J. Franks, M. Culjat, C.-H. King, M. Franco, J. Bisley, W. Grundfest, and E. Dutson. Pneumatic balloon actuators for tactile feedback in robotic surgery. *Industrial Robot: An International Journal*, 35(5):449–455, 2008.
- [12] M. Gaudina, V. Zappi, E. Bellanti, and G. Vercelli. elaparo4d: A step towards a physical training space for virtual video laparoscopic surgery. In *Complex, Intelligent, and Software Intensive Systems (CISIS), 2013 Seventh International Conference on*, pages 611–616. IEEE, 2013.
- [13] L. Gavrilov. Use of focused ultrasound for stimulation of nerve structures. *Ultrasonics*, 22(3):132–138, 1984.
- [14] L. R. Gavrilov, G. V. Gersuni, O. B. Ilyinski, E. M. Tsirolnikov, and E. E. Shchekanov. A study of reception with the use of focused ultrasound. i. effects on the skin and deep receptor structures in man. *Brain research*, 135(2):265–277, 1977.
- [15] T. Gavrilov, L. R. Mechanisms of stimulation effects of focused ultrasound on neural structures: Role of nonlinear effects. *Nonlinear Acoustics at the Beginning of the 21st Century*, pages 445–448, 2002.
- [16] B. L. Gray and R. S. Fearing. A surface micromachined microtactile sensor array. In *Robotics and Automation, 1996. Proceedings., 1996 IEEE International Conference on*, volume 1, pages 1–6. IEEE, 1996.
- [17] G. Hoelzl. A personalised body motion sensitive training system based on auditive feedback. In T. Phan, A. Montanari, and P. Zerfos, editors, *Proceedings of the 1<sup>st</sup> Annual International ICST Conference on Mobile Computing, Applications, and Services (MobiCASE09)*, volume 35 of *Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering*, San Diego, California, USA, October 26-29 2009. ICST, Springer. ISBN: 978-3-642-12606-2.
- [18] G. Hoelzl, A. Ferscha, P. Halbmayer, and W. Pereira. Goal oriented smart watches for cyber physical superorganisms. In *Workshop on Collective Wearables: The Superorgansim of Massive Collective Wearables, at 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp 2014), Seattle, USA, September*, pages 1071 – 1076, September 2014.
- [19] G. Hoelzl, P. Halbmayer, H. Rogner, C. Xue, and A. Ferscha. On the utilization of smart gadgets for energy aware sensitive behavior. In *The 8th International Conference on Digital Society, ICDS 2014, March 23 - 27, Barcelona, Spain*, pages 192 – 198, March 2014.
- [20] G. Hoelzl, M. Kurz, and A. Ferscha. Goal processing and semantic matchmaking in opportunistic activity and context recognition systems. In *The 9th International Conference on Autonomic and Autonomous Systems (ICAS2013), March 24 - 29, Lisbon, Portugal, Best Paper Award*, pages 33–39, March 2013.
- [21] T. Hoshi, T. Iwamoto, and H. Shinoda. Non-contact tactile sensation synthesized by ultrasound transducers. In *EuroHaptics conference, 2009 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2009. Third Joint*, pages 256–260. IEEE, 2009.
- [22] R. D. Howe, W. J. Peine, D. Kantarinis, and J. S. Son. Remote palpation technology. *IEEE Engineering in Medicine and Biology Magazine*, 14(3):318–323, 1995.
- [23] S. Inoue, Y. Makino, and H. Shinoda. Active touch perception produced by airborne ultrasonic haptic hologram. In *World Haptics Conference (WHC), 2015 IEEE*, pages 362–367. IEEE, 2015.
- [24] T. Iwamoto, M. Tatzono, and H. Shinoda. Non-contact method for producing tactile sensation using airborne ultrasound. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*, pages 504–513. Springer, 2008.
- [25] J. H. Killebrew, S. J. Bensmaia, J. F. Dammann, P. Denchev, S. S. Hsiao, J. C. Craig, and K. O. Johnson. A dense array stimulator to generate arbitrary spatio-temporal tactile stimuli. *Journal of neuroscience methods*, 161(1):62–74, 2007.
- [26] K. Kim, X. Liu, Y. Zhang, and Y. Sun. Micronewton force-controlled manipulation of biomaterials using a

- monolithic mems microgripper with two-axis force feedback. In *Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on*, pages 3100–3105. IEEE, 2008.
- [27] S. P. Lacour, S. Wagner, Z. Huang, and Z. Suo. Stretchable gold conductors on elastomeric substrates. *Applied physics letters*, 82(15):2404–2406, 2003.
- [28] A. R. Lanfranco, A. E. Castellanos, J. P. Desai, and W. C. Meyers. Robotic surgery: a current perspective. *Annals of surgery*, 239(1):14–21, 2004.
- [29] D. D. Marucci, J. A. Cartmill, C. J. Martin, and W. R. Walsh. A compliant tip reduces the peak pressure of laparoscopic graspers. *ANZ journal of surgery*, 72(7):476–478, 2002.
- [30] T. H. Massie, J. K. Salisbury, et al. The phantom haptic interface: A device for probing virtual objects. In *Proceedings of the ASME winter annual meeting, symposium on haptic interfaces for virtual environment and teleoperator systems*, volume 55, pages 295–300. Citeseer, 1994.
- [31] A. Menciassi, A. Eisinger, G. Scalari, C. Anticoli, M. Carrozza, and P. Dario. Force feedback-based microinstrument for measuring tissue properties and pulse in microsurgery. In *Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on*, volume 1, pages 626–631. IEEE, 2001.
- [32] H. Muhammad, C. Oddo, L. Beccai, C. Recchiuto, C. Anthony, M. Adams, M. Carrozza, D. Hukins, and M. Ward. Development of a bioinspired mems based capacitive tactile sensor for a robotic finger. *Sensors and Actuators A: Physical*, 165(2):221–229, 2011.
- [33] D. Ni, W. Y. Chan, J. Qin, Y.-P. Chui, I. Qu, S. S. Ho, and P.-A. Heng. A virtual reality simulator for ultrasound-guided biopsy training. *IEEE computer graphics and applications*, 31(2):36–48, 2011.
- [34] O. J. T. Ottermo, MV.; Stavadahl. Electromechanical design of a miniature tactile shape display for minimally invasive surgery. *First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (World Haptics)*, pages 561–562, 2005.
- [35] Y.-L. Park, C. Majidi, R. Kramer, P. Bérard, and R. J. Wood. Hyperelastic pressure sensing with a liquid-embedded elastomer. *Journal of Micromechanics and Microengineering*, 20(12):125029, 2010.
- [36] P. Peng and R. Rajamani. Flexible microtactile sensor for normal and shear elasticity measurements. *IEEE Transactions on Industrial Electronics*, 59(12):4907–4913, 2012.
- [37] M. A. Qasaimeh, S. Sokhanvar, J. Dargahi, and M. Kahrizi. Pvd-based microfabricated tactile sensor for minimally invasive surgery. *Journal of Microelectromechanical Systems*, 18(1):195–207, 2009.
- [38] E. Ricardez, J. Noguez, L. Neri, L. Munoz-Gomez, and D. Escobar-Castillejos. Suturehap: A suture simulator with haptic feedback. 2014.
- [39] J. K. Salisbury and M. A. Srinivasan. Phantom-based haptic interaction with virtual objects. *IEEE Computer Graphics and Applications*, 17(5):6–10, 1997.
- [40] J. K. Salisbury Jr. Making graphics physically tangible. *Communications of the ACM*, 42(8):74–81, 1999.
- [41] S. Sokhanvar, M. Packirisamy, and J. Dargahi. A multifunctional pvdf-based tactile sensor for minimally invasive surgery. *Smart materials and structures*, 16(4):989, 2007.
- [42] Y. Sun, W. M. Choi, H. Jiang, Y. Y. Huang, and J. A. Rogers. Controlled buckling of semiconductor nanoribbons for stretchable electronics. *Nature nanotechnology*, 1(3):201–207, 2006.
- [43] Z. Sun, M. Balicki, J. Kang, J. Handa, R. Taylor, and I. Iordachita. Development and preliminary data of novel integrated optical micro-force sensing tools for retinal microsurgery. In *Robotics and Automation, 2009. ICRA'09. IEEE International Conference on*, pages 1897–1902. IEEE, 2009.
- [44] H. V. A brief taxonomy of tactile illusions and demonstrations that can be done in a hardware store. *Brain Research Bulletin*, 75:742–752, 2008.
- [45] P. V. N. T. Yi-Je Lim, Tuan Le. Simulation-based military regional anesthesia training system. *Energid Technologies*, 2007.

# Overview of medical applications of Brain-Computer-Interfaces

Daniel Münzhuber  
Universität Passau  
Lehrstuhl für Informatik mit Schwerpunkt Eingebettete Systeme  
Innstr. 43  
94032 Passau, Germany  
muenzhub@fim.uni-passau.de

## ABSTRACT

Since the early 1960s, Brain Computer Interfaces (BCI) have been actively researched and further developed. Due to the scarce computing power of the computers at that time, the development of BCIs has been very slow and laborious, but since the millennium, BCIs are making rapid progress. Where as this technology was initially restricted to animal experiments with minimal application possibilities, it is already applied to humans today. While this technology has great potential in the field of entertainment electronics, it is also desirable to use the possibilities of this technology in medicine in order to facilitate disabled people's everyday life and assist sick people in rehabilitation.

First of all, this document should provide a brief insight into the functioning of a BCI system. In order to show possible limitations, some methods are described to record signals from the brain in order to subsequently process them. For this purpose, the mode of operation as well as the advantages and disadvantages of invasive and non-invasive sensors are presented and the various measuring methods are described. In addition, first impressions are shown of the areas in which BCIs can be used or are already being used. In the end, we consider a possibility for the language recovery of patients. One focus is on approaches to the control of electric wheelchairs to restore the mobility of paralyzed persons. The field of monitoring the recovery process in neuronal rehabilitation, which is a high cost factor in today's rehabilitation medicine, is also described. Finally, we will look at existing and future problems with regard to the financing of such systems as well as the acceptance of the different sensors among the users. Similarly, the prospects for the future of BCIs in the home application and in the everyday life of the users are examined without a supervising laboratory team.

## Keywords

Brain-Computer-Interfaces, BCI in medicine

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, to republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

*Overview of medical applications of Brain-Computer-Interfaces* '16 Passau, Germany  
Copyright 2016 ACM X-XXXXX-XX-X/XX/XX ...\$15.00.

## 1. INTRODUCTION

"A BCI is a computer-based system that collects, analyzes, and converts brain signals into commands that are passed to an output device to perform a desired action." [1] BCIs have a broad range of applications, ranging from home automation, gaming applications and ultimately medicine. It is already possible to switch lights using BCI, to dim it and to change the light color. In addition to home automation, the gaming sector also offers a wide range of possible applications. Thus all imaginable games could be controlled by thought, which makes completely new demanding scenarios and game variants possible. Even though commercial systems, especially in consumer electronics, will have a decisive influence on the development, the question should be asked how this new technology can be used in medicine as well, as it can not only make the lives of average people more comfortable and exciting but also those of sick and disabled people.

In order to answer this question, it is first necessary to clarify the possibilities of the signal recording and the advantages and disadvantages of the respective method. When brain activity is detected with a certain sensor modality, algorithms prepare the signals and extract the user command from the acquired data, which causes movements of a prosthesis or a wheelchair or moves a cursor on a screen. What appears to be a relatively simple task for the user often requires long and intensive training for both the user and the BCI, since even the smallest deviations in the measurements can lead to unintended or even dangerous actions of the actuators.

As the most critical and perhaps most demanding part of a BCI, the sensors that record the brain currents could be exposed. These must not only be selected and coordinated according to the respective disease pattern but also adapted to the environment in which the user resides later. Particularly in the case of invasive sensors, the highest demands on the long-term stability as well as the durability of the power supply must be made. Particularly in the case of non-invasive sensors, a high wearing comfort and an aesthetic application must be made possible.

In order to enable a solved and secure system, it is imperative that the researchers from various disciplines recognize problems and work out solutions together. Even if great progress has been made, it is still a far way from the lab into daily life. [16]



## 2. COMPONENTS OF A BCI

A BCI uses brain signals to capture the user's intention and to generate a command for controlling an external device. For this purpose, four essential components are necessary. First of all, the signal must be taken from the human brain. Some possibilities for signal recording are discussed in the next section. If the signals were successfully recorded, the feature extraction follows. This is a process in which the recorded data is freed from foreign content and the intention of the user is extracted. The resulting signal characteristics are now further processed by a characteristic transformation algorithm to obtain commands for external devices. With these commands, various devices can now be operated as described in Section 3.[16, 2]

## 3. POSSIBILITIES OF SIGNAL ACQUISITION

There are several ways to record brain signals which are pre-eminently and adversely affected. The most used techniques of signal acquisition are shown below. A possible classification of the different sensors is the distinction between invasive and non-invasive methods. In general, it can be said that invasive sensors provide more accurate results but their implantation is very complex, expensive and dangerous. Non-invasive systems, on the other hand, are easy to setup, but they are not very precise and deliver far less accurate results.

### 3.1 Noninvasive BCIs

#### 3.1.1 Electroencephalography

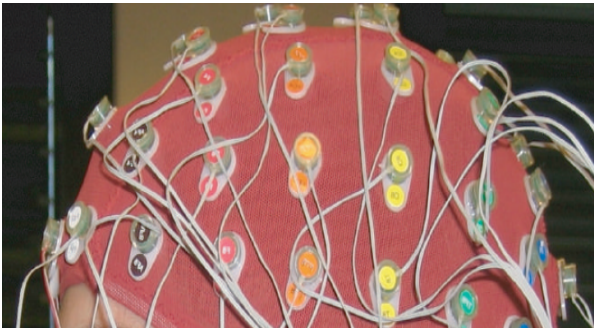


Figure 1: A hood with several EEG electrodes

Among the non-invasive recording techniques, electroencephalography (EEG) is used most frequently. Individual electrodes are applied to the scalp, which can then measure the cerebral currents. While initially conductive gel had to be applied to the scalp, so-called dry electrodes are now also used. A significant disadvantage of non-dry electrodes is the signal change which is associated with the drying of the gel as well as the damping of the signals by the skull. Furthermore, signals from different brain regions are mixed, which leads to a further discrepancies of the measurement results.[4]

Besides the risk-free application, it offers the best temporal resolution and is very cost-effective to use. In addition, no long lasting power supply is required, as batteries or accumulators can be replaced at any time, failed sensors can

also be replaced easily. Despite the relatively low cost and ease of maintenance and the resulting low demand for long-term stability, the critical disadvantage of this system is its low reliability and accuracy compared to other techniques, as well as the low wearing comfort.

