MAGNETIC HUMAN INTERFACES

Utilizing magnetic fields and materials to build unconventional human computer interactions

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Declaration

I hereby declare that the thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis.

This thesis has also not been submitted for any degree in any university previously.

Kasun Karunanayaka on 11th April 2014

I would like to dedicate this thesis to my loving parents, and family

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Abstract

This research work implements unconventional human computer interactions using some of the selected magnetic materials and field properties. The interaction methods facilitated by the conventional interfaces have several shortcomings. For instance, Tangible User interfaces provide constrained interaction with their limited metaphors and physical objects. Traditional pointing interfaces lack the near surface haptic sensations which is crucial for effective touchless-interaction. Creating and reproducing perceptions are limited by factors such as sensors of the human body in conventional human computer interfaces.

This research contains three components to address above limitations; (1) Liquid Interfaces a Ferro-fluid based organic user interactions with haptics, (2) Haptic mouse: a magnetic field based near surface haptic pointer interface, (3) Pulse: a user interface using Transcranial Magnetic Stimulation (TMS) for human feeling rendering.

The contributions of this research are as follows. Firstly, the Liquid Interfaces is a novel way to provide rich interactive metaphors and objects, in particular the touchless input, three-dimensional Ferrofluid buttons, like-polarity haptics. Secondly, the Haptic Mouse is the first pointing interface to couple the near-surface sensing and the haptic-actuation. It brings haptic sensations to 3D spaces near to the surface.Thirdly, the Pulse can create or reproduce the feelings and sensations on the skin of the fingertip such as numbness, stiffness, and parasthesia.

The experimental results imply positive effects on interaction with systems. Liquid Interfaces shows possibilities of effective interaction as an Organic User Interface (OUI). The non-invasive 3D haptic sensations of the Haptic Mouse delivers rich interactions as a pointing interface. User studies of the Pulse shows the capabilities of using Transcranial Magnetic Stimulation (TMS) pulses to create

or modify the sensations.

Research contributions made in this thesis can be broadly applied to fields such as Mixed Reality, Human Computer Interaction, New Media Arts, and Medicine.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Machines, from the inception of mankind has always revolutionized the way humans do things. From the age of leavers and wheels to the modern day super computer, machines of various types have helped humans to achieve unprecedented level of productivity. Machines have enabled them to get things done more easily,faster and efficiently. Invention of the first automated computer (Z3) [100] in 1941 gave rise to a whole new level of machine automation. Invention of the transistor [12] has paved the way to make computers smaller and more powerful. Miniaturization of the computer [56, 80] has resulted in it being embedded in to various other machines and has redefined the way we live, work and communicate.

Advent of new technologies has popularized diverse technical terminologies which we now use in our daily conversations. The word 'interface' is defined as a point where two systems, subjects, organizations, meet and interact [85]. Interfaces related to machines can be found in two types: machine-machine interfaces, and man-machine interfaces (user interfaces) [29]. As computer systems became more and more complex humans started finding new ways to make them interact with computers more easily. This necessity gave rise in developing various types of user interfaces for computerized systems [19].

During the early days of machines, interactions were done using buttons and leavers. Advancements in electronics have helped humans to improve the way they interact with machines. It started with low resolution displays and gradually fully fledged Graphical User Interfaces (GUIs) [45] emerged. GUIs incorporated new pointing technologies, multi touch systems, air gestures [79], automatic feedback technologies to enrich the user experience when interacting with machines.

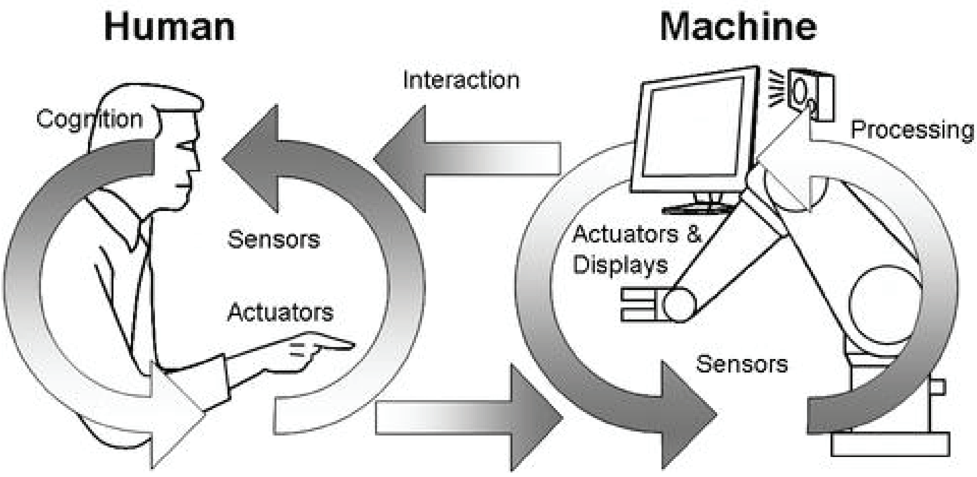

Figure 1.1: How the humans interact with computers

As depicted in figure 1.1 when a person interacts with a computerized system the sensors of the body are utilized and capture the information from the output interfaces such as monitors, and speakers. At the same time a person uses his actuators in the body such as fingers, hands and the skin to feed the data to a computer system [103]. In the same way for a computer input interfaces will be it's sensors and output interfaces will be it's actuators. These interfaces should effectively collaborate and coordinate with human senses in order to achieve optimum user experience when interacting with computers.

1.1 Unconventional Human Computer Interfaces

The human body encompasses different sensors which are capable to detecting changes that occur in the external environment. Vision, sound, taste, smell, and touch are the major elements of sense that we experience. However, humans can also sense temperature, kinaesthetics, pain, balance and acceleration. All these sensations are sent to the brain either via cranial nerves [86] or the spinal cord. Cranial nerves are directly connected with the brain and they transfer the sensations such as smell, taste, sound, vision and the touch (detected on the face). The touch sensations detected from the rest of the body is sent to the brain via the spinal cord.

In the field of Human Computer Interaction, "User Interfaces" can be considered as a key element. Conventional human computer interfaces such as keyboard, mouse, screen, speakers and printers stimulate a limited number of sensors in the human body such as eye, ear and skin. Developments of the interaction methods of these conventional human computer interfaces have now reached a standstill due to the continuous innovation over the last few decades [67]. Computers and computer based systems have redefined the way we think about them, way we use them and most importantly the what we expect from them. To cater these new requirements, novel human computer interactions and interfaces should be introduced.

To fulfil these gaps a new field called Unconventional Human Computer Interfaces (UHCI) has emerged [17]. The primary objective of the UHCI is to improve performance or ergonomics, enabling new interactions methods and increasing the user involvement. These interfaces use input and output methods which are not common when interacting with machines. According to Beckhaus et,al. three different development approaches can be used by UHCI . Namely human oriented approach, device oriented approach and application oriented approach.

Human oriented approach capitalize on the potential power of human input and output capabilities. This includes stimulating the senses that are not common in computer interfaces (ex. virtual retinal displays [64]), using the potential of a human sense to further extend (ex.haptic displays [41]) and use of human metaphors instead of device metaphors (ex. natural gestures).

Device oriented approach is mainly focused on introducing new technological possibilities such as using devices from other application areas for I/O purposes (ex. use a mobile phones accelerometer to play a computer game), using I/O devices in an alternative way (ex. controlling a joystick with the chin),using emerging technologies or inventions (ex. brain implants [110]) and beyond conventions (ex.keypad vs. footpad)

Application oriented approach explores the new application possibilities like new application areas (ex.wearable computing [74]), new interaction paradigms (ex. 'weird' or 'magic' interactions) and extending or improving functional characteristics of current applications (ex. increase 'fun factor' in game fighting)

1.2 Importance of magnetic fields and materials for UHCI

Although we harness the power of magnetic fields generated by various machines in our day to day life including motors, generators, transformers, and other electro mechanical devices, it is still intangible. Due to the nature of the magnetic fields, direct human interaction is not possible. Theories based on magnetic fields are developed, learned and used in universities and labs all around the world. It's applications are immense and widely used in fields such as physics, electrical engineering and electro mechanics. Even though magnetic fields are safe to be exposed to, interacting with them is still in its infancy largely due it's intangibility.

Experiments on magnetic fields have been conducted for centuries. Apart from magnetic stimulation in human brain for treating patients in medical arena, only small number of research works that can be found which exposes human directly with magnetic fields. Human cannot see or feel magnetic fields but they could be transformed into different forms of energies or signals which can be felt by humans.

Magnetic materials such as permanent magnets, electromagnets, ferrofluids, magnetorheological fluids [55], magnetic puttys [4], magnetic sand, ferromagnetic cores were used inside machines and devices. Magnetic materials and fields has some interesting features and capabilities to implement unconventional human computer interactions. It is possible to generate actuation, kinaesthetic feelings [42], pressure kind of feelings [53] [108] [88]. Magnetic materials can be used to develop attractive displays and surfaces [105] [35] [48]. In-addition, magnetic field stimulation techniques are widely used in the medical field to stimulate human brain [26] [6] [15]. It also has the potential to stimulate the nerve pathways [89].

1.3 Research Statement

The interaction methods facilitated by the conventional interfaces have several shortcomings such as limited input and output methods, discrete behaviors, connected with limited number of senses in the human body, lack of adaptivity to the dynamic environments, stimulation is limited to the receptors, and being solid tangible surfaces. This thesis has identified three key issues related to the conventional interfaces that can be addressed by developing unconventional human computer interfaces using magnetic fields and materials.

1.3.1 Research Problem

The author has identified three shortcomings of the conventional user interfaces. They are,

- Tangible User interfaces provide constrained interaction with their limited metaphors and physical objects.
- Traditional pointing interfaces lack the near surface haptic sensations which is crucial for effective touchless-interaction.
- Create and reproduce perceptions are limited by factors such as sensors of the human body in conventional human computer interfaces.

1.3.2 Research Question

Does unconventional user interfaces based on magnetic fields and materials offer enhanced interactions and address the possible issues which have been identified under the research problem?

1.3.3 Hypothesis

This research is developed three components as proof of concept to address the above mentioned limitations in conventional methods. (1) Liquid Interfaces a Ferro-fluid based organic user interactions with haptics, (2) Haptic mouse: a magnetic field based near surface haptic pointer interface, (3) Pulse: a non-invasive user interface using Transcranial Magnetic Stimulation (TMS) for human feeling rendering.

It is hypothesized that the magnetic field based interactive surfaces can address the three issues which has been listed previously by,

- Providing the organic user interactions with their rich metaphors and physical objects.
- Near surface sensing and actuation for the effective touchless-interaction in the pointing interfaces.
- Allowing to create or reproduce the feelings and sensations on the skin of the fingertip such as numbness, stiffness, and parasthesia

1.4 Prototypes

1.4.1 Liquid Interfaces

Liquid Interface is an Organic User Interface (OUI) [46] that combines Hall Effect sensing and actuation through electromagnetically-manipulated ferrofluid. The movement of magnets worn on the fingertips, over a surface embedded with a Hall Effect sensor array and electromagnets, gives user the ability to interact with

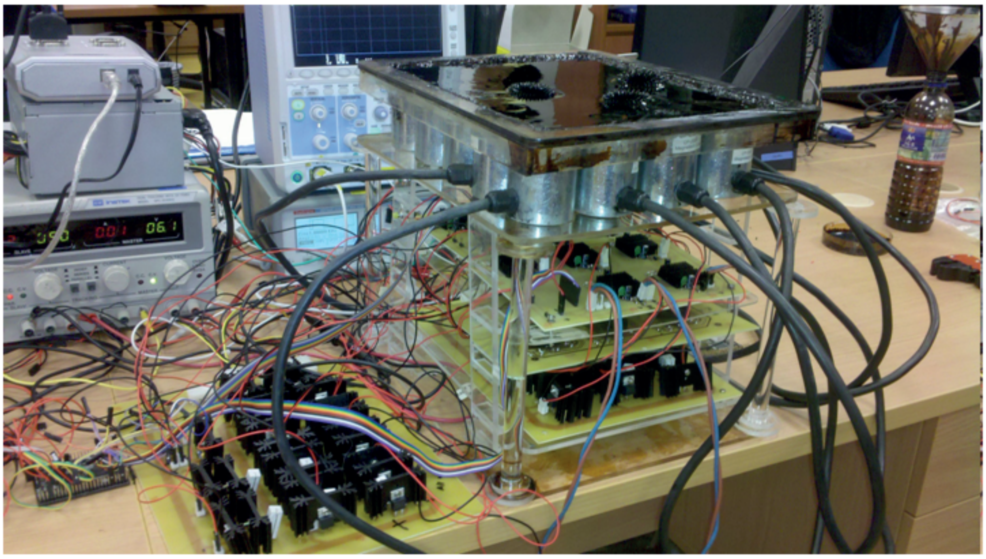

Figure 1.2: Liquid Interface system

the ferrofluid. This system provides a three-dimensional, physically animated response, as well as three-dimensional, spatial-sensing inputs. The vibration of the magnets worn on the fingertips, produced by the repulsing polarity of the electromagnets, provides the user with haptic feedback. Linetic is a multimodal interface with a visual, audio and haptic experience.

1.4.2 Haptic Mouse

Haptic Mouse (Figure 1.3) is a new type of pointing interface which provide mouse interactions, haptic feedback and additional enhanced features. The key advantage of this system when compared to the other haptic pointing interfaces is that the users are able to control the mouse cursor and feel haptic sensations upto 6cm above the device surface. This enables the haptic sensations in near 3D space which can be considered as a novel experience. Varied haptic sensations provided by this system can be felt like attraction, repulsion, and various patterns of vibrations. These sensations can be easily configurable as feedbacks for different mouse commands using the specially developed mouse driver.

The system provides attraction and repulsion sensations by changing the polarity of the electromagnets. Polarity of an electromagnet can be changed by swapping the positive and negative voltage supply to the electromagnet using a controller circuit. When the neodymium magnet worn on the finger tips and the electromagnet array underneath the device positioned in the opposite polarity, (N S or S - N) users feel an attraction towards the device surface. With those magnets are in like polarity (S - S or N-N) positions users feel the repulsion sensation.

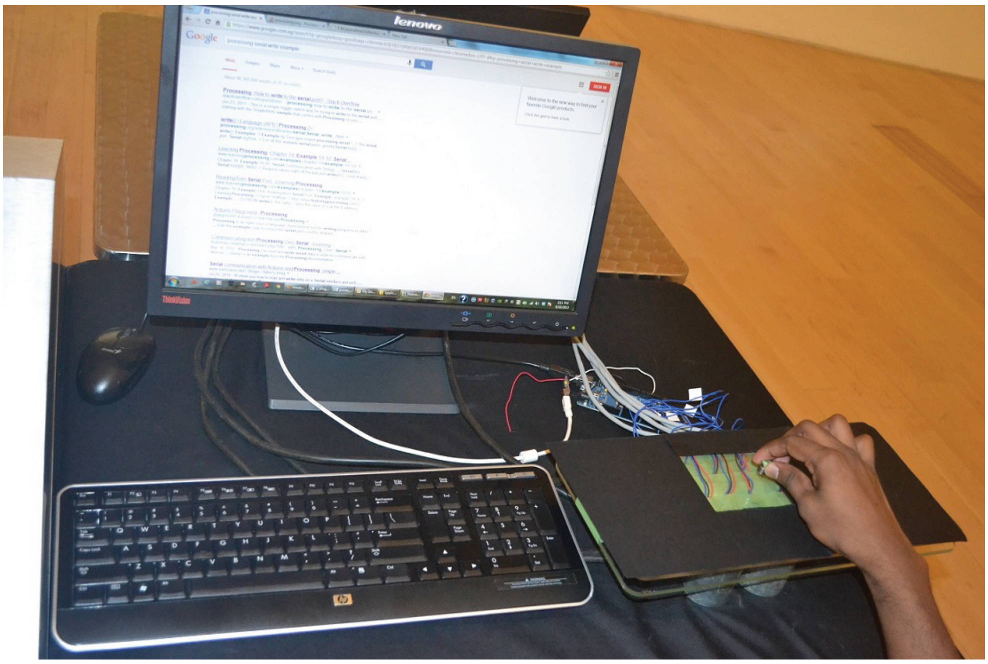

Figure 1.3: Usage of the system

Vibration sensations are initiated by setting up neodymium magnet and magnetic array in a like polarity position and then rapidly switching on and off the electromagnets in the array in certain frequencies. This rapid switching on and off dynamically changes the magnetic field it produces and affects the static magnetic flux developed by the neodymium magnet. While the electromagnet is switched off, the neodymium magnet drops towards the device surface, but when the electromagnet is switched on, the neodymium magnet rises due to the repulsion force felt as a vibration.

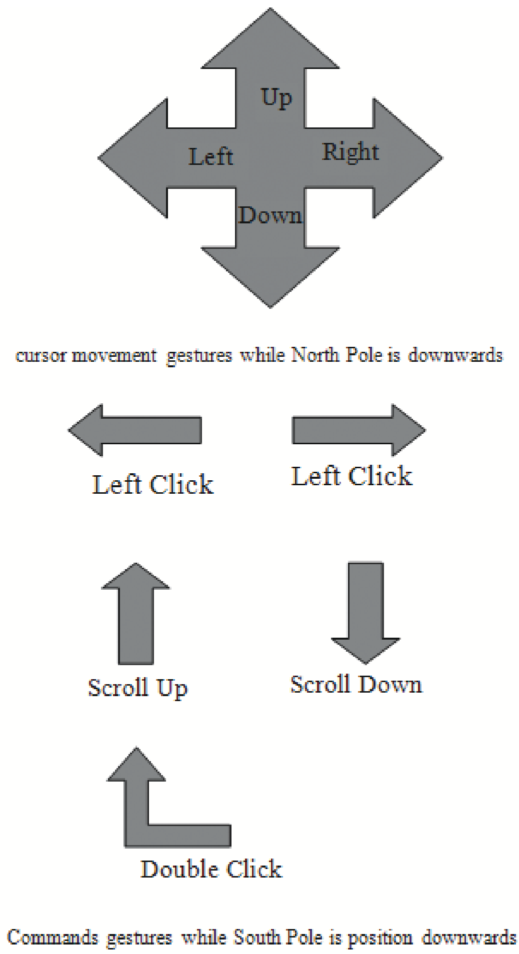

Figure 1.4: Pointer control and command gestures of the interface

Haptic Mouse allows users to both control and interacts with the graphical user interfaces as similar to other pointing interfaces. Figure 1.4, shows the related gestures of 2D cursor movements and Commands of the system. Users can easily move the neodymium magnet attached to the finger tip on top of the device surface and control the GUIs. This can be visualized as a movement of an invisible mouse on the mouse pad.

Furthermore, this interface can be configured as a low resolution haptic display. It is possible for the user to move his/her finger on top of the surface and sense the basic shapes of the objects on the screen. This is achieved by providing one kind of vibration pattern once the user moves the cursor on top of the interested object and then change to a different kind of vibration pattern when the cursor crosses the border of that object. Simple geometrical shapes which are bigger than 200 pixels * 200 pixels can be sensed and identified (In the haptic mouse system the distance between two sensors is 2.5cm for all the directions. This 1cm distance is denoted by 40 pixels by the mouse driver. So the actual dimension of the 200*200 pixels is 5cm * 5cm.). The sensing of simple gestures will be helpful for users to increase their interaction with computers.

1.4.3 Pulse

At present human brain interfaces are a popular research topic. Brain interfaces bypass the receptors of the human body and communicate with the brain as used in the applications such as visual retinal displays, direct visual input, stimulate the auditory nerve or the brain stem to enable hearing to deaf people, stimulate 8th-cranial nerve stimulation for vestibular cues, and artificial vision system/direct visual input.

Trancranial Magnetic Stimulation (TMS) [26] is a well known clinical stimulation technology in the field of medicine. In the TMS devices, a magnetic field is produced by passing a pulsed current through an insulated coil. The stimulation on the human body produces a rapidly changing magnetic field that can induce an electric field in the underlying tissue [72]. If the amplitude, frequency and direction are appropriate, this magnetic field can generate action potentials in the neuron [14]. These action potentials are sent to the brain as signals and become perceptions in the brain.

Moreover, a variety of pulse electromagnetic fields have already been experimentally used, for example, It has been reported that pulsed magnetic fields have been used to promote and enhance the healing process. In this experiment, use of the same principle to study the effect on human skin of fingers. The strength of the magnetic field used is less than 5mT, and these type of fields are considered as very safer ranges to be exposed. During the conducted user study most of the subjects felt numbness, stiffness, and mild parasthesia [82] states in the stimulated area. These sensations are reversible and after a few minutes the subjects are feeling sensations as the same as they sensed before the study.

1.5 Key contributions of the research

Liquid Interfaces introduces a novel way to provide rich interactive metaphors and objects, in particular the touch-less input, three-dimensional ferrofluid buttons, like-polarity haptics. The experimental results imply positive effects on interaction with systems using organic user interactions. Input and output interactions of these interface are both coupled into a single display. Further, shape changeable surface was developed using a malleable material where the user could control and repeat the user interactions. These types of interfaces will be useful to operate in dynamic environments where the user interface should adapt itself to the external signals. As an example, the system senses the surrounding magnetic fields while it starts and self-configure the interface and shapes ferrofluid patterns, input and outputs to filter-out the magnetic anomalies.

Haptic Mouse couples the near-surface sensing and the haptic-actuation together. It brings haptic sensations to 3D spaces near to the surface. Users are able to manipulate the objects in the screen on or above the surface. which added an extra dimension as the input. Haptic sensations can be felt on top of the surface as well as above the surface. Different vibration pattern based feedback allows this interface to be used as a haptic display.

Pulse create and reproduce the feelings and sensations on the skin of the fingertip such as numbness, stiffness, and parasthesia. It shows that the new magnetic user interfaces can be built using low power, low frequency magnetic stimulation and they will be useful for the future applications in the medical field. More controlled and sophisticated clinical tests need to be carried out to explore the benefits to the medical field. Next generation interfaces for anaesthetic treatments could be built using this type of technology because of the reversible loss of sensation. Which relieve pain without eliminating sensation and may be facilitate for surgeries.

Research contributions made in this thesis can be broadly applied to fields such as Mixed Reality, Human Computer Interaction, New Media Arts, and Medicine.

1.6 Thesis Structure

This thesis has been organized in to chapter as described below to add more clarity and to present the study in a well organized and detailed manner.

Chapter 1 gives a general overview for thee thesis, describes the research statement, brief the research method and major contributions of the thesis.

Chapter 2 presents background knowledge related to this thesis work is introduced. Magnetic field based sensing and actuation technologies and related works for the three research components will be discussed in this chapter.

Chapter 3 describes in detail the methodology and prototypes development of Liquid Interfaces research. Further, technical and user study findings are also presented in this chapter.

Chapter 4 presents the method, implementation, and technical experimental results of the Haptic Mouse research.

Chapter 5 describes in detail the methodology , the development process of various stimulation coils, technical experiments and results of the Pulse research.

Chapter 6 summarizes this dissertation findings.

Appendix A is a short summary of the concept of reproduction and creation of perceptions by electrically modifying neural firing research. This research is an attempt to reproduce smell based sensations on human brain using improved transcranial magnetic stimulation.

Appendix B List of Publications

Chapter 2

Literature Review

This Literature Review chapter is divided in to five sections. First two sections presents the magnetic field related sensing and actuation technologies. The next three sections of the chapter, discusses the prior works related to Liquid interfaces, Haptic Mouse and Pulse research works. Throughout these sections advantages, disadvantages and contributions of the prior works will be highlighted and compared against the Liquid interfaces, Haptic Mouse and Pulse.

2.1 Magnetic field related sensing technologies

Presently magnetic sensors are being used to control devices such as magnetic hard disks, tape drives, compasses, and factory machines. In general magnetic sensors provide a cost efficient way to carry out operations involving precise manipulation of devices or equipments. Magnetic sensors do not usually measure the field directly by itself. Hence they measure changes, disturbances, modifications and induced current caused by the electromagnetic field using properties

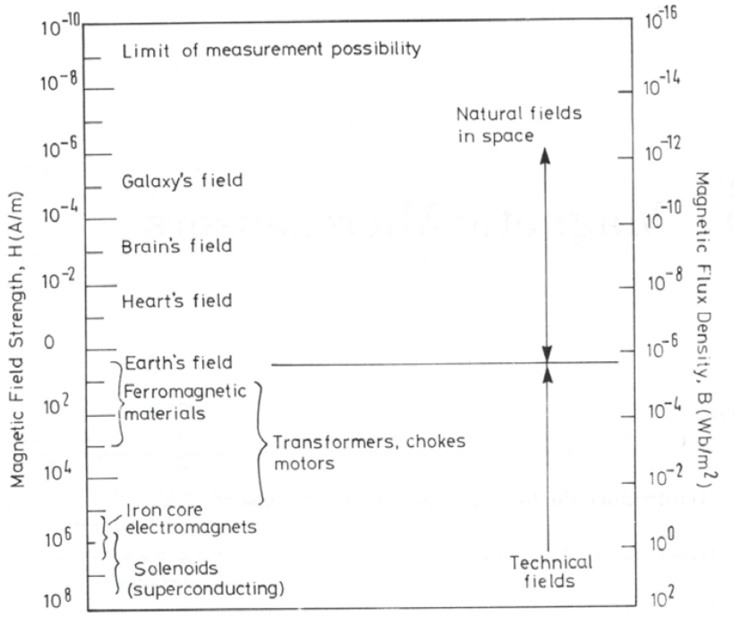

Figure 2.1: comparison of magnetic field strength in different type of fields [2]

like direction, presence, rotation, angle,voltage or current [22]. Magnetic fields are vectors and they have both magnitude and direction. Sensors measures one or both of them based on it's application. Some of the popular magnetic fields sensing technologies and their effective sensing ranges are shown in the Table 2.1. When compared to other types of sensors, magnetic sensors are usually considered reliable, accurate and cost effective technologies [69].

Magnetic sensors can be divided in to three categories based on the sensing range. They are low-field sensors (<1 µG), Earth's field sensors (1 µG - 10 G) and bias magnet field sensors (>10 G) [68]. Figure 2.1 illustrates the comparison of field strengths of different type of magnetic fields.

SQUID [40] is a low field sensor type which measures extremely low current ranges above femtotesla. SQUID stands for super conducting quantum interface device. These sensors are largely used in medical applications to measure neu-

Magnetic Sensor Technology	**Detectable Field(gauss)**
Search-Coil Magnetometer	10^{-8} - 10^{8}
Flux-Gate Magnetometer	10^{-7} - 10^{2}
Optically Pumped Magnetometer	10^{-8} - 10^{0}
Nuclear Precession Magnetometer	10^{-7} - 10^{2}
SQUID Magnetometer	10^{-10} - 10^{-4}
Hall Effect Sensor	10^{0} - 10^{6}
Magnetoresistive Magnetometer	10^{-7} - 10^{2}
Magnetodiode	10^{-1} - 10^{4}
Magnetotransistor	10^{-2} - 10^{4}
Fiber-Optic Magnetometer	10^{-9} - 10^{1}
Magneto Opticle Sensor	10^{-0} - 10^{7}

Table 2.1: Comparison of sensing ranges of different magnetic sensors [69]

romagnetic effects in human brain. Search coil sensors uses the Faraday's Law of induction. The amount of current induced in the search coil depends on the changes that occurs in the magnetic field. These sensors are not able to measure static magnetic fields. Some of the other Low-Field sensors are nuclear precession, optically pumped, and fiber-optic magnetometers.