In principle, the brain waves that can be measured by means of EEG can be divided into four frequency ranges. Beta waves ( $> 13$  Hz), alpha waves (8 to 13 Hz), theta waves (4 to 8 Hz) and delta waves (0.5 to 4 Hz). The best known and most frequently used rhythm is the alpha rhythm with an amplitude of 50 micro volts (peak to peak). Unfortunately, the alpha rhythm is strongly influenced by the facial muscles such as the closing of the eyes, which leads to significant changes in the recorded signals. Furthermore, the signals that can be measured by EEG also depend on the mental state of the patient, circumstances such as stress or fatigue alter the signal sequences. In general, the following types of EEG electrodes are distinguished:

- disposable (gel-less, and pre-gelled types)
- reusable disc electrodes (gold, silver or stainless steel)
- headbands and electrode caps
- saline-based electrodes
- needle electrodes

Conventional electrodes have a diameter of 1 to 3 mm and have long flexible lines which can be connected to a measuring system for evaluating the measured signals.[17, 3]

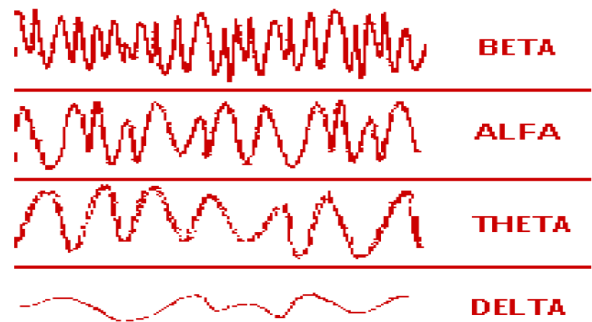


Figure 2: Wave forms of the four brain waves

#### 3.1.2 Magnetoencephalography

A method similar to EEG is magnetoencephalography (MEG). It measures the magnetic fields caused by the currents measured by the EEG. However, in the MEG method, much more measuring points can be detected and frequency spectra can be scanned, which are not measurable in EEG, which makes this system much more precise. Because of the need to operate in shielded rooms, the enormous dimensions and costs of the devices, it is hardly possible to use them in home operations. Like the EEG, chirurgical surgery is not necessary, which reduces the risk for patients to an absolute minimum.[12]

## 3.2 Invasive BCIs

#### 3.2.1 Single-unit recording

Another way to detect brain signals is to detect firing rates of individual neurons. For this purpose, an electrode is connected directly to a single neuron in order to record



the desired signal. However, to use this method, it is necessary to identify a neuron that correlates with the desired command. At the moment this is the most difficult problem with the use of single neuron signals. Although this method has already been used successfully in monkeys, it is still inaccurate for the use in BCI systems.[15]

### 3.2.2 Microarrays

When not only the action potentials of a single neuron but of several neighboring neurons should be measured, intracortical electrode arrays are recommended. These arrays are used directly in the brain, which allows very accurate signal recording. A single electrode array can be composed of 100 or more single electrodes and has a size of only 4.2x4.2 mm. A major drawback are the risks associated with implantation and the high costs. Furthermore, long-term stability is still lacking. Nevertheless, microelectrode arrays provide promising results and are often used in animal experiments.[11, 5]

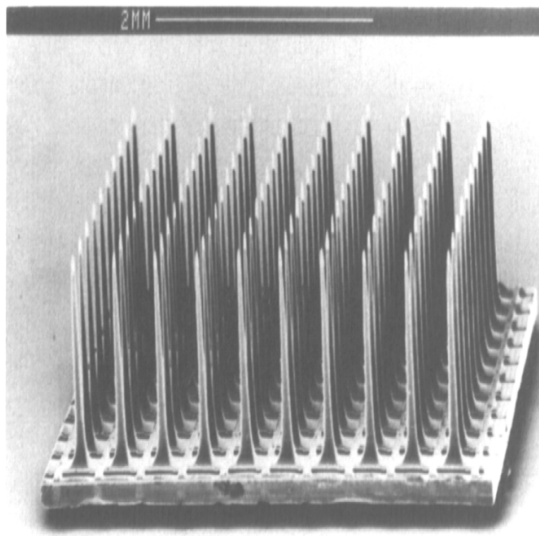


Figure 3: A 100-electrode microarray with a dimension of 4.2x4.2mm

### 3.2.3 Electrographicography

In electrocorticography (ECoG) the brain signals are measured directly on the surface of the brain. As a result, attenuation of the signals by the cranium as in EEG is excluded and the signal quality thereby substantially improved. Furthermore, this method offers a higher spatial resolution and bandwidth and is less susceptible to external influences than non-invasive methods. In contrast to the single-neuron measurement, these electrodes do not have to be implanted directly into the brain, which significantly reduces the risk to the user. However, a very difficult and complex intervention is necessary to implant these sensors, which is associated with high costs, and yet no accurate statement can be made about the long-term stability. However, in spite of the risks, ECoG is a very good way to capture signals, since a lot of signals can be recorded undisturbed and so many different control commands can be extracted for external devices.[8]

## 3.3 Differences in signal quality

In an experimental set-up carried out on rats, the differences in the quality of recording between EEG and ECoG are shown. In this experiment, five ECoG electrodes were implanted and two scalp electrodes were applied. While even the shortest stimuli could be absorbed by the ECoG electrodes, eruptions on the EEG electrodes were only visible when several of the ECoG electrode signals had already been recorded. It is also observed that the EEG can recognize the signals only after a clear, spatial spread. In addition, stimuli from ECoG electrodes could be perceived much earlier than EEG. This is mainly due to damping by the skull, but also due to the greater distance of the EEG electrodes. Although the experiment was carried out on rats, the differences in the signal quality of both techniques are clearly shown.[6, 1]

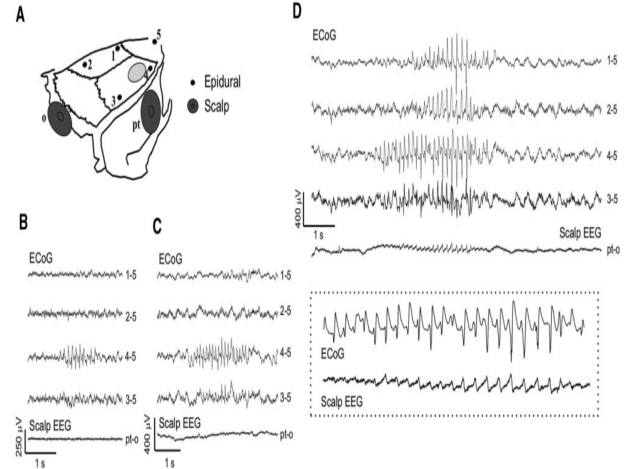


Figure 4: Comparison between EEG and ECoG Signals

## 4. APPLICATION AREAS

### 4.1 Restoration of speech

"Restoration of communication has been a main focus of BCI research to date. Several specific electroencephalography (EEG) features have been proposed as control signals for such BCI communication systems."[9]

On a screen in front of the user, rows and columns alternate with letters and numbers. The user concentrates on the next character he wants to bust. If the desired letter appears on the screen, a signal in the partial slider can be measured approximately 300ms after the character appears. This period of time gives the so-called P300 spellers their names. By recognizing this signal, the desired letter could then be putout on the screen or appended to the word to be spelled. In order to increase the hit probability, several characters are made per character until this is permanently stored. The main problem is the secure recognition of the desired character. [7, 4] In addition to the P300 events, steady-state visually evoked potentials (SSVEP) can also be used for character recognition. By combining both technologies, systems with an average information transfer rate (ITR) of 20.13 bits/min can be realized with a hit rate of 97%. Both impulses are innate and do not have to be trained, but the

hit rate of the classifiers can be improved by training. Due to the low cost and ease of use, EEG is usually used for signal acquisition, but other technologies could also be used.[13]

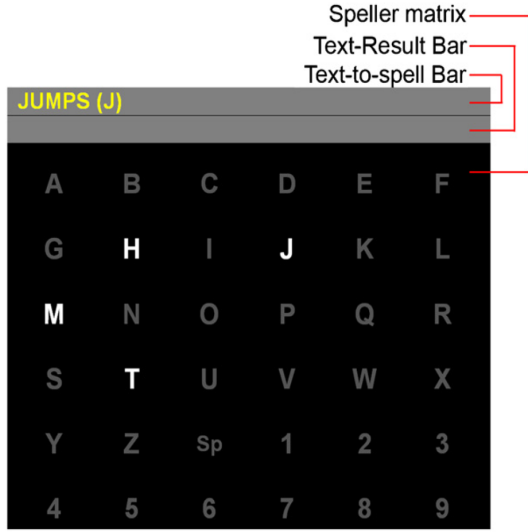


Figure 5: Possible display of a P300 speller

## 4.2 Control of wheelchairs

This section presents two basic concepts for controlling BCI based wheelchairs. Basically, wheelchairs have higher security requirements than P300 spellers, for example, because they could endanger the user by incorrect information. One of the concepts offers the user the possibility to select targets from a prefabricated menu, which is then automatically approached by the wheelchair. This not only greatly simplifies the user's operation, but also simplifies the necessary BCI system since only very few data have to be transmitted and evaluated. In the second concept, direction data is extracted from the brain currents of the user, which is then converted into movements by the wheelchair. This system allows greater freedom of movement but is more complex because of the much higher data volume. Both systems rely on P300 signals because they are measurable by non-invasive methods, which can reduce both the risk to the user and the cost of the system.[6, 18, 14]

### 4.2.1 Control per menu

While many BCI based wheelchairs are equipped with a variety of sensors for obstacle detection, this approach is designed to rely on user intention as much as possible to avoid obstacles. As a result, less sensors are needed, but it also increases user comfort if the chosen path overrides the algorithm. Through the cooperation of humans and computers the most efficient and secure way is found. To support the human being and to simplify the sensors and algorithms, predefined paths are used here, which are proposed to the user in the event of an obstacle. An important point in this approach is a sufficiently accurate position feedback. To this end, bar codes are applied to the floor at key points in the room, for example on doors or other bottlenecks, which are detected by a sensor and are reported back to the system.

This procedure provides a cost-effective and sufficiently accurate position feedback. The accuracy is less than 10cm if a mark is applied after every 10m. By using predefined paths, which will only be read in the event of an obstacle, it is very easy to ensure operation even complex buildings. In order to record a new building or changes in the placement of furniture system, for example, several possibilities are available. One way is to introduce new paths in the system through by the so-called "Walk Through Programming" (WTP). For this purpose, the wheelchair is simply pushed from mark to mark and the necessary movements are recorded and stored by the system. Another tool that is used to edit already learned paths as well as to create new paths is a simple software with graphical user interface. This allows you to connect paths already routed, creating a whole network of possible ways in which the user can navigate to the destination. The operation of this system is very easy for the user, since the user only has to select the desired route from his / her path from a list of possible ways. The selection of the current possible paths is displayed on a display and selected by the user similar to the P300 speller. The wheelchair then automatically moves along the selected path until the user decides for the next path. In this case, the user is only offered paths which are accessible from the current position. If, for example, the wheelchair is navigated to a lift, a selection of possible floors is displayed in the menu which is automatically activated after the selection. One problem with this system is the long reaction time, which can be several seconds. Due to this long period of time, it is not possible for the user to react to suddenly occurring obstacles. In order to avoid this problem, the wheelchair is equipped with sensors which can detect an obstacle and immediately stop the wheelchair. Such events are then solved by user decision. The user has to select one of the possible actions to move around the obstacle or call for help.[6, 14]



Figure 6: Possible path selection

### 4.2.2 Control per single commands

A further possibility for controlling BCI-based wheelchairs is the control by means of directional signals, which are ob-

tained from brain signals of the user. These directional signals differ from those of a joystick as they offer a low spatial resolution, because the number of different commands which can be extracted from the measurements is strongly limited. Thus, only three commands can be distinguished for forward, left and right. The speed can be increased up to a predetermined maximum by multiple consecutive forward commands. By a left or right command the wheelchair is decelerated but not fully brought to a stand, so a hazardous ride is prevented. In order to ensure safe travel, the environment is recorded by a laser scanner and its data is compared with the intension of the user. As a result, it is not possible for the user to approach a hazard source such as a wall or a staircase closer than by a predetermined limit. As a result it is only possible to move into obstacle-free areas. Knowing about the environment allows the system to calculate the probability of a user action by requiring the user to move safely and efficiently. This probability and the data recorded by the EEG now serve as the basis for the next movement.[18]



Figure 7: BCI controlled wheelchair

### 4.3 Neurorehabilitation

"In addition to their uses for communication and control, BCI systems also have potential to serve as therapeutic tools to help people whose neuromuscular function has been impaired by trauma or disease to relearn useful motor function."[7]

The use of BCI systems in neural rehabilitation, eg. after a stroke can be divided into two different strategies. In the first, the learning progress is monitored by the BCI and visualized to the user, so to speak, for motivation purposes. This also allows specific training plans to be displayed based on the training results, as some methods are more effective than others. In the second strategy, a BCI is intended to support the desired movement in order to relieve the patient's muscles, but to promote mental work.[10]

## 5. PROBLEMS AND PROSPECTS

All current BCIs have their problems and limitations. In principle, the safety of BCIs, their long-term stability and the accuracy of the measurements are the main problems. Most of these problems can be significantly improved or even eliminated by improvements in the recording electrodes. However, the electrodes can now only be implanted in relatively few brain regions and can thus only absorb limited neural activities. Although EEG-based BCIs do not have the high demand for long-term stability as invasive electrodes, they can be easily emitted, but they are not able to record very weak signals. Nevertheless, they have so far been used against invasive electrodes since they can also be operated relatively easily and independently from the laboratory. This is shown by the fact that a few people already use this type of BCIs at home. Nevertheless, a further development of these systems is indispensable in order to offer them to a wider audience. Thus BCI systems have to be developed, which offer several independently working control channels. A further difficulty of these systems is their high demand on the concentration of the user which leads to a rapid fatigue of the user and thus to reduced system performance. Equally important are improvements in the area of performance as well as mobility and look and feel. Only if all these points are considered and improved such a system can be successful.[10]

## 6. CONCLUSION

In summary, in spite of poorer signal quality, non-invasive measurement methods are preferred to invasive methods. This can be attributed to the high costs and the high risk of invasive methods as well as the handling simplicity of EEG based systems. In order to make full use of the advantages of microarrays and ECoG, researchers from the field of computer science will have to work more closely with medical professionals to be able to implant risk-reduced and cost-effective hardware. Since signal acquisition is one of the most important areas in BCI research, technical progress to increase the signal quality and the yield of evaluable signals is essential, as well as finding new signal sources within the brain. Despite the limited possibilities of signal acquisition and the early stage of research in BCI, systems are already available today which can significantly improve the lives of patients. Through further research and cooperation in different disciplines of science, BCIs could one day find their way from the laboratory to the patient and be available to the broad masses.

## 7. REFERENCES

- [1] R. D. Ambrosio, S. Hakimian, T. Stewart, D. R. Verley, J. S. Fender, C. L. Eastman, A. H. Sheerin, P. Gupta, R. D. Arrastia, J. Ojemann, and J. W. Miller. Functional definition of seizure provides new insight into post-traumatic epileptogenesis. September 2009.
- [2] G. Hoelzl. A personalised body motion sensitive training system based on auditive feedback. In T. Phan, A. Montanari, and P. Zerfos, editors, *Proceedings of the 1<sup>st</sup> Annual International ICST Conference on Mobile Computing, Applications, and Services (MobiCASE09)*, volume 35 of *Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications*

- Engineering*, San Diego, California, USA, October 26-29 2009. ICST, Springer. ISBN: 978-3-642-12606-2.
- [3] G. Hoelzl, A. Ferscha, P. Halbmayer, and W. Pereira. Goal oriented smart watches for cyber physical superorganisms. In *Workshop on Collective Wearables: The Superorgansim of Massive Collective Wearables, at 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp 2014), Seattle, USA, September*, pages 1071 – 1076, September 2014.
  - [4] G. Hoelzl, P. Halbmayer, H. Rogner, C. Xue, and A. Ferscha. On the utilization of smart gadgets for energy aware sensitive behavior. In *The 8th International Conference on Digital Society, ICDS 2014, March 23 - 27, Barcelona, Spain*, pages 192 – 198, March 2014.
  - [5] G. Hoelzl, M. Kurz, and A. Ferscha. Goal processing and semantic matchmaking in opportunistic activity and context recognition systems. In *The 9th International Conference on Autonomic and Autonomous Systems (ICAS2013), March 24 - 29, Lisbon, Portugal, **Best Paper Award***, pages 33–39, March 2013.
  - [6] K. Iqbal. Brain-computer interfaces in neurological rehabilitation. 2013.
  - [7] P. J. Kindermans, H. Verschore, D. Verstraeten, and B. Schrauwen. A p300 bci for the masses: Prior information enables instant unsupervised spelling.
  - [8] E. C. Leuthardt, K. J. Miller, G. Schalk, R. P. N. Rao, and J. G. Ojemann. Electrocorticography-based brain computer interface—the seattle experience. June 2006.
  - [9] J. N. Mak, D. J. McFarland, T. M. Vaughan, L. M. McCane, P. Z. Tsui, D. J. Zeitlin, E. W. Sellers, and J. R. Wolpaw. Eeg correlates of p300-based brain–computer interface (bci) performance in people with amyotrophic lateral sclerosis. February 2012.
  - [10] J. N. Mak and J. R. Wolpaw. Clinical applications of brain-computer interfaces: Current state and future prospects. May 2010.
  - [11] E. M. Maynard, C. T. Nordhausen, and R. A. Normann. The utah intracortical electrode array: a recording structure for potential brain-computer interfaces. September 1996.
  - [12] J. Mellinger, G. Schalk, C. Braun, H. Preissl, W. Rosenstiel, N. Birbaumer, and A. Kübler. An meg-based brain-computer interface (bci). July 2007.
  - [13] R. Panicker, S. Puthusserypady, and Y. Sun. Asynchronous p300 bci: Ssvep-based control state detection. August 2010.
  - [14] B. Rebsamen, E. Burdet, C. Guan, H. Zhang, C. L. Teo, Q. Zeng, M. Ang, and C. Laugier. A brain-controlled wheelchair based on p300 and path guidance. bar.
  - [15] E. M. Schmidt. Single neuron recording from motor cortex as a possible source of signals for control of external devices. July 1980.
  - [16] J. J. Shih, D. J. Krusienski, and J. R. Wolpaw. Brain-computer interfaces in medicine. March 2012.
  - [17] M. Teplan. Fundamentals of eeg measurement. 2002.
  - [18] G. Vanacker, J. del R. Millan, E. Lew, P. W. Ferrez, F. G. Moles, J. Philips, H. V. Brussel, and M. Nuttin.