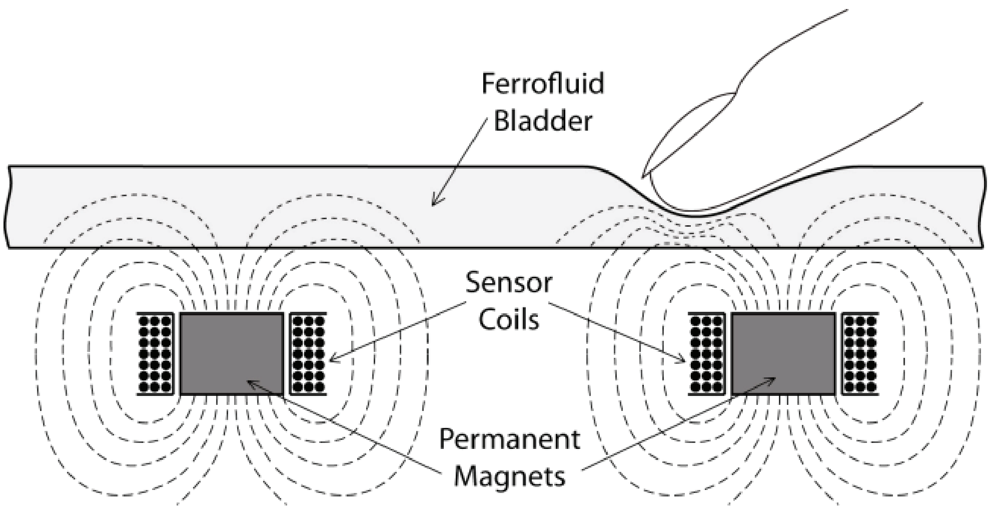

Figure 2.2: Use of sensor coils to detect magnetic fields

Medium field sensors use the Earth's magnetic fields to sense the other fields. Practical applications involved the compass based navigation, and vehicle detection. Fluxgate magnetometers [95] are a type of Earth's field sensors that can be found in compass navigation systems. These sensors are made by wrapping two coils around a single ferromagnetic core. Magnetic induction of the the core get changed when the sensor is exposed to a external magnetic field. As a result magnetic core oscillates.

Bias magnetic field sensors are mostly used in industrial applications. Usually, these sensors measure the fields generated by the permanent magnets. Sensors in this category includes reed switches [49], hall effect sensors [94] and GMR (Giant Magnetoresistance) [27].

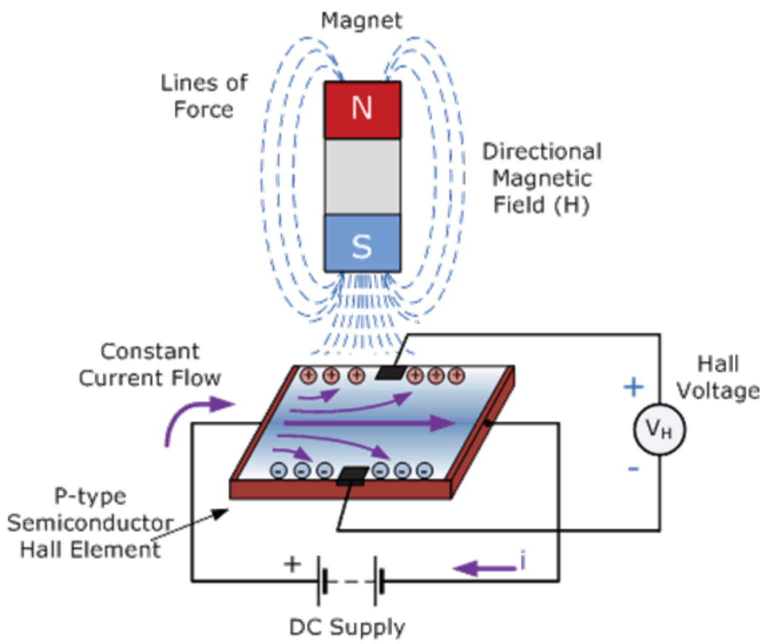

Figure 2.3: Hall Effect Sensor

Hall effect sensor (Figure 2.3) is a transducer that varies its output voltage in response to a magnetic field [43]. Hall effect sensors are used to detect proximity switching, positioning, speed detection, and current sensing applications. Using groups of sensors, the relative position of the magnet can be deduced. Advantages of the Hall effect sensors are they can be easily connected with the micro-controller's, low cost sensors, provide accurate readings, can be used in different environments. Therefore, Hall Effect sensors were used as the sensors for both Liquid Interfaces and Haptic mouse prototypes.

2.2 Magnetic field related actuation technologies

Using magnetic forces to provide actuation feedback is an area that remains largely unexplored and provides exciting opportunities for interaction.There are two kinds of approaches. The first approach is to use the like polarity repulsion property of the magnetic fields. When two magnets are at like polarity position they generate repelling force. When one magnetic field is switch on and off it can be felt as a vibration sensation to the other magnet. The other approach is to use Transcranial Magnetic Stimulation (TMS) based techniques to stimulate human tissues and nerves. The following sections will discuss using magnetic repelling/ attraction forces and TMS based techniques to give feedback sensations.

2.2.1 Like polarity haptics

The Phantom device [76], was the first magnetic field based interface which rendered the kinesthetic information. Kinesthetic information is gathered by sensors in the muscles, tendons and joints, and allows us to feel motion and forces. Cutaneous information is gathered by receptors beneath the skin and conveys information relating to pressure, temperature and pain [83]. Importantly, human body also uses cutaneous information to feel textures [61].

Magnetic forces can offers many advantages. They can provide haptic feedback beyond just fingertip interaction by using an untethered magnetic stylus or glove to give a full hand haptic experience. Furthermore, augmenting a touch surface with electromagnets allows the users hand to be rested upon a surface when interacting, rather than extended as it is when using some other haptic rendering technologies.The generation of cutaneous information could be better achieved with magnetic forces.

Arranging electromagnets as a grid and use as an actuation technique can be found in the applications such as Madgets [107] and the actuated workbench [87]. Also these electro-magnetic arrays were used to actuate the magnetic fluid interfaces such as the Liquid Interfaces [59] and Reconfigurable Ferromagnetic Input Device [48].'Using magnetic forces to convey state information' [101] paper presented a novel magnetic force interaction interface which is well suited for the table top applications.

These prior works shows that magnetic forces should be explored further as a haptic technology, as there offer exciting opportunities for interaction that may not be possible with other technologies.

2.2.2 Transcranial Magnetic Stimulation (TMS)

TMS is a magnetic field based stimulation technique which can be used to excite both neurons and tissues [26]. When a neuron or a tissue gets stimulated it induce eddy current on the nerves which is similar to the current that passes inside the nerves. Usually up to 1 Tesla of field is being used for this type of stimulations. TMS is used as a therapy for illnesses such as migraine, stroke, Parkinson's disease, dystonia, tinnitus and depression.

The effective stimulation depth of the TMS is currently limited about 2cm. These fields can penetrate the skull and stimulate the cortexes under the skull. The Visual cortex and the Motor cortex are the most popular places where TMS is used [6] [23]. Stimulation of the visual cortex has been reported with the result that subjects see visual flashes of various shapes [39].

Stimulation of the motor cortex has resulted in sudden hand and finger movements. [62] Some ongoing experiments in the field are testing the possibilities to stimulate nerve pathways using TMS. Therefore, it is worth trying to for test the new possibilities by without restricting TMS technologies into the field of medicine.

TMS is often considered as a safer technology. The number of reported side effects cases are around 20. Pulse study is focused on exploring the effect on human skin. Appendix one is an attempt to stimulate the olfactory cortex and reproduce the smell sensations in the human mind.

2.3 Similar Works for Liquid Interfaces

SnOil (Figure 2.4) is an interface inspired by the popular mobile game Snake by Nokia. Electromagnet arrays beneath the fluid turn on and off to form the outline of a snake on the ferrofluid screen. The movement of the snake can be controlled by tilting the interface via a built-in tilt sensor [35]. The actuation of ferrofluid for Liquid Interface is based on the similar principle used in SnOil of turning the electromagnet on and off to switch between two states of actuation (On and Off) in the liquid. Mud Tub is [37], an interface that utilises the semi fluid qualities

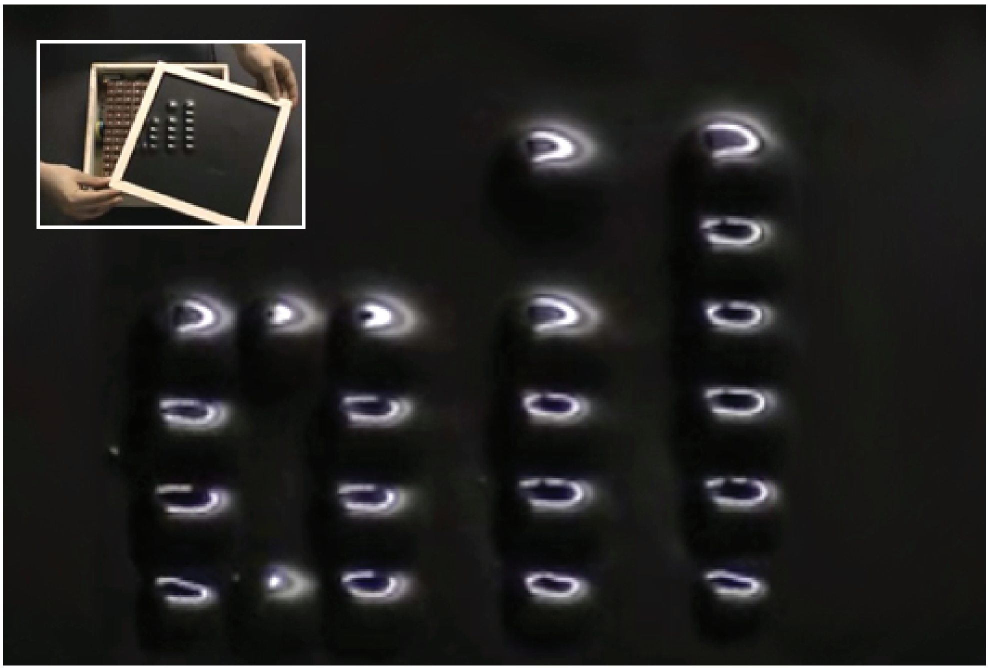

Figure 2.4: SnOil

of mud as an input means but falls short of the definition of OUIs set by Holman and Vertegaal [46]. This is because the output of the system is a video which is projected on the mud; there is no visual change to the mud itself. In addition, while Mud Tub is similar to Liquid Interface in offering a morphable computer form of interaction, the implementation is not as fluid and flexible. On the other hand, Liquid Interface offers a higher degree of controllability of the shapes of ferrofluid.

Blob Motility [105] is an interface based on actuated shape display using a gel with magnetic properties (Figure 2.5). While the instrument differs from Liquid Interface in its use of a magnetic gel as opposed to fluid properties of ferrofluid, it is similar to Liquid Interface in its use of electromagnets in a honeycomb arrangement underneath the gel to dynamically shape it. Liquid Interface uses an array of electromagnets side by side in a 5 by 2 configuration. However, response time for Blob Motility is slow as it takes time for the shapes in the semi solid gel to form. Liquid Interface aims to have a fast response time so that users will be able to manipulate the shape of the interface in real time. Mud Pad [53] (Figure 2.6) is a user interface capable of localized active haptic feedback on multitouch screens. Like Liquid Interface, it utilises an array of electromagnets combined with an overlay of magnetorheological (MR) fluid [21] to actuate a tablet-sized area. The fluid itself is contained beneath a screen. Therefore, the user does not interact with the material directly. While the hardware design is similar to that of Liquid Interface in its use of fluid and electromagnets, the goal of Mud Pad was to provide haptic feedback on existing touchscreens whereas Liquid Interface aims to introduce a new method of interaction in HCI. Reconfigurable ferromagnetic input device [48] mainly consists of an array of permanent magnets which are surrounded by a sensing coil, a micro controller and a ferrofluid bag. The sensing coil surrounding the permanent magnets senses the change in the magnetic field. When and object is placed on the ferrofluid bag, some of the fluid

Figure 2.5: Blob Motility

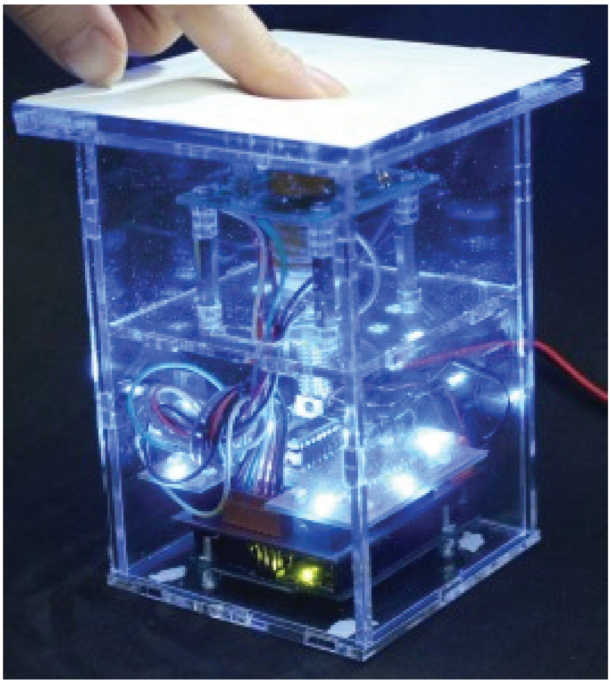

Figure 2.6: Mud Pad

at the position flows away from the object because of the weight of the object. The user would be able to play with the ferrofluid bag by hand to change the shape of the bag or can make some gestures on the bag. These gestures are recognized by the microcontroller and output is send to the PC. They had built two example applications using this technology. The first one was a virtual representation of the sculpting application and the other one was a simple synthesizer [10].

Drawing upon the ideas the aforementioned examples were based on, Liquid Interface seeks to expand upon their work to devise an OUI that can double as an input and output device by combining hand gestures (input) with three dimensional actuation of organic materials (output).

2.4 Similar works for Haptic Mouse

In general use, Pointing devices are used to control and provide data to the graphical user interfaces (GUI) using physical gestures [104]. Movements and commands sent by pointing devices are echoed on the screen through movements of the mouse pointer (or cursor) and other visual changes. Mouse is the most common and popular pointing device in use nowadays. Pointing interfaces have been in the use along with computers for almost four decades [92]. They have been continuously improved by adding new features like dragging, scrolling, multi-touch and recently, attempts were made to include haptic feedback sensations. It was argued that the addition of haptic sensations will create excitement, realism, and an added natural feel for the users [96].

Implementing the haptic interactions for mouse interfaces goes back to the mid 1980's. Modifications to existing mouse with piezoelectric transducer attached which provides vibrations to the tip of the index finger was developed in 1988 [99]. Later many technologies were emerged and different types of haptic interfaces for mouse were developed.

In 2003 Choi et, al. presents a novel haptic mouse system as a new human computer interface, which has a force feedback capability [24]. This haptic mouse prototype is able to provide 1 DOF grabbing force and 2 DOF translation force which is helpful for providing realistic virtual experience to the users. In addition, they have developed a haptic rendering algorithm to render feelings such as weight, shape and surface textures.

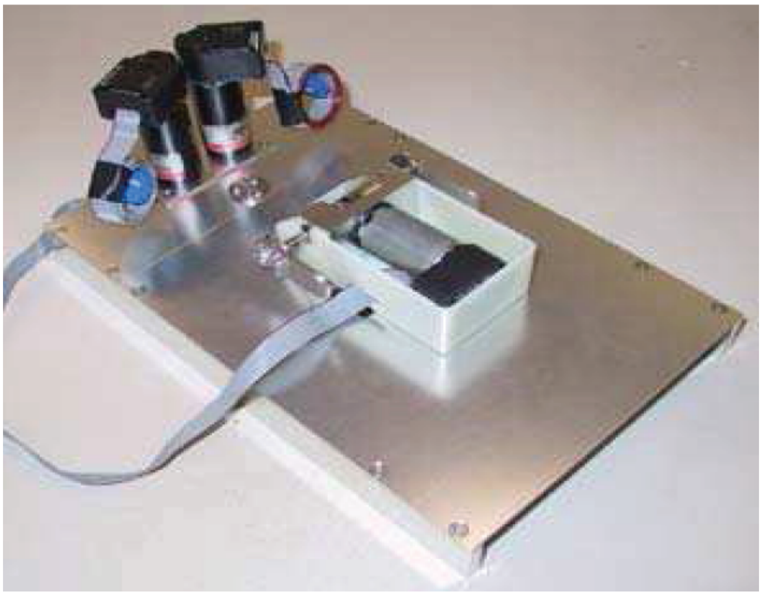

Figure 2.7: Kyung's Haptic Mouse System for Holistic Haptic Display

Kyung has developed a haptic mouse which can render kinesthetic and tactile information [111]. This system provides 2-DOF force feedback, vibration, pressure, and thermal feedback. Textures and shapes are actuated on the skin by 6x8 pin array.

Figure 2.8: Ubi-Pen: A Haptic Interface with Texture and Vibrotactile Display

Kyung also designed a pen-like haptic interface (Figure 2.8) which can be used as a stylus with tablets [66]. Tactile actuation is implemented by specially designed compact tactile module. This device enables texture information when a user rubs an image in the screen and provide various tactile feeling using vibrations while clicking buttons in the GUI.

Park proposes a haptic feedback mouse (Figure 2.9) that is actuated by an electromagnet [88]. An optical mouse is modified by adding a neodymium magnet inside the mouse. Under the mouse pad an electromagnet is placed and once it switched on, it produces attraction forces. These attraction forces are felt by the users as friction. Therefore this device can be used to improve the user interactions like pointing to a icon in a GUI, selecting lines in a CAD design, provide tactile sensations in computer games.

Bat levitating wireless mouse is a device is developed to prevent the 'Carpal

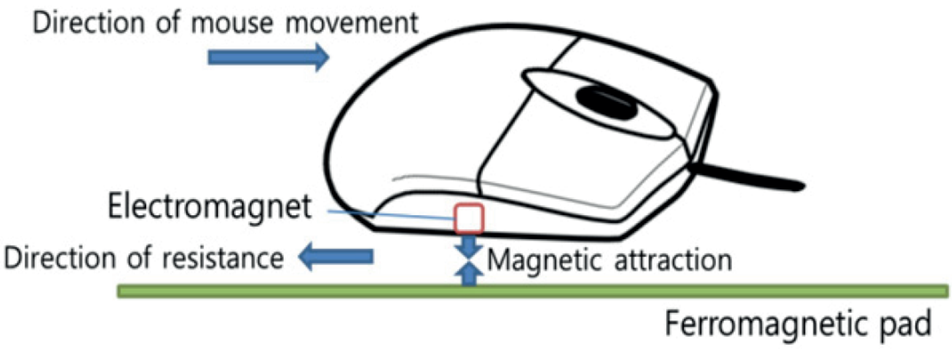

Figure 2.9: Haptic Mouse Interface Actuated by an Electromagnet

Tunnel Syndrome' for computer users [36]. Carpal tunnel syndrome results in numbness, tingling, weakness or muscle damage in the hands or fingers due to continuous pressure put on median nerve. Bat levitating mouse is a floating mouse which is positioned above the surface. Magnetic force provided by the pad underneath is powerful enough to cushion users hand while using the mouse and carry significant amount of the weight of the hand. However, this design is yet to be developed as a prototype and still is in the designing phase.

A mouse shaped haptic device proposed by Udea [102] which has a multiple finger input system developed using anatomical knowledge and neurophysiology to carry out complicated tasks while adapting to the environment. This device is tested for remotely control robotic arms and also to interact with the virtual objects in the virtual environments.

Kumazawa introduces a mouse with a tactile display (Figure 2.10) that generates tactile feedback for multi-modal user interface [65]. The control system to generate tactile feedback imitates the biological nervous system that has multiple feedback loops for quick and flexible reaction against sensory inputs.

FingerFlux [108] is an output technique which generates near-surface haptic

Figure 2.10: Haptic Mouse with Quick and Flexible Tactile Feedback Generated by Double Control Loop

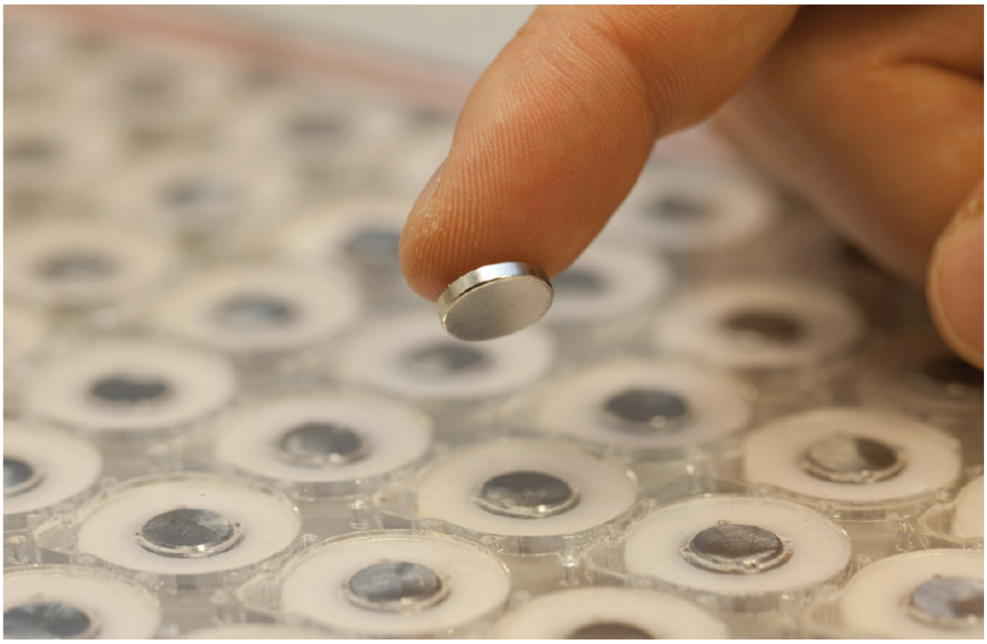

Figure 2.11: FingerFlux: A near surface haptic feedback interface for tabletops

feedback on interactive tabletops. It combines electromagnetic actuation with a permanent magnet attached to the user's hand. FingerFlux (Figure 2.11) provides enhanced features like, feel the interface before touching, attraction and repulsion, development of applications such as reducing drifting, adding physical constraints to virtual controls, and guiding the user without visual output. They have achieved the vibration sensations up to 35mm above the table. As limitations, Fingerflux only works with table top computers. It uses camera tracking based sensing and the maximum vibration feeling height is comparatively lower than our system.

GaussBits [70], is a system of the passive magnetic tangible designs that enables 3D tangible interactions in the near-surface space of portable displays. When a thin magnetic sensor grid is attached to the back of the display, the 3D position and partial 3D orientation of the GaussBits can be resolved by the proposed bi-polar magnetic field tracking technique. This portable platform can therefore enrich tangible interactions by extending the design space to the near-surface space.

TeslaTouch [16], is a new technology for enhancing touch interfaces with tactile sensations. TeslaTouch is based on the electrovibration phenomenon.This technology provides a wide range of tactile sensations to fingers sliding across surfaces of any shape and size, from small mobile displays to curved or wall-sized screens. TeslaTouch can be easily combined with a wide range of touch sensing technologies, including capacitive, optical and resistive touch screens.

Tactile Explorer [5] is a device which provides access to computer information for the visually disabled based on a tactile mouse. The tactile mouse resembles a regular computer mouse, but differs in having two tactile pads on top that have pins that move up and down. These translate the data on the screen to tactile sensation. Tactile Explorer provides possibilities to find and select desirable on-screen information and study it with different options.

Microsoft tactile mouse [3] is a commercially available mouse implementation which combines haptic sensation and will be developed to support rich features of their latest operating system. This mouse has a touch sensitive strip which contains two buttons, one on each end. Haptic-feedback, in the form of vibration through the touch-sensitive strip, indicates which one of the three scrolling speeds has been selected. Both Tactile Explorer and Microsoft tactile mouse are mouse implementations combined with Haptic. It supports enhanced haptic interactions. However, operations and sensations are limited to the device surface. Furthermore, the haptic actuation is limited to a small area of the device surface.

2.5 Similar works for Pulse

Using the polarization of the nerves cells it is possible to induce electrical current inside the nerves. These induced current flows to the nearby neurons via dendrites and synapses [60]. By doing the stimulation with different frequencies and different flux levels it is possible to trigger neurons as different types of signals.

Influence of Permanent Magnetic Field Therapy on Wound Healing in Suction Lipectomy Patients [73] has presented the healing influence of permanent magnets on postoperative wounds. The responses of 20 patients who underwent suction lipectomy and postoperative negative magnetic field therapy were studied in a double-blind fashion. The obtained results demonstrated that commercially available magnets have a positive influence on the postoperative healing process in suction lipectomy patients. They have also found that the magnitude of the reduction in postoperative pain was quite significant, allowing for a decrease in the need for analgesic medication. The authors have stated that in their attempt to use magnetic field therapy in plastic surgical patients, a beneficial effect is clearly exerted and it markedly improved many of the undesirable factors associated with the healing process, with no side effects observed.

Harvey and Edye carried out a study to investigate whether a local static magnetic field of a permanent magnet, of either pole, affects resting skin blood perfusion. The experiments were done on human fingers using static field of 4024 gauss (0.4024 tesla). Results shown that for the magnet type, field strength and application duration used, a magnet-related reduction in skin blood perfusion was observed, with no evidence of a difference in effects due to magnet polarity [77]. They have found that the skin blood perfusion difference is significantly less during north and south pole exposure intervals as compared to the baseline sham interval.

Steven et al. has carried out a study to evaluate the effect of static magnetic fields on skin wound healing in an animal model. The results of the study suggest that exposure to a static magnetic field increases the rate of wound healing on the skin by secondary intention and provide further testimony to the notion that magnetic fields can influence the physiology of the human body [44]. However, the precise mechanism and clinical applicability of this effect are still poorly defined. Given the fact that the skin circuits in humans and are similar in magnitude to those demonstrated in amphibians, it is plausible that external magnetic therapy could influence soft tissue healing in humans as well. Several laboratory studies support this theory and most implicate a vascular mechanism of action.

Similarly, Athanasios et al. have done a similar study to investigate the Effect of Pulsed Electromagnetic Fields on Secondary Skin Wound Healing using rat models [9]. Results have shown that there is a statistically significant acceleration of the healing rate for the first 9 days in the group of rates that are exposed to pulsed electromagnetic fields. In addition, all wound sites went through the normal wound healing process, with no signs of infection. Parameters used for the experiment are amplitude on the order of 12.5 mT, rise time 0.1 ms, fall time 10 ms, repetitive frequency of 3 Hz.

In a web article, William [89] stated that in diabetic neuropathy, Pulsed Electromagnetic Fields (PEMF) treatment every day for about 12 minutes, improves pain, paresthesias, vibration sensation, and increases muscular strength in 85% of patients compared to controls. PEMFs have also been shown to improve circulation. Skin infrared radiation increases due to immediate vasodilation with low frequency fields and increased cerebral blood perfusion in animals. Pain syndromes due to muscle tension and neuralgias improve. In his articles, he emphasizes that PEMP could produce many positive clinical benefits. On neck pain, low-power pulsed short wave 27 Hz diathermy has successfully treated persistent neck pain and improved mobility. For neck pain, PEMFs may have more benefit, compared to physical therapy, for both pain and mobility.

2.6 Conclusion

This chapter has provided two detailed descriptions about magnetic field related sensing and actuation technologies. Then prior works which are related to the three research work has been discussed. How those research works differ from the proposed methods are also highlighted.

Chapter 3

Liquid Interfaces : A Haptic, Ferrofluid-Based, Organic User Interface

This chapter explains the liquid Interfaces study from a technical, usability and aesthetic viewpoint. it outlines experimental results and the significant contributions to the field of organic user interfaces. Furthermore, it presents the results of a study to understand the usability of the system, as well as discusses the philosophical and aesthetical implications of the Liquid Interfaces system.

3.1 Introduction

Recent progress in human computer interaction has paved the way for a new body of research known as Organic User Interfaces (OUIs) [25] [51]. OUIs are defined by three factors: 1. the input interface and output display should be the same;

2. the form of the object should change continuously and correlate directly with the function it embodies; 3. the function performed by the object depends on how the physical shape of the said object is changed [47]. This field focuses on the need to further explore possibilities for interactive user interfaces using the advances made in electronics and material sciences [50].