Context-based filtering for assisted brain-actuated wheelchair driving. May 2007.

# Magnetic Field for Haptic Feedback

Daria Ivanova  
Universität Passau  
Lehrstuhl für Informatik mit Schwerpunkt Eingebettete Systeme  
Innstr. 43  
94032 Passau, Germany  
daria.ivanova@uni-passau.de

## ABSTRACT

Haptic technology recreates a tactile sensation by applying different kinds of mechanical stimulation to the user. An application of magnetic field is one of the ways to provide haptic feedback. Magnetic field is applied in Haptics for its ability to provide a strong continuous force feedback to the user. This paper includes an overview of three haptic devices that allow the user to receive force feedback from the system by means of magnetic repelling force. The paper provides a detailed comparison of these technologies on several criteria.

## Keywords

haptic feedback, magnetic field

## 1. INTRODUCTION

Haptic technology assigns a tactile feedback response to the designated input. It is an innovative way of interaction with the human used in electronic devices by recreating the sense of touch. Haptic technologies have already been used in projects in such fields as virtual reality (computer games), teleoperations, medical training (rehabilitation therapy, surgical simulators). There are several approaches to create haptic systems. Usually these systems look absolutely different, but they all have two important things in common - software to determine the forces that result when a user's virtual identity interacts with an object and a device through which those forces can be applied to the user. There are many ways to provide tactile feedback to the users: by means of an air (air-jet, air-vortexes), ultrasound or magnetic field, with electric current, piezoelectric sensors, etc.

This paper analyzes features of a magnetic field to define to what extent a magnetic repelling force is applicable to provide haptic feedback. The paper discusses the following questions. Which benefits has magnetic force over other methods used to create Haptic effect? Which unwanted characteristics have to be taken into account when dealing

with Magnetic field? What are the common features of existing technologies based on magnetic force actuation for haptic feedback? What are the modern devices that apply magnetic field to provide tactile sensation? Which comparison criteria of these technologies (devices) are applicable? What are the potential applications with respect to Haptics of devices based on magnetic field?

The second section of this paper describes general desirable and objectionable characteristics of magnetic force with respect to the Haptics concept. Sections 3,4,5 provide an overview of three modern devices that use magnetic field to provide tactile sensation to the user based on three research works and some additional literature. In section 6 a comparison of these inventions on different criteria is given. In Section 7 the devices are discussed from the point of current stage of development and future expectations.

It is important to differentiate between three definitions: which type of a force is used for haptic effect, the groups of Haptic interfaces and the invented devices which represent these groups of interfaces. The type of the force discussed in this paper is the magnetic repelling force. There are three groups of Haptic interfaces that have been studied: Co-located 3D visual and haptic display, Magnetic Levitation and Magneto-Rheological fluid based technologies.

Three devices which represent the concepts named above have been described and compared. The first device represents the concept of Magnetic rendering. The magnetic field is generated by a specifically designed electromagnet array driven by direct current. A tactile feedback can be perceived by the user through small magnet disks attached on the hand. In the second technology, so-called Lorenz force magnetic levitation, a levitated handle grasped by the user reproduces the dynamic physical behavior of a rigid tool interacting with a remote or virtual environment. The third device is based on Magneto-Rheological Fluid. The authors designed a special excitation system to distribute magnetic field inside MR fluid in a desirable way.

It is important to mention, that there are other devices exist that could be included in one of the defined groups of magnetic Haptic Interfaces, that are not described in this paper due to the similarity to the devices mentioned above or because they are not yet developed enough or outdated.

## 2. MAGNETIC FIELD: HAPTICS RELATED BENEFITS AND DRAWBACKS

To understand what makes magnetic field a desirable mechanism for haptic interaction it was compared with other haptic technologies. The devices based on air force (air jet, air

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, to republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

*Advances in Embedded Interactive Systems* '16 Passau, Germany  
Copyright 2016 ACM X-XXXXX-XX-X/XX/XX ...\$15.00.

vortex) and ultrasound are known for a long operation distance but only discrete focal force points can be generated. An ultrasound force is very weak and only limited amount of focal force points is possible to generate. The considerable disadvantage of air based methods is a low fidelity due to non-focused stimulation area.

Technologies that apply magnetic field has several benefits in comparison to the other methods, because of considerably higher force possible to generate within a short distance. Magnetic force is sufficient to counteract gravity or other imposed force. Magnetic field is able to pass through most of the materials, for example, glass. Another advantage is an opportunity to form a smooth, continuous force field in space.

However, the magnetic field decreases rapidly (with the square of distance), which is a critical issue for some developments. The second drawback is a natural non-linearity of magnetic field. It influences the precision of control in all developments, that use magnetic repelling force for a haptic feedback. Despite of these issues, modern researches proposed methods that deal with occurred problems to provide an acceptable accuracy.

The further detailed comparison with actual not magnetic field based haptic devices are provided in section 6, subsection 6.5.

### 3. MAGNETIC RENDERING

This section provides an overview of a system designed by Zhang et al. in 2016 [14, 4]. The proposed model represents the group of devices: Co-located 3D visual and haptic display.

#### 3.1 Purpose of a research

The device has been designed for rendering of volumetric shapes in mid-air. In context of Haptic interaction, rendering is a process of informing the user about the properties of a virtual object through effect of certain stimulation. Among the properties of the object are shape, texture, elasticity and so on. The force field can be felt as magnetic repulsive force exerted on the hand through the attached magnet disks. The authors characterize their model mathematically, and apply recursive least squares adaptive control algorithm for controlling the magnetic field. The invented model is the first prototype based on magnetic field that can render a continuous volume shape with strong force feedback for users to perceive.

#### 3.2 Background work

There are two well-known projects related to usage of magnetic repelling force for tactile sensation and included in a defined group of Co-located 3D visual and haptic display interfaces. The first one, FingerFlux [12], is a device that generates near surface force feedback for tabletops to guide the users when approaching the screen. It deals with attractive and repulsive magnetic force and vibration. The system similarly consists of an array of electromagnet as force feedback actuator and magnets attached on the hand as force receiver but is not specifically designed for creation of volumetric shapes in mid-air and the force produced is not strong enough. Further more, the authors do not provide numeric analysis of the magnetic force generated by the array of electromagnets, so it is impossible to derive a control method. The second device presented in a project "a

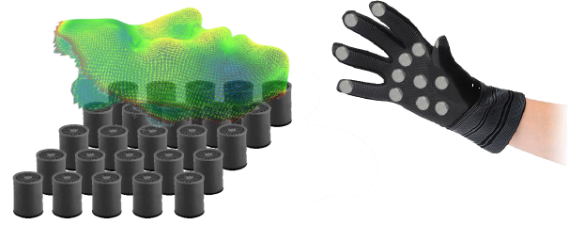


Figure 1: Magnetic rendering concept

Co-located 3D graphic and haptic display" [3, 5], uses a pen with attached magnets as a force receiver, so that the user can perceive force feedback. A limitation of this project is that a pen provides only a single point tactile sensation at the moment of time.

The advantage of the new model comparing with previous ones is the ability to provide a multiple point tactile sensation of enough strength to be perceived by user's fingers and palm of the hand. With only a small attachment on their hands users can perceive the shapes just by moving their hands through the air.

#### 3.3 Model of the device

The system consist of an array of electromagnets acting as a force feedback actuator. On the user's hand multiple magnets disks are attached performing as force feedback receiver. The model of the system is presented on **figure [1]**.

The center of each electromagnet has a solenoid structure, so that the central metal core of cylindrical shape is tightly wound by a coil of insulated wire. A solenoid is surrounded by concentrator, which concentrates magnetic field to the upper part of a cylinder. All construction is surrounded by isolator that shields the magnetic field between each two elements to avoid severe interference.

#### 3.4 Working principles

The goal of the research work was to maximally increase the distance between electromagnet part of the device and the point, at which the user could still perceive tactile sensation, in other words to increase the height of mid-air force feedback, to overcome the limitation of the background studies [12, 7].

It is known that human hand stiffness perception is considered as firm when it is above  $350 \text{ N} \cdot \text{mm}^{-1}$ . For fingertips the minimum force that can be perceived is 0.8 mN and for a palm of a hand is 1.5 mN. According to the performed simulations of magnetic force at different vertical distances the endmost distance where the force can be felt by the whole hand is about 5.1 cm.

The magnetic force, as it was mentioned before drops with the square of distance. To achieve an acceptable distance between an array of electromagnets and the surface, where the generated magnetic repelling force is strong enough to create perceptible by hand volumetric shapes, the authors of an invention proposed two additional elements: concentrator and isolator.

The main purpose of the concentrator is a concentration of magnetic field on the upper pole to increase an overall vertical magnetic force. The concentrator is a radially magnetized permanent magnet cylinder ring with the North Pole



pointing to the axis. It contributes to the top surface current in solenoid with a counter-clockwise magnetization current and to the bottom surface current with a clockwise magnetization current. As a result, it reduces magnetic flux at the bottom and increases it at the top.

An Isolator is made of Mu-metal that is nickel-iron mix with nearly 80 percent of nickel. It has much higher permeability than air that makes it one of the most efficient materials for magnetic field shielding. The shield acts as better conductor of magnetic flux. It forces the magnetic field to concentrate at the upper part of the core resulting in a stronger magnetic field above the electromagnet.

A simulation has been performed to test the concentrating effect of the concentrator and the shielding effect of the isolator. It showed a considerable improvement over the basic solenoid model. However, the shielding effect becomes weaker with the vertical distance. At 2 cm distance models with and without isolator show nearly the same performance.

For electromagnets used for haptic force actuation purpose, ferrite cores are desired because they have high magnetic permeability which can help generate strong magnetic field, whereas results in non-linearity of the produced magnetic force with respect to the stimulating current. When it comes to an array of electromagnets, the coils can not be controlled individually due to the superposition of magnetic field.

Consequently, the authors of the project had to consider several parameters when constructing an array of electromagnets. The challenging parameter is a superposition effect that, on the one hand, helps to form a smooth magnetic field, but on the other hand reduces a precision of control. The simulation of the force field produced by two adjacent electromagnets with different spacing strategies showed that the magnetic force superposition effect attenuates with the spacing. To increase the overall magnetic force the authors preferred the model with no spacing between elements. The authors chose a square layout over hexagon to reduce interference between single elements.

### 3.5 Linearity of the system

The authors proved that a vertical force on the disk above the single element caused by all electromagnets can be modeled as a linear dependency from stimulating current. According to the simulations performed for one electromagnet stimulated by current from -20A to 20A the magnetic force is almost proportional to the current value in a range of current  $[-1,1]$  A, which is the maximum current used for experiment with shapes rendering. The simulation with 2 electromagnets proved that each of the forces generated by electromagnets depends on both current values, and the resulting forces are linear combination of both currents.

Recursive least squares (RLS) control method was used to estimate the current to force transformation matrix of the multiple-input-multiple-output linear system, where matrix dimensions are the number of electromagnets on X and Y axes in the array.

### 3.6 Human face rendering

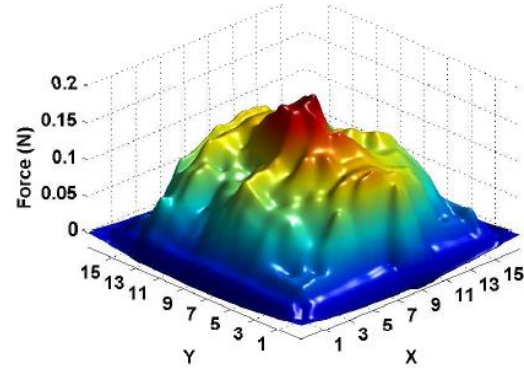


Figure 2: Force field of 15x15 electromagnet array at 3 cm above

To test the proposed model the human face rendering was performed in a simulating environment on the 15 by 15 array of electromagnets. The result is presented on **figure [2]**.

Despite of the fact that the magnetic force drops with the square of distance, at 3 cm above the array the strength is still acceptable for perception, while the performance in terms of visual accuracy considerably increases as magnetic field becomes smoother within the distance. The human face is visually distinguishable with minor deviations. The model demonstrates desirable performance in terms of the magnitude of the produced vertical force, the magnetic field isolation property, and stiffness with high fidelity via Finite Element Method simulations.

### 3.7 Drawbacks

Despite of an obvious improvement of previous technologies, the new proposed device belongs to the group of so-called wearable haptic devices, which are cumbersome in terms that they need fitting to the user's hand before using.

There are two possible ways to boost the overall magnetic field above the electromagnet: to increase the number of turns of the coil or raise the stimulating current value. However, the current running in the wires has a strict constraints due to material and manufacturing limitations such as the current capacity of the wire and the heating effect of the coil. Moreover, small electromagnets are desired so that the force field generated can be felt with detail, which renders a large number of wire turns impossible.

Using concentrator and isolator for each electromagnet in the array the authors could considerably increase the overall magnetic force above the model by concentrated the magnetic field on the upper poles of electromagnets. Nevertheless, the maximum height where the magnetic force is still sufficient enough to be perceived by the user's hand is 5 cm.

### 3.8 Future work

The performance of the designed system was evaluated based on modeling and simulation. The authors planned to construct a real electromagnets array to perform a real world experiments. A thin 3D hologram print are going to be placed above the electromagnet array to enable the user to see the 3D object while feeling the corresponding tactile sensation.



## 4. MAGNETIC LEVITATION FOR HAPTIC INTERACTION

This section refers to the concept of Magnetic Levitation haptics and summarizes the main features of basic technology as well as the modern version of the device described in Berkelman et al. 2010 [2]. To operate the Magnetic Levitation device the user has to hold a levitated 6 degrees-of-freedom handle similar to the computer mouse or so-called joystick. When the user interacts with a 3D virtual object using this handle, electric currents are directed through embedded coils. These currents interact with permanent magnets fixed along the device's inner walls to give the force feedback sensation.

### 4.1 History and purpose of a research

Magnetic levitation of a rigid body using Lorentz forces was invented by Dr. Ralph Hollis in 1984. The first device demonstrated the magnetic levitation used for haptic feedback has been proposed in early 90-ties.

Magnetic levitation haptics is an approach to provide a 6-DOF user interface. The first prototype has been applied as a vibration isolation method for microgravity experiments. The prototype developed in 1997 has been used for many psychophysical investigations of hard contact, texture synthesis and perception, and deformable object perception studies and is still in use today.

### 4.2 Basic model of the device

The prototype of a basic system has been proposed already in 1997 [1]. The system consists of a spherical shell, so-called flotor, made of flat coils. This shell levitates between permanent magnets that provide a strong magnetic field. A handle that designed to be manipulated by the user is mounted at the center of the flotor. Large, curved iron pole pieces pass above and around the levitated coil assembling to form a magnetic flux path from one magnet to the other on the opposite sides of each gap **figure [3]**.

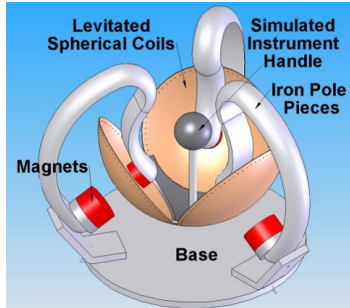


Figure 3: Magnetic levitation basic system

The centers of the coils are arranged at 0, 120, and 240 degrees around a spherical surface of a 125 mm radius, and each coil spans a solid angle of 90 degrees. A single Lorentz force actuator consists of two opposing fixed magnets and an oval wound coil suspended between them in the magnetic circuit air gaps.

The position and orientation of the flotor is tracked by optical sensors. Position is sensed by three LEDs mounted on the flotor and three planar position sensitive photo-diodes on the outer stator. The position and orientation of the flotor can be calculated from the combination of the six sen-

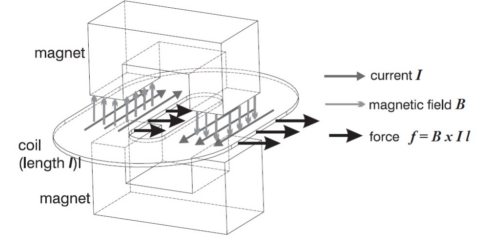


Figure 4: Lorentz force actuation

sor signals (x and y LED spot position from each sensor). The three sensors are mutually orthogonal to maximize position accuracy and simplify the geometric calculations. The sensed position-orientation information is used by the control algorithm to provide stable levitation and to impart the correct forces and torques to the user's hand.

### 4.3 Lorentz force actuation

The Lorentz forces  $\mathbf{f}$  on the coil are generated in the two air gaps where the coil current loop  $\mathbf{I}$  intersects the magnetic flux loop  $\mathbf{B}$  and are perpendicular to both the current and the magnetic field vectors **figure [4]**.

The forces and torques generated when the flotor is in the centered position can be expressed as a product of  $\mathbf{I}$  and  $\mathbf{A}$  where  $\mathbf{I}$  is a vector of coil currents and  $\mathbf{A}$  is a transformation matrix mapping currents and forces.  $\mathbf{F}$  is a vector too and consists of forces and torques exerted on the flotor center.

### 4.4 Improved model of the device

In the improved model presented in [2] racetrack-shaped coils in which the coil windings follow oval paths were replaced by a new coil shape in which the windings follow straight paths across the centers of the coils, and curved return paths around the periphery of the round coils.

This allows the coils to be arranged in two layers with the straight wires across the centers of the coils orthogonal to one another. In this arrangement, the areas of the coils can be increased considerably without increasing the radius of the spherical shell, and each pair of layered coils requires only two magnets to generate their shared magnetic field. The performance characteristics of an improved model are the following: a motion range is 50 mm in translation and approximately 60 degrees in rotation in all directions. The improved coil configuration is depicted on **figure [5]**.

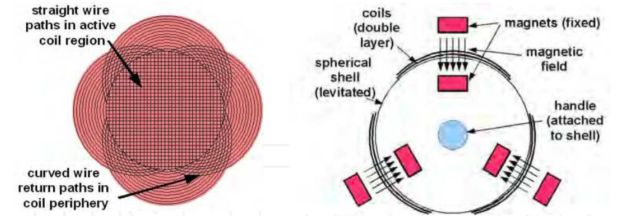


Figure 5: Magnetic levitation improved system

Further more, in a new model the iron pole pieces on two of the magnet assemblies have been rotated about the magnet axes by approximately 30 degrees to provide more ergonomic access for the user to more easily grasp the levitated handle without affecting the magnetic fields or the range of motion of the device.

## 4.5 Working principles

As the user moves the handle through its motion range in 6 degrees-of-freedom position information is sent to the user's application. Conversely, forces and torques are sent to the handle from the user's application.

Electromagnetic finite element analysis was performed to find magnet shapes and dimensions to concentrate and maximize magnetic fields necessary for levitation. This analysis indicated that the minimum field strength in between magnets is approximately 0.25 Tesla that is considered to be sufficient for levitation and high-fidelity haptic interaction.

## 4.6 Important characteristics

The following characteristics are declared for the commercial project Maglev 200<sup>TM</sup> System of Magnetic Levitation Haptic Consortium (Butterfly Haptics LLC).

The modern magnetic levitation device version's most relevant characteristics are the following. It has full six degree-of-freedom rigid body motion capabilities - three in translation and three in rotation. A wide stiffness range make the device capable of rendering a range of stiffness from essentially imperceptible to extremely hard. The Maglev 200<sup>TM</sup> does not have any static friction, so that the precision of the motion is not violated by this factor. It has a small amount of physical damping, strictly proportional to the speed of the flotor, which aids in control. Additional damping or even stick-slip friction can be easily simulated through software.

Because of a zero mechanical backlash, in other words an effect of lost motion the unwanted delays has been avoided. The very high position bandwidths enable high-fidelity rendering of subtle friction and texture effects. A position resolution is near the limits of human perception. There is an essentially direct electrodynamic connection between the computer and the hand, conveying force and torque effects to the proprioceptive sensors as well as subtle vibratory effects to the skin sensors.

The high forces bandwidths are achieved by using high slew rate low-noise linear amplifiers, very low coil inductances, and rigidly connecting the handle to the flotor. As a consequence of its simple rigid body control model and high resolution, the Maglev 200<sup>TM</sup> is capable of rendering a range of stiffnesses from essentially imperceptible to extremely hard. At the highest stiffnesses, it is difficult to distinguish between contacting virtual surfaces and contacting real surfaces. The impedance range of the device in stiffness is greater than three orders of magnitude.

The measured control bandwidths for the device are the highest yet reported for any 6-DOF haptic interface device and the device dynamics are frictionless.

## 4.7 Possible future improvements

The magnetic levitation concept can be improved in terms of achievable stiffness and motion resolution as well as functionality of related API. During the past 10 years the authors published several research works related to the improvement of coils shape and configurations, design and control methods, enhancement of the dynamic performance of the device.

# 5. MAGNETO-RHEOLOGICAL FLUID-BASED HAPTIC INTERFACES

## 5.1 Purpose of a research

In a paper [9] the authors evaluated the possibility to employ Magneto-Rheological fluids to mimic the compliance of biological tissues in order to create haptic displays for surgical training. There are also several research works that used MR fluid for simulation of syringe injection (anesthesiology training). A new system of permanent magnets and coils was designed in order to produce a proper distribution of a magnetic field inside the fluid.

## 5.2 A concept of Magneto-Rheological fluid

a Magneto-Rheological Fluid (MRF) is a type of carrier fluid, where the magnetic particles, which are typically micrometer or nanometer scale spheres or ellipsoids, are suspended within the carrier oil or water and distributed randomly in suspension under normal conditions.

When an external magnetic field is applied, the particles change their rheological behavior, so that the fluid greatly increases its apparent viscosity as a function of the intensity of the magnetic field and become a viscoelastic solid [13] when the fluid is magnetically saturated. This phenomenon is reversible and the fluid can return to its liquid state in a very short time (approx. 10 ms) by removing the magnetic field. The concept of MR fluid is presented on figure [6].

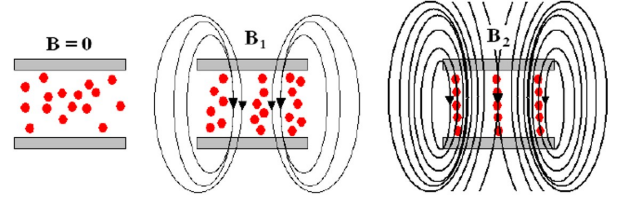


Figure 6: Magneto-Rheological fluid influenced by magnetic field

## 5.3 Background work

Before creating their own prototype, the authors of the paper studied the related projects. The previously developed system consists of a plastic box of cylindrical shape containing the MR fluid and a series of solenoids and iron pistons. The magnetic field in those prototypes has been produced by solenoids properly placed to provide a desired distribution in a given region of the fluid. The advantage is that it allows direct hand contact with an object reproduced in fluid. The old prototype is depicted on figure [7].

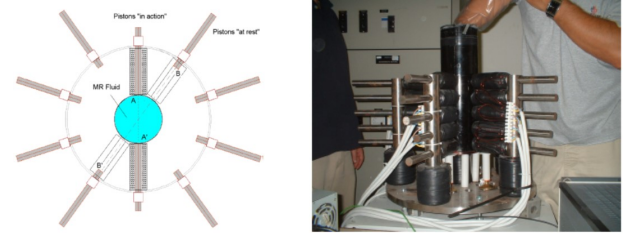


Figure 7: Prior prototype of MR fluid based device

The configurations can act both electrically (by varying the value of the current in some of the coils) and mechanically (by moving the pistons along their axial direction). In other words the solenoids are able to control the position

of the iron pistons by moving them in a radial direction in order to reduce or increase the magnetic path's reluctance inside the fluid.

### 5.3.1 Limitations of previously developed prototype

Although a properly designed control strategy has allowed to mimic a wide range of rheological behaviors, this system has limitations. It is known that a static magnetic field, governed by Laplace equations, has its maximum on the external border and results in a weaker field value in the inner part of the fluid. However, in proposed system the number of the pistons and the coils, composing the excitation system, is not high enough to properly excite all the parts of the fluid.

### 5.3.2 Excitation system performance criterion

The potential performance of the excitation system can be determined by the ratio between the surface of the fluid and the total surface of the excitation system. The value of the ratio A can be calculated by taking into account the number of pistons and their diameter for calculation of total based surface and diameter of the cylindrically shaped plastic box for calculation of a fluid surface as described:

The total base surface of the 72 pistons (diameter  $d = 2$  cm):

$$S_{pist} = \frac{\pi * d^2}{4} * N_{pist} \approx 226cm^2$$

The MRF surface (diameter of the cylindrically shaped plastic box  $D = 15$  cm and useful height  $h = 25$  cm):

$$S_{mrf} = \pi * \left( \frac{D^2}{4} + D * h \right) \approx 1355cm^2$$

$$A = \frac{S_{pist}}{S_{mrf}} * 100 \approx 17\%$$

It occurred that the ratio for the system is only 17 %. The authors proposed their own prototype that willing to increase this ration in 2.7 times.

## 5.4 New prototype

The main idea in a new prototype was that the magnetic field in the inner part of the fluid can be strengthen by using a flexible box and the permanent magnets as a source of field capable to properly excite such part of the fluid.

In the newly designed prototype MR fluid fills a flexible plastic balloon internally equipped with a latex glove able to handle the fluid. The balloon is placed inside a cubic plastic box whose base and lateral surfaces compose the exciter system. The excitation system is based on an array of exciters, whose single units are composed of small permanent magnets, coils and plastic coaxial columns. In a single unit, a permanent magnet (PM) is placed on the head of the inner column and on the outer column a coil is mounted to provide fine control of the field intensity and resolution inside the MRF and to facilitate the separation between the magnet and the fluid after they come into contact.

Each column is equipped with a linear stepper motor that is able to supply the required movement. The excitation system is arranged in 5 set of exciters array (4 for the lateral surfaces and 1 for the base surface, each of them composed of 25 single units, so that a total number of units is 125. Consequently, the ratio between the surface of the fluid and

the total surface of the excitation system is considerably increased till 45 %. The system is presented on **figure [8]**.

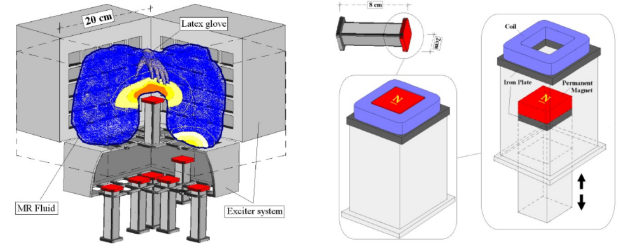


Figure 8: New model of MR fluid based device

## 5.5 Working principles

To excite a specific portion of MRF to be felt by hand the corresponding columns must be activated moving them along their axial directions. Each column is initially at rest and far enough from the MRF so that the magnetic field does not excite the fluid. During the movement of the column, as the distance between the exciter system (PMs and coils) and the fluid is reduced, the magnetic field inside the MRF increases.

The highest values of the magnetic field is obtained when the PM comes into contact with the balloon containing the fluid. However, besides controlling the distance between the magnet and the fluid, the magnetic field could also be modulated by tuning the current in the coil. The ability of the device to address the magnetic field inside the MRF allows the achievement of various quasi-3D virtual objects, showing a higher flexibility than the previously developed devices.

## 5.6 Validation of FEM model

In order to validate the Finite Element Method model, some measurements have been taken of a preliminary simplified prototype, composed of four excitation columns, properly positioned in the space. The validation purpose was to verify the device capability to properly excite the fluid, producing a given magnetic field distribution inside specific regions of the MRF.

It can be easily obtained comparing the simulated magnetic field with the measured one on the test prototype. Since it is quite difficult to measure the magnetic field inside the MRF without altering the flux lines, indirect measurements were taken just outside the balloon filled with MRF. For different configurations results showed a good agreement between the simulated field and the measured one with an error less than 10 %.

Preliminary tests have confirmed an improvement in terms of softness and/or shape reconstruction with respect to the previous prototypes.

## 5.7 Simulation of the model

The simulation is needed to find the optimal structural parameters and come to a compromise between the distribution of the magnetic field and the dissipated energy due to overheating. In order to assess the performance of the device, several simulations for different configuration were carried out. When two adjacent PMs are "active" an operator who inserts his/her hand into the fluid should be able perceive one hemisphere positioned at the base or lateral surface of the system. Controlling the PM distance from

the fluid and/or the current in the coil, fingers should be able to detect a hemispherical object as of different softness and consistencies.

The flux density is high enough ( $B \approx 0.5 - 0.6$  T) to result in a high shear-stress and consequently in a semi-solid state of the MRF. In case when two opposite columns are “active” it has to be possible to perceive a little parallelepiped with softness and consistence related to the applied magnetic field. However, by properly activating several “exciting” units, many other field configurations could be obtained. Therefore it is possible to mimic different objects of desired shapes.

The results of simulation are depicted on **figure [9]**.

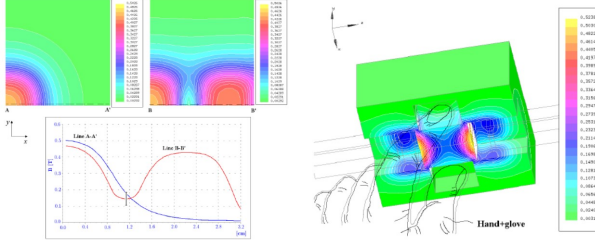


Figure 9: Simulation results

The authors of research work constructed a real world device consisted of 4 excitation units to demonstrate a test example in which the hollow square-shaped object is distinguishable (**figure [10]**).



Figure 10: Real world test example

## 5.8 Interaction between user and MR fluid

The important topic of discussion is an interaction between operator’s fingers and fluid. As it was mentioned above the proposed device is equipped with a latex glove allowing an operator to feel and explore the excited fluid.

When the fingers are inserted into the fluid, the force lines’ paths are altered with respect to their distribution previous to the hand insertion. Obviously the device expected behavior must be independent from the hand insertion. Once chosen portion of a fluid is energize the hand’s presence in the proximities of the magnetic flux must not interfere with the distribution of the flux itself.

The authors proposed a solution based on the choice of a proper glove material. If the hand+glove system is able to exhibit an average magnetic reluctance similar to that of the fluid, then the interaction between the operator’s hand and the fluid would produce a reduced perturbation of the magnetic flux density in the surrounding fluid.

Using the theory of the magnetic flux tubes, the domain occupied by the hand and the glove material (thickness of about 1 mm and unknown magnetic permeability ) has been subdivided into several flux tubes. The whole domain reluctance is obtained by means of magnetic circuit laws. Then, equating this reluctance with that of the same region, supposedly filled with fluid, a quadratic equation is obtained in terms of the unknown permeability of the glove material. The solutions of this equation magnetic permeability equal to 10.5.

A numerical simulation has been performed in order to verify the chosen solution. It showed that with standard glove the field altering on approximately 22 %, while, when using the proposed glove, the flux density in the evaluated region (the one where the fluid has a semisolid behavior) has a value only slightly altered and this demonstrates the quality of the proposed solution.

## 5.9 Future work

As a future work, the authors has planned the actual realization of the full-scale prototype. Also it was planned to perform some psychophysical tests needed to verify the capability of the device to mimic virtual objects of different shapes, softnesses and compliances. During tests some volunteers have to be asked to interact with the MR fluid at different excitation grades and required to describe the perceived sensations. Several experiments should be developed in which the subjects should recognize the position, shape and orientation of simple figures inside the MRF.