OUIs open a path to morph the shape and the form of the actual computer interface itself. The interface could be a flexible material such as fabric, acrylic, liquid, sand, clay, etc. As a result, OUIs facilitate the users to interact with the system by manipulating the intrinsic properties of these materials by performing actions such as bending, stretching, pulling, stroking, etc. This new paradigm moves away from the traditional approach of metaphors and physical objects as defined by Tangible User Interfaces (TUIs), and explores next generation interfaces focused on the analog, continuous and transitional nature of physical reality and human experiences, as Schwesig points out [97].

With advances in technology pushing the boundaries in regards to the materials used to create ubiquitous interactive systems [106], it is now possible to expand the computer into the everyday environment through softer, and flexible formats [11]. Using these materials and technologies, this study presents the implementation of an innovative OUI system based on liquid. This interface explores the potential of liquids as an interface and display device, where the manipulation of liquid becomes both the input and output. Liquid Interfaces can provide the user with a natural and fluid experience where three-dimensional, tangible interaction takes place.

Building on the idea of a ferrofluid display created by Kodama [63], Liquid Interfaces provides an input-output solution based on ferrofluid. Ferrofluid is

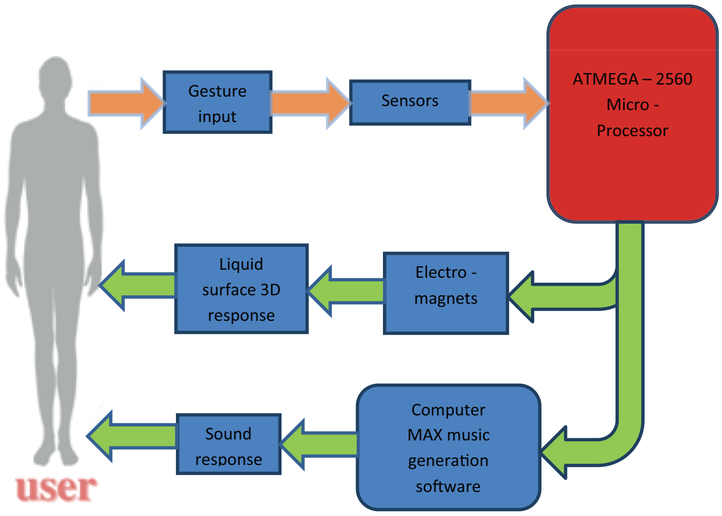

Figure 3.1: A System diagram of the Liquid Interface system.

essentially a liquid that reacts to magnetic fields. The system is composed of a pool of ferromagnetic liquid combined with a sensing and actuation mechanism. The Sensing system uses an array of Hall Effect sensors or camera tracking, while actuation is produced by an array of electromagnets. Sound generation using a MAX/MSP patch running on a connected server augments the output experience.

Through natural movements of the hand, the interface is able to morph from a two-dimensional surface to a three-dimensional form fluidly and dynamically. Using the shape changing quality of ferrofluids, liquids could become a novel form of OUI. In sum, Liquid Interfaces provide a tangible, touch interface with haptic feedback that produces a real 3D morphing surface.

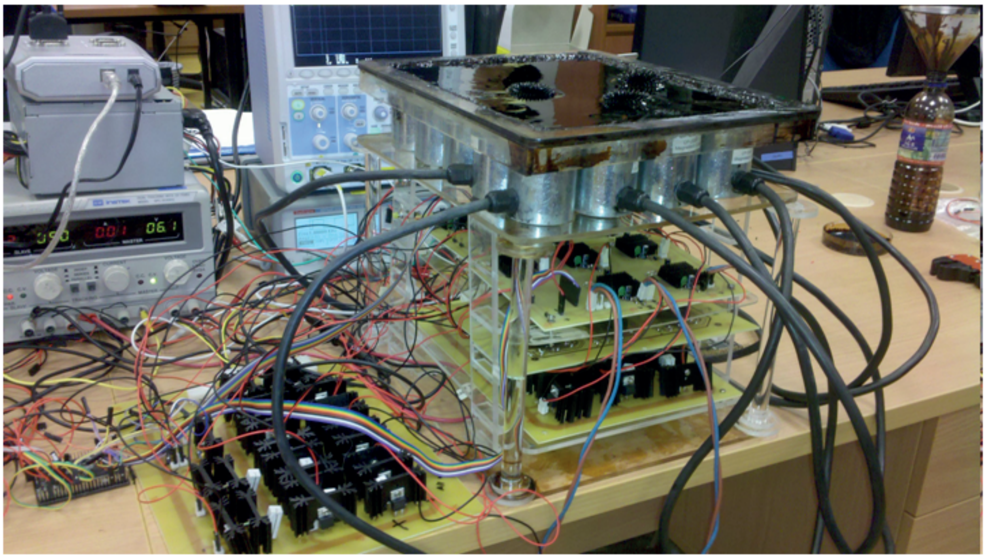

Figure 3.2: Version one of the Liquid Interfaces system

3.2 Prototypes

3.2.1 Prototype 1

A system diagram is shown in Figure 3.1 and the first version of the Liquid Interfaces system is shown in Figure 3.2. By moving fingers over the ferrofluid buttons, users can manipulate shapes in the liquid in order to interact with the system. It requires the use of gloves as the interaction involves direct contact with the ferrofluid screen. The first prototype of the Liquid Interfaces has a display of 4 × 4 pixels where a pixel is a ferrofluid bubble. To generate the ferrofluid bubbles on the screen, an array of 16 electromagnets were used. Users interact with the liquid surface using a neodymium magnet worn on the finger tip covered with the gloves. The system identifies a magnetic flux change when a finger moves perpendicular and vertically in relation to the surface. The flux change is detected by the Hall Effect sensors embedded beneath the surface of the ferrofluid, which sense the magnetic field produced by the magnets worn on the fingers. In turn, an electromagnet also contained beneath the surface of the ferrofluid is activated and produces a field in which the ferrofluid reacts to, producing a ferrofluid bubble. The distance between the finger and the ferrofluid bubble is mapped to the pressure and intensity of the click. Haptic feedback is felt by the user through ferrofluid and like-polarity magnetic field forces.

3.2.2 Prototype 2

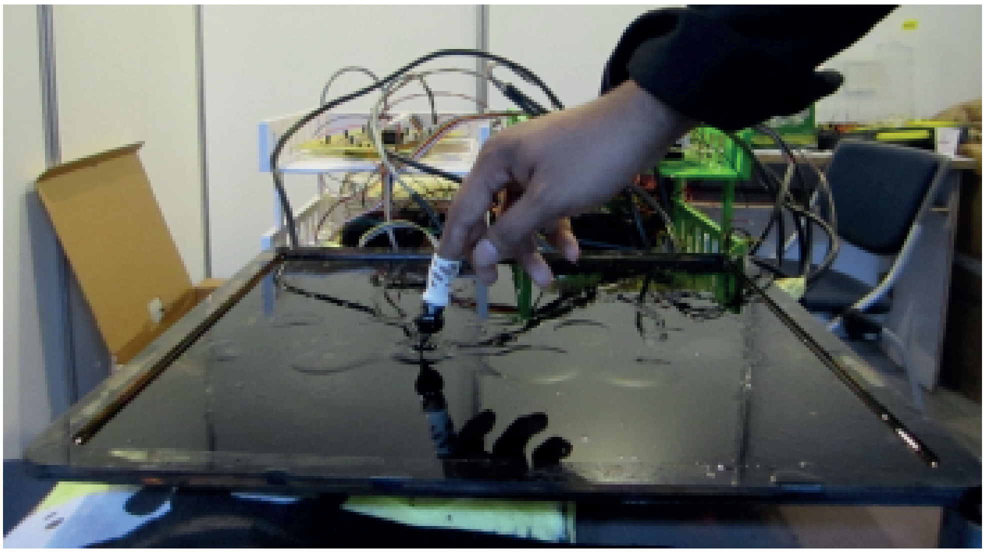

Figure 3.3: Liquid Interfaces Piano version

To show the applicability of the magnetic user interface in real life problems, a second prototype is constructed as a musical instrument with 13 notes. The system contains 13 magnets to generate ferrofluid buttons and 13 hall effect sensors mounted on top of the electromagnet to sense the user input. Interaction with the setup involves using a neodymium rare earth magnet. Special wearable accessories are developed to interact with the system.

Figure 3.4: Liquid Interfaces Piano version with wand

Wearing a set of magnetic rings, the user can interact with the ferrofluid. The magnetic ring position is detected by the array of Hall Effect sensors, which in turn actuates the electromagnets and the sound server. The magnetic field of the active electromagnets produces the morphing of the ferrofluid to create transitional physical buttons in conjunction with the gesture, which then generates a sound. At the same time, the pulse of the matching polarity electromagnets produces a force-feedback vibration on the rings, giving the user haptic feedback.

3.2.3 Prototype 3

Version three of the liquid interface system is experimented with a use of a single Hall Effect sensor attached to the fingertip as the input mechanism. In order to avoid the messiness due to attracted ferrofluid onto the neodymium magnet, the

Figure 3.5: Liquid Interfaces system hall effect sensor based input

neodymium magnet is replaced with a hall effect sensor. Hence, in this prototype, only one Hall Effect sensor is used as the sensing instrument. To interact with the interface, the user holds the Hall Effect sensor and positions it above any one of the six electromagnets. As the Hall Effect sensor is non-magnetic, it does not attract any ferrofluid and avoids creating a mess during usage. The system is able to discern the different electromagnets through the use of the Hall Effect sensor by using a probing sequence of turning off and on of the magnets in a sequential order that the hall effect sensor can detect, allowing the user to achieve the same effect as the previous setup.

Figure 3.6: Version four of the Liquid Interfaces system without the splash cover

3.2.4 Prototype 4

Version four marks the latest iteration of the project (Figure 3.6). It entails the idea of having the user interact with the liquid surface by waving his/her hands at a safe distance above the ferrofluid surface without the use of any instrument. This is achieved by utilizing camera vision to track the position of the user's hands and actuating the electromagnets that corresponds to the hand's position. The result is a pool of fluid that responds to the user's action by changing its shape in a three dimensional manner as he waves his hand above the fluid. It manages to strike a balance between eliminating the hassle of using an intermediary tool while offering an interaction method that is not dirty and uncomfortable for the user.

3.3 Method

This section describes both the hardware (sensing and actuation) and software design of the system in detail. In essence, the Liquid Interfaces system consists of a set of controller circuits to control the system, a sensing system to detect user inputs, actuation system to actuate the ferrofluid and provide force feedback, a pool of ferrofluid, and set of software components.

3.3.1 Sensing System

For the first three prototypes, sensing is performed by magnetic Hall Effect sensors (manufactured by Hamlin Electronics). Hall Effect sensors measure the density of a magnetic field. The sensor produces an analog output when it is under the influence of any magnetic field. The sensor output is connected to the analog-to-digital converter of the micro controller used. The sensor is placed directly on top of each electromagnet while the user's finger carries a powerful neodymium magnet with like poles of each magnet facing one another. When the electromagnet is turned on, the sensor output becomes fully saturated. If a neodymium magnet of the same pole is brought close to the surface, the sensor output drops and this is detected as the presence of the user's finger. The voltage drop of the sensor is dependent on the strength of the external magnetic field. Therefore, a sensor voltage drop is much higher when the distance between the finger and the ferrofluid display is reduced. This measurement is used as an input to control the height of the spikes, which are a product of the system.

In the final iteration of the system a Logitec high definition web-cam is used to capture the user's hand movement in real time. Using a hand movement recognition algorithm user input is detected and will be discussed with more detail in the later section.

3.3.2 Actuation Accessory

The actuation of the system, as seen in Figure 3.3, takes place when the user moves his fingers across the ferrofluid surface while wearing a magnetic finger accessory. To design this accessory, various accessories musicians wear on their fingers are considered, such as guitar picks, to give an idea on how to design an accessory that acts as a natural extension of the finger. A 'wand' that can be waved over the surface in order to provide an alternative method of interaction with the system is also developed.

Figure 3.7: Design iterations for wearable component

Fells [32] suggests that for a user to have an aesthetic experience with a system, they need to develop an intimate relationship with the object. One of the ways in which to achieve this relationship is for the user to embody the object. The ring allows for this embodiment of the system where the system becomes an extension of oneself comparable to how a calligrapher uses a paintbrush. The system becomes a tool in the hands of the user.

Therefore, a ring type wearable accessory is designed as that can be worn on the index finger of each hand. Figure 3.7 shows some of the design iterations. The ring contains a magnet that allows the user to actuate the ferrofluid through natural gestures and finger movements. The ring has a cylindrical base made of plastic with a metal, cone shaped tip containing a magnet. When the user plays with the system, he can sense a subtle haptic feedback through magnetic repulsion. This enables the user to judge the distance from the liquid surface without touching it. It is important to note that when the user gets too close to the fluid (The minimum operational distance is 1.5 cm between the fluid and the metal cone), the liquid will become attracted to the metal cone. To avoid this, the haptic feedback enables the user to use the fluid interface without wetting or staining the fingers. Furthermore, polarity of the electromagnet is configured to repel with the magnet on the user's finger, once again subtly directing the user to not place his/her hands too close to the liquid. This system uses 1cm diameter neodymium magnet and to feel the repel forces the electromagnets were producing 450 gauss of field (at 6V with 1.9 A with 10% duty cycle).

The screen consists of ferrofluid placed in a shallow acrylic container. This container is placed on top of an array of electromagnets. These electromagnets, when turned on, actuate the fluid, causing it to form bumps and/or spiky buttons depending on the strength of the magnetic field produced. The first spike on the surface of the ferrofluid is produced when the electromagnet uses 0.2 A at 4.7V. It reaches a maximum height of 14.3 mm at 2.2 A. This topic is discussed in detail in the Technical Results section (Experiments Measuring Spike Height versus Current and Measuring Spike Distance versus Current). The system is powered using an array of ATX power supplies. These power supplies are then fed to a current limiting circuit. The output current from the current limiter circuits is distributed to the magnet driver board consisting of full-bridge drivers. By feeding the microcontroller's pulse-width modulation (PWM) signals to the magnet drivers, the electromagnetic field produced by the electromagnet array is controlled. This electromagnetic field creates spikes in various shapes and sizes on the surface of the ferrofluid display.

3.3.3 Actuation System

3.3.3.1 Motor Driver Version 1

The systems electronics are divided into main three parts. The ATmega circuit, the magnet driver circuit and the power regulation circuit.

ATmega2560 Microcontroller

As the microcontroller for the actuation circuit ATmega 2560HD1 circuit board is chosen. The ATmega 2560 is used because it has 16 channel independent Pulse Width Modulation (PWM) channels which can be programmed individually. PWM is used to vary the voltage across the magnets depending on the input signal. The ATmega board also comes with two serial USART.

Magnet driver

The Magnet driver circuit consists of 20, 5 Amp H-bridge drivers (MC33886) and surrounding Resistor Capacitor components. The MC33886 has PWM frequency up to 10 KHz and can deliver a current of 5 Amp constantly. However, the system will only drive maximum up to 3 Amps for a chip. The input to the

MC33886, IN1 is connected to the PWM channels of the ATmega2560. As the Atmega2560 has only 16 PWM channels, the remaining four drivers is connected to the Standers I/O Port F, the last 4 bits to be controlled by software PWM. The flag signal output from the Driver is connected to Port A, Port C and Port F. Ports A and C are fully utilized while only the first 4 bits of the Port F are used to makeup 20 flag inputs to the controller. Power to the Drivers will be supplied by the Power regulation circuit. The Schematic of the Magnet Driver Circuit is shown in Figure 3.8.

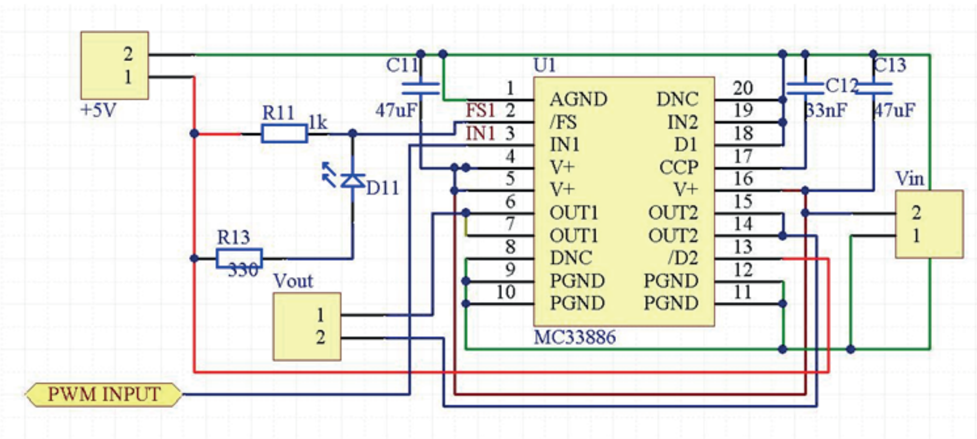

Figure 3.8: The magnet driver circuit

Power Regulation Circuit

The Power regulation circuit mainly consists of 5 Amp adjustable Regulators (LM338). The main power supply to the system is an ATX computer power supply. The ATX power supply with a Power of 350W supplies 15 Amps of Current at 12V. The LM338 is configured as a Current limiter to supply a constant current of 3 Amps to each magnet Driver. Power diodes are connected at the output of the regulator and at the input from the ATX power supply to prevent backwards flow of current which might occur due to a slight voltage difference. Each of the power regulation circuit supply power to only ten magnets. Therefore, two separate circuits are used to power the twenty magnets. Figure 3.9 shows the Schematic of the current limiter circuit diagram. The electromagnets used

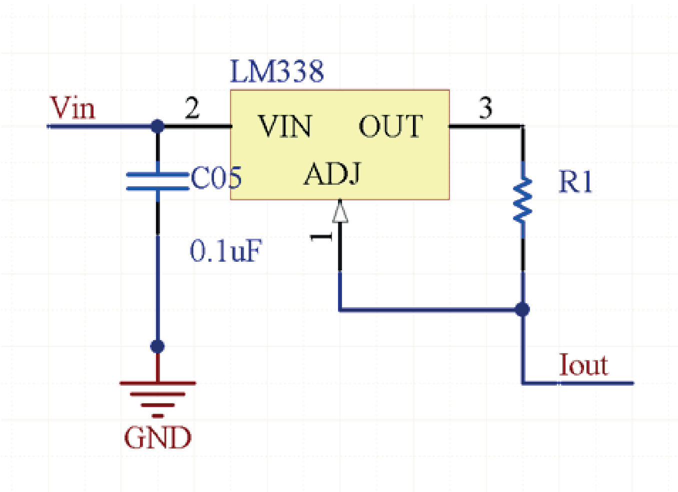

Figure 3.9: The Current Limiting Circuit

for this interface are the OP-2025 models manufactured by Magnetech. Their operating ratings are shown in the Table 3.1.

Applied Voltage	Current Draw	Average Flux Density
6 V.DC, 100% Duty Cycle	1.9	450
12 V.DC, 25% Duty Cycle	3.7	950
18 V.DC, 10% Duty Cycle	5.6	1450
24 V.DC, 5% Duty Cycle	7.5	1950

Table 3.1: Operation rating of OP-2025 Electromagne

Due to power constraints, the rating of 100% Duty cycle at 6V DC and 1.9A is selected. This is because the total power requirement for the 16 electromagnets is high and there is a need to design for the high current requirement. A higher current flow will require thicker wires and thicker connections on the printed circuit board (PCB) that can withstand the high current flow without causing the connections to burn up.

The total Voltage required for 10 electromagnets = 6 V

The total Current required for 10 electromagnets = 16 1.9 = 30.4 A

At this rating, the electromagnets are able to produce an average flux density of 450 Gauss. This magnetic field strength is sufficient to produce a discernible shape on the ferrofluid surface. Therefore, the power rating of 6V and 1.9A is sufficient to drive the electromagnets.

3.3.3.2 Motor Driver Version 2

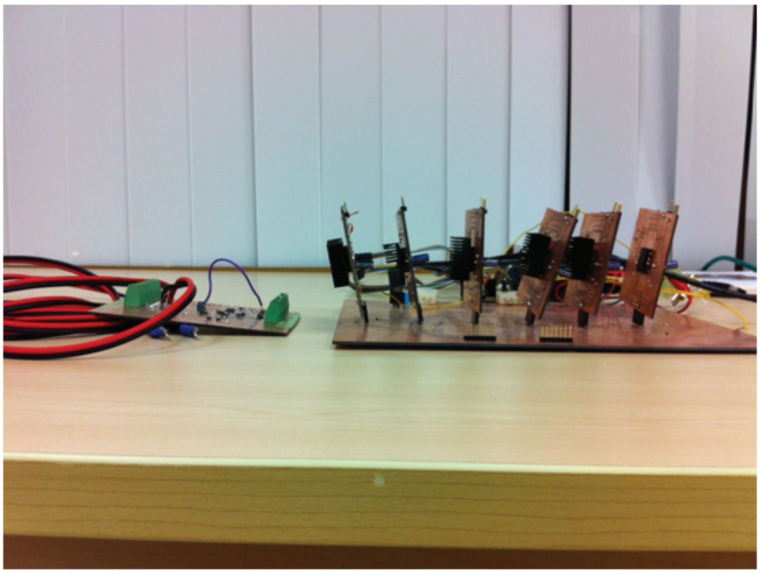

Figure 3.10: Motor Driver Plug and Play Version

The circuit boards inherited from previous versions suffered from a series of reliability issues. Due to the nature of the modular design, each PCB board that drives each of the electromagnet is held in an unstable manner as the entire weight of each PCB board has to be supported by only pin headers, leading to unstable performance during operation. Loose connections are a common occurrence as well. This also proved to be a problem during packaging as the pin headers that support the boards are prone to damage during transport. In addition, as the entire board is significantly large, troubleshooting proves to be difficult. Scalability is also an issue as the board is too high and large, making it difficult to scale the interface to include more magnets to improve the resolution without occupying too much space.

Reliability issues can also be found in the power supplies and the connections. As the current needed to drive the electromagnets need to be high, the wires and connections on the PCB boards have to be able to withstand the high current flow. Connections also needed to be secure to prevent current leakage.

The PCB is also not user friendly as there are numerous wire connections that have to be made in a certain order before the system could turn on, making it difficult to setup every time the board is taken apart to troubleshoot.

Therefore, a second version of the prototype is developed as a miniature version of the bulk circuitry. Motor driver circuits are isolated as independent modules that are directly plug and play to the power controlling board as can be seen in 3.10. This system is used for the 2nd and 3rd versions of the Liquid Interfaces system. ATX power suppliers used as in the previous version. This version considerably reduces the size of the circuits and number of connections. The whole Liquid interface system becomes portable with this prototype design.

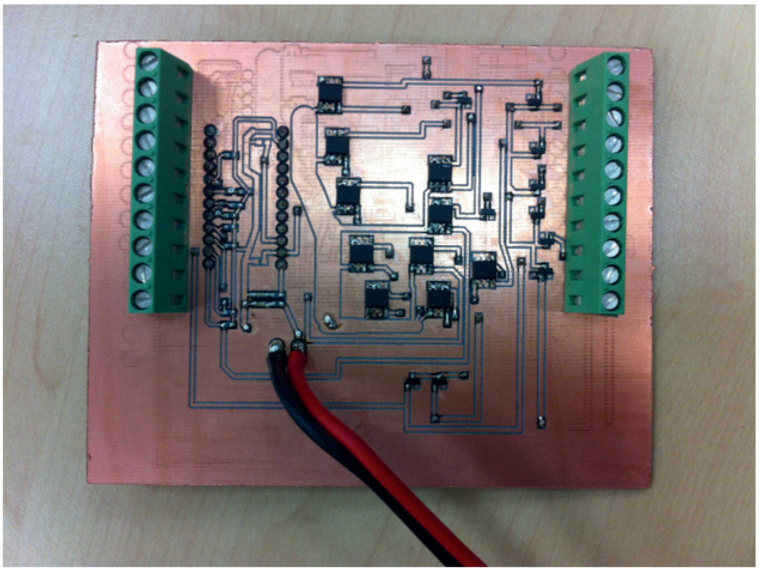

Figure 3.11: MOSFET Based Magnet Relay Circuit

3.3.3.3 MOSFET Version

This version has further minimized the size of the circuits and made the system more robust and portable. The H-bridges are replaced with MOSFETs in the new board's design. They have fewer connections to make as opposed to the H-bridge design of the previous versions, making it easier to solder on the board.

To allow for more stable power flow, thicker 5mm wires are used. Terminal connectors with 5.08mm pitch are used to secure the electromagnets wires to the board. ATX power supplies are unstable in the previous iterations. Therefore, the power supply was also changed from ATX to a more stable DC power supply source with a secure connecting end to prevent current leakage.

More importantly, the size of the circuit board has been reduced significantly, allowing for easy removal for troubleshooting and transport. The fewer connections also meant there are few points to check for if the board malfunctions. An

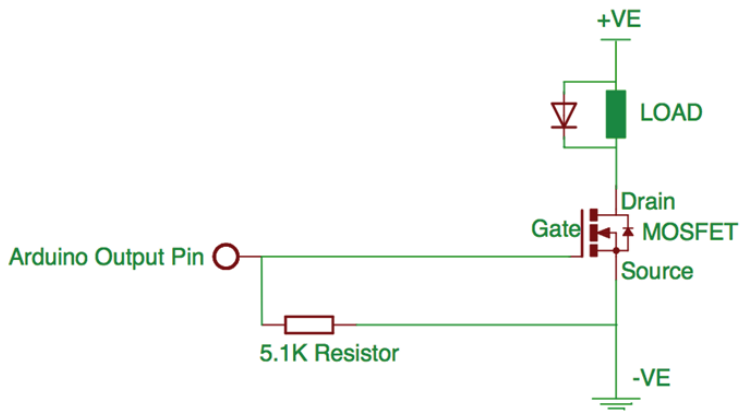

Figure 3.12: MOSFET Schematic for One Electromagnet

added benefit of a smaller board is scalability. As the board occupies a significantly smaller space in terms of height and width, it is easy to scale the interface to include more magnets so that the resolution of the system can be improved by increasing the number of boards and power supplies without occupying a large space.

The connections leading from the positive and negative terminals of the power supply are made wider. This is because these connections are expected to take in a large amount of current, up to about 20A. As the current branches out into the source terminals of the MOSFETs, the current it has to carry is reduced. As such, the thickness of the connections leading to the latter electromagnets can be thinner.

5.08 mm pitch terminal connectors are used to connect the board to the electromagnets. This is because the wires of the electromagnets are thicker and requires a screw to hold the cables firmly in place. The added security provided by the screws also prevents wires from coming into contact with other parts of the board and shorting the connections.

5mm wires are soldered directly onto the board to eliminate the problem of current leakage from the board due to poor connections. The 5mm thickness of the wire is able to withstand the high current flow from the power supply. Screw connectors are crimped at the leading end of the wire and screwed into the power supply to ensure that the board is securely connected to the power supply.

Female Pin headers are used to connect the Arduino Pro Mini to the bottom of the Relay circuit board due to the lack of space on the top of the board.

Two power supplies of 3.30V, 30A rating are used to supply power to the electromagnets. They are connected in a series configuration to provide a total of 6.60V and 30A rating to the electromagnets. These power supplies are significantly more stable and robust than the ATX power supplies used in the previous version of the interface and are also less prone to disconnect due to the more secure connections that are screwed directly into the power supply. The power supply is used solely to power the electromagnets. Other systems in the interface (Arduino Pro Mini and the Web Camera) is directly powered by their USB port from the computer running the vision tracking system and powers on independently from the power supply.

The aim of these experiments is to evaluate the behavior of the magnetic field generated by the electromagnets and its effect on the ferrofluid. The results obtained are used to control the actuation behavior of the ferrofluid and the user experience. They form the basis for the design of the hardware and software used.

3.3.4 Software Design

The next section will outline the various software components developed for the Liquid Interfaces system. These software components are Liquid Interfaces OUI Framework, sound generation, hand tracking algorithm and the circuit firmware.