## 6. COMPARISON

In this section the three devices discussed above (magnetic rendering, magnetic levitation device, magneto-rheological fluid based haptic interface) are compared with each other using several criteria: modernity of an approach, form of tactile sensation, field strength, application on practice. These comparison criteria reveal and summarize the main features, benefits and limitations of proposed devices. In practical application criterion not only the specific devices but also the related Magnetic Haptic Interfaces groups (Co-located 3D visual and haptic display, Magnetic levitation and MR fluid based concepts in general) are taken into account.

The additional criterion is the comparison with some non-magnetic devices. The purpose of this comparison criterion is the understanding, to what extent magnetic field based haptic devices can provide the whole spectrum of possibilities related to Haptic technology and reveal positive and negative aspects of proposed magnetic field based technologies.

The three technologies are similar in terms of application of a certain number of electromagnets (solenoids). In other words a uniform magnetic field is produces in a volume of space within the coil of wire wrapped around a metallic core when an electric current is passed through it. However, the Magneto-Rheological fluid based technology uses an array of electromagnets only as a source of a magnetic force that cause the particles in the fluid to create desired touchable objects. Other required components, the number and arrangement of electromagnets, etc. considerably influence the overall performance and obviously specify these devices for different purposes.

### 6.1 Modernity of an approach



The discussion of modernity identifies future expectations about development of these inventions. According to search data given by several banks of publication the recent studies for all technologies were published in 2010-2016 that confirms the modernity of proposed devices.

The so-called magnetic rendering is a new concept being firstly presented in 2016. Although, Co-located 3D visual and haptic display is known since 2012, was studied previously in [3, 6] and [12] and the working devices exist, they have limitations, the real-life working device for magnetic rendering have been not yet demonstrated. The device described above that is able to create touchable volumetric shapes in mid-air [14] is only at the prototype stage and the working real device still does not exist.

The magnetic levitation concept has been applied for haptics since early 90-ties and still developing in terms of increasing accuracy, usability and adaptation for new applications.

The Magneto-Rheological fluid has been used for haptics providing a direct contact between the operator and the MR fluid in 2000. In the paper of 2010, however, only an improved prototype of system was proposed, that increases performance characteristic of previously designed and working on practice device. The real world working system with the same characteristics as the model still in a development stage.

## 6.2 Form of tactile sensation

All devices provide different forms of tactile sensation. The magnetic levitation device provides a sense of touch as the user grabs a handle. However, the user feels the pressure on the handheld handle and not directly into their skin, so that the only sense available is a resistance of the handle when trying to move it. Because this method provides point-wise force feedback, it is not intuitive in terms of human perception using hands. On the other hand, except for the ability to provide subtle vibratory effects to the skin sensors, the device affords force and torque effects to the proprioceptive sensors.

On the contrary, the magnetic rendering device, that uses a glove with permanent magnets attached as force feedback receiver, allows nearly direct mid-air tactile sensation generation for the hand, however limited by the number of permanent magnets on the wearable glove.

The most proximate sense of touch is provided by the device that allows interaction of the hand with shapes created in a volume of a Magneto-Rheological fluid. Despite the fact that it is also a wearable haptic device (the hand is in a latex glove), the feeling of touch is more realistic and intuitive among three devices.

## 6.3 Field strength

The devices are not comparable directly in terms of field strength. Because there are different requirements depending of the purpose of a device. At [14] the force only has to be strong enough for hand perception and it meets this requirement. The range of vertical force generated by a designed model is between 1 - 3.2 N at a vertical distance of 1 cm and 0.25 N - 0.7 N at 2 cm above.

At magnetic levitation device the force feedback has to be sufficient to stop an operator from moving a handle in certain cases. The peak force for Z axis is 40 N (for Maglev 200 TM).

The behavior of a Magneto-Rheological fluid depends on the magnetic field applied to the fluid. After it reaches a maximum point, the further increase of a magnetic flux density have no effect, as the fluid is then magnetically saturated. The shear strength in this case is maximum 100kPa in the absence of external pressure. However, if the fluid is compressed in the magnetic field direction and the compressive stress is 2 MPa, the shear strength is raised to 1100 kPa [13]. This strength is high enough to use MRF for magneto-rheological dampers in the automotive industry. By regulating the applied magnetic field it is possible to create in MR fluid the profiles of prescribed shapes and softness, in order to mimic real objects.

## 6.4 Application on practice

In general, Co-located 3D visual and haptic display interfaces are used nowadays for tabletops. Magnetic repelling force and vibrations actuated by array of electromagnets help to guide the user through the screen when working with some applications. The development of the volumetric shapes device despite of having the successful simulation performed in virtual environment is only in a prototype stage and has not been yet constructed on practice. The technology potentially would be useful as a part of interface for visually impaired people. With properly developed control system the magnetic rendering would be beneficial for hologram's interface improvement. Obviously, so called touchable holograms would bring a very high impact in future applications related to virtual environments and gaming.

Magnetic levitation device is applied nowadays in several areas: remote robot control, micro- and nano- manipulations (microsurgery), surgical training and virtual dentistry. Among the existing projects are the psychophysical investigation of human touch with virtual environments simulating hard contact, textured surfaces, and deformable objects; teleoperation of a robot arm and control of a mobile robot. Several user applications were designed where Magnetic levitation device is used as an advanced substitute of computer mouse.

In one of the recent research works Magnetic Levitation Haptic Device has been used for augmentation of tissue stiffness perception in a virtual environment [11]. The operator can sense the tissue in the virtual environment using the magnetic stylus to detect the presence of tissue lesions in a natural manner.

For Magneto-Rheological fluid technology the authors of the paper [9] built a simplified device with only 4 exciter units, that showed a good performance. However, increasing the number of exciter units can lead to certain problems and probably decrease an accuracy. Potentially the new proposed device is applicable for to mimic the compliance of biological tissues, their shapes, softness and consistency. There are many other projects related to the usage of Magneto-Rheological fluid as a Haptic technology, especially for medical training. In the case of minimally invasive surgery the fluid could be incorporated in the handle of a surgical end-effector, whereas in the open surgery the operator would interact with a haptic box containing the fluid. In 2008 MR fluid haptic system for regional anesthesia training simulation system has been developed [8]. It provides accurate haptic feedback for needle insertion and syringe injection imposing simulated force for the regional anesthesia simulator.



In 2016 on AsiaHaptics - International conference for the haptics fields the device for medical purposes has been demonstrated. The authors developed a surgical simulator based on MR fluid. A developed haptic interface displays resistance force of soft tissue (cutting, retraction force). Operators can feel the force through interchangeable surgical tools. The proposed system can display arbitrary force by controlling the magnitude of yield stress of MR fluid and provide realistic visualization by displaying computer graphics images on the container of MR fluid directly. An operator can feel resistance force by putting instruments in the MR fluid container and can sense reality by virtue of the visual display on the MR fluid container.

## 6.5 Comparison with non-magnetic field based devices

This section is related to some extent the second section of this paper "magnetic field: haptics related benefits and drawbacks" but is more detailed and includes real devices examples. The following devices has been chosen for comparative analysis being commercially available haptic interfaces, which means their relative completeness and applicability in real life.

The PHANTOM® is the famous device similar to Magnetic Levitation device in terms of usage of the handle grasped by the operator. The PHANTOM® interface from SensAble Technologies simulates touching at a single point of contact. It achieves this through a stylus which is connected to a lamp-like arm. The manipulations are controlled by direct current (DC) motors that have attached sensors and encoders. The user can feel for example the elasticity of a virtual balloon or the solidity of a brick wall. He or she can also feel texture, temperature and weight. On the other hand, in Magnetic levitation approach by moving and rotating the levitated handle, the user can feel the motion, shape, resistance and surface texture of simulated objects. Furthermore, the PHANTOM® interface only allows three active degrees of freedom, while the Magnetic levitation device provides constrained motion in six degrees of freedom.

The CyberGrasp (the one of the CyberGlove Systems LLC) is a device, that fits over the user's entire hand like an exoskeleton and adds resistive force feedback to each finger. Five actuators produce the forces, which are transmitted along tendons that connect the fingertips to the exoskeleton. With the CyberGrasp system, users are able to feel the size and shape of virtual objects that only exist in a computer-generated world. There are five actuators, one for each finger, which can be individually programmed to prevent the user's fingers from penetrating or crushing a virtual solid object.

In comparison to Magnetic levitation device a CyberGrasp system has an advantage, because it allows full range-of-motion of the hand and does not obstruct the wearer's movements. However, Magnetic levitation approach reduces friction and other interference so the user experiences less distraction and remains immersed in the virtual environment.

The CyberGrasp is comparable with Magneto-Rheological fluid based device in terms that in both cases the operator can freely move his or her hand and feel the size and shape of the recreated objects. But these devices were designed for completely different purposes, so a further comparison does not make sense.

The UltraHaptics is a technology is based on acoustic ra-

diation force. A system provides haptic feedback above interactive surfaces and requires no contact with either tools, attachments or the surface itself. Instead, haptic sensations are projected through a screen and directly onto the user's hands. This characteristics make the technology preferable over magnetic rendering because of an absence of any hand attachments and over magnetic levitation because of realistic and intuitive sense of touch. However, both magnetic rendering and magnetic levitation have considerably higher field strength.

## 7. DISCUSSIONS

The positive characteristics of Magnetic rendering device are that it provides a strong tactile force and avoids cumbersome attachments with wires. The main difficulty of the magnetic rendering technology lies in the correct control method to provide sufficient fidelity. Due to the non-linear behavior of magnetic field the control is usually sophisticated and nowadays, according to the simulation results depicted on related figure still insufficient to perfectly render exact objects like human face. Further more the technology is not capable to render angular shapes, some geometrical objects due to magnetic field smoothness. In my opinion, the practical application of this invention is not possible in the near future, due to the low accuracy, despite of used control method. The creation of full-scaled real life device in laboratory conditions is doubtfully possible due to the high complexity, uncertainty of possible limitation connected with overheating.

Magnetic levitation is used in a wide range of applications. It potentially can be used in any application that involves a user physically interacting with some sort of simulated or virtual environment, for example a CAD (computer-aided design) system. Nowadays it is often used for simulation of medical procedures: grasping a scalpel and feel it cutting bone or tendons or other kinds of internal tissues. The physical simulation runs on separate computer and the controller of the device interacts with that physical simulation to reproduce those forces and sensations that user actually feels. Overall, the application of magnetic levitation haptic device brings considerable impact in areas such as training and design. On the other hand, due to the separation of the visual image and haptic interface, this method is not suitable for co-located 3D visual and haptic display.

In general Magneto-Rheological fluid based device has already been used for different kind of medical simulation that confirms the relevance of the technology. The new prototype of Magneto-Rheological fluid based device proposed in [9] seems to be sophisticated, considering the number of electromagnets in the array, interacting with each other in non-linear way, which can cause the lost of precision of control the same as in case of magnetic rendering device. Although the authors claim that non-linearity of the materials as well as the feeding condition of the coils have been taken into account, however, the full-scaled model has been tested only in simulation environment.

## 8. CONCLUSIONS

General advantages and drawbacks of an application of a magnetic field for haptic feedback has been discussed. An overview of three technologies, which applied magnetic field to provide haptic feedback was given. The comparative anal-

ysis of three devices was performed.

The concept "Magnetic rendering of volumetric shapes in the mid-air" [14] is the newest and least developed being only a prototype of the real system, however, tested and showed a good performance in a modeling and simulation environment and the control method has been derived. The concept of magnetic rendering seems appealing, but a lot of parameters have to be considered and complicated calculations have to be performed to make the model work properly.

The Magneto-Rheological fluid based device [10] of 2007 is a real system with certain limitations discussed above, but the improved model proposed in [9] is also in a development stage tested by means of simulations and simplified real-world prototype that can't clearly show all capabilities of proposed model.

From description of devices and their comparison with each other it can be concluded that the most developed and widely applied technology nowadays is the magnetic levitation. The research in this area has been done for more than 20 years and the perfect results in terms of performance and related applications have been achieved.

Haptic technology that applies magnetic field can potentially be used in all kind of applications. It can provide a sense of touch of virtually created objects as well as mimic the shape, softness and consistency of real objects. Magnetic field based Haptics is widely used in medicine (training, simulation, micro-manipulations), where the exceptional accuracy and reliability of technologies is vital. In fact, these requirements can be guaranteed only by Magnetic levitation device.

Overall, the positive aspects of magnetic force for Haptic technologies were confirmed by a number of research works and existing applications in different fields. Nowadays, a special attention is paid for derivation of control methods that are capable to deal with natural non-linear behavior of magnetic field with respect to stimulation current; the choice of materials that are resistant of heating effect; improvement of shapes and arrangements of coils on electromagnets; application of additional components like permanent magnets in order to increase the magnetic force.

## 9. REFERENCES

- [1] P. Berkelman, Z. J. Butler, and R. L. Hollis. *Design of a hemispherical magnetic levitation haptic interface device*. Carnegie Mellon University, Engineering Design Research Center, 1997.
- [2] P. Berkelman and M. Dzadovsky. *Using Magnetic Levitation for Haptic Interaction*. INTECH Open Access Publisher, 2010.
- [3] P. Berkelman, M. Miyasaka, and J. Anderson. Co-located 3d graphic and haptic display using electromagnetic levitation. In *2012 IEEE Haptics Symposium (HAPTICS)*, pages 77–81. IEEE, 2012.
- [4] G. Hoelzl. A personalised body motion sensitive training system based on auditive feedback. In T. Phan, A. Montanari, and P. Zefos, editors, *Proceedings of the 1<sup>st</sup> Annual International ICST Conference on Mobile Computing, Applications, and Services (MobiCASE09)*, volume 35 of *Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering*, San Diego, California, USA, October 26-29 2009. ICST, Springer. ISBN: 978-3-642-12606-2.
- [5] G. Hoelzl, A. Ferscha, P. Halbmayer, and W. Pereira. Goal oriented smart watches for cyber physical superorganisms. In *Workshop on Collective Wearables: The Superorganisms of Massive Collective Wearables, at 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp 2014)*, Seattle, USA, September, pages 1071 – 1076, September 2014.
- [6] G. Hoelzl, P. Halbmayer, H. Rogner, C. Xue, and A. Ferscha. On the utilization of smart gadgets for energy aware sensitive behavior. In *The 8th International Conference on Digital Society, ICDS 2014, March 23 - 27, Barcelona, Spain*, pages 192 – 198, March 2014.
- [7] G. Hoelzl, M. Kurz, and A. Ferscha. Goal processing and semantic matchmaking in opportunistic activity and context recognition systems. In *The 9th International Conference on Autonomic and Autonomous Systems (ICAS2013)*, March 24 - 29, Lisbon, Portugal, **Best Paper Award**, pages 33–39, March 2013.
- [8] Y.-J. Lim, P. Valdivia, C. Chang, and N. Tardella. Mr fluid haptic system for regional anesthesia training simulation system. *Studies in health technology and informatics*, 132:248–253, 2007.
- [9] R. Rizzo. A permanent-magnet exciter for magneto-rheological fluid-based haptic interfaces. *IEEE Transactions on Magnetics*, 49(4):1390–1401, 2013.
- [10] R. Rizzo, N. Sgambelluri, E. Scilingo, M. Raugi, and A. Bicchi. Electromagnetic modeling and design of haptic interface prototypes based on magnetorheological fluids. *IEEE Transactions on Magnetics*, 43(9):3586–3600, 2007.
- [11] Q. Tong, Z. Yuan, M. Zheng, W. Zhu, G. Zhang, and X. Liao. A novel magnetic levitation haptic device for augmentation of tissue stiffness perception. In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology*, pages 143–152. ACM, 2016.
- [12] M. Weiss, C. Wacharamanotham, S. Voelker, and J. Borchers. Fingerflux: near-surface haptic feedback on tabletops. In *Proceedings of the 24th annual ACM symposium on User interface software and technology*, pages 615–620. ACM, 2011.
- [13] t. f. e. Wikipedia. Magnetorheological fluid. [https://en.wikipedia.org/wiki/Magnetorheological\\_fluid](https://en.wikipedia.org/wiki/Magnetorheological_fluid).
- [14] Q. Zhang, H. Dong, and A. El Saddik. Magnetic field control for haptic display: System design and simulation. *IEEE Access*, 4:299–311, 2016.

# Survey on Technologies for Contact Haptic Feedback

Ankit Sharma  
Universität Passau  
Lehrstuhl für Informatik mit Schwerpunkt Eingebettete Systeme  
Innstr. 43  
94032 Passau, Germany  
Ankit.Sharma@uni-passau.de

## ABSTRACT

Haptic feedback or simply 'Haptics' is the use of sense of touch in a user interface environment to provide information to the end user. Video and audio feedback are easy to replicate in a computer generated model but haptic feedback or tactile feedback is more difficult. Since 1970 lot of work is done in this field [?]. Now a days lot of new technologies are available in market and also lot of research is going on this field. There are many areas which can be really beneficial with the introduction of haptics for example in Medical field, Data visualization, Education, Ecommerce etc. This paper provides a survey on some of the technologies in the fields like Medical, Audio applications and Entertainment and Data visualizations.

## Keywords

Haptics feedback, contact haptics, medical and dental simulation, haptic interfaces, multimedia, data visualization

## 1. INTRODUCTION

Haptics is the term is a term that was derived from the Greek verb "haptesthai" meaning "of or relating to the sense of touch. Touching of virtual objects or environment can be made by either humans or machines or combination of both [16]. Haptics has brought bio mechanics, psychology, neurophysiology, engineering, and computer science together in the study of human touch and force feedback with the external environment. Touch is one the unique senses of a human being in which there is a bidirectional flow of energy between real or virtual environment and end user[16]. For example if there is an object such as cup, if we hold that cup and run our finger across it, then we will get to know about the shape of cup.

Researchers has organized the rapidly increasing multidisciplinary research of haptics into four subareas: human haptics, machine haptics, computer haptics, and multimedia haptics.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, to republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

*Survey on Technologies for Contact Haptic Feedback* '16 Passau, Germany  
Copyright 2016 ACM X-XXXXX-XX-X/XX/XX ...\$15.00.

## 1.1 Human Haptics

Human haptics refer to the study of human sensing and manipulation through tactile and kinesthetic sensations. Whenever user holds an object or touch an object, forces started acting on the skin. The sensory system of our body then conveys this information to our brain through which human can perceive about that shape and structure of that object. The human haptic system comprises four subsystems: the mechanical, the sensory, the motor, and the cognitive.[16, 8] So, human haptics is the study of how people sense and manipulate the world through the sense of touch. Human haptics can be further evaluated on different criteria like biomechanics of skin, tactile neuroscience, haptic and multimodal psychophysics, and computational theory of haptics [17]. Biomechanics is whenever we touch some object it results on the stressing and strain at the mechanoreceptive nerve terminals within the skin, which then sends signals to the brain. Tactile Neuroscience is concerned with the study of neural process which is present under the skin and acts when we touch something. Psychophysics is the study of relation between physical stimuli and perception. It is a very important part for the field of haptics. After understanding the science behind the human haptics, specifications and criteria for machine haptics can be set. [17]

## 1.2 Machine Haptics

Machine haptics involve designing, constructing, and developing mechanical devices that replace or augment human touch [16]. These devices are put in contact with the human body or by either holding those devices or wearing them.

## 1.3 Computer Haptics

Just as computer graphics deal with generating and manipulating visual images similarly computer haptics is an area which deals with development of algorithms and software that generate and render the touch of virtual environment or objects. Computer haptics has two main components, haptic rendering and visual rendering. Haptic rendering manages all the algorithms which detect that where contact between virtual device and virtual environment has occurred and with how much force. On the other hand, visual rendering deals with the algorithms and techniques which compute real time behavior of virtual environment graphics[16].

## 1.4 Multimedia Haptics

These days, lot of research is going on adding haptics in multimedia applications. Multimedia haptics is also known as

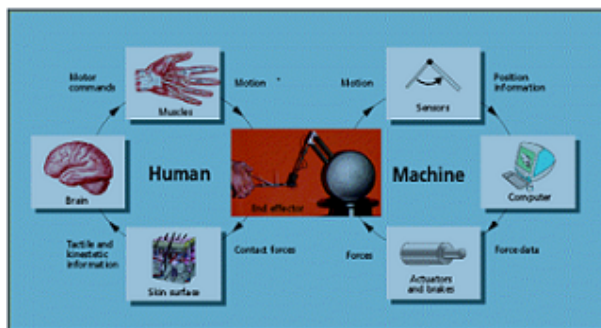


Figure 1: In the figure, a human (left) senses and controls the position of the hand, while a robot (right) exerts forces on the hand to simulate contact with a virtual object. Both systems have sensors (nerve receptors, encoders), processors (brain, computer), and actuators (muscles, motors). Applications of this science and technology span a wide variety of human activities such as education, training, art, commerce, and communication.[17]

haptic audio visual environment (HAVE). Multimedia haptics can enhance the user experience because not only user can see and listen to things, but he can also feel things[16].

## 2. HAPTIC FEEDBACK APPLICATIONS

Haptic research and development focus on the designing, development and evaluation of different prototypes with distinguishable characteristics and capabilities, which can be use in virtual environment. Some of these devices are already available in market and also lot of research is going on. Applications from this area is spreading rapidly in areas like graphical user interfaces, games, multimedia publishing, scientific discovery and visualization, arts and creation, editing sound and images, the vehicle industry, engineering, manufacturing, telerobotics, teleoperations, education and training, the military domain, as well as medical simulation and rehabilitation. Therefore application spectrum is quite vast. But still these devices are not yet ready to become common devices like computers because of some limitations. These devices are expensive, computation power needed to run these devices is very high. This paper deals with the survey of some of the haptic technologies that are existing in areas like Medical and Dental simulation, Audio Applications, Entertainment.

### 2.1 Medical and Dental simulation

The medical area has been an abundant source of haptic development. In open heart surgeries or in any medical procedure, doctors are heavily rely on the sense of touch, either with hand or with operating tools. Introduction of haptics into medical field can be really beneficial. Doctors or practitioners can practice with different haptic devices in a virtual environment as many times as they want, before proceeding on the human or animals. Also it can be very beneficial in measuring and evaluate the performance of an individual. Haptic applications include surgical simulations, telesurgery systems, rehabilitation, and medical training. In the next section we will talk about some of technologies in this field

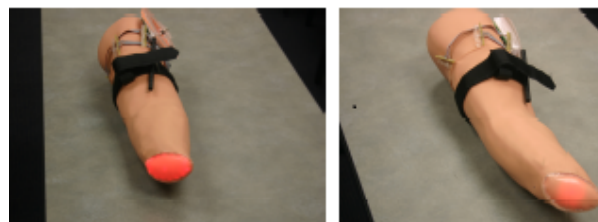


Figure 2: Tourniquet application reducing bleeding [11].

like E-MAT (The Extremities-Multiple Application Trainer for Haptic-based Medical Training ) which is a haptic device which provide life saving skills to soldiers in the battle field. The second device technology we will talk about is "Dental Skills Training Simulator", which is very beneficial in the dental field for tooth cutting and exploration.

#### 2.1.1 E-MAT: The Extremities-Multiple Application Trainer for Haptic-based Medical Training

There are many researches going on in medical field from many years. But in recent years, to make simulations more effective, haptics has been introduced in this field. Usually in medical training, patient contact is often limited. One can not practice on a living person. Introducing haptics in medical field has proven very effective and in training and assessment of an individual. These include elements such as cutting, grasping, needle insertion, and suturing required for manipulating tools during medical task procedures, and direct manipulation of the patient. In military, medics are often trained using old methods like using a log of wood to act as limb and an instructor is always needed to assess whether haemorrhage has been properly controlled. Haemorrhage is a very difficult and precise procedure. If pressure applied on the infected limb is too less then it wont stop bleeding and if pressure applied is too much then it can even destroy the tissue. Also procedures should be refresh after certain amount of time.

EMAT[11] : Researchers has developed a haptic device which provide life saving skills to soldiers on the battle field(Figure 2 and 3). This device was design to serve as a haemorrhage control simulator. It allows medics to experience the force required in applying on a particular limb of different body sizes. This design is also consists of illuminating LED's which tells about the blood flow. For example, the limb when turned on illuminates all LED's to represent massive bleeding. As soon as the pressure applied on limb is sufficient enough to stop bleeding outermost LED's will turn off. When green light in the starts glowing, that signals that pressure applied is enough to stop bleeding.[11]

EMAT can be operated in two modes. First one is standalone mode in which user can define an injury location by using a control panel. In second mode, device always communicates with the host PC, through which by using different command set, you can define the nature and location of injury depends on training needs. This device is quite inexpensive and portable, so that you can use it anywhere.

#### 2.1.2 Dental Skills Training Simulator Using Virtual Reality and Haptic Device

Dental students usually do training to increase their op-

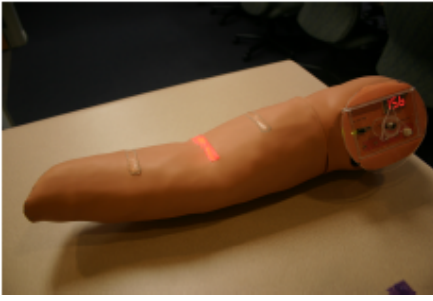


Figure 3: Example of alternate wound site [11].

eration skills by using different sources like practicing on plastic teeth or some time directly on patients in guidance of their supervisor. But as tools are becoming more complicated and safety of patients is also a concern these training methods are not feasible. With the recent development in Virtual reality technology, many virtual reality simulators are introduced in market. The benefits of these simulators are that dental students or surgeons can practice on them as many times as they want and they can do it anywhere. By introduction of haptic devices with these simulators surgeons can touch and feel the objects and organs in virtual world and can perform different types of operation and also they can access their skills. There are many virtual dental simulators that are available but they are either limited in scope or functionality and many of them are in early and experimental stage. Phattanon Rhienmora [15], present a virtual reality dental simulator which introduces some new techniques and also deal with the limitation of previous systems. These are as follows

- Representation of tooth as a 3D model, which is taken from a patient's data.
- Collision detection and collision response algorithms are applied which can handle a cylindrical shape tool which was not done before in any research.
- Surface displacement technique is applied for tooth surface exploration and cutting.
- Evaluation of prototype is done by some dental students.

System architecture of dental skill training simulator : The prototype system operates on a HP Pavilion dv5000 laptop with 1.6 GHz Intel processor and 2 GB of main memory. The graphics card used is nVIDIA GeForce Go 7400 with 256 MB of video memory. They used a PHANTOM Desktop haptic device which allows six degrees of freedom positional sensing and generates 3 degrees of freedom force feedback with a maximum of 7.9 Newton. The simulator software is developed with C++, OpenGL, OP CODE, and OpenHaptics SDK (HD API) [15].

The system is composed of two different loops. 1. Haptic loop 2. Graphics loop. Both loops work at different frequencies.(Figure 4) Cylindrical shape dental tool has six degrees of freedom and can move according to the position of haptic probe. For haptic stability update rate of 1kHz is maintained. The haptic thread is running at higher rate as

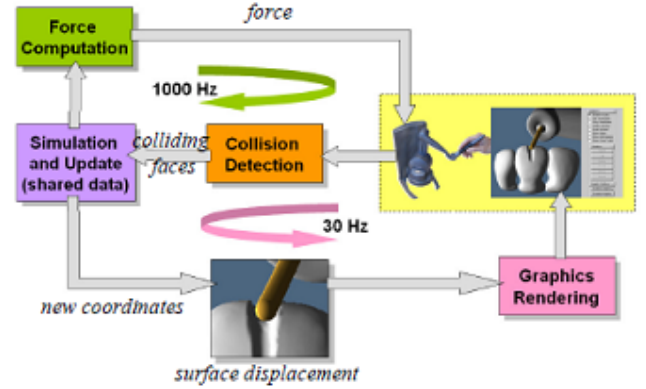


Figure 4: System architecture [15].

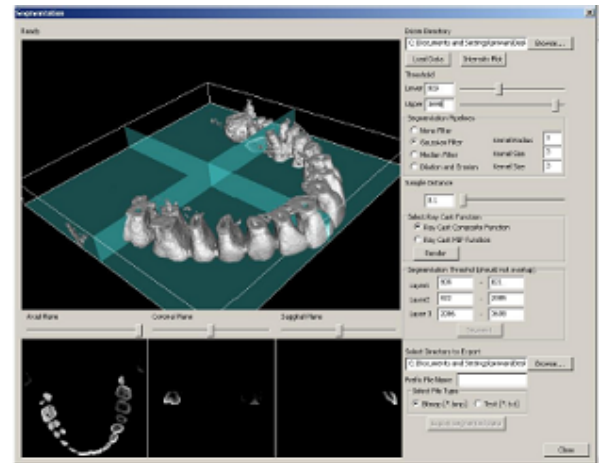
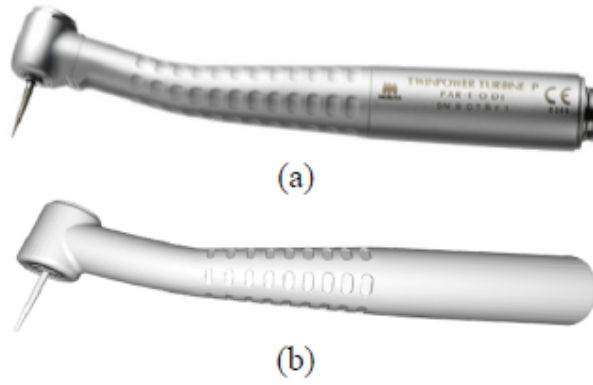


Figure 5: A segmentation tool showing three-dimensional volume of teeth with Gaussian filter applied [15].





**Figure 6:** A dental handpiece used in a real tooth preparation (TWIN POWER TURBINE P, J.MORITA CORP.) (a) and a virtual handpiece (b) [15].

compared to graphics thread and it doesn't wait for graphics thread to complete its rendering task.

Volumetric teeth data is taken from volunteer and processed using three dimensional volume visualization and segmentation software (Figure 5). They reconstructed the surface mesh using marching cube algorithm. Only three of upper teeth are chosen for the experiment. They further subdivided the mesh of this particular teeth using loop subdivision algorithm [15]. They also constructed a three dimensional surface model of a dental hand piece with three different burrs, but only cylindrical shape burr is evaluated (Figure 6).

To detect collision between tool and the teeth they used AABB collision detection which is implemented in Optimized Collision Detection (OPCODE) which is an open C++ library, which provides fast and reliable collision detection. Force is calculated when there is a collision between tooth and the tool. The reaction force and the depth of penetration are directly proportional to each other as shown in equation (1).

$$F = kx \quad (1)$$

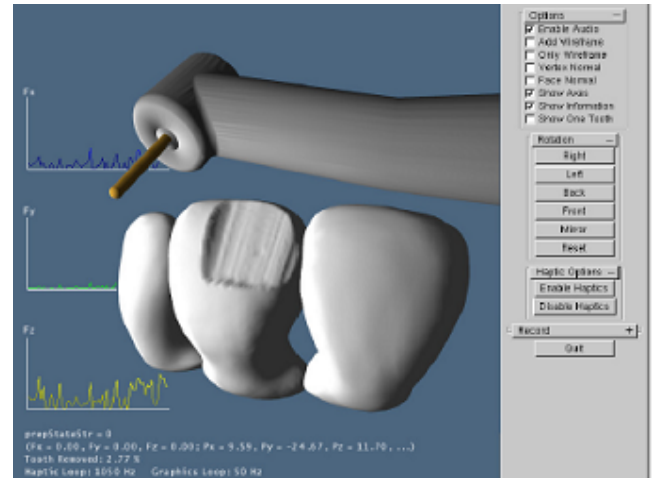
Where,  $F$  = 3d force vector,  $K$  = stiffness constant, which tells the hardness of tooth surface and  $X$  = maximum depth of penetration.

Graphical user interface (Figure 7) is used to evaluate the prototype, which consists of workspace for dental operation on left side and control panel on right side. Current position of tool and force feedback of the tool are displayed on the bottom on GUI. Prototype is evaluated by group of dental students from the school of dentistry, Thammasat University.