3.3.4.1 Liquid Interfaces OUI Framework

One of the objectives of the research is to develop a software framework for the project and make it easier to integrate with other systems. The framework mainly consists with a system background service and a Java API extension. The system background service contains the algorithm which accepts user inputs and decide output patterns based on the identified user gestures. Mean while the Java API hides the complexity of the overall hardware and low-level software code from the third party users and provides a convenient way to plug external systems with the the Liquid Interfaces system. Using the API, Liquid Interfaces system can be configured as a tangible input device, a tangible display, or perform both operations to the external system.

As an example for using of the API is that third party application can use read() and write() methods to access the Liquid Interface system. Using read() commands it takes inputs and write() can be used to display different patterns in the ferrofluid surface. Mean while musicPlay() method provides the facility of playing different musical notes based on the user requirements.

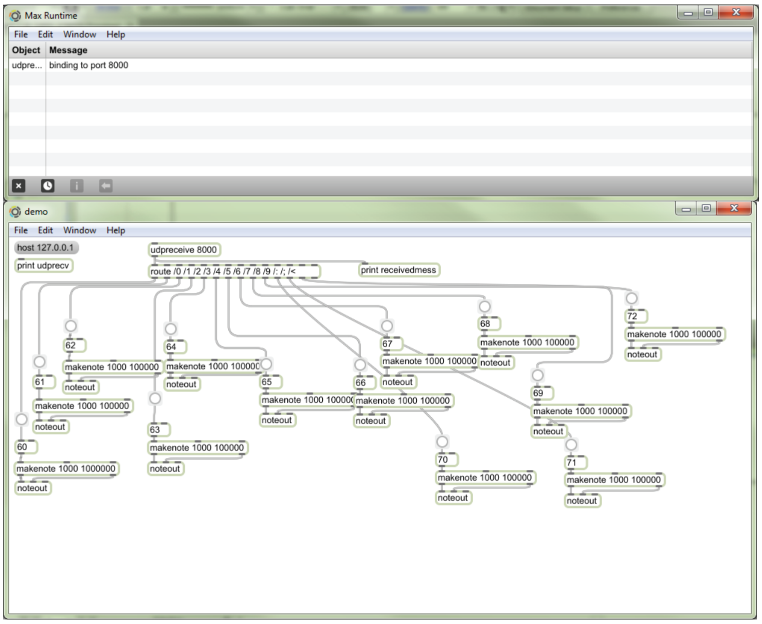

Figure 3.13: Max/MSP sound generation Program

3.3.4.2 Sound Generation

This is an instrumental music generation program developed in the MAX/MSP environment. The Max/MSP patch that is developed detects incoming signals from the framework and activates appropriate midi piano keys to create music. Communication between the framework and music generation programme was implemented using UDP sockets.

3.3.4.3 Computer Vision based hand tracking software

The algorithm used to track hand movements is written in C. Using libraries from OpenCV, the video transmitted by the web cam is first converted to a predefined colour scale for processing.

The program is configured to detect features within a colour scale in the

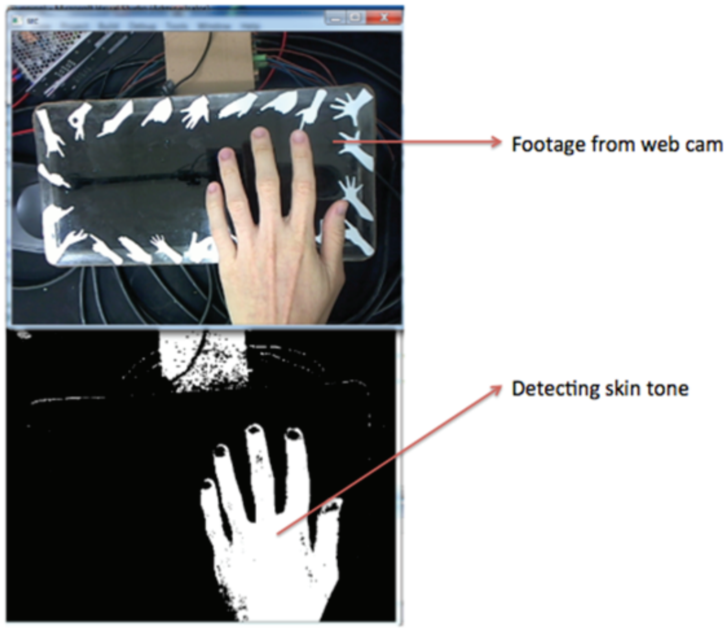

Figure 3.14: Video Footage from Web Cam (above) and Processed Video to skin tone (below)

processed video that corresponds to the skin colour of most humans. This adds to the robustness of the system as any number of hands can be used, allowing for multiple users interaction and multi-touch applications. Once the position of the hand is determined, the program transmits a series of 20 characters to the Arduino Pro Mini. As the algorithm is only concerned with the colour scale of the pixels, processing is fast, and set at 10ms, allowing for real time manipulation of the surface of the liquid. The 10ms response time was chosen to match the 10ms response time of the Arduino Pro Mini in actuating the electromagnets.

The webcam was mounted with a spot light at about two feet above the surface and it is hidden. Since the webcam is hidden from the user we have expected users will move the hand on top of the surface or near the surface. However, if a user moves his hand near the webcam, the hand covers a large area of the video and the position is incorrectly detected. This results more magnets to activate at once.

The video transmitted by the webcam has a resolution of 640 x 480 pixels. This is split equally into 10 equal areas, each approximately the size of the area occupied by one electromagnet at 128 x 240 pixels (3.16).For each area, the program will scan through all the pixels and determine the percentage of area that is within the predefined skin colour scale range corresponding to human skin colour. If the area of the skin colour detected occupies exceeds a threshold percentage (in this case 30%) of the area occupied by one electromagnet, the algorithm will output a 1 for that particular magnet index, which commands the Arduino to turn on the electromagnet associated with that index. Otherwise, if the threshold is not met (area detected is less than 30%), the algorithm will send a 0 instead which disables the electromagnet.

This threshold was determined by studying on two factors. 1.) Experimenting on the area of the surface which users usually cover, while they move the hand on top of the surface. 2.) Experimenting on color of the skin and tracking capability. So these two experiments were done with five people and testing different threshold values for the algorithm. Final conclusion after the two experiments was to use 30% of threshold as the threshold value.

This algorithm also allows for flexibility because it determines the electromagnets to actuate by the area that is covered up by the hand. As such, if the hand is positioned closed to the camera, the area detected will be larger and the vision tracking algorithm will actuate more electromagnets. This translates to a system that is only able to respond to user input in a 2 dimensional plane (XY direction).

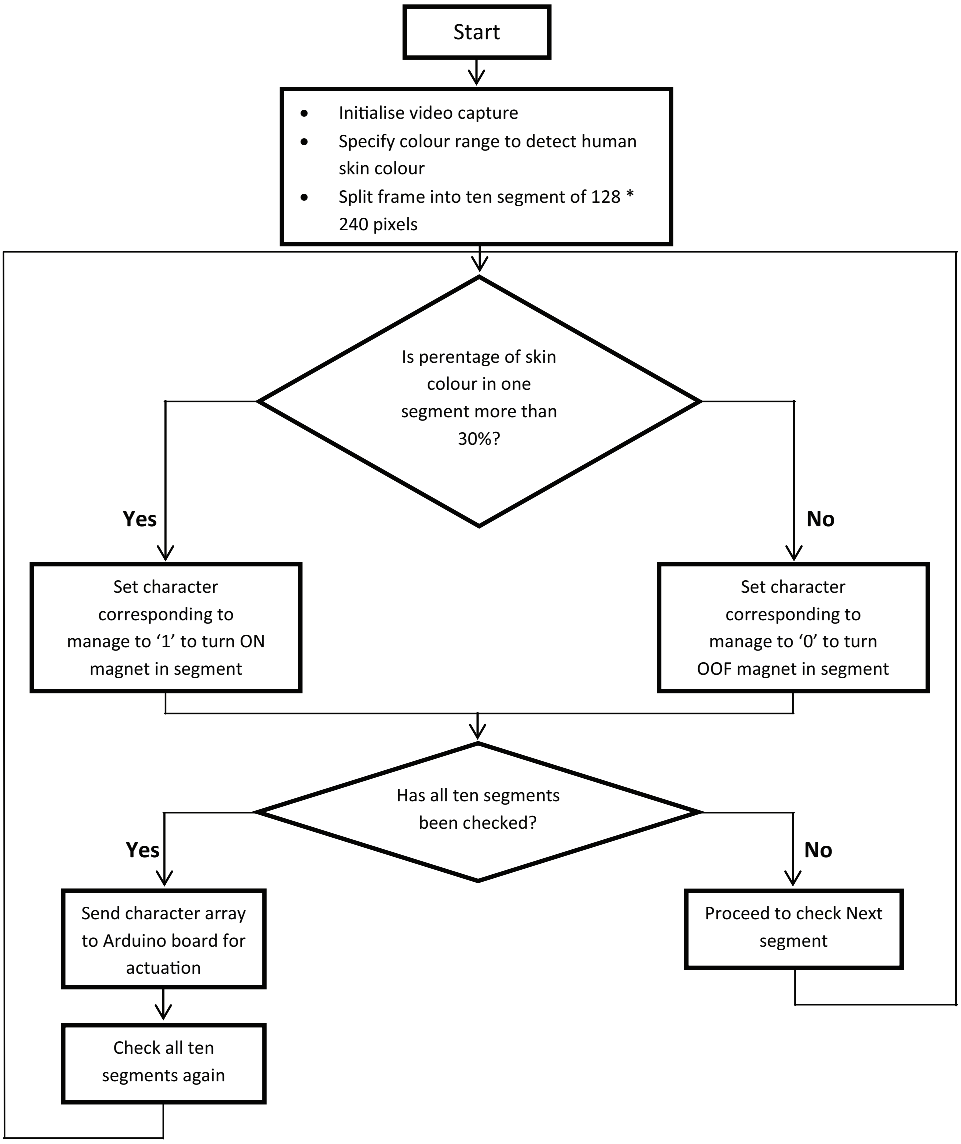

Figure 3.15: Flowchart for the hand tracking algorithm

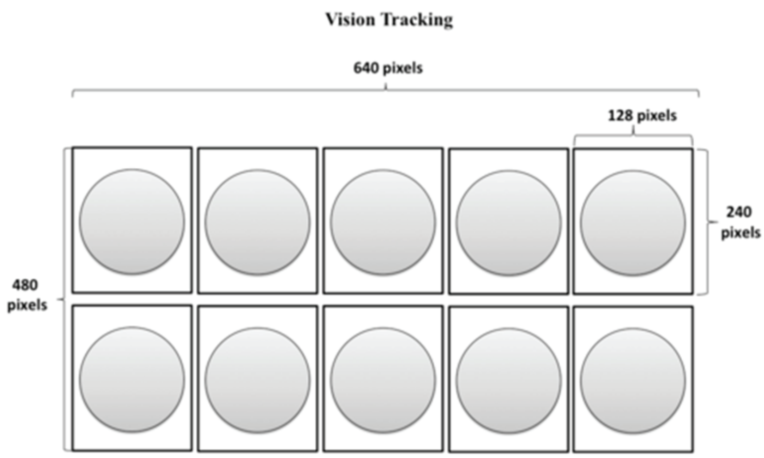

Figure 3.16: Sketch of the electromagnet layout and the image as seen by the web camera

3.3.4.4 Circuit Firmware

The circuit firmware is written in C/Arduino and programmed into the microcontroller (ATMEGA 2560) within the circuit. It communicates with the PC through USB interface and receives data for ferrofluid actuation patterns. According to the given information, it dynamically actuates the ferrofluid and creates dynamic patterns in the ferrofluid display by changing the current of the electromagnet grid underneath the ferrofluid container. Further. it detects the touch interactions made by the actuation accessory using hall effect sensor readings and send those data to the PC to decide on next output pattern.

3.3.4.5 C++ Implementation

The microcontroller embedded in the sensing system, reads all the input pins at once. In the case of hand recognition algorithm, it takes the input image by image. Therefore, the electromagnetic actuation array is also getting activated at once. The delay between the data packets for the communication was set to 20ms with the current prototype where we used two inch diameter electromagnets.

The system's main function will initialize and clear all the flags at the startup. It will then wait for the Interrupt Service Routine (IRS) to set the newinfo flag after updating the variables with data received from the PC. When the newinfo flag is set, the system will write the new duty cycles to the PWM registers. The ISR of the system will run an interrupt every 20 ms to check for the data transmition from the PC every 40 ms, to read the fault flags from the magnet driver circuit. If a fault flag is raised by the magnet driver circuit, the system will restart.

The Firmware communicates with the PC, using the serial communication through channel0 of the RS232 interfere implemented on the ATmega2560 Board. The Universal Synchronous and Asynchronous serial Receiver and Transmitter (USART) is highly flexible serial communication device. The USART is connected to the MAX232, a multichannel RS-232 driver chip to elevate the voltage signals to 12 V and -12 V. The USART is configured to transmit at a baud rate of 9600. The Interrupt Service Routine (ISR) triggers a system interrupt in every 20 ms, which checks the UASRTs receiver bugger for data availability. Here 20 ms is chosen because human interaction speed with the touch screen would not be faster than 20 ms. However, if the electromagnet size is smaller the rate of reading the inputs needs to be higher to produce smooth interaction experience.

All The control signals send to the magnet driver circuit is PWM signals. PWM is used to vary the voltage output to the electromagnets depending on the input received from the touch screen. PWM channels are configured to fast PWM mode and a prescale vale of 1024 is used. PWM frequency, 60 Hz, is calculated using Equation 3.1, where N is the prescale value and fclk I/O is the system clk signal, which is 16 MHz.

$$DutyCycle = (OnTime)/(PWMPeriod) \tag{3.1}$$

3.3.4.6 Arduino Implementation

The electromagnets require PWM to run. The purpose of PWM is to simulate an analog voltage by rapidly toggling a digital pin between on and off. The percentage of time the digital pin is ON over the total time period is known as duty cycle.

Although the Arduino supports PWM outputs natively, only 6 of its 14 digital pins can be used as PWM outputs. A total of 10 PWM output pins are needed, one of each to drive each of the 10 electromagnets. To make up for this, a program was used to have 10 of the 14 digital pins (pins 2,3,4,5,6,7,8,9,11 and 12) produce PWM outputs. Dubbed Soft PWM, the program simulates the turning on and off to produce pulse widths using software. While the PWM outputs produced using the program is not as fast as the native PWM outputs, they are sufficient to drive the relay circuit and the electromagnets as the electromagnets do not require fast PWM to actuate.

The Arduino Pro Mini has one serial UART port for communication with other devices. In this interface, the port is used to communicate with a computer running the vision tracking algorithm.

To initialise serial communication, the baud rate used is 9600 bits per second. Subsequently, the Arduino will use the function Serial.available() (from the Arduino library) in an if statement to check for the availability of data for reading from the serial port. If so, the command serial.read() is used to read the data from serial port.

To signal the Arduino on which electromagnet to turn on and to turn off, the Arduino is programmed to receive a series of 20 characters from the vision tracking system every 10ms via a USB connection. These series of characters are interpreted as commands to turn on the electromagnets that correspond to the position of the hand. Due to the delay, each electromagnet will be on for only 10ms as well. While this is too fast for any visible transformation of the liquid, the human hand moves much slower and the electromagnet to be turned on will receive the command to turn on for the duration the hand is positioned above the magnet which is likely to be a few seconds. This is enough time for the liquid actuation to be visible.

3.4 Technical Results

Ferrofluid is a special kind of fluid that is influenced by magnetic properties. This fluid made with magnetic nano particles mixed with mineral oil. When approached by an external magnetic field the ferrofluid morphs, its shape resembles spikes on the surface of the liquid. This effect is called as magnetoviscous effect [84]. Due to this nature ferrofluid is considered as an non newtonian liquid. Non-newtonian liquid is a fluid whose flow behavior departs from that of a Newtonian fluid, so that the rate of shear is not proportional to the corresponding stress [8]. The ferrofluid forms spikes along the magnetic field lines when the magnetic surface force exceeds the stabilizing effects of fluid weight and surface tension. Therefore, ferrofluid performs as a liquid in general and when it exposed to extrnal magnetic field it becomes more like a solid material.

Technical experiments were conducted for ferrofluid, hall effect sensors, electromagnets, permanent magnets and for the complete system. Main idea of these experiments were to identify the behaviours, limitations, energy requirements, inputs, outputs of the individual sub elements of the system and measure the controllability of the complete system. Experiment methods, results and outcomes are discussed in detailed in the following sub sections.

3.4.1 Measuring Spike Height Versus Current

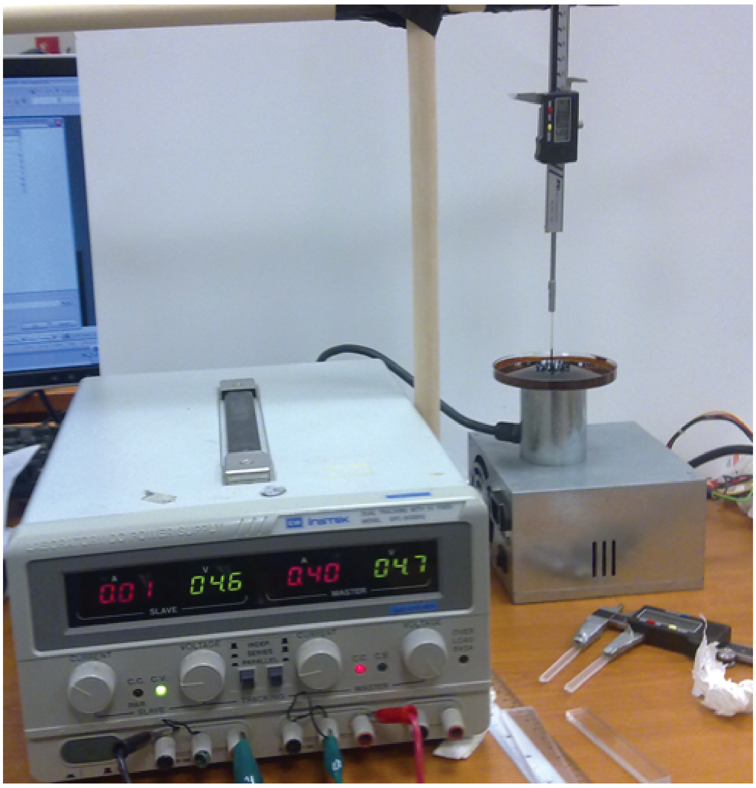

Figure 3.17: Experiment setup of Spike Height versus Current

This experiment measures the height of the ferrofluid spikes formed by the external electromagnetic field. The system setup for the experiment is showed in Figure 3.17. Since the experiment involves measuring the height of the spikes and the vernier caliper is made of metal, a small wooded strip is attached to the vernier caliper so that there is no interaction of metal with the fluid. The vernier caliper reading is set to zero after attaching the wooden strip.

An acrylic container with a surface thickness of 2mm contains a 2mm layer of ferrofluid. The tested ferrofluid is type EFH1 ferrofluid, which contains 5% of volume of 10nm size magnetic particles, 10% of surfactant and 85% of light mineral oil medium. The liquid possesses 400 Gauss saturation magnetization, 1.21gm/ml density, 6 cp at 27C of viscosity, and 29 dynes/cm surface tension. EFH1 Ferrofluid is a member of Ferrotecs family of EFH Series ferrofluids for educational markets. EFH1 ferrofluid is Black-brown color fluid and it uses a light Hydrocarbon carrier liquid. Therefore, EFH1 ferrofluid is lighter, easy to control by magnetic fields. Further, EFH1 ferrofluid has no smell. So EFH1 ferrofluid is selected as the type of ferrofluid to be used in the project.

An opposite pole electromagnet is used. This electromagnet generates an average flux density on the surface from 450 to 1950 Gauss for the range of 6V to 24V with 1.9 to 7.5 A of current. The measurements are taken using a Vernier calliper giving readings of up to 0.01mm.

Figure 3.18 shows the maximum height achieved, 14.3 mm. The first spike on the surface of the ferrofluid is produced when the electromagnet uses 0.2 A at 4.7V. Spike height increases after 1.2 A of current, after which spike height increased slowly compared to the initial spike generation. It reaches a maximum height of 14.3 mm at 2.2 A. There is a slight decrease of the spike height of 0-0.5mm after 2.3 A. This is most probably because of the heating effect of the

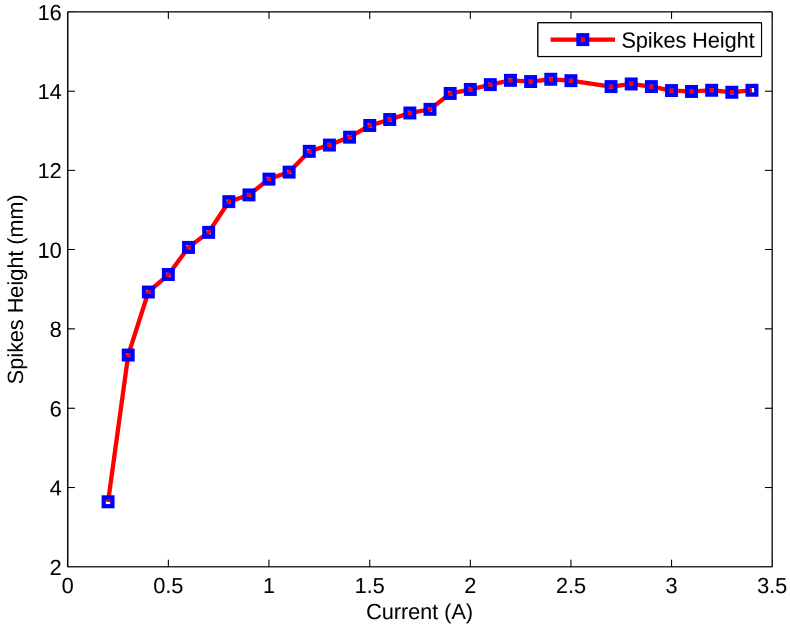

Figure 3.18: Spike Height versus Current

electromagnet which reduces its efficiency. The reason for the spike height to saturate at 2.5 A is because the suitable working range of the electromagnets used was from 0 to 2.5 A. The additional current passed is dissipated as heat energy.

Figure 3.18 shows that as the current through the electromagnet was increased, the height of the spikes also increases. But the relationship is not strictly linear. According to the Ampere Law, magnetic field B through a solenoid is equal to the current I passing through it, provided that the number of turns per unit length (n) and permeability of the core material is constant. B= nI. Therefore, even thought the current passing through the solenoid and magnetic field relationship is linearly proportional, the relationship between ferrofluid spike height is non linear.

3.4.2 Measuring Spike Distance Versus Current

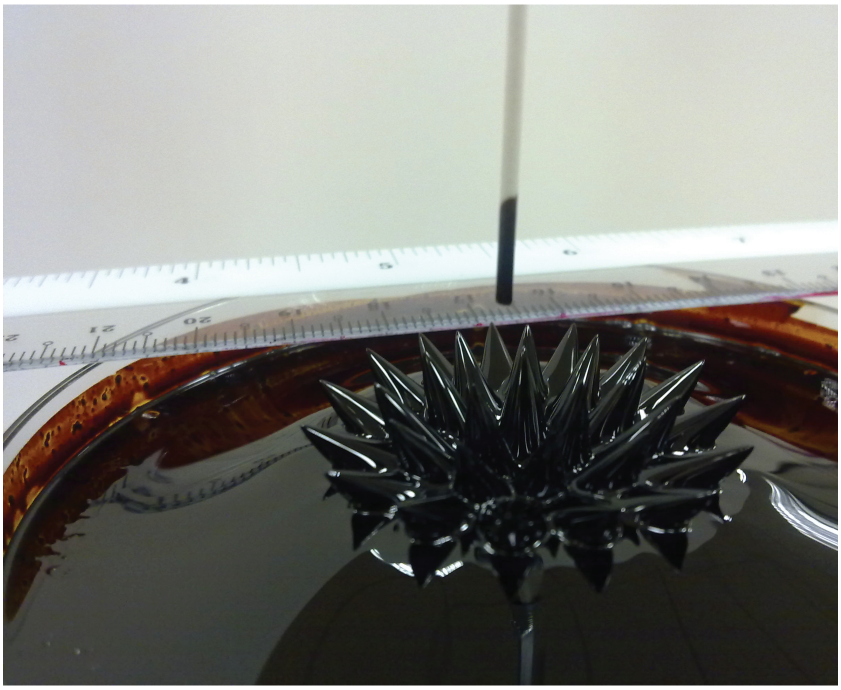

Figure 3.19: Experiment Setup for Spikes Distance

The second experiment measured how the distance between two adjacent spikes changes with the current. To get precise measurements, high resolution photos of the ferrofluid surface from the top view and a millimeter scale are used while taking pictures of the system after increasing the current using intervals of 0.1A for 34 different stages. Figure 3.19 shows the experiment setup.

As can be seen in Figure 3.20, that as the current is increased, the distance between the spikes decrease. They are inversely related. From the magnetism point of view, the correctness of the experimental results can be confirmed. In magnetism, if the field lines are closely packed, its strength is said to be strong. If the field lines are far apart, its strength is weak. As the supplied current increase,

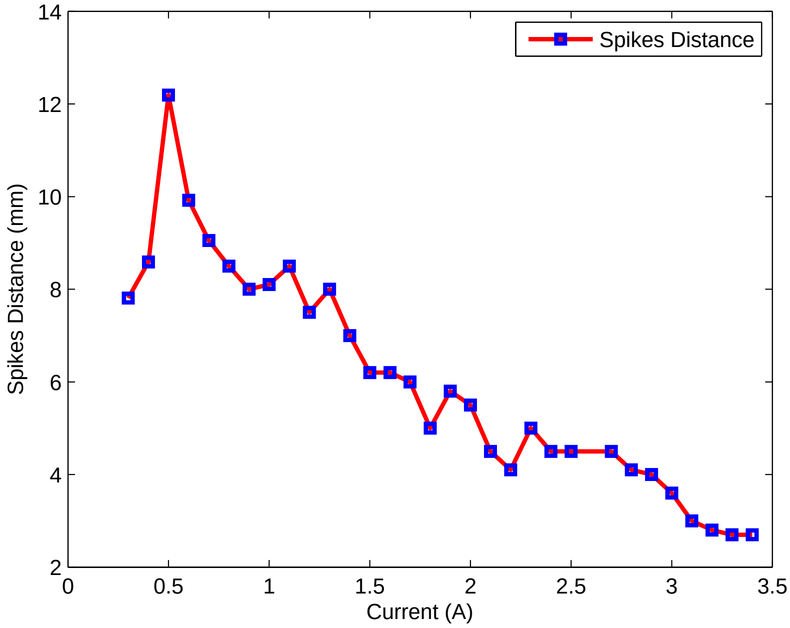

Figure 3.20: Distance between Two Adjacent Spikes versus Current

the strength of the electromagnet was increased, and the field lines are closely packed. Therefore the distance between the adjacent field lines was decrease.

3.4.3 Hall Effect Sensor Reading Versus Vertical Distance

The idea behind this experiment is to understand the Hall Effect sensor readings in relation to the vertical distance of the actuator (in this case, the finger-worn actuation ring) from the surface. This experiment has been conducted using a Hall Effect sensor and an electromagnet, which generates an average flux density on the surface from 450 to 1950 Gauss for the range of 6V to 24V with 1.9A to 7.5A of electrical current. In the experiment the power of the electromagnet was kept at a constant voltage of 10V and a driven current of 2.44A, with the sensor on the vertical axis on top of the electromagnet. The sensor reading is measured versus the distance to the electromagnet. The value of the sensor output voltage taken is the mean value in one second.

Figure 3.21 shows that the sensor is most sensitive with respect to the vertical distance from 0cm to 3cm. When the distance is greater than 3cm, the change in output is much lower. At larger distances, for example the values of 6cm and 7cm, the difference in voltage is only 0.011 volts. However such a small voltage difference is not detected by the microcontroller used for this iteration of the system. Therefore, the sensor cannot detect motion from 6cm to 7cm, but it can detect longer distance motion, e.g. moving from 6cm to 8cm.