The prototype can simulate continuous and stable tooth exploration and cutting for tooth. The collision between tool and tooth are calculated efficiently and the appropriate forces are sent to the operator through haptic device.

## 2.2 Audio Applications

Adding audio makes haptic-based systems closer to the real simulation. User can interact with more sensory channels and can feel a better experience. When a haptic device collide with something in a virtual environment and if



**Figure 7:** Graphical User Interface of the prototype [15].

sound produce while colliding it give more realism. This can be very beneficial for visually impaired and blind persons. The technologies which are presented in the next sections are HABOS (Haptic online based online shopping) which is a client server prototype and can be very beneficial for visually impaired persons to shop online. The second technology is VirtuNav which is virtual reality indoor navigation simulator with haptic and audio feedback.

### 2.2.1 VirtuNav (A Virtual Reality Indoor Navigation Simulator with Haptic and Audio Feedback for the Visually Impaired)

A high proportion of the global population suffer from sight impairment; in 2010 there were approximately 285 million people reported with varying degrees of visual impairment, of which 39 million were blind. One of the biggest problem for the people who have vision loss is to navigate from one place to another. Several devices such as handheld GPS can somehow help to overcome this problem however it still difficult for these people to navigate in unfamiliar locations like in a room which has chairs and tables or in a stairs. VirtuNav [19] offers a solution for this problem. It provides a support tool that is a haptic device and audio prompts as navigational aids, within a reconstructed 3d virtual environment. The user moves in a virtual environment using a haptic device and a keyboard. The system tracks the position of the user and also provide audio cues representing objects and collision by the user. Virtual environment is the safe space where user can familiarize himself about the surroundings before going in the real world indoor locations. To know about how much this system is helpful to the user, system verification, validation and testing is conducted. There are two types of persons who can interact with the system. Users who can explore the environment and second are the administrators who manage all the information of the users and can validate results. Construction of 3D virtual environment is done by the administrator. An administrator can create a virtual environment according to the needs, such as, he can define the parameter of the rooms, different boundaries, and can also place furniture like

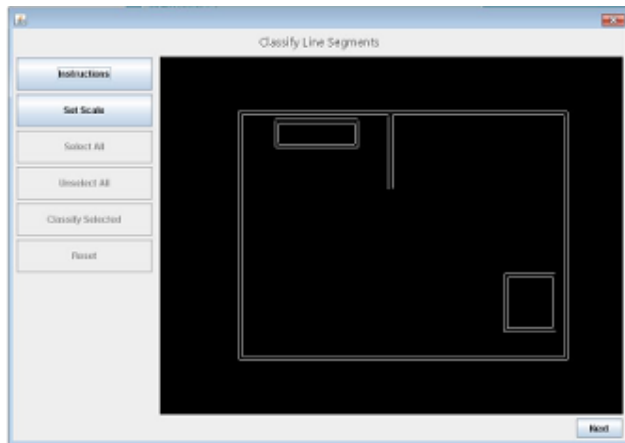


Figure 8: Administrator for classification of existing line segments

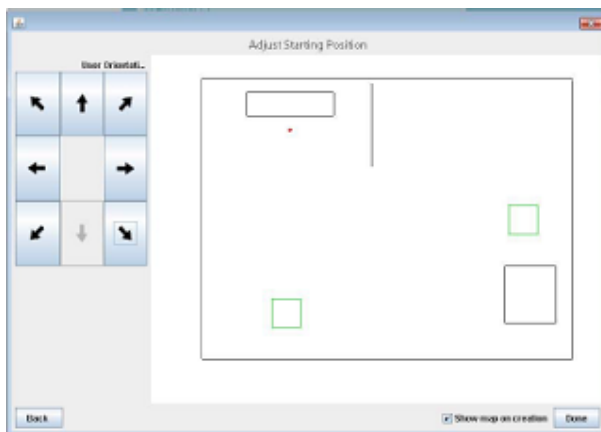


Figure 9: Administrator GUI for optional placement of additional furniture objects, and for selecting a user starting position and orientation..

tables and chairs which is available in the library. A user can interact with the virtual environment using Novint Falcon 3Dof haptic device supported by keyboard functionality. A user can also move linearly and rotate 45 degrees to left and right. When an avatar is collided with furniture or wall, a force is triggered to the haptic device and also an audio response is sent to the user. Data acquisition, registration and object and wall reconstruction are semi-automatic process.

**Implementation :** An image file is provided to the system which has a floor plan. The coordinator extractor class converts the image floor plan input to a set of line segmented coordinates.

Administrator can construct these line segments with cursor from a drop down menu.(Fig 8). Another GUI (Fig 9) allows administrator to add furniture at desired location.

Indoor scene is then constructed into 3d. Software x3D is used to create the 3D based environment.

### 2.2.2 HABOS (Haptic online based online shopping)

Due to poor accessibility of online shopping websites for



Figure 10: HABOS Home Page.

blind people, visually impaired people do not shop online or if they do, they often request help from other people. E-commerce has become increasingly prominent as many consumers buy their products online. But as Falcon haptic devices are becoming more affordable, there is a possible solution which is based on haptics and audio technologies which enable visually impaired persons to shop online. However the research on this field is very less, One of the main reasons behind this is currently all the existing browsers like Firefox, Internet explorer, Google chrome, Opera and Safari does not have required plug-ins that can help in integrating haptic devices with the web browsers. Hence according to Eu Jin Wong [20, 6], they developed a haptic based online shopping system in which they investigated whether visually impaired people can shop online without any help of third person. The overall system is divided into two parts, client part and server part, the client part of the system consists of a haptic-audio enabled browser to enable the visually impaired to receive haptic feedback via a haptic device and to issue voice command to interact with the system. The server part of the system consists of an online store which has conventional shopping features such as product catalogue, shopping cart and payment system to allow users to browse, interact, evaluate and purchase products.

**HABOS Website :** The haptic-audio based online shopping (HABOS) system is a client-server prototype. The client side consists of a haptic audio enabled Opera-based web browser and the server side consists of an online store which was developed using XHTML markup language, VoiceXML programmable voice, H3D haptic API, X3D scene graph, C++ and Python programming language running on the Windows, Apache, MySQL and PHP (WAMP) platform. The design of the website is divided into 3 sections, the top banner which contains information about the shopping cart. Middle section, which contains all the products. Every page of website is induced with an audio message which describe the layout of the page and also to warn users that pointer had reached the edge of the page (Figure 10). User can interact with the website either with his voice or through falcon device.

After evaluation with many visually impaired users, re-

sults showed that most of the participants found the catalogue system quite usable and the website design is quite effective for online shopping. This study could provide the basis for future research into design of haptic-audio based online based shopping applications and also there is a need for new browser plug-ins which can interact with haptic devices.

## 2.3 Entertainment

Haptic research is on the top in the field of home entertainment and computer games. In last few year, lot of new devices are available in market. Game experience has four pillar aspects: physical, mental, social, and emotional [16]. By including haptics in a gaming, it always enhances physical aspects of gaming experience. Not only in gaming industry, haptics has been adopted in movie industry too. Integration of haptics in movies, also increase the user experience. Not only physically but also emotionally. In next section, one technology from each area is described.

### 2.3.1 Haptic-based Serious Games

As haptic devices are getting cheaper, there is a big scope for haptic based computer games to be developed and commercialized in the market. There are four important aspects in the user game experience: physical, social, emotional, and mental [16, 7]. The haptic based game always provide user a real world experience. For example, in the game Haptic Battle pong [12], user uses a haptic device to control the movement of a paddle. Whenever there is a contact between paddle and the pong, a force is applied to the users hand through haptic feedback device. Now a days, 3-DOF haptic devices, whose haptic algorithms follow point-based approach, are widely used for game development. As 3-DOF Haptic devices are mostly used in entertainment games, in nearest future there is a time of 6-DOF haptic device. As 6-DOF Haptic devices are becoming more affordable, they as a virtual tool can be used in serious games. The serious game refers to computer games used with a purpose beyond entertainment including: medical training, exploration, analytics, simulation, education, and therapy [14]. The 6-DOF haptic rendering algorithms always provide user to have more control over the virtual environment, so that they can explore it more. 6-DOF Haptic rendering algorithms can be classified into two categories, Direct Rendering and Virtual coupling based rendering. For the direct rendering, the force/torque is calculated directly from the pure geometry contacts. Virtual coupling based rendering To improve stability of 6-DOF haptic rendering, the virtual coupling based rendering are proposed for the haptic manipulation of both rigid and deformable models [?, ?]. So, the researchers have extended the application of haptic device to serious games. Researchers had proposed a game which is based on the 6-DOF haptic rendering. ‘T Puzzle’, in this game user has to finish the task by rotating and moving 3D puzzle pieces. Each piece is assigned with different weight and mass. This game can be used to improve users’s spatial ability. **“T PUZZLE” GAME** : The T Puzzle game consists of four polygonal shapes. A user can form different figures by using these different polygonal shapes. A player can solve the puzzle by fixing different shapes either horizontally or vertically. When a player play this game in a 3D environment, the player can improve his/her spatial ability to manipulate 3D objects. Though this game appears to be simple but

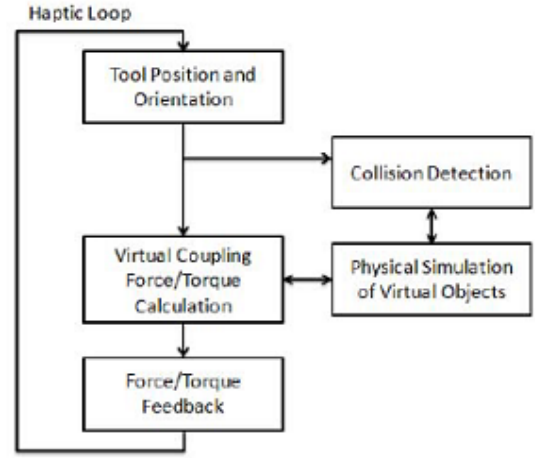


Figure 11: The pipeline of haptic rendering in “T Puzzle” game [10]

it is sometimes very hard to solve a puzzle. CHAI 3D Library is used to develop a haptic based game. Originally in CHAI 3D System, feedback is based on 3-DOF Haptic rendering, it means player can manipulate with the objects by only touching and pushing them. User cannot grasp and rotate a virtual object realistically. To solve this problem, researchers used the proposed stable adaptive haptic rendering algorithm based on virtual coupling to calculate the interaction force in physical simulation [?, 9]. Adaptive virtual coupling model is used to connect the motion of users hand and motion of the object. The haptic interaction force is calculated by following equation :

$$F_{Haptic} = -k_t(P_{HIP} - P_{Tool} + b_t(V_{HIP} - V_{tool})) \quad (2)$$

Where  $P_{HIP}$  is the position of haptic handle,  $V_{HIP}$  is velocity of haptic handle,  $P_{TOOL}$  is the position of virtual tool,  $V_{TOOL}$  is the velocity of virtual tool, where  $k_t$  is spring stiffness for translation and  $b_t$  is damping for translation

The pipeline of haptic thread is shown in figure 11. Stable haptic rendering algorithm is used to calculate force and torque which is generated by colliding of different puzzle pieces in virtual environment, this program then send the calculated values to the haptic device. .

The game is implemented on the Windows XP Professional PC with Intel® Core™2 Quad Q9400 2.66 GHz CPU and 3.25GB memory. The CHAI 3D library and Open Dynamic Engine (ODE) are used for the game design. For the haptic device, they use PHANTOM Premium 6-DOF haptic device from SensAble Technologies with both force and torque feedback.

In this proposed T Puzzle game, users can feel the force feedback and collision among different objects in virtual environment. The user can also adjust the distance between objects and window of computer screen. Player can also press a hint button if he/she got stuck in solving a puzzle. On the right side, the menu is located as shown in Figure 12 The complete configuration of the “T Puzzle” game with a PHANTOM 6-DOF haptic device is shown in Fig. 12[10].

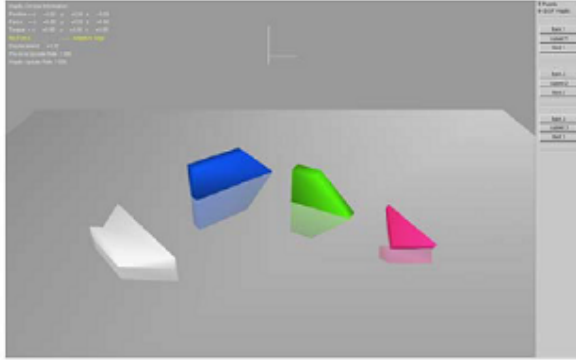


Figure 12: The user interface of the “T Puzzle” game [10].

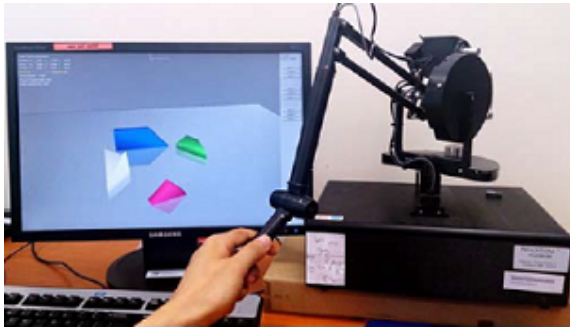


Figure 13: The PHANToM 6-DOF haptic device is used for objects manipulation in the game[10].



Figure 14: Workflow Overview. Data are simultaneously captured by a camera and a motion sensor. Then motion data are converted into a signal suitable for the dedicated haptic renderer. Finally both video and motion are rendered simultaneously [2].

### 2.3.2 Enhancing Video Viewing Experience with Haptic Effects of Motion

From a long time, lot of research is going on to improve images and sound quality in multimedia applications. But now, this research is not only limited to the sense of sight and hearing but also to the sense of touch. It has been observed that, by the addition of haptics in multimedia, always enhances the user experience. The user could expect to receive an additional piece of information. Now a days, haptic audio visual(HAV) can be experienced in lot of 4D cinemas and amusement parks. Some devices like D-Box bringing this technology to customers. So, researchers here are focusing more on developing a framework which can enhance a video viewing experience with haptic effects which are more realistic in a customer environment. So in this context, researchers has presented a comprehensive framework which includes [2]:

- A way to capture both motion and video of the scene of interest.
- A comprehensive method which is used to send the captured motion information to the back-end haptic device.
- A particular scheme for haptic rendering which can induce a motion effect on a force-feedback device.
- An evaluation method for this framework.

Outline of the system (Figure 14) :

- Production of haptic effects.
- Processing of created haptic effects.
- Rendering of haptic effects on a haptic feedback device.

**Motion capture with physical sensors :** The first step in this system is to capture the motion effects for the renderer and also to record the audio visual content that should be displayed together with renderer. The system consists of an Ultimate IMU board which combines an ADXL345 accelerometer, an ITG-3200 gyroscope and a HMC-5843 electronic compass (cf. Figure 2-Left,B).All of these 3 components have different roles. There's also a space for an additional memory card on the board. A dedicated middle-ware has been developed and uploaded to the Ultimate IMU to set the recording process to 30Hz. Additionally, there's also a Camsports HDS-720p (figure 15) which is a HD bullet camera consists of 120 degree wide-angled lens and also a



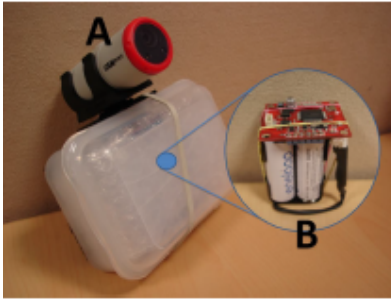


Figure 15: Camsports HDS-720p [2]



Figure 16: The prototype is fixed on an actor's chest and records his motion on 3 axes. [2]

4GB memory chipset. It is used to record the scene corresponding to the current point of view of the actor. The complete prototype consists of the combination of IMU, its battery and camera. Prototype should be enough robust to handle different recording conditions, as this is designed to be mounted on the actors chest (Figure 16) which is also known as first person point of view recording. 2. **Processing of the captured motion signals** : Once the different motions have been recorded from the previous step, these has to be processed to make it compatible with the input of the haptic device. When a user is watching a movie, he must feel a force on his hand related to the motion of the actor in the video. Is always creates an illusion of self motion even though the application point is different from stimulating point. To modulate the 3-axis effort applied to the subjects hand they used a three raw accelerations which is recorded during the capture step at each sample  $k$ . The procedure that has been used here is very generic and can be implemented to other kind of rendering devices. Gravity removal (Figure 17) always helps in enhancing user experience because it can mask some useful information which is needed



Figure 17: Processing Overview. The gravity is removed from the accelerations motion signals captured. Optionally extra processing can be performed such as low-pass filtering [2].

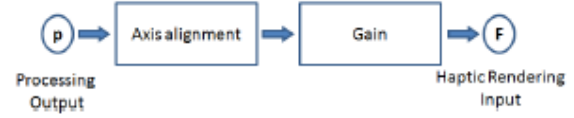


Figure 18: Pre-Rendering Overview. The signal from the processing step is aligned to the axes of the haptic device and then amplified [2].

to render a motion feeling. A two step methodology is applied for removal of gravity. After removing gravity from the signal, next step is to reduce the noise of the original signal which can be achieved by filtering of signal. For some practical reasons, filtering is usually performed on IMU. Some extra operation to enhance the signal for better rendering for the end user can also be performed. These include simple operations for reduction and amplification of the signal.

3. **Haptic rendering of the motion effect** : To render the signal  $p$  as a force vector  $F$ , it has to go through few transformations, so that it can render a force which suitable for a haptic device (Figure 18). To render a signal  $P$  on a haptic device, axis permutation is performed on  $P$  which align the axis of the accelerometer with the axis of the device. After axis alignment, gain in the raw data is necessary so that amplitude of signal  $P$  can be adapted according to renderer input range. The scaling factors  $s_x$ ,  $s_y$  and  $s_z$  for each axis are assumed to be constant and empirically set according to experimental feedback. After computing the force  $F$ , it is sent to haptic feedback device for rendering. The rendering algorithm was integrated in a home-made multimedia player allowing the haptic rendering and the A/V rendering in a synchronized way.

A dedicated protocol is setup by the researchers to evaluate the quality of experience on a user.

**Experimental setup** : 4 scenarios are taken into consideration to capture different kinds of motion feelings. Different samples of audiovisual content which is enriched with haptic data is taken into consideration. . 4 different scenarios are (Figure 19):

1. Bike : In this scenario actor is driving a bike and different Small amplitude vertical movements are captured by him.
2. Horse : Actor is riding a horse and objective is to capture high amplitude vertical or Top-Down movements.
3. Car Turning : In this scenario, actor is turning a car and feel a force which push him to the side.
4. Car Parking : Actor is parking a car, and for that he applies brakes. In this movement he feels strong force which push him forward for few seconds.

**Haptic Setup** : The whole system consists of a 15" laptop and a Novint falcon device which is a haptic feedback device. The user sits in front of the laptop and from one hand hold Novint falcon device. The user experience haptic feedback when captured video sequence is played on the home made Haptic/Audio/Video Player. (figure 20)

## 2.4 Data Visualization

Interactive graphics and animations are the best way to visualize or solve any problem. Introduction of haptics in data visualisation makes this task simpler. Haptic applica-





Figure 19: Tests Scenarios. Top Left - Outdoor cycling. Top Right - Horse riding. Bottom Left - Car engaged in a roundabout. Bottom Right - Car strongly braking [2].



Figure 20: A participant experiences an audiovisual content enriched with haptic feedback [2].

tions for data visualization can be categorized into two main categories [16] : Applications that are used by scientists to solve or visualize any scientific data. And second is the applications which are helpful for visually impaired human beings. Incorporating haptics into scientific data visualization helps user to get high level view of data. There are many applications that exists in market, but here we are gonna discuss about two applications, one is know as SCIRun which is an example of scientific data visualization and used to solve problems related to scientific data. Second one is a system for Interactive Molecular Dynamic simulation. Which is another application in which haptics is incorporated into bio molecular simulation.

#### 2.4.1 SCIRun Haptic Display for Scientific Visualization

To enhance the scientific visualization and to analyse or to solve a problem, researchers have incorporated haptic interface into a full featured scientific visualization tool. Scientists usually create animations or interactive graphics to visualize any problem. These visualizations are almost exact representations which helps to solve a problem or make it easier to understand. Researchers from the university of Utah, developed a problem solving environment for scientific computing know as SCIRun[3]. System here interacts with 3-D volumes, in which every point in a volume is associated with a vector. Vectors are gravity, pressure, force, current and velocity. SCIRun is interfaced with a haptic device and they used it to create two displays , haptic display and graphic display and both displays run together. User can simultaneously see and feel vector fields. SensAble PHANTOM Classic 1.5 is used as a haptic feedback device. For graphics display SGI octane is used. This haptic/graphic display is useful for displaying flow fields, vector fields such as fluid flow models for airplane wings in which the vectors tend to align into strong directional paths [5]. The haptic feel is like, if you put your finger in the flowing water, vectors will force your finger to move in the same direction as of the flow of water even if you don't apply any force. The graphical display always reinforces the haptic display to move along the flow line and also it shows some part of the flow line which is lying ahead of the current position. The haptic and visual feedback always helps user to follow the line and stay on the path (Figure 21 and 22).

System Architecture : SCIRun and Phantom haptic device, they both are two different applications which interact with each other as a client server. The phantom controller acts as a server and SCIRun acts as a client. Programs in SCIRun are used to handle all the data and computations. The program has two loops, haptic display loop and graphic display loop. Haptic display loop consists of programs which calculate current position of the PHANTOM endpoint, calculate the force and sends that force to the Phantom controller. Graphic display loop has programs which after calculating current position of phantom controller, redraws the endpoint again and recalculate and redraw the vector field display.

#### 2.4.2 A System for Interactive Molecular Dynamics Simulation

Interactive Molecular Dynamics(IMD) [18] is a system which can be very important in providing solutions for biologically relevant problems. It allows the manipulation of molecules in a molecular dynamics simulations with real-

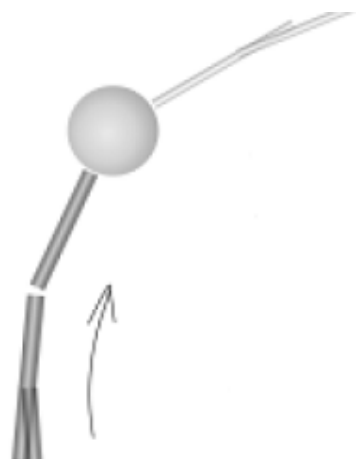


Figure 21: Illustration of user interaction with flow line. The display sweeps out the path to and from the current endpoint position. The pencilled arrow indicates the direction of travel. The sphere represents the current PHANToM endpoint position; the fatter, darker lit lines are the path already taken by the user; the thin, lighter lines are the flow line leading from the current position  $n$ [3].



Figure 22: Illustration of 3 separate flow line traces composited into one image. As the user interrogates the volume, the display forms an image of the flow lines within the field [3].

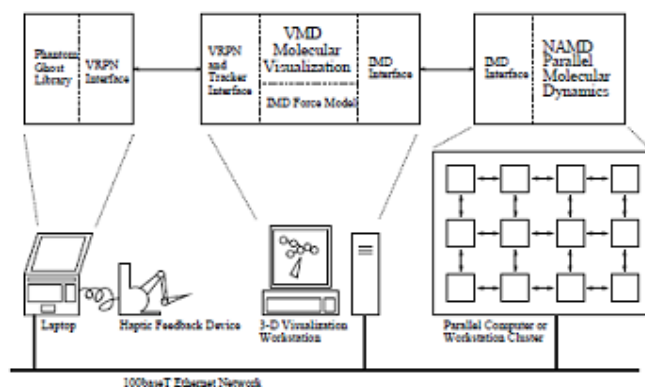


Figure 23: Decomposition of IMD components into asynchronous communicating processes. [18]

time force feedback and graphical display. IMD is basically the incorporation of haptics into steered molecular dynamics, which has already provided important qualitative insights into biologically relevant problems. Software plays a very crucial role in an IMD system. A software here is designed to handle large and complex bio molecular systems. An IMD consists of 3 primary components : a haptic device which is used to render force feedback, a molecular dynamics simulation and a visualization program. All three components can reside on different machines, because they can communicate with each other through TCP/IP network (Figure 23) connections. NAMD and VMD are the names of the program that are used to implement later two components. VMD is designed to animate the progress of molecular dynamics simulations. VMD code structure allows it to extend its program to add haptics interface. The molecular dynamics platform for IMD has been NAMD [4, 13], a fast, scalable [1], program which implements the popular Charm force field for molecular dynamics. Due to large computational power and high scalability of NAMD it allows us to study large and biologically important systems.

Implementation : One of the major concerns in implementation of IMD is latency, as network bandwidth requirements for performing IMD are quite low when compared to the computational latency. In some earlier efforts , researchers have used MDComms. But when MDComm is coupled with a haptic device its buffering mechanism would have imposed unacceptably high communication latency. Due to these drawbacks in MDComm, researchers had replaced MDComms with custom sockets code, so that VMD and NAMD can communicate efficiently. If user applies force ,through a haptic device, this force is sent by VMD to NAMD, which then leads to the motion of a molecule. Time to time updates of coordinates are sent to VMD from NAMD. These updated values are required to know the haptic restraint point. The time when VMD is waiting for updates, the haptic server keeps on applying smooth haptic feedback forces to the position of last restraint point.

### 3. CONCLUSION

There are many application areas in which this technology is useful, but in this paper I have summarized different technologies in these specific 4 application areas, those

are medical, Entertainment, Audio applications and Data visualization. One of the major concern of choosing these specific areas are, there is a lot of work already done on these specific areas and many technologies are already available in the market. Introduction of haptics in medical field has revolutionized the medical industry. Haptics has solved many problems, simulators, on which doctors can practice to operate, before diving into the real life operations on living human being or animals. Haptics in medical is also very beneficial in rehabilitation of humans, As we know there is a significant progress and researches in this area of haptic technology, but still this area is infancy. By applying certain forces on the disabled or injured limb, it can regain its strength. Similarly, Audio applications are very much beneficial for visually impaired people. Entertainment is one of the areas in which haptics market is on boost, human species always needs enjoyment and happiness in life to keep away from stress. Haptics has increased the user experience mentally and physically. Humans can enjoy and indulge more in the things which can entertain them. Data visualization is one of the areas which is really beneficial for scientists. So far, Haptics has been proved to be really beneficial in solving many biological and molecular problems, which can be very beneficial for the development of the society.

But inspite of this significant progress, there are many limitations and challenges which are still exists, due to which this technology is not full fledged and available in market and neither accepted by everyone. Some of the limitations like, Large haptic interface which makes it difficult to work with a haptic device for a longer time. Bandwidth limitations is also one of the shortcomings, haptic data is too bulky and sending it over the network needs a high bandwidth. Many haptic devices are just developed for a specific purpose which makes its use limited to only one application.

Despite of these challenges and limitations, as the technology is getting cheaper and applications are more advance, this field will can be groundbreaking in the nearest future.

## 4. REFERENCES

- [1] R. K. Brunner, J. C. Phillips, and L. V. Kale. Scalable molecular dynamics for large biomolecular systems. In *Proceedings of the 2000 ACM/IEEE SC2000 Conference*, 2000.
- [2] F. Danieau, J. Fleureau, and A. Cabec. Framework for enhancing video viewing experience with haptic effects of motion. *Haptics Symposium (HAPTICS)*, 2012 IEEE, March 2012.
- [3] L. Durbeck, N. J. Macias, D. M. Weinstein, C. R. Johnson, and J. M. Hollerbach. Scirun haptic display for scientific visualizaion. *Proc. 3rd Phantom User's Group Workshop, MITRLE Report TR624, Massachusetts Institute of Technology, Cambridge, MA*, 1998.
- [4] L. K. e, R. Skeel, M. Bhandarkar, R. Brunner, A. Gursoy, N. Krawetz, J. Phillips, A. Shinozaki, and K. Varadaraja. Namd2: Greater scalability for parallel molecular dynamics. *J. Comp. Phys.*, pages 283–312, 1999.
- [5] J. Helman and L. Hesselink. Visualizing vector field topology in fluid flows. *IEEE Computer Graphics and Applications*, May 1991.
- [6] G. Hoelzl. A personalised body motion sensitive training system based on auditive feedback. In T. Phan, A. Montanari, and P. Zerfos, editors, *Proceedings of the 1<sup>st</sup> Annual International ICST Conference on Mobile Computing, Applications, and Services (MobiCASE09)*, volume 35 of *Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering*, San Diego, California, USA, October 26-29 2009. ICST, Springer. ISBN: 978-3-642-12606-2.
- [7] G. Hoelzl, A. Ferscha, P. Halbmayer, and W. Pereira. Goal oriented smart watches for cyber physical superorganisms. In *Workshop on Collective Wearables: The Superorgansim of Massive Collective Wearables, at 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp 2014)*, Seattle, USA, September, pages 1071 – 1076, September 2014.
- [8] G. Hoelzl, P. Halbmayer, H. Rogner, C. Xue, and A. Ferscha. On the utilization of smart gadgets for energy aware sensitive behavior. In *The 8th International Conference on Digital Society, ICDS 2014, March 23 - 27, Barcelona, Spain*, pages 192 – 198, March 2014.
- [9] G. Hoelzl, M. Kurz, and A. Ferscha. Goal processing and semantic matchmaking in opportunistic activity and context recognition systems. In *The 9th International Conference on Autonomic and Autonomous Systems (ICAS2013)*, March 24 - 29, Lisbon, Portugal, **Best Paper Award**, pages 33–39, March 2013.
- [10] X. Hou, O. Sourina, and S. Klimenko. Haptic-based serious games. *Cyberworlds (CW)*, 2014 International Conference on, October 2014.
- [11] T. Lazarus, G. A. Martin, and R. Nayeem. E-mat: The extremities-multiple application trainer for haptic-based medical training. *Virtual Reality Conference, 2008. VR '08. IEEE*, March 2008.
- [12] D. Morris, N. Joshi, and K. Salisbury. Haptic battle pong: Highdegree-of-freedom haptics in a multiplayer gaming environment,. *Proceedings of Experimental Gameplay Workshop at Game Developers Conference (GDC)*, 2004.
- [13] M. Nelson, W. Humphrey, A. Gursoy, A. Dalke, L. Kale, R. D. Skeel, and K. Schulten. Namd -a parallel, object-oriented molecular dynamics program. *Int. J. Supercomput. Appl. High Perform. Comput.*, pages 251–268, 1996.
- [14] M. Orozco, J. Silva, A. E. Saddik, and E. Petriu. The role of haptics in games, in haptics rendering and applications. *A.E.Saddik, Ed., ed: InTech*, 2012.
- [15] P. Rhienmora, P. Haddawy, M. N. Dailey, P. Khanal, and S. Suebnukarn. Development of a dental skills training simulator using virtual realityand haptic device. April 2014.
- [16] A. E. Saddik. The potential of haptics technologies. *IEEE Instrumentation & Measurement Magazine*, 10(1):10–17, Feburary 2007.
- [17] D. M. A. Srinivasan, D. S. J. Biggs, D. G. Liu, D. D. W. Schloerb, D. L. Zhou, S. N. I. of Health Grant RO1-NS33778, and D. A. R. P. Agency. *Human and Machine Haptics*.

- [18] J. E. Stone, J. Gullingsrud, and K. Schulten. A system for interactive molecular dynamics simulation. *Proc. ACM Symp. Interactive 3D Graphics, Research Triangle Park, NC, USA*, pages 191–194, February 2001.
- [19] C. Todd, S. Mallya, and S. Majeed. Virtunav: A virtual reality indoor navigation simulator with haptic and audio feedback for the visually impaired. *Computational Intelligence in Robotic Rehabilitation and Assistive Technologies (CIR2AT), 2014 IEEE Symposium on*, December 2014.
- [20] E. J. Won, K. M. Yap, and J. Alexander. Habos: Towards a platform of haptic-audio based online shopping for the visually impaired. *Open Systems (ICOS), 2015 IEEE Conference on*, August 2015.

## Copyright Notes

Permission to make digital or hard copies of all or parts of this technical report for personal use is granted without fee provided that copies are not made or distributed for profit or commercial advantage. The copyright remains with the individual authors of the manuscripts.