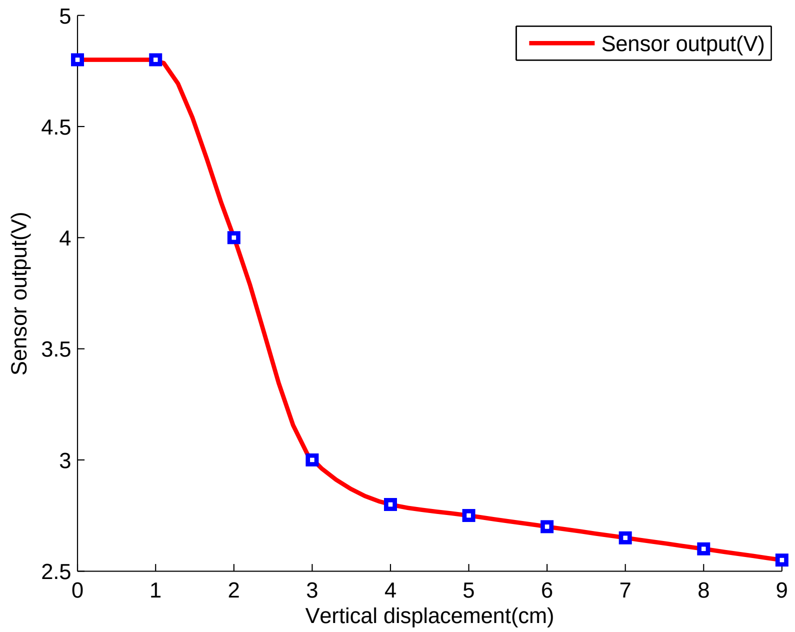

Figure 3.21: Sensor output versus vertical distance.

3.4.4 Hall Effect Sensor Reading Versus Horizontal Distance

This experiment is similar to this first experiment, but looks at horizontal distance as opposed to vertical distance. Once more keeping the power of the electromagnet constant, the sensor is placed on the vertical axis of the electromagnet at 2cm, since at this distance the sensor is most sensitive, registering the largest change in values with respect to the distance moved. An oscilloscope was used to measure the voltage output of the sensor. The sensor reading is measured against the horizontal distance to the electromagnet. The value of the sensor output voltage taken is the mean value in one second.

In this experiment the change of driven current is also recorded. After the conducting of previous experiment the electromagnet temperature increases, which in turn affects the driven current. Driven current will be used as a reference for the change of power in the electromagnet as the power of the electromagnet is directly proportional with the current. Due to this phenomenon, it is easy to compare the result by making a scaling.

This experiment has been conducted using the following settings: Zero magnetic field value: 2.490V Electromagnet driven voltage: 10V Diameter of the Electromagnet: 5cm The value of the sensor output voltage taken is the mean value in one second. Figure 3.22 shows that the sensor voltage is close to 2.5 volts (zero field voltage) after 3.5cm of displacement. Previous experiment shows that the resolution of the system cannot distinguish any smaller changes. Within 0.02 volts, the magnetic field at 3.5cm and beyond is too small to cause a change in the microprocessor. This experiment shows that the magnetic field from the

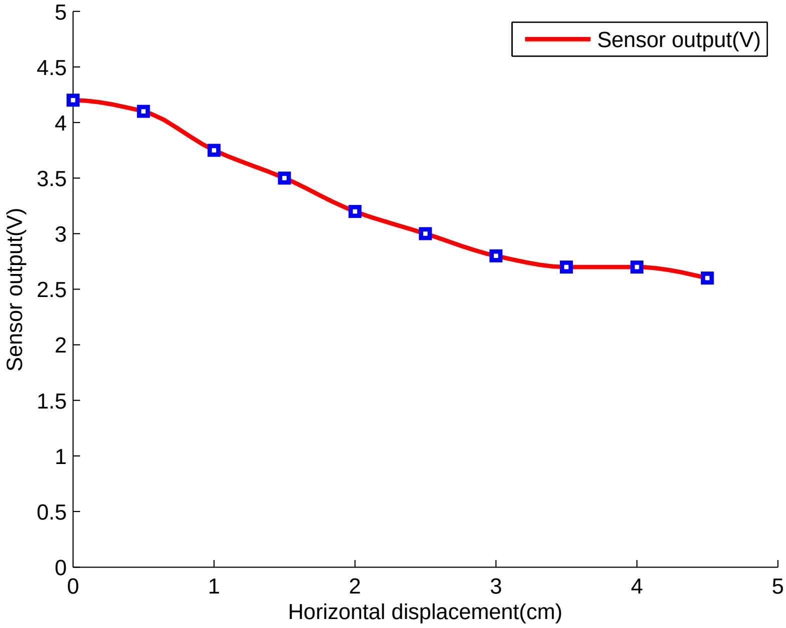

Figure 3.22: Hall Effect sensor output versus horizontal displacement.

horizontal area of the magnet is too small to be detected at the optimal vertical distance. This is advantageous for the system since the tracking system gives an almost perfect horizontal reading without external noise from the neighbouring magnets.

3.4.5 Characterization of Magnetic Hall Effect Sensor Readings Under the Influence of Multiple Magnetic Fields

In this experiment the readings of the Hall Effect sensor are measured to determine the influence of the magnetic fields generated by the electromagnets and neodymium magnets. These readings will provide the appropriate parameters for the microcontroller firmware. Previous experiments have shown that the optimum position is to place the sensor such that the readings are minimally affected by the electromagnet, while still being close enough for the sensor to be associated with the electromagnet, and in a position such as to be able to detect a neodymium magnet above its surface. This position is right next to the electromagnet, level with the top surface of the magnet.

Under these conditions, the sensor shows slight changes in readings when the electromagnet is turned on. The goal of this experiment is to determine which combinations of the two magnetic fields (electromagnet and neodymium) cancel one another, making it impossible to detect the position of the hand. The electromagnet is connected to a power supply, supplying 10V and up to 2A of current. Its output magnitude is controlled by a Pulse-Width Modulated (PWM) input to the driver circuit. It is positioned such that the field of the North Pole is directed vertically upwards and the South Pole vertically downwards.

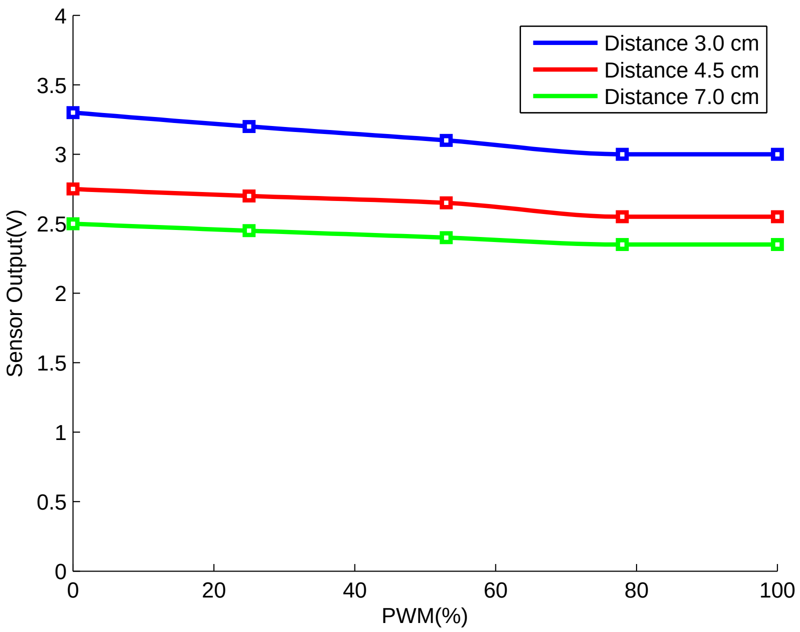

Figure 3.23: Sensor reading values obtained for different distances versus PWM.

The sensor is supplied the rated of 5V and is positioned such that it is in level with the top of the electromagnet and directly next to it. Its output is connected to an oscilloscope. A non-magnetic material at varying heights directly above the sensor holds the neodymium magnet. Its pole direction is fixed, with the South Pole facing downwards. The reading of the steady-state output voltage of the sensor is recorded using the oscilloscope, while varying the height and direction of the neodymium magnet and the PWM input to the electromagnet.

First the default sensor value is taken. Without the neodymium magnet or electromagnet influence, the reading is 2.50V. Next, with the neodymium magnet pole at South Pole (facing down), the PWM values and distances are measured.Results of this experiment is shown in Figure 3.23.

Here the strength of the electromagnets field serves to decrease the reading of the sensor, whereas the position of the neodymium magnet field serves to increase the reading of the sensor. This results in a case where the value of the sensor is unable to detect the presence of the neodymium magnet due to the electromagnets field.

From the data that gathered, this occurs in the case when the distance of the neodymium magnet is 7.0cm. If the electromagnet is off, the reading is 2.53V, but if the electromagnet is turned on, the reading falls below the 2.50V neutral value. To circumvent this problem, it is possible to use like poles instead of unlike poles, i.e. the North side of the neodymium magnet facing the North side of the electromagnet. This causes both magnets to boost each others readings, which can be compensated for by changing the sensitivity in the software. This approach has the peripheral advantages of preventing the two magnets from attracting each other and preventing the neodymium magnet from picking up the ferrofluid contained on the surface of the system. It also provides a means for haptic feedback while using the system

3.4.6 Transient response of the system

The transient state of the system is measured by recording a video using a high definition camera and measuring the delay between the time of the input and time of the maxi-mum level of actuation. The results of experiment 1 is used to take 2.3 A of current and measured the time until it reach 14.20 mm height and then the current produced to the electromagnet was cut off and measure the time taken for the liquid to settle in the surface. The results of the experiment are shown

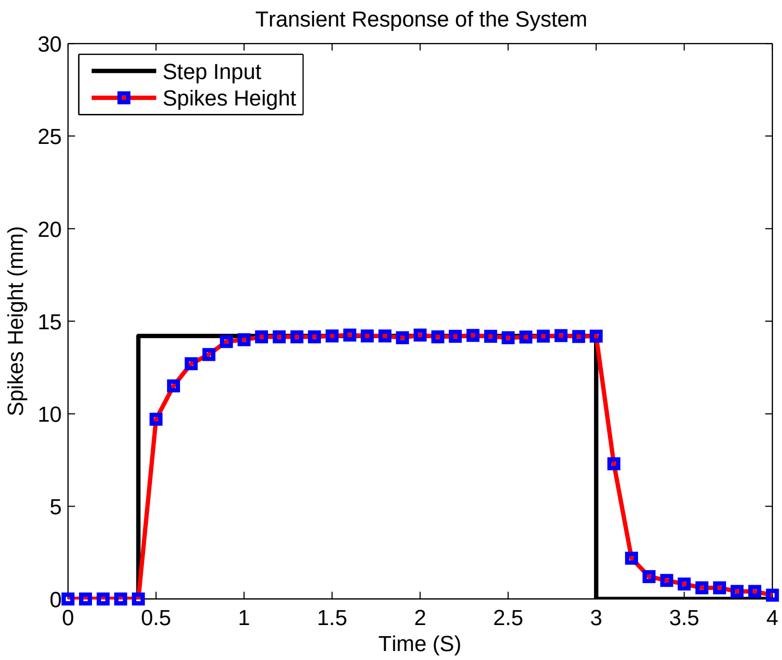

Figure 3.24: Transient response of the system

in Figure 3.24. The time that system takes to produce the expected height of ferrofluid is approximately 0.6 seconds and time it takes to settle down the liquid is approximately 0.6 seconds as well. This delay of the producing the expected result was due to many factors like actuation response time of the ferrofluid, the delay for the electromagnet's core to become magnetized, processing time of the touch input, time takes for the software driver, time taken in the micro-controller.

The results of the experiments conducted shows that the behaviour of the ferrofluid, namely the transient response and the physical height of the spikes can be controlled. This controllability offered by the interface means that it is possible to customise the behaviour of the interface depending on the user experience they wish to create.

3.5 User Evaluation

User interaction methodology has attempted to simulate some interactions that reflect both the aesthetics and playfulness of the system. Although the dramatic effects of water as a tactile surface has been previously explored [91], no precedent in regards to the interaction with ferrofluid, which has distinct fluid characteristics, has been recorded. Due to this, an adaptation of previous methods as well as trial and error was employed. Due to the messy nature of ferrofluid as well as the nature of sensing inherent to the system, a finger accessory that allowed users to interact with the fluid (without actually touching it) was used. This reduced the methods of interaction to that if simple mid-air gestures, some of which are employed in [11]. These gestures included waving and tapping. Like-polarity between the surface and fingertip magnets allowed a force resistance that made tapping a particularly compelling interaction. The haptic subsystem was also removed in order to concentrate on the visual and audio effects of the system. As a result of that third iteration of the Liquid Interfaces system was developed.

3.5.1 User Study & Method

For the fourth iteration of the system, a preliminary field test was performed in order to understand the possible challenges and limitations of studying the usability of such a unique system. This user study has attempted to measure three items. Firstly, to understand if gender affected the overall success rate users could achieve when asked to perform precise tasks using the interface. Secondly, to see if the users performance improved through repetitive use. Lastly, to gain knowledge regarding the experience of the user when interacting with the system. To find answers to these three questions, task success data recorded by the system during the performance were analysed, and then asked users to answer a Likert-style questionnaire upon completion of the tasks. With the display and input functionality of the system in mind, a simple task was designed. Similar to the hardware-based game Simon [30], users were briefed to watch a sequence of ferrofluid buttons become active and were then asked to replicate the sequence in the same order by using the mid-air gesture of pressing. Two practice rounds were allowed before data recording for the study was conducted. Two sequences of 3 patterns each were played and then mimicked by the user. The success rate of the user performing the task was recorded by the system. Both a preliminary ethnographic survey as well as a self-reporting, Likert-style post-task surveys were performed and were modelled after usability survey examples provided in "Handbook of usability testing" book [54].

3.5.1.1 Experiment Setup

For the purpose of this user study, the system was configured without haptic feedback, as seen in Figure 3.6. This was done by replacing the normal sensing subsystem of Hall Effect sensors with camera vision. New completely covered container to housed the ferrofluid was also developed for the user study. This system make sure that the liquid would not stain the participants' clothing.

Once the preliminary ethnographic survey was completed, participants then stood in front of the system with the researcher monitoring their performance. Researcher would explain the system and task during the practice rounds and would refrain from helping the user during the actual test. The computer automatically recorded the success/failure results of the user during the experiment. Once the test was finished, users were then brought to another station. At this station a computer with a self-reporting survey was presented. Users were then asked to fill out the survey, thus completing the user study. Photos of the user study setup and some of its participants are depicted in Figure 3.25.

As this preliminary user study was conducted not only to gain an understanding of the usability of the system but also explore possible challenges and limitations of studying the usability of Liquid Interface system, participants were sourced using an accidental/convenience sample model. Twenty participants (10 male, 10 female) were chosen for the study, consisting entirely of students and staff from our laboratory. Figure 3.25 represents some of these participants. Because each participant (mean age=27.8, SD=3.8) works in some way or another within an engineering laboratory as either a researcher, student or support staff, each test subject has had experience participating in studies for the testing of

Figure 3.25: User study participants using version three of the Liquid Interfaces system.

interactive systems. However, all the participant did not have any experience using this version of Liquid Interfaces system. Therefore, this was the first time each test subject has used the third version of Liquid Interfaces system.

3.5.2 Results & Analysis

All the data was analysed using StatSoft Statistica [5] and was checked for normality using Kolmogorov Smirnoff test for normality [18] and Shapiro Wilks test [98]. The first result of the experiment is the effect of gender on the number of correctly performed tasks using the Liquid Interfaces system. The gender affect was tested to see that both of the genders perform the tasks equally using Liquid Interface system.

There are some evidence that both genders are using the computers for different tasks and different interests. As an example men earning computer-science degrees outnumber women 3 to 1. Another research suggested [109] ”a world without emotions” - an image that seems to scare off girls. In 2013 [31] survey finds the women in Britain now own more tablet computers than men. Therefore, It is an interesting idea to check the Liquid Surface system can be used equally by both the genders.

Female participants completed on average of 65% of tasks successfully. Male participants completed on average 68.7% of tasks successfully. These statistics are represented in Figure 3.26. An ANOVA [34] showed that gender holds no significant effect [$F(2,20) = 0.18$, p ¡ 0.6] in regards to using the Liquid Interfaces system for the specified tasks. In terms of learning curve between the first

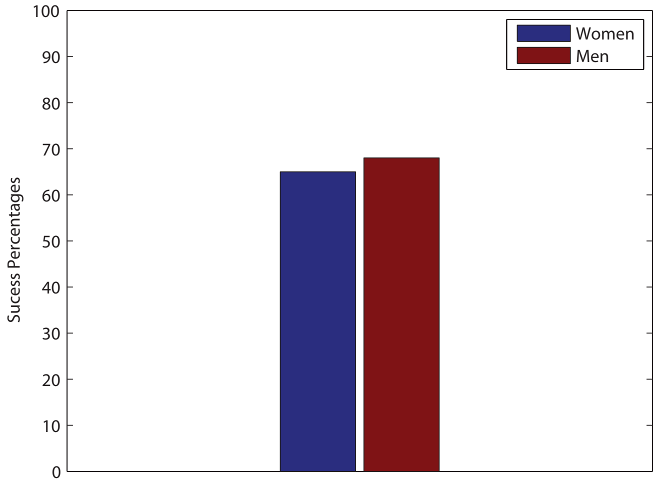

Figure 3.26: Female versus male average overall performance.

set of three tasks (tasks 1 to 3) and the last set of three tasks (tasks 4 to 6), users performed better during the second set of tasks. For the sum total of all participants, users performed an average of 13.7% better during the last three

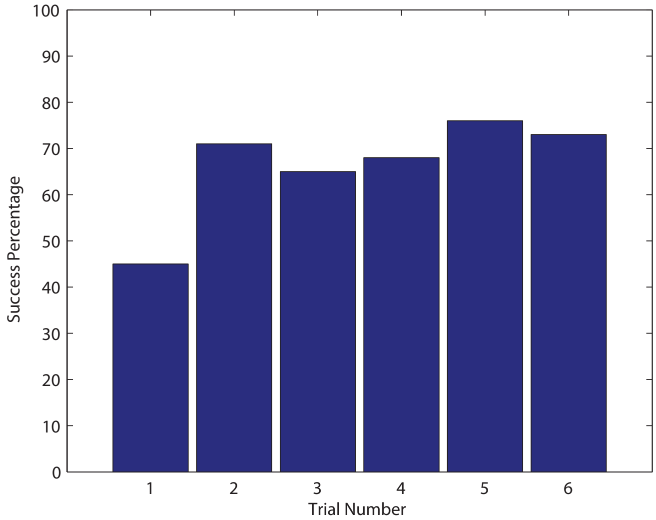

Figure 3.27: Average performance over all six task trials.

tasks compared to the first three tasks. An ANOVA showed that performance does indeed improve as users familiarize themselves with the system to significant effect [$F(2,20) = 4.3$, p ¡ 0.04] when comparing the first set of tasks performed to the second set of tasks performed. This shows that through familiarization of the system, user accuracy increased. These statistics are represented in Figure 3.27. The final, post-questionnaire included a number of statements that were presented to each user, posed in the Likert style. Some of these were:

- I thought Liquid Interfaces was easy to use (over 50% of participants rated the system 3 or higher, 1 being hard to use and 5 being easy to use)
- Liquid Interfaces has a very attractive presentation (100% of participants rated the system 3 or higher, 1 being not at all attractive and 5 being very much attractive)

- The content of the interface is clear and simple to understand (5% of participants rated 2 or lower and 95% or participants rated 3 or higher, 1 being not at all clear and simple and 5 being very much clear and simple)

- I found what I was looking for quickly and easily (10% of participants rated 2 or lower and 90% of participants rated 3 or higher, 1 being not at all and 5 being very much)

By analyzing the data, number of key lessons were learnt. As a system, users were more involved when free-playing with the material aspects of the system. When using the system to perform tasks that required specific accuracy. As a logical information system, Liquid Interfaces fails to provide the precision that more concrete representational systems provide. Due to the limited input and display capabilities of the system, users could use the system quickly but more complex interactions were limited. The reason for this is most likely the combination of the simplicity of the metaphors used in the system, as well as the design of the task users were asked to perform. Still even with these limitations outlined by users in the self-reporting survey, user unanimously enjoyed playing with the system despite its technical limitations.

3.6 Discussion

Developed to investigate the viability of using ferrofluid as a novel way of interacting with computers, Liquid Interface deviates from the use of solid materials that is ubiquitous in physical computing such as the buttons in keyboards and has the potential to be a paradigm shift in human-computer interaction (HCI) methodology. The changing of shapes on the ferrofluid, moving in tandem with the users hands in real time provides for a visual experience for the user as the three dimensional physical transformations actuating on the surface of the system are real-world and actual morphing objects.

The liquid interface system offers a new way of representation information in the physical world. Unlike the virtual and arguments reality, the shapes formed by the LI are real. Liquid interface would be able to offer a seamless means for users and performers to create animated, musical and visual compositions. This new, innovative and malleable way of representing digital information would be the next in line of research.

The simple and intuitive interaction of the LI system provides a shallow learning curve, in which the competency of the system functions can be achieved in moments, offering an additive complexity for creating a rewarding composition. LI is an interactive tool for creative expression to spark the imagination.

The latest version of the interface combines the morphable qualities of the ferrofluid with a camera based vision tracking system to produce a three dimensional interface that users can interact with by waving their hands above the ferrofluid, giving the user the ability to create shapes in the liquid without having to touch the liquid itself, thereby eliminating messiness and staining that was a common recurrence in previous versions of the interface. Applications for Liquid Interface can be a three dimensional display screen and input interface for computers at the same time.

Liquid Interfaces keeps the user engaged by using art in the form of ferrofluid sculptures to capture the audiences attention. The appeal of art and music can transcend over generations, long after the creator has passed [71]. By comparison, interfaces today have yet to captivate users in the same manner as what art and music has. No matter how advanced a new technology is, people will adapt to it quickly and once they do so, the novelty wears off. Using liquid as an interface to enhance the interactive experience in HCI methodology has the potential to engage audiences in the way art and music has. As such, the future of liquid as the next generation button in HCI is an area worth looking at.

There are some improvements can be made to the Liquid Interfaces system to provide better interactivity. Firstly, the resolution of the interface can be improved. These involve the use of smaller electromagnets in larger numbers. An increased resolution offers a better accuracy and representation of the hands gesture during interaction. This would improve upon the relationship of the user communicating with the object and user embodying the object.

Secondly, ferrofluid is just one of many viable materials. To achieve increased controllability and different visual effects, continual experimentation with other types of liquid materials such as magnetorheological (MR) and electrorheological (ER) fluids are needed to evaluate their response and suitability for Liquid Interface.

Thirdly, the current vision tracking is limited to position tracking. Adapting the system for gesture recognition will allow for multiple applications to explore different interaction methods for the system.

Chapter 4

Haptic Mouse : Magnetic Field Based Near Surface Haptic and Pointing Interface

4.1 Introduction

In touch screens, all the contents of the screen are separated by the user from a piece of glass and the contents can not be felt to the user. However, haptics may cross that border and make the contents tactile. Currently, computer applications are equipped with high resolution fancy GUIs but it can be quite disappointing for the users because they may not feel those high resolution contents like buttons or the textures. Haptics makes holistic user experience and allows the interfaces to be more pleasurable to use.

The meaning of haptic is 'relating to the sense of touch'. Haptic sense works with the motor control system of the brain to coordinate movement, and enable perception. There are two aspects of touch, cutaneous and kinesthesia. Cutaneous,refers to the senses that are related to the skin, like temperature, texture, slip, vibration, force. These features are provided by the mechano-receptors. The aspect of Kinesthesia is more about large scale forces and movements. This is what gives us the ability to understand the location and the configuration of objects and space simply through touch. Kenesthisia aspects are understood by analysing the motion, force and compliance or stiffness sensed by the receptors.

The sense of touch is perhaps the most important sense for the humans. Imagine what life would be like without touch. You would lose the control over your body, fail to grasp things or perform any motor activities. Haptics plays a key part of emotional and expressive connections.

Generally, magnetic fields are spread in the environment as 3D shapes. In previous study some haptic sensation mechanism was developed using the like polarity repulsion of magnetic fields. Further, hall effect sensor based magnetic field touch system was also developed. By improving those two systems by implementing new type of algorithms for magnet tracking and generating haptic feedbacks a novel pointing interface is developed. Which was called as the 'Haptic Mouse'.

Haptic mouse is an innovative pointing interface for computers, which provides mouse functionalities with near surface haptic sensations. The device could also be configured as a haptic display, where users can feel the basic geometrical shapes in the GUI by moving the finger on top of the device surface. These functionalities are attained by tracking the 3D position of a neodymium magnet using Hall Effect sensors grid and generating like polarity haptic feedback using an array of electromagnets. Where previously haptic sensations were felt only on top of the buttons of the haptic mouse implementations, this interface brings the haptic sensations to the 3D space.

The next sections of this chapter will discuss the system implementation and the improvements that have been made in detail and the results obtained during the experiments with the Haptic Mouse. As shown in Figure 4.1, the complete system of Haptic Mouse contains six different, but closely coupled modules as listed as follows,

- Interface Driver and Sensing System
- Haptic Feedback System
- System Firmware

The following sections provide detail descriptions about these modules.

4.2 Sensing System

4.2.1 Neodymium Magnet and Hall Effect sensors Grid

A neodymium magnet attached to the user's fingertip is used to move the mouse pointer in the screen. Then by moving the finger on top of the surface the user is able to change the position of the mouse pointer. The position of the fingertip is detected by tracking the position and movements of the neodymium magnet using an array of Hall Effect sensors. The neodymium magnet attached to the finger tip allows users to actuate the Hall Effect sensors grid which is placed below the acrylic surface. Polarity of the neodymium magnet and various gestures made by the user are identified with the help of the Hall Effect sensors grid.

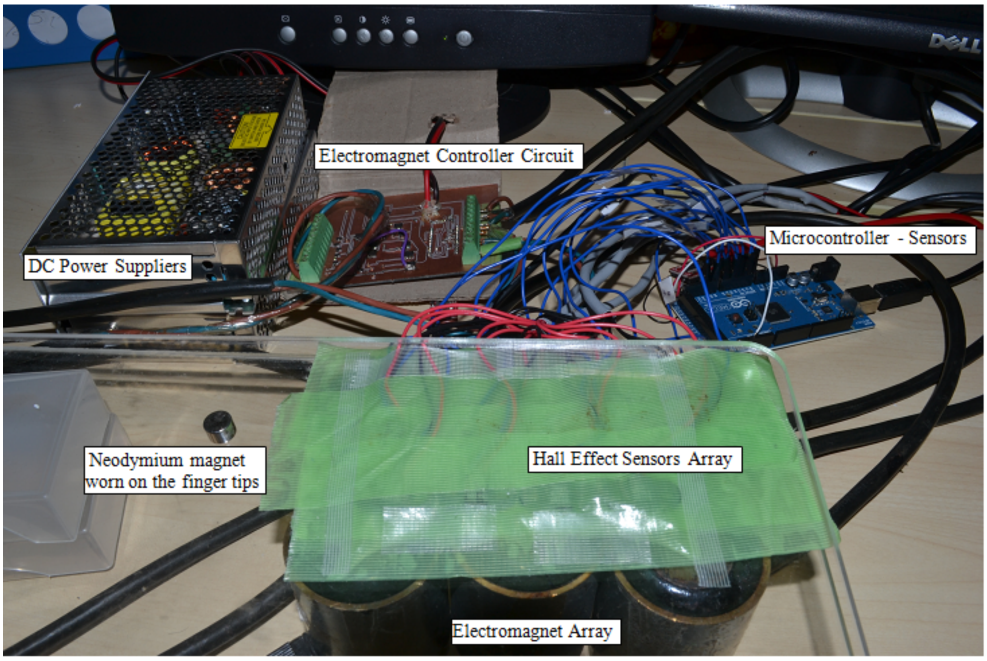

Figure 4.1: Complete system of the Haptic Mouse Implementation

Neodymium magnets could generate higher density of magnetic flux compared to other permanent magnets. As the size and weight of the permanent magnet which is going to be worn on the finger tip is important, neodymium magnets become the right kind of choice for the system. Further, if the magnet is covered with some kind of material it reduces the magnetic field and affects the accuracy of the system. To minimize this effect a ring type wearable accessory and a finger extension kind of accessory is developed.

An Arduino based microcontroller [1] has been used for processing the Hall Effect sensor readings. Analogue voltage readings of the sensors are then converted to digital values using the built-in analogue to digital converters and fed in to interface driver software to identify the gestures and commands. The Hall Effect sensor grid used in this device is a 4*3 array (4 sensors along the X axis and 3 sensors along the Y axis).

4.2.2 2D Sensing System

4.2.2.1 2D Localization Algorithm

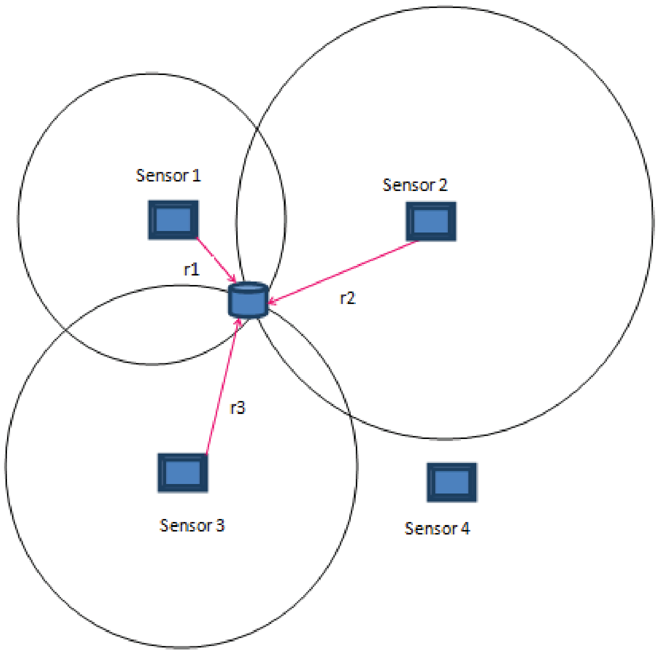

Figure 4.2: 2D Localization Algorithm - Sensor Placements

For the precise operation of the pointing device, there has to be a device driver which can integrate with the operating system. Therefore a software device driver is developed using the Windows API in Visual C++. This driver includes magnetic field based touch recognition and feedback generation algorithms. Execution flow of the device driver is illustrated in Figure 4.3.

The driver accepts the digital sensor readings from the micro-controller of the Hall Effects sensors grid as the input. When the North Pole of the neodymium

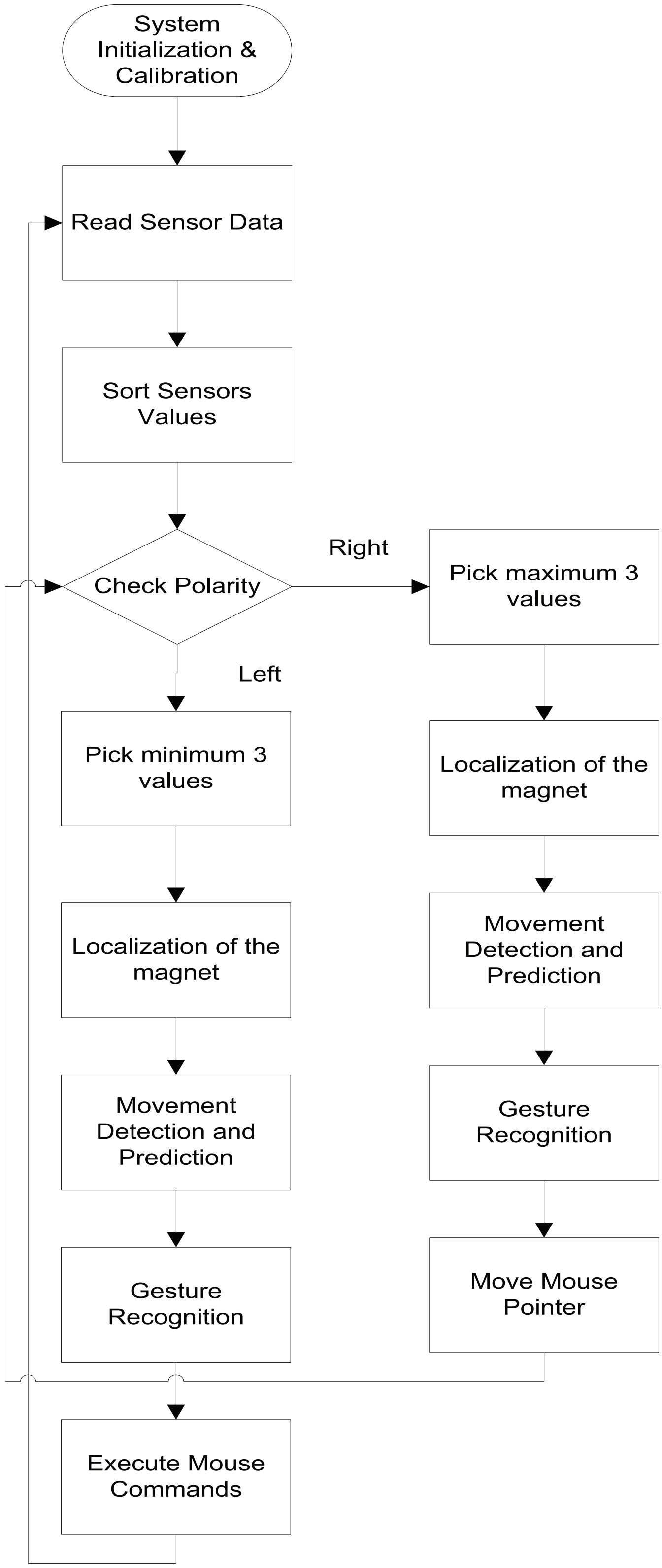

Figure 4.3: Execution flow of the interface driver software

magnet is positioned downward, sensor values are fluctuate between the range of 512 -1024 and when the South Pole is downward, sensor values are fluctuate between 0 and 512 of range. These sensor values are sorted in the descending order and if the magnet is North Pole downwards, the software searches for the sensors in the grid where it received the maximum readings. Sensors which are nearest to the neodymium magnet output the maximum values in this case. Based on those intensity values, relative distance to the neodymium magnet from the nearest three sensors is calculated. The localization algorithm of the neodymium magnet is derived from the 2D trilateration technique [57]. Trilateration [75] is the process of determining the absolute or relative locations of points by measurement of distances using the geometry of circles, spheres or triangles. Different trilateration based techniques are used in GPS, RF based indoor positioning, navigation, and survey systems.

4.2.2.2 Implementation

The space between two Hall Effect sensors is taken as 100 pixels. Physically, the distance between two sensors is 2cm for X axis and 1.36cm for Y axis. All the sensor values recorded are represented as X,Y coordinates (0-300 in X axis and 0 to 132 in Y axis). As illustrated in Figure 4.4, the distances to the neodymium magnet is calculated from the expressions found in the table 4.2.These distances can form circles and are based on their intersections, the position of the sensor can be located. To increase the probability for intersections distances are multiplied by a constant factor (which is greater than one) and this makes the three circles intersect in most of the scenarios. The current prototype uses the constant value 1.1 as the factor. This is done to taken out the sensor errors. Sometimes sensor

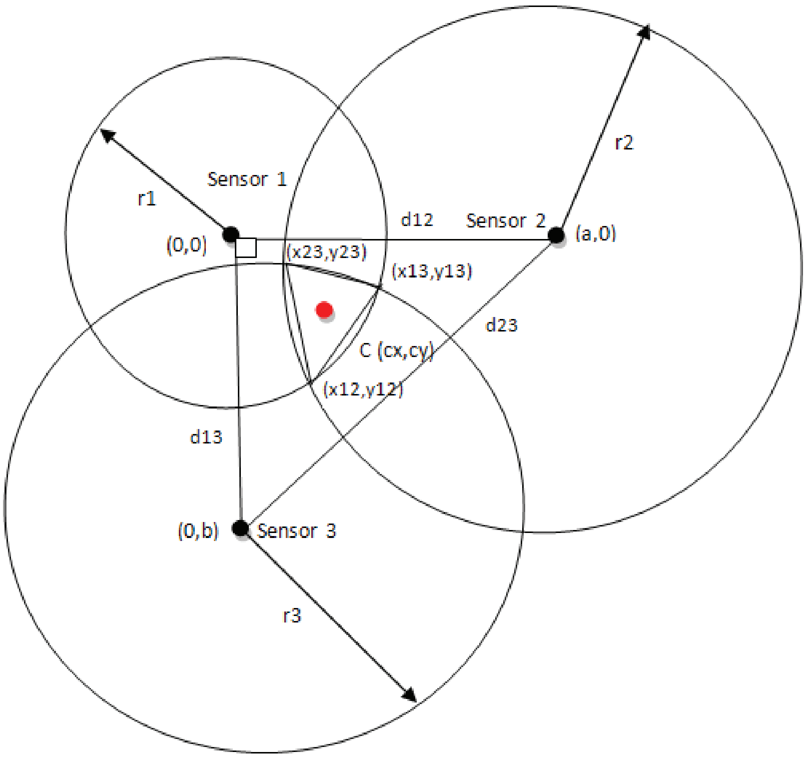

Figure 4.4: 2D Localization Algorithm - Coordinates System

errors causes lesser output voltage which results three circles are not overlapped each other in the trilateration algorithm. Therefore, the values are multiplied by a constant factor which is more than 1 (1.1 in this case). This forms a circular triangle [(x12, y12), (x13, y13), (x23, y23)] and the position of the neodymium magnet can be identified by finding its center.

Figure 4.6 shows the accuracy results of this experiment. If the sensors do not detect the magnetic field created by the neodymium magnet they output lower values. This often happens when the users hand is placed few centimeters above the surface. This causes problems for the trilateration algorithm. If three circles not intersecting it could not determined the position of the neodymium magnet. The published paper "Haptic Mouse : A Magnetic Pointing Interface with Near Surface Haptics" [58] shows the accuracy of the algorithm for different heights.

The mathematical method we derived is explained below. Let's assume that all three circles formed by the readings intersect with each other. Therefore, the conditions for the circles to intersect are as follows.

$$r_1 - r_2 < d_{12} < r_1 + r_2 \tag{4.1}$$

$$r_2 - r_3 < d_{23} < r_2 + r_3 \tag{4.2}$$

$$r_1 - r_3 < d_{13} < r_1 + r_3 \tag{4.3}$$

By following Fewells [33] method to calculate area of circular triangles, we can calculate the coordinates of the intersection points, (x12, y12), (x13, y13) and (x23, y23) as follows. By assuming the origin of the coordinate system is placed at circle 1 and the X axis is passed through the center of the circle 2,

$$x_{12} = \frac{r_1^2 - r_2^2 + d_{12}^2}{2d_{12}} \tag{4.4}$$

$$y_{12} = \frac{1}{2d_{12}} \sqrt{2d_{12}^2(r_1^2 + r_2^2) - (r_1^2 - r_2^2)^2 - d_{12}^4} \tag{4.5}$$

By assuming origin of the (x,y) system is located at the center of the circle 1 and x axis passes through center of circle 3,

$$x'_{13} = \frac{r_1^2 - r_3^2 + d_{13}^2}{2d_{13}} \tag{4.6}$$

$$y'_{13} = \frac{-1}{2d_{13}} \sqrt{2d_{13}^2(r_1^2 + r_3^2) - (r_1^2 - r_3^2)^2 - d_{13}^4} \tag{4.7}$$

By transform back to the (x,y) coordinates system and obtaining (x13, y13),

$$x_{13} = x'_{13} \cos\theta - y'_{13} \sin\theta \tag{4.8}$$

$$y_{13} = x'_{13} \sin\theta - y'_{13} \cos\theta \tag{4.9}$$

$$\sin\theta = \sqrt{1 - \cos^2\theta} \tag{4.10}$$

$$\cos\theta = \frac{d_{12}^2 + d_{13}^2 - d_{23}^2}{2d_{12}d_{23}} \tag{4.11}$$

By assuming origin of the (x,y) system is located at the center of the circle 2 and x axis passes through center of circle 3,

$$x''_{23} = \frac{r_2^2 - r_3^2 + d_{23}^2}{2d_{23}} \tag{4.12}$$

$$y''_{23} = \frac{1}{2d_{23}} \sqrt{2d_{23}^2(r_2^2 + r_3^2) - (r_2^2 - r_3^2)^2 - d_{23}^4} \tag{4.13}$$

By transform back to the (x,y) coordinates system and obtaining (x23, y23),

$$x_{23} = x''_{23} \cos\theta'' - y''_{23} \sin\theta'' + d_{12} \tag{4.14}$$

$$y_{23} = x''_{23} \sin\theta" - y''_{23} \cos\theta'' \tag{4.15}$$

$$\sin\theta'' = \sqrt{1 - \cos^2\theta''} \tag{4.16}$$

$$\cos\theta'' = \frac{d_{12}^2 + d_{23}^2 - d_{13}^2}{2d_{12}d_{23}} \tag{4.17}$$

and are the angles between the x axis and respective abscissas of the two additional coordinate systems. After calculating the intersections of the circular triangle we can obtain the center of the triangle where the neodymium magnet is located as follows.

$$C_x = \frac{(x_{12} + x_{13} + x_{23})}{3} \tag{4.18}$$

$$C_y = \frac{(y_{12} + y_{13} + y_{23})}{3} \tag{4.19}$$

By finding the position of the neodymium magnet and comparing it with the next position, the relative X,Y displacement can be calculated. Then these relative displacements are mapped to the last coordinates of the mouse cursor position and the cursor is moved to the new X,Y location.

In the case of identifying mouse commands, firstly, the driver identifies the neodymium magnet which is placed South Pole downwards by reading the digitally converted values. If the magnet is South Pole downwards, the software driver searches for the three minimum sensor reading values and determines the coordinates of those sensors. Then, the distance to the neodymium magnet from each sensor is calculated and its position is determined. The movement path of the neodymium magnet is tracked and if the path follows the gestures defined for the mouse commands, the driver activates the appropriate commands. As the final step, it updates the Electromagnet controller circuit with the necessary vibration pattern which eventually provides the user with the vibration feeling.

In the case of sensing the shapes, the driver software keeps a selected vibration pattern until the user moves the mouse cursor on top of the interested object in the screen. Once the cursor is moved away from the object boundary, the driver sends commands to the microcontroller of the electromagnet controller circuit to change the output frequency.

4.2.2.3 Results

A. Hall Effect sensor reading versus horizontal and perpendicular distances to the neodymium magnet

Distance (mm)	X	Y	Z
0	963	960	955
2.5	933	933	931
5	895	893	898
7.5	840	839	835
10	765	760	757
12.5	672	675	665
15	635	635	636
17.5	597	588	590
10	563	565	564
22.5	543	542	543
25	528	527	523
27.5	519	518	530
30	513	514	516

Table 4.1: Hall effect sensor readings for the X,Y and Z axis

The objective of this experiment is to investigate the variation in the magnetic field strength vs. the distance of all three axes and determine the strength of the magnetic field needed to be produced by the neodymium magnet to achieve the desired tracking ability. The experiment is conducted by positioning the neodymium magnet on top of the Hall Effect sensor and measuring the output readings at various distances (Taking a reading after moving away from the center of the sensor by 2.5 mm in a particular axis at a time) in all three axes and results are shown in the Table 4.1. According to the results shown in Figure 4.5, it is clear that sensor reading values follow non-linear curves, but the readings are approximately the same along the X and Y axes. Therefore based on the X and Y axis sensor readings, a set of equations is derived to calculate the distance

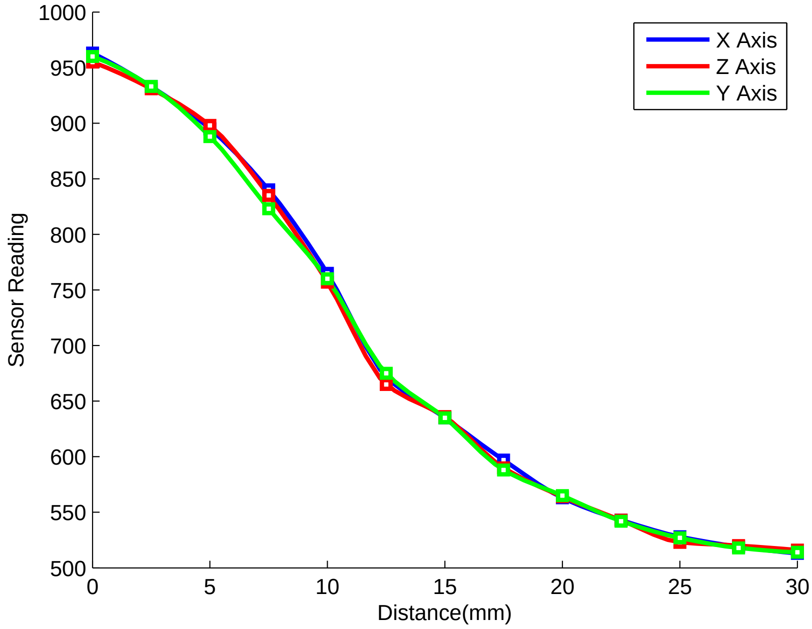

Figure 4.5: Plot of Sensor Output vs. perpendicular distance to the neodymium magnet

between the sensor and the neodymium magnet which is presented in the Table 4.2. These expressions are used to calculate the distance values needed by a 2D trilateration based localization algorithm to obtain the position of the neodymium magnet.

Distance (mm)	M	C	Expression
0 - 2.5	-12	963	Y = -12X + 963
2.5 - 5	-15.2	973	Y = -15X + 971
5 - 7.5	-22	1005	Y = -22X + 1005
7.5 - 10	-30	1065	Y = -30 + 1065
10 - 12.5	-37.2	1137	Y = -37.2X + 1137
12.5 - 15	-14.8	857	Y = -14X + 857
15 - 17.5	-15.2	863	Y = -15.2X + 863
17.5 - 20	-13.6	835	Y = -13.6 + 835
10 - 22.5	-8	723	Y = -8X + 723
22.5 - 25	-6	678	Y = -6X + 678
25 - 27.5	-3.6	618	Y = -3.6X + 618
27.5 - 30	-2.4	585	Y = -2.4X + 585

Table 4.2: Expressions to determine the distance between the hall effect sensor and neodymium magnet based on the hall effect readings

B. Accuracy test of the 2D localization algorithm

The purpose of this experiment is to measure the accuracy of sensor readings and algorithms written in the interface driver software. This experiment is conducted by moving the neodymium magnet on top of the device surface towards for direction as four straight lines at 3 different heights respectively; 0cm, 2cm and 4cm. Readings of the surface level are illustrated in Figure 4.6. According to the results obtained, the 2D localization algorithm is capable of detecting the the position accurately more than 90% of points with less than 5% of error. Mouse cursor position is updated only when there are two adjacent accurate neodymium magnet position readings exists and then calculate the X,Y displacement from the previous cursor position. This improved the accuracy of the movement of the mouse cursor. When the neodymium magnet is placed from 2 cm above the device surface, sensors are only capable of tracking the position of about 60% of the movements. At 4cm above the device surface, the sensor array is only able to track the position of the neodymium magnet less than 40% of the movements. Therefore detecting the cursor movement at this height is fairly inaccurate. Because the interface driver has to cancel out inaccurate localization data and use only the accurate data to move the mouse pointer.

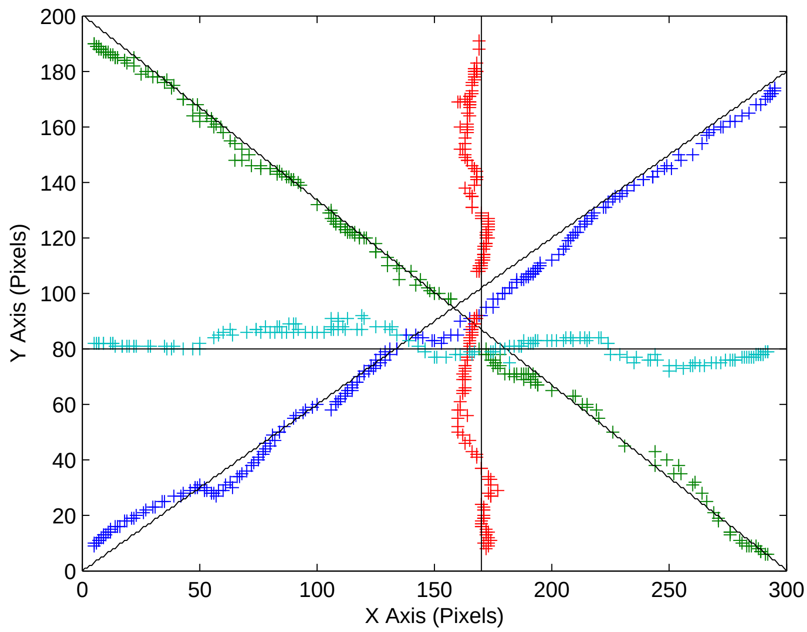

Figure 4.6: Accuracy test of the X and Y axes for the 2D algorithm

4.2.3 3D Sensing System

4.2.3.1 3D Localization Algorithm

It is crucial to detect the correct position of the neodymium magnet over time because failing to localize the magnet interrupts the continuous movement of the mouse pointer. Initially, a 2D localization algorithm is presented to determine the position of the magnet. However, its accuracy is limited to the surface of the device, as the system fails to consistently detect the magnet once the neodymium magnet was more than 20mm above the surface. To overcome the shortcomings of the previous algorithm and to look for the possibility of detecting 3D gestures, a new 3D localization algorithm is developed.

4.2.3.2 Implementation

According to the results shown in Table 4.2, it is clear that the sensor reading values follow non-linear curves but along the X,Y and Z axes the readings are approximately the same. As shown Figure 4.7, the distances to the neodymium magnet from a sensor can be illustrated as circles or a spheres. Data from a single sensor helps to narrow the possibility of the neodymium magnet's position down to a large area of sphere around the particular sensor. Adding data from a second sensor narrows position down to the region where two spheres overlap. Adding data from a third sensor provides two possible points where the magnet can be exists. However, in this setup we place all the sensors such as Z=0 and coordinates of the two possible points becomes (x,y,z) and (x,y,-z). Since the magnet is placed on top of the surface we have the freedom to select (x,y,z) as the correct position. Further, to simplify the calculations, the equations are formulated as the location

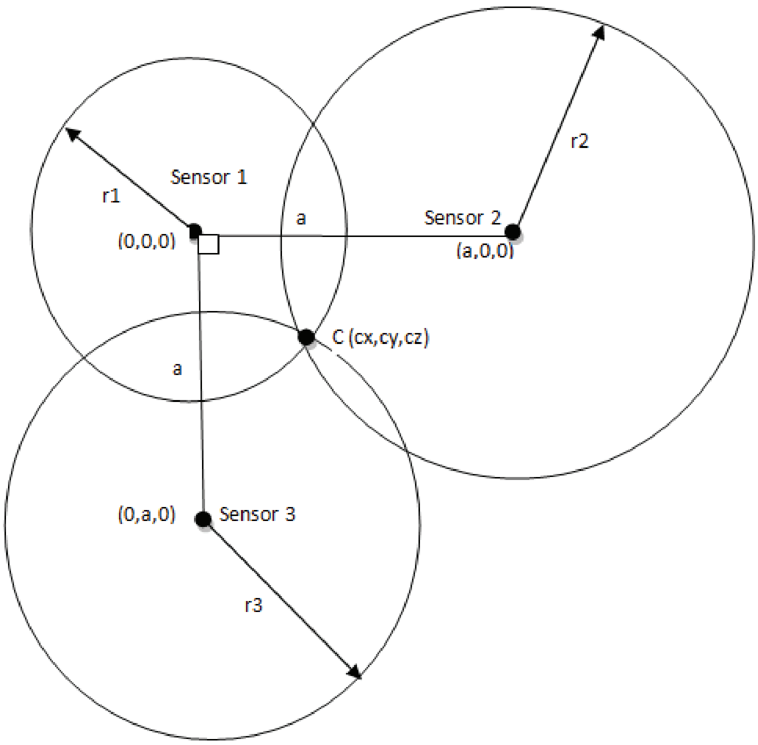

Figure 4.7: 3D Localization Algorithm - Coordinates System

of the sensor which forms a right angle triangle (Sensor 1) is at the origin, and one other is on the x-axis (Sensor 2). By using the general equation for spheres,

$$r^2 = x^2 + y^2 + z^2 \tag{4.20}$$

We write the expressions for the S1, S2, and S3 as follows

$$r_1^2 = x^2 + y^2 + z^2 \tag{4.21}$$

$$r_2^2 = (x-a)^2 + y^2 + z^2 \tag{4.22}$$

$$r_3^2 = x^2 + (y-a)^2 + z^2 \tag{4.23}$$

By subtracting the third equation from the second equation we can obtain a solution for x,

$$x = \frac{r_1^2 - r_2^2 + a^2}{2a} \tag{4.24}$$

We assume that S1 and S2 spheres intersect in more than one point. In this case substituting the equation for x back into the equation for the S1 produces the equation for a circle, the solution to the intersection of the first two spheres,

$$y = \frac{r_1^2 - r_3^2 - x^2 + (x-a)^2 + a^2}{2a} = \frac{r_1^2 - r_3^2 - 2ax + 2a^2}{2a} = \frac{r_1^2 - r_3^2}{2a} + (a-x) \tag{4.25}$$

By rearranging the formula for the first sphere to find the z-coordinate,

$$z = \pm\sqrt{r_1^2 - x^2 - y^2} \tag{4.26}$$

After finding the solution relative to the point which causes a right angle triangle (sensor 1), the position of the neodymium magnet to the original three dimensional Cartesian coordinate system is transformed using the coordinates of S1.

4.2.3.3 Results

The accuracy of the 3D localization algorithm is evaluated similar to the 2D algorithm. Hall Effect sensor grid used in this device is a 4*3 array (4 sensors along the X axis and 3 sensors along the Y axis). The space between two Hall Effect sensors was taken as 100 pixels. Therefore, all the sensor values recorded are represented as X,Y coordinates (0-300 in X axis and 0 to 200 in Y axis). This experiment is conducted by moving the neodymium magnet on top of the device surface along four straight lines which are randomly picked. The lines used were Y=80,Y=(3/5) X, Y= -(2/3)X +200 , X=170.Two rulers and a digital Vernier caliper are used to place the Neodymium magnet in the correct position. The result of the experiment is illustrated in the Figure 4.8 and Figure 4.9.

According to Figure 4.9, the sensors are capable of detecting the motion of the neodymium magnet in near linear fashion on the surface. Further, the sensors manage to detect the position of about 80% of points with less than 10% error. These lines do not reflect the movements of the mouse cursor. Mouse cursor position is calculated by adding the difference of the X,Y displacement between

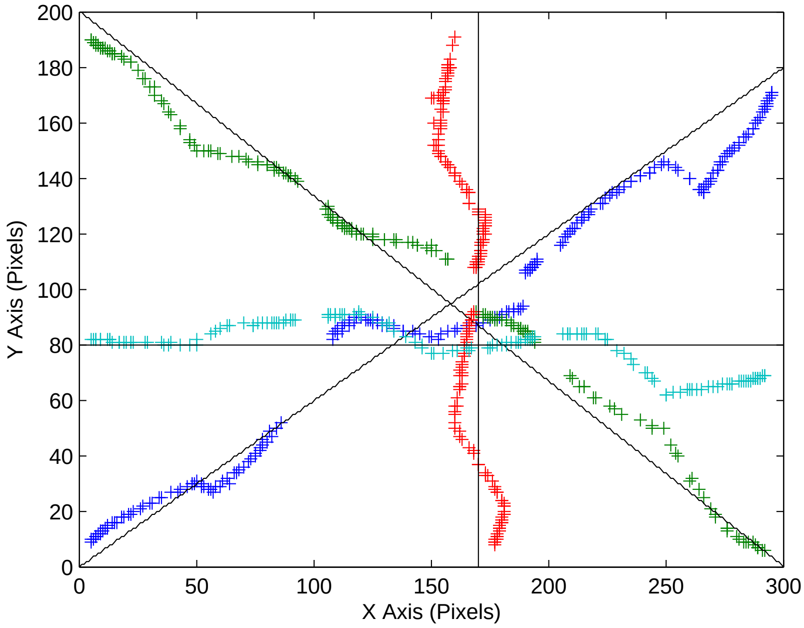

Figure 4.8: Accuracy test of the X and Y axes for the 3D algorithm

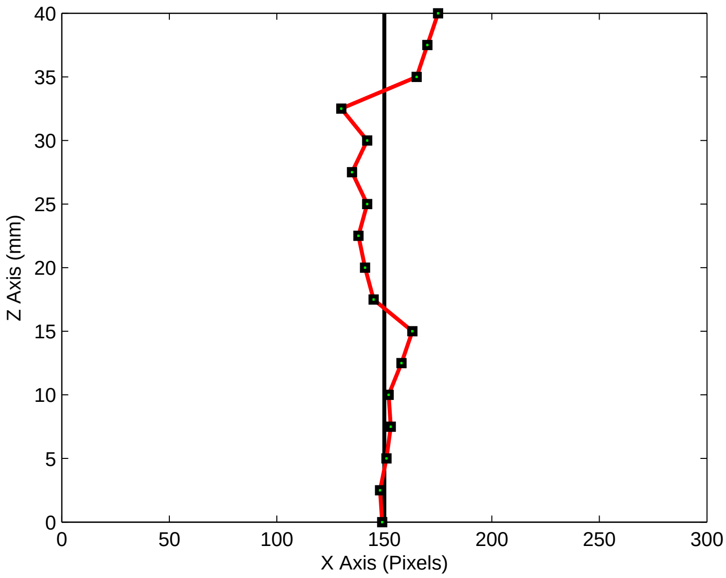

Figure 4.9: Accuracy test along the Z axis

two neodymium magnet position readings but, the accuracy of the movement of the mouse cursor is further improved by canceling out differences above a certain threshold value. Figure 4.9 also shows the position detection readings of the neodymium magnet along the Z axis up to 4cm above the device surface. Sensors are able to track the position with good accuracy; however, increasing the height from the surface level along the Z axis sensing module causes a loss of accuracy. This may be due to two reasons, the limitations of the Hall Effect sensors and inaccuracies of the 3D localization algorithm.

4.3 Haptic Feedback System

Haptic Mouse provides attraction and repulsion sensations by changing the polarity of the electromagnets. Polarity is changed by swapping the positive and negative voltage supply to electromagnets using a controller circuit. When the neodymium magnet is worn on the fingertips and the electromagnet array positioned in the opposite polarity (N S or S - N) the user feels an attraction towards the device surface. The user feels the repulsion sensation when those magnets are in like polarity (S - S or N-N) positions.

Vibration sensations are provided by setting up neodymium magnet and magnetic array in a like polarity position and then rapidly switching on and off the electromagnetic array in certain frequencies. This rapid switching on and off dynamically changes the magnetic field it produces and affects the static magnetic flux developed by the neodymium magnet worn on the finger tips. While electromagnet is switched off neodymium magnet comes down but when the electromagnet is switched on it rises and this is felt by the user as a vibration.

4.3.1 Implementation

This part of the system consists of six electromagnets. The magnet controller circuits are identical to the MOSFET based circuits used in the third version of the Liquid Interfaces system. Arduino based microcontroller is used to send and receive control signals between the computer and the circuits. As the total power required by the electromagnets array is high at 6V and 13A, it becomes necessary to control the power supplied to the electromagnets via a relay circuit. The relay circuit acts as a mechanism that is able to switch on a much larger power to drive the electromagnets. For this to power up the electromagnets, six N-Type MOSFET [7] are used, one for each electromagnet.

The software Interface Driver sends a 20 character length data frame for every 10ms via the serial connection to the microcontroller to activate the required electromagnets. These data frames are interpreted as commands to turn on the electromagnets that correspond to the Haptic feedback sensations felt by the user. Due to the limitations of the electromagnet, the maximum frequency that can be achieved is 100 Hz. Therefore, different frequencies between 5 Hz to 100Hz are used to provide different Haptic sensations to the user.

4.3.2 Results

Height of Haptic sensation felt vs. Pulse Width Modulation for different voltage levels

The purpose of the experiment is to evaluate the relationship between the PWM and the maximum height that haptic sensations can be sensed above the device surface by running electromagnets in three different voltage levels. With the results, the PWM values and voltage levels that correspond to achieve haptic sensations at a certain heights can be determined. In addition, the optimal PWM values that need to be set during actuation can be verified.

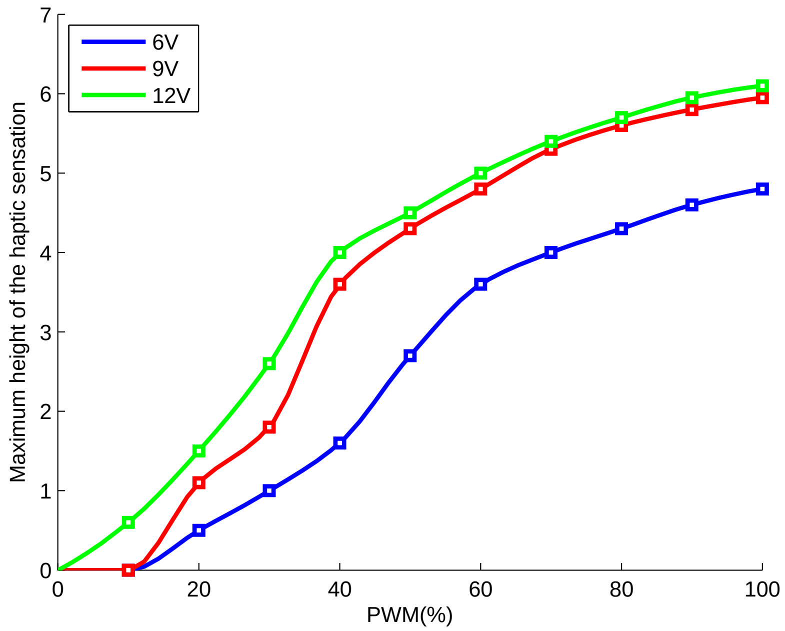

Figure 4.10: Plot of the maximum haptic sensation height achieved vs. PWM values

As shown in Figure 4.10, the relationship between the PWM and the maximum height that haptic sensation can be sensed follows an increasing linear trend in all three different voltage levels, suggesting that the system is linearly controllable. However, it is noted that the haptic sensations start to be felt from PWM running on 11% for 6v and 9v mode, but when electromagnets operate on 12v, the haptic sensations can be felt at 0.6 cm. Under this configuration, the haptic sensation is only limited to the surface. When the PWM values are between 90% and 100%, it is hard to notice the maximum difference of the actuation for 9v and 12 v. With these results we are able to provide haptic sensations up to 6.1cm above the device surface. However, by changing the type of the electromagnets, it may be possible to increase the height that haptic sensations can be felt.

4.4 Discussion

Figure 4.11: Users use the Haptic Mouse interface to play games

Haptics is the branch of virtual reality that refers to the sense of touch. It lets the user interact with the virtual environment by means of force through a haptic interface. Compared with visual interfaces, haptics prove to be more challenging. Indeed, visual interfaces display an environment to the user, and the users vision cannot influence the interface. Haptic interfaces give force to the user, but the user influences the interface as well as by the force he applies. There is an active interaction between the user and the interface. This bidirectional flow of information makes haptics a challenge.

The haptic mouse system is improved as a game play interface exhibited at the Art Science Museum in Singapore. Three open source games are selected and combined with the haptic mouse driver. Haptic mouse interactions is also

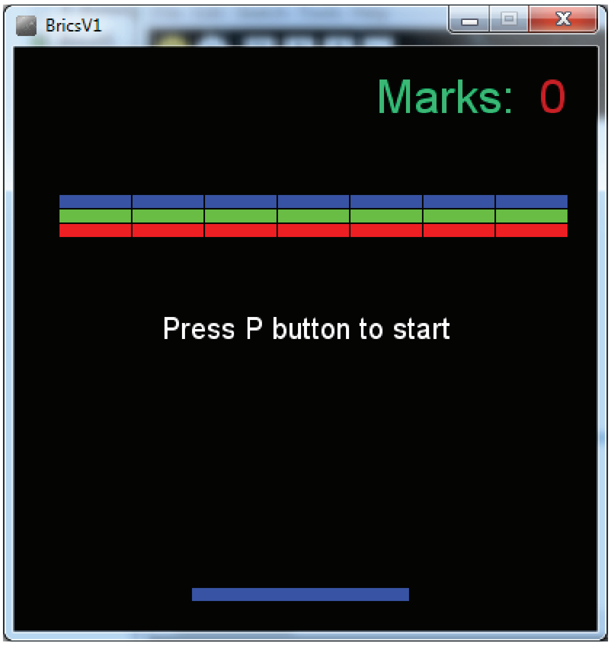

Figure 4.12: Bricks

changed to perform like a pointing stick interface.

The three games selected are Brics, Vitage Pong and Maze. Bricks game utilizes X axis movements of the mouse pointer while Vintage Pong games utilizes Y axis movements. Maze game utilizes both X and Y movements of the mouse pointer. When there is a collusion between the objects, notifications of haptic feedback are produced by the interface. These three games are played by more than 70 people in the exhibition. Out of 70 people, 46 played the Bricks game, 13 persons played Vintage Pong Game and 11 persons played the Maze game.

To get an idea of how users utilize the surface area of the interface the position of the neodymium magnet is recorded while users played the Maze game. The surface area is divided as 6*4 grid. Table 4.3 shows the percentages that users positioned the neodymium magnet in the surface.

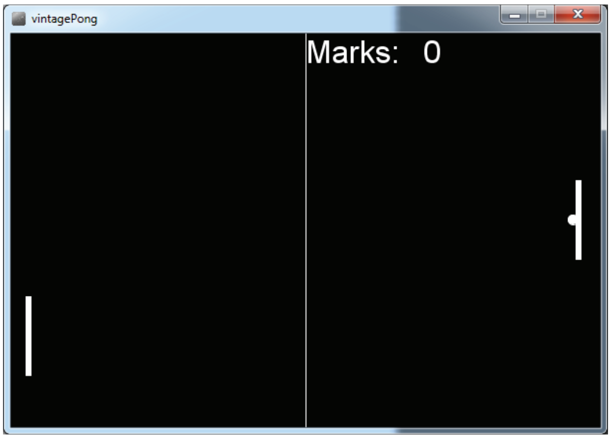

Figure 4.13: Vintage Pong

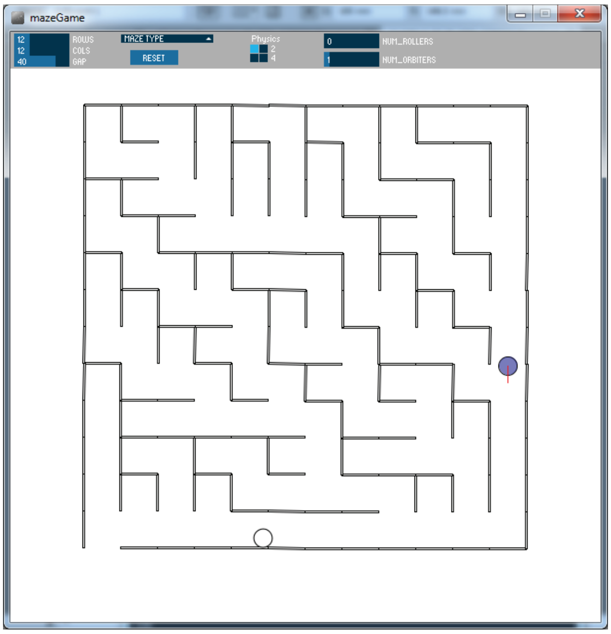

Figure 4.14: Maze

	X1	X2	X3	X4	X5	X6
Y1	2.269693%	2.7147307%	2.9372497%	5.4294615%	6.0302625%	5.838006%
Y2	4.47263%	2.2002670%	2.9345794%	1.8246553%	2.93992%	3.547632%
Y3	2.010681%	3.5576324%	5.6270583%	4.3337783%	3.710365%	2.027592%
Y4	7.262127%	8.372051%	7.991099%	4.8452368%	3.2265244%	4.289632%

Table 4.3: Utilization of the device surface by the users while playing Maze game

In order to get a better understanding on the usability of this kind of interface, a user study needs to be conducted. The results of that can be used to identify the ideal variables that will make for an optimum user experience. Several possible problems to look at include whether the loss of haptic feedback will affect the user experience, such as resting the hand on the device surface once using the device rather than keep some distance above the surface become more easy and productive, successfulness of mapping clicks and scrolling for gestures are needed to be answered.

The haptic feedback resolution of the interface can be improved. These involve the use of smaller electromagnets in larger numbers. An increased resolution offers a better accuracy and representation of the virtual objects in the computer screen when the device used as a haptic display. This would improve upon the relationship of the user communicating with the object and user embodying the object.

This device can be improved as an interface for visually handicapped who rely mostly on touch sensation. In order, to improve to this level of proficiency, this system is required to minimize the size of the electromagnets and increase the density of electromagnets packed in the electromagnets array which will provide a better resolution. This device could also be improved as an easy learning tool for children, which can be used to draw some basic shapes or characters that will enhance the interactive enjoyment. The neodymium magnet could be replaced with other forms of magnetized materials in future.

Chapter 5

Pulse : Exploring the effects of Electromagnetic Fields on Human Skin

5.1 Introduction

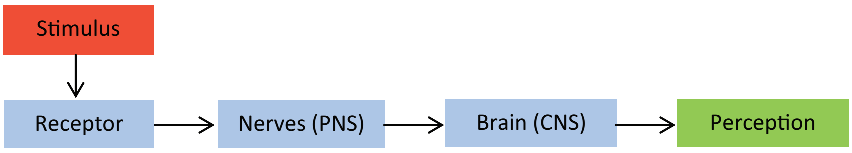

Figure 5.1: Traditional Human Computer Interfaces

User Interfaces can be considered as a key aspect in the field of Human Computer Interaction. Traditional user interfaces usually stimulate the receptors of the human nervous system as shown in Figure 5.1. Unconventional Human Computer Interfaces (UHCI) use input and output methods that are not commonly used to connect man and machine [17]. This study is focused on developing a magnetic user interface which can stimulate the human nervous system. Therefore, this research can be categorized as an Unconventional Human Computer Interface as can be seen in Figure 5.2.

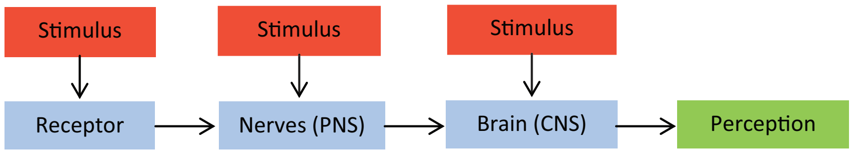

Figure 5.2: Unconventional Human Computer Interfaces

Researchers have suggested that it is possible to stimulate nerve pathways [72] and produce perceptions in brain [13]. With these results of such experiments, it seems a new era in human computer user interfaces is emerging; there is a move towards the interfacing of digital devices with the human brain.

After a stimulus received from the environment by the receptors, the energy of the stimulus is converted to a simple form of electricity and passed into the neurons. The subsequent neurons are connected via nerve fibres. Neurons are considered as the basic transmitting units of the nerves and basic building blocks of the human brain. The structure of a neuron is illustrated in the figure 5.3. The nucleus of the neuron is placed inside the cell body. Synapse and Dendrites are making the connection between two neurons with a thin gap. The dendrites works as the neuro-receivers of the information from the other neurons. The axon is a special part of a neuron which extends the cell body towards the other neurons. Synapses are placed at the end of the axon which looks like a set of terminals and emits neurotransmitters. Neurotransmitters transport the neural signals in chemical form and travel the short gap between the synaptic terminals of the

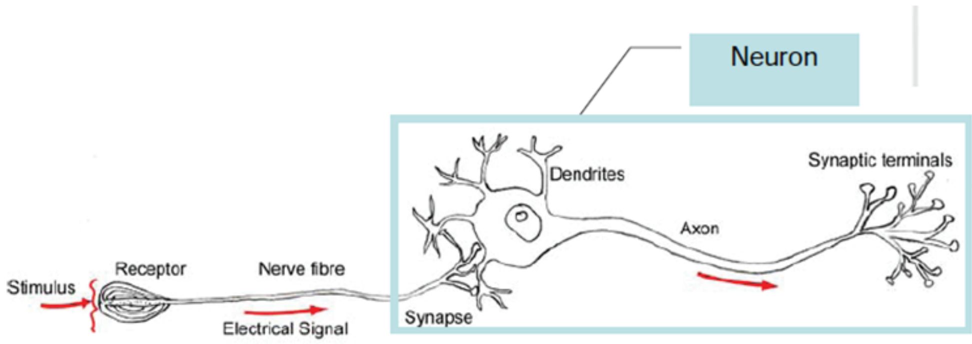

Figure 5.3: Structure of a neuron

firing neuron and the dendrite endings of the receiving neuron. It then attaches to the dendrites. From there the neural information travels further again as electrical signal. Most importantly this signal flow is unidirectional.

The aim of the study is to explore the possibilities of generating some kind of sensation on the human skin by stimulating nerve cells using magnetic fields. If a nerve cell is stimulated, the trans-membrane voltage changes in two ways. The stimulation may be,

- **Depolarizing** (characterized by a change of the potential inside the cell relative to the outside in the positive direction, and hence by a decrease in the normally negative resting voltage) or

- **Hyperpolarizing** (characterized by a change in the potential inside the cell relative to the outside in the negative direction, and hence by an increase in the magnitude of the membrane voltage). [72]

The neuron cells use the membrane potentials to send signals from organs to the brain and vise-versa. Due to sodium ions, the potential changes of the membrane takes place within a thousand of a second and these electrical current passes to the brain by rapidly travelling along the nerves. There is a threshold to activate the transmembrane potential. If the signal is lower stimulation signals doesn't flow to the nearby neurons. Therefore, these kinds of stimulus are called as passive stimulus. If the external stimulus is strong enough to overcome the threshold those are considered as the active stimulus. Only the active stimulus becomes signals which travel to the brain.

Transcranial Magnetic stimulation [52] is a method for stimulating excitable tissue with an electric current induced by an external time-varying magnetic field. It is important to note here that, as in the electric and magnetic detection of the bioelectric activity of excitable tissues, both the electric and the magnetic stimulation methods excite the membrane with electric current. The former does that directly, but the latter does it with the electric current which is induced within the volume conductor by the time-varying applied magnetic field.

The reason for using a time-varying magnetic field to induce the stimulating current is, on the one hand, the different distribution of stimulating current and, on the other hand, the fact that the magnetic field penetrates unattenuated through such regions as the electrically insulating skull. This makes it possible to avoid a high density of stimulating current at the scalp in stimulating the central nervous system and thus avoid pain sensation. Also, no physical contact of the stimulating coil and the target tissue is required, unlike with electric stimulation.A magnetic stimulator is a coil that can be placed near to the skin. With a strong and rapidly changing magnetic field it is possible to induce current in neural tissues. The principle of a magnetic stimulator is illustrated in Figure 5.4.

Usually the effective stimulation depth is considered as 50mm. However for stimulation of nerve placed in the finger is possible with this technique. TMS

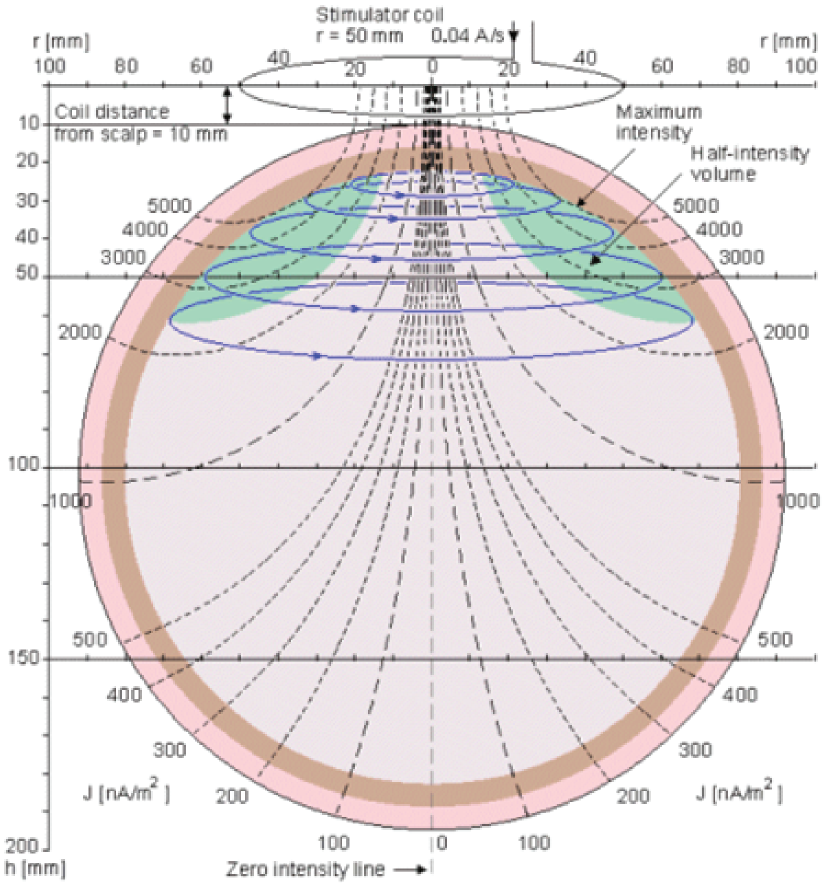

Figure 5.4: magnetic field generated by a single coil magnetic stimulation device

has been tested as a treatment tool for various neurological disorders by stimulating the brain. Studies have also shown that low frequency electromagnetic field increases the rate of wound healing on the skin and reducing pain in the process. However, the visible immediate effects of these electromagnetic fields have not been explored presently. Through this study the visible effects of pulsed electromagnetic fields on human skin will be explored.

Rest of the chapter discuss mainly two parts, the initial steps that have been taken to investigate the magnetic flux patterns on different types of coils, the latter portion presents the user study results of low frequency pulsed electromagnetic fields on the human skin.

5.2 Technical Section : The Study of Magnetic Flux Patterns

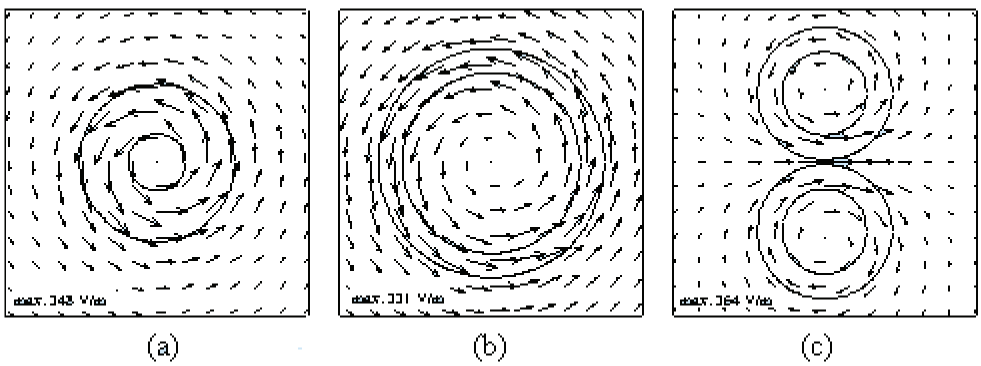

Figure 5.5: Magnetic Field Directions

The geometric shape of the coil affects the focalization, shape and depth of cortical penetration of the magnetic field(Figure 5.5). The main issue for the

TMS method is the focalization of the stimulation. Another issue is the low efficiency of power transfer from the coil to the tissue. To address these issues, a suitable shape of the stimulation coil needs to be properly designed. Some examples of the stimulation coils are round coils, figure eight (butterfly) coils, double-cone coil, four-leaf coil. The figure-eight coil results in a focal pattern of the stimulation, double-cone is suitable for deeper penetration, and four-leaf is used for stimulation of peripheral nerves. For human fingers, circular coils are chosen to experiment as they provide evenly distributed fields around them. Often an electromagnet is wrapped around a core of ferromagnetic material like steel, which enhances the magnetic field produced by the coil.

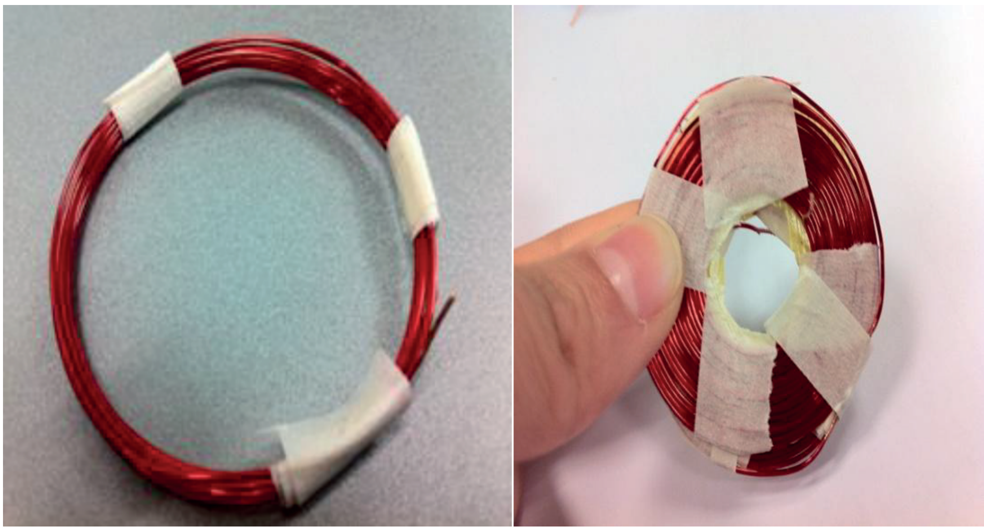

Figure 5.6: Multilayer cylinder coil (left) and Flat Coil (right)

Magnetic coil design is very important in the TMS technique. Precise spatial localization of stimulation sites is the key of efficient functional magnetic stimulations. Different types of coils have been developed using copper wires with a variety of sizes and inductance to analyze the coil properties. Experiments

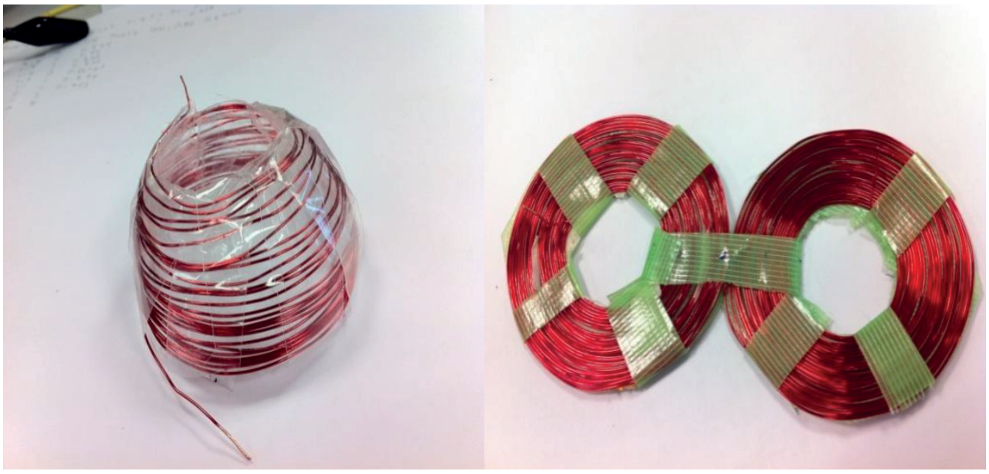

Figure 5.7: Cone coil (Left) and Butterfly Flat Coil (right)

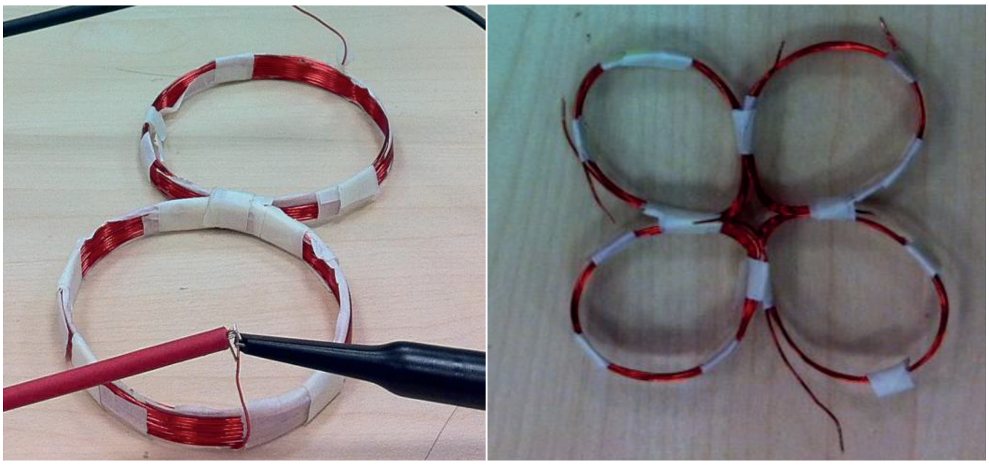

Figure 5.8: Butterfly Multilayer Coil (Left) and Four-leaf Coils (Right)

are conducted on the coils to study the magnetic flux patterns. The developed designs are round coil, figure eight coil, four-leaf and cone coil. The round and figure-eight coils are also divided into two different types, i.e flat and multilayer cylinder. The materials used for the coils are copper wire of 0.55mm diameter. The range of inductance are from 8uH to 1000uH. Using a function generator and

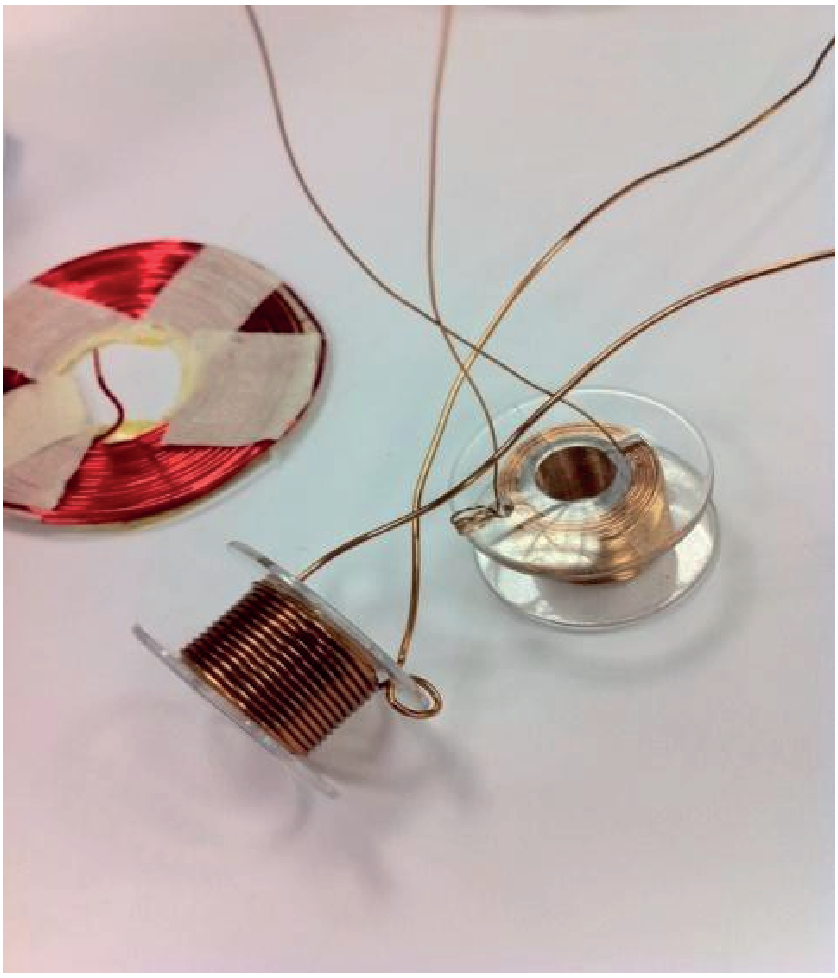

Figure 5.9: Mini Cylindrical Multilayer Coils (2cm external diameter)

oscillator, we can manually measure the inductance of the coils by first setting the function generator to a sine wave of 20 kHz with amplitude of 1V peak to peak. The 50-ohm output of the function generator is connected to the oscillator. To measure the inductance, the coil is connected in parallel to the oscilloscope. The frequency is then adjusted until half of the amplitude set earlier is achieved. In the case of 2V peak to peak, the frequency is adjusted until 1V peak to peak is achieved [28].

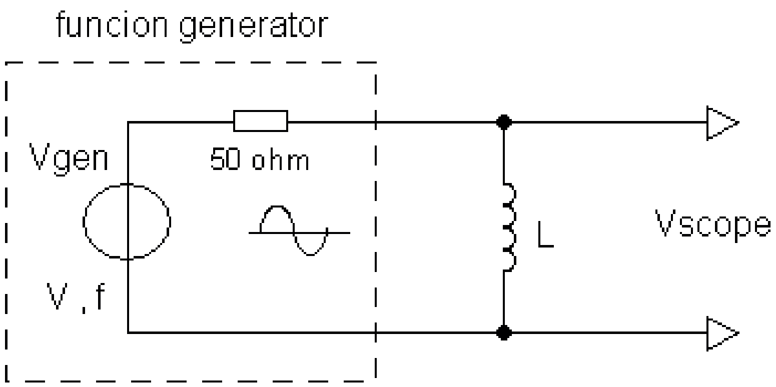

Figure 5.10: Circuit diagram inductance

Step 1: Function generator set to 20 kHz and 1V peak to peak, 50 ohm output of function generator connected to oscillator Ch 1

Step 2: Coil connected in parallel to oscilloscope. Amplitude of signal decreased

Step 3: Frequency of function generator is adjusted until half of the amplitude is achieved.

Step 4: Half of the amplitude achieved. The inductance can be calculated using the formula explained below.

In this formula L represents the inductance, R the resistance (50 ohm), and omega the radial frequency (= 2*pi*f with f in Hz).

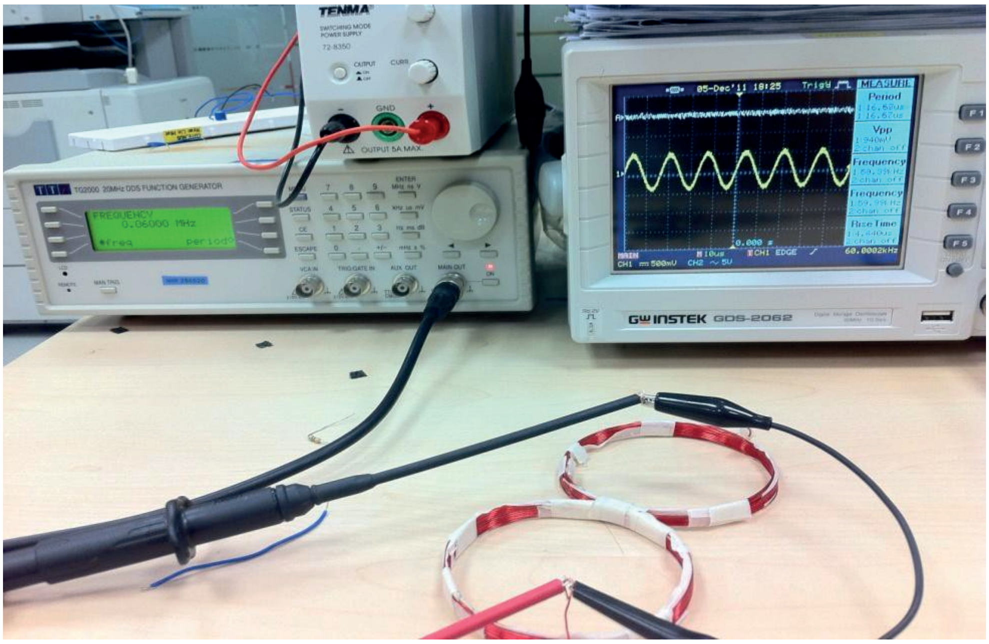

Figure 5.11: Experiment Setup

For what frequency (Vscope/Vgen) = 0.5:

The frequency to get half of the amplitude is 280kHz as shown above, so

L =4.57/280k = 16.32uH

This proves that the formula is accurate enough to measure the inductance of the unknown coils.

5.2.1 Methodology of Experiment on the Distribution of Magnetic FluxPatterns

To get a fixed pattern for the magnetic fields, the supply of a DC current is used to supply current to the coils. However because a DC current is supplied to the coils continuously, the voltage is limited at a value of 10V to prevent overheating of the coils. For coils that have very small inductance value, i.e. less than 5uH,

$$\left|\frac{Vscope}{Vgen}\right| = \frac{1}{2} \quad \Rightarrow \quad \frac{\omega L}{\sqrt{R^2 + \omega^2 L^2}} = \frac{1}{2}$$

$$\frac{\omega^2 L^2}{R^2 + \omega^2 L^2} = \frac{1}{4}$$

$$4\omega^2 L^2 = R^2 + \omega^2 L^2$$

$$L^2 = \frac{R^2}{3\omega^2}$$

$$L = \sqrt{\frac{1}{3}}\,\frac{R}{\omega} = \sqrt{\frac{1}{3}}\,\frac{R}{2\pi f} \quad \rightarrow \quad L = \sqrt{\frac{1}{3}}\,\frac{R}{2\pi f} = \sqrt{\frac{1}{3}}\,\frac{50}{2\pi f} = \frac{4.57}{f}$$

Figure 5.12: equation

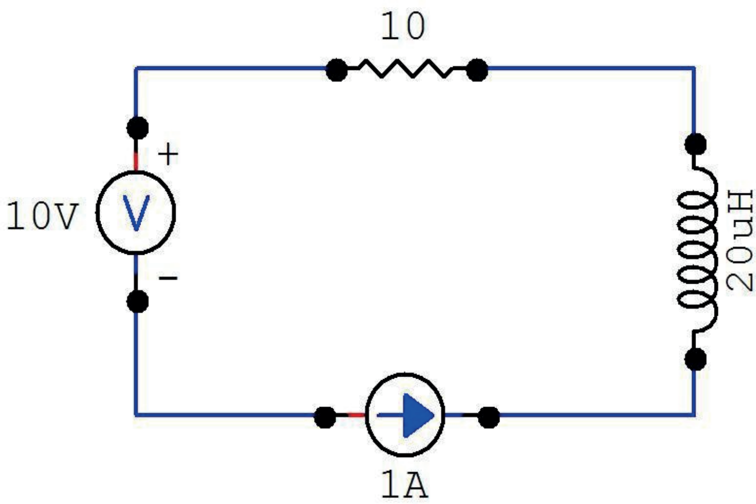

Figure 5.13: Schematic for experiment circuit

voltage value of 2.5V and current in the range of 0.23-0.25A are used. A gauss meter is used to measure the magnetic field.

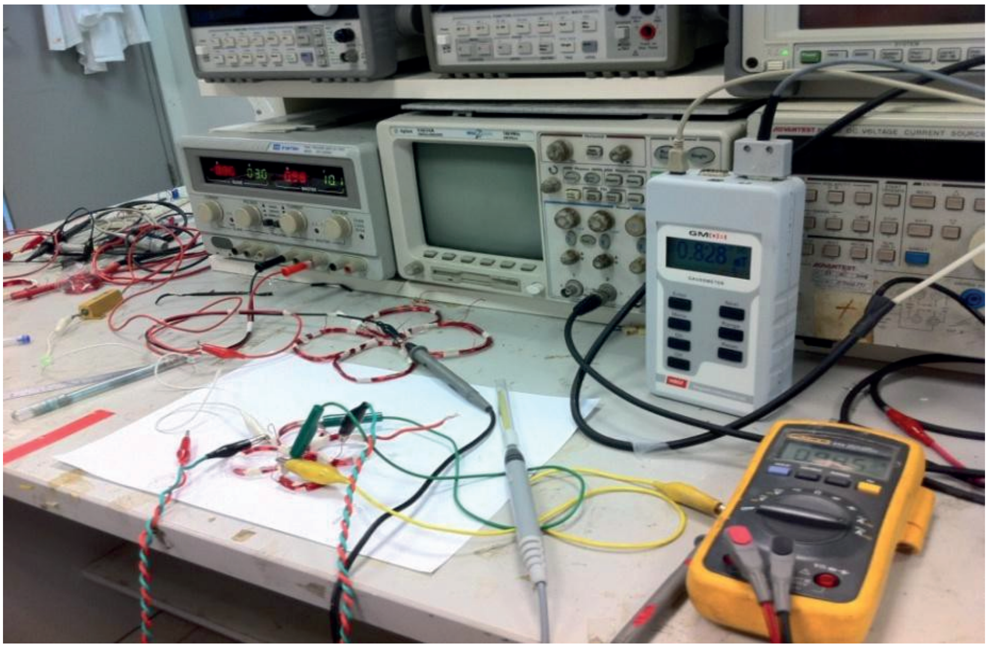

Figure 5.14: Connection of the coils and power supply

The first step to conduct the experiment is to measure the magnetic field of the environment when the voltage supply is off. When the voltage supply is turned on, the measurements are taken for each position below the surface of the coils respectively. The results of the experiments will be illustrated later for further understanding. To study the effect of the inductance, the values to be kept constant are the voltage values and the distance. All results of the magnetic field below are taken for 2mm below the surface of the coil.

5.2.2 Experiment Results and Observations

Case 1: Multilayer Cylinder Coils

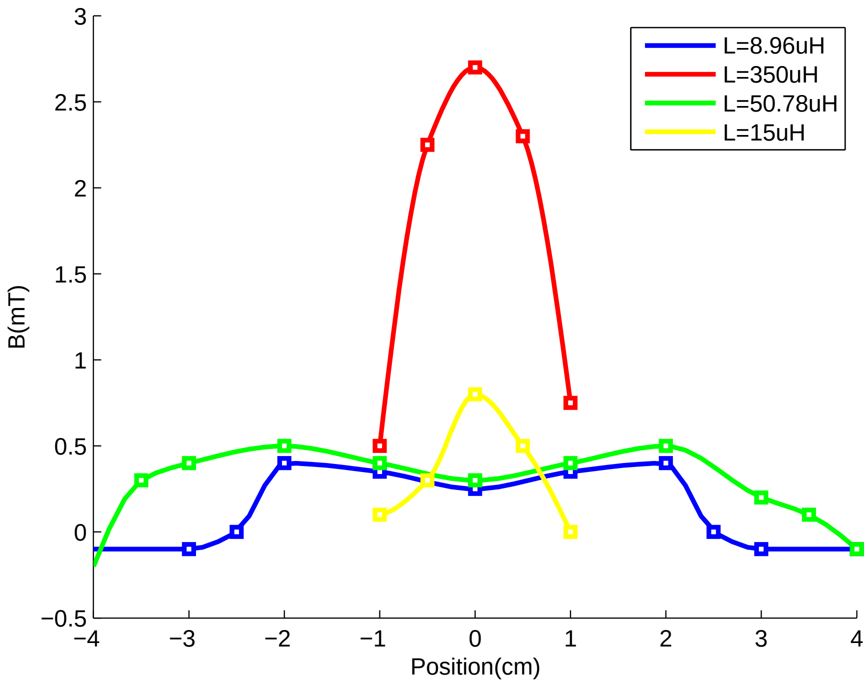

Figure 5.15: Distribution of Magnetic Field for Multilayer cylinder coils with 10V supply

The figure shows the magnetic field distribution for four multilayer cylinder coils of different range of inductance, 8.96uH, 15uH, 50.78uH, and 350uH. The table shows the properties for the coils.

Inductance(up)	8.96	15	50.78	350
Diameter(cm)	5	2	6.5	2
Size of center hole(cm)	4.75	0.03	6.3	0.03
Resistance(ohm)	0.4	0.4	0.4	0.4

Table 5.1: Properties for Multilayer Cylinder Coils

As we can see from the table, the coils are of different inductance, also of different diameter and the size of the center hole. It is observed that generally, as the inductance increases, the overall magnetic field increases. The pattern of the magnetic is symmetrical. Position 0 refers to the center of the coil while +1 refers to 1cm to the right of the centre and vice versa. The center of the coil is the critical area of the magnetic field, meaning that the field generated at that area is the highest. However, if the center hole is large, the field could be distributed all over in the middle of the coil which results in a spread out of the field. This is observed on the 8.96uH and 50.78uH coils with larger center hole size.Towards the edge, a negative field is observed as the flux is turning downwards.

The 15uH and 350uH coils are of the same size in diameter, size of center hole and resistance. The only difference between them is the inductance. The 350uH coil is made of thinner wires while the 15uH coil is made of thicker wires. Coils are shown in Figure 11. It is observed that coils with small inner diameter results in an extreme value at the center of the hole. For a stimulation where focality is a concern, the coil must be designed such that the center area is small enough to let the magnetic fields intersect.

Case 2: Flat Circular Coils

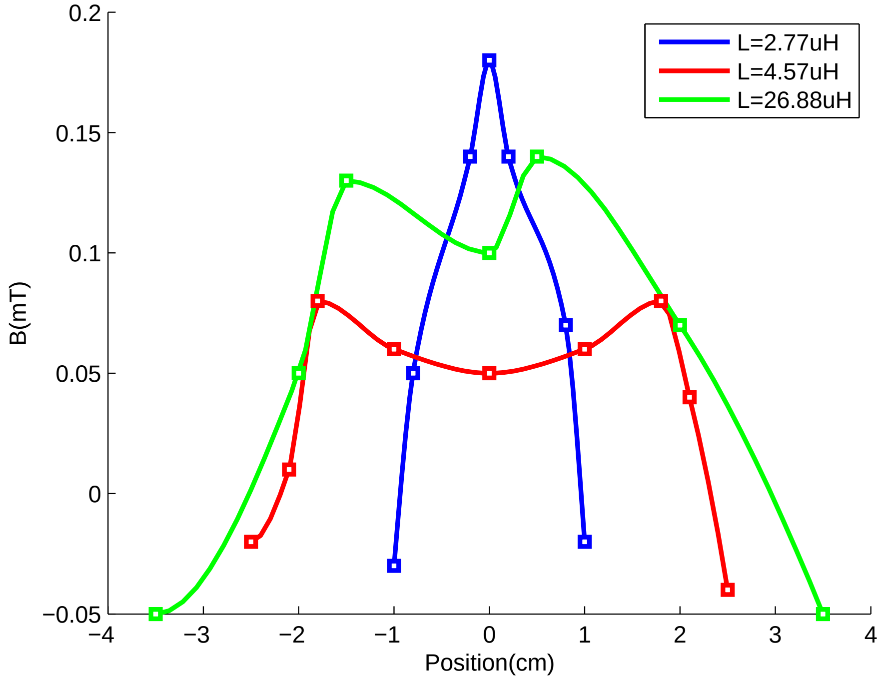

Figure 5.16: Distribution Field for Flat Coils with 2.5V supply

Inductance(up)	2.77	4.57	26.88
Diameter(cm)	2	5	7
Size of center hole(cm)	0.5	3.5	3
Resistance(ohm)	0.4	0.4	0.4

Table 5.2: Properties for Flat Circular Coils

It is observed that the overall field is proportional to the inductance. When the center hole is small the critical area generates the strongest field. Negative values of magnetic fields are obtained at the edge of the coils due to the magnetic field turning downwards similar to the cylinder coils. We have also supplied different voltages to the 26.88uH and the difference in the magnetic field is shown.

Case 3: Multilayer Butterfly Coils

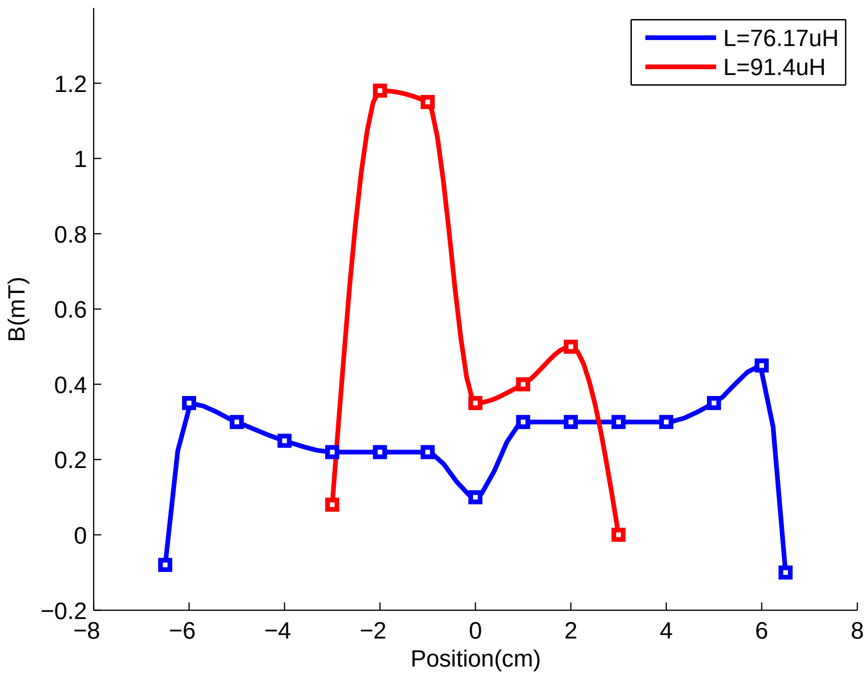

Figure 5.17: Distribution field for multilayer butterfly coils with 5V supply

Inductance(up)	76.17	91.4
Diameter(cm)	6.2 x 2	2.5 x 2
Size of center hole(cm)	6.4	2.2
Resistance(ohm)	0.4	0.4

Table 5.3: Properties for Multilayer Butterfly Coils

The self made 91.4uH coils do not come in two equal perfect circles, the field is not symmetrical and undesirable. It is found that the butterfly multilayer coil can produce a magnetic field which has symmetrical intention and deep stimulating distance where the array element has better ability of focus than circular coil. From our experiment, though the plotting appears to be symmetrical, the critical area, between the two circles, do not provide a critical field. Further development need to be done to ensure the results.

Case 4: Flat Butterfly Coils

Position (cm)

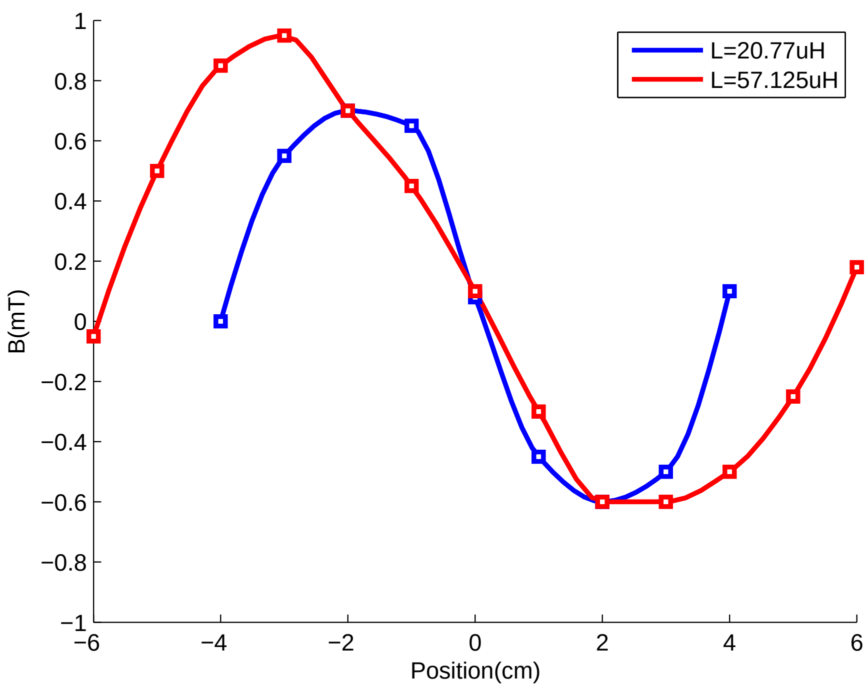

Figure 5.18: Distribution of magnetic field for butterfly flat coils with 10V supply

Inductance(up)	20.77	57.125
Diameter(cm)	4 x 2	6 x 2
Size of center hole(cm)	2.5	2.5
Resistance(ohm)	0.4	0.4

Table 5.4: Properties for Butterfly Flat Coils

The two coils generate field in an opposite direction. This is due to the coils turning that the 2 coils are connected in opposite directions, i.e. clockwise and anticlockwise. So the current supplied for the two coils are in opposite directions. For each of the circles, it generates a very much similar pattern that of a flat coil. If the current supplied to the coils are both in the same direction, the center part of the coils can generate a critical field.

Case 5: Multilayer Cylinder Cone Coils

Position (cm)

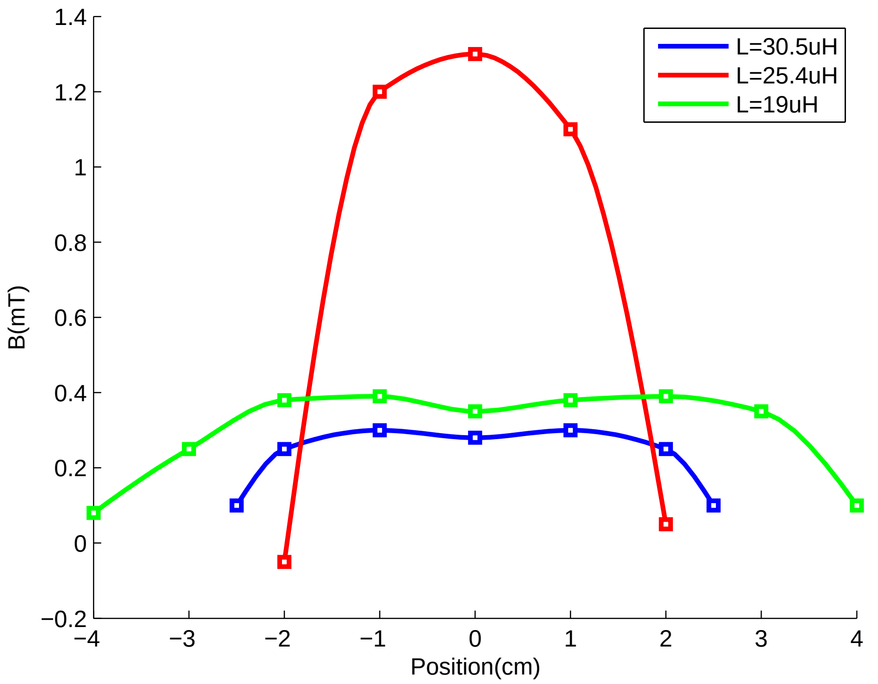

Figure 5.19: Distribution of magnetic field for cylinder cone coils with 10V supply

Inductance(up)	19	25.4	30.5
Diameter(cm)	5	4	6.5
Size of center hole(cm)	3	1.5	3.5
Resistance(ohm)	0.4	0.4	0.4

Table 5.5: Properties for Multilayer Cylinder Cone Coils

Again, it is observed that the field for the cone coil with a small center hole has the highest field in the critical area. It can be concluded that to generate a flux pattern with a more focussed field, though the inductance plays an important role, the center hole and spacing of the coil must be carefully designed to obtain an optimum result, i.e. small center hole to enable fields to intersect at a center point, small spacing to prevent field to flow through.

Case 6: Four-leaf Coils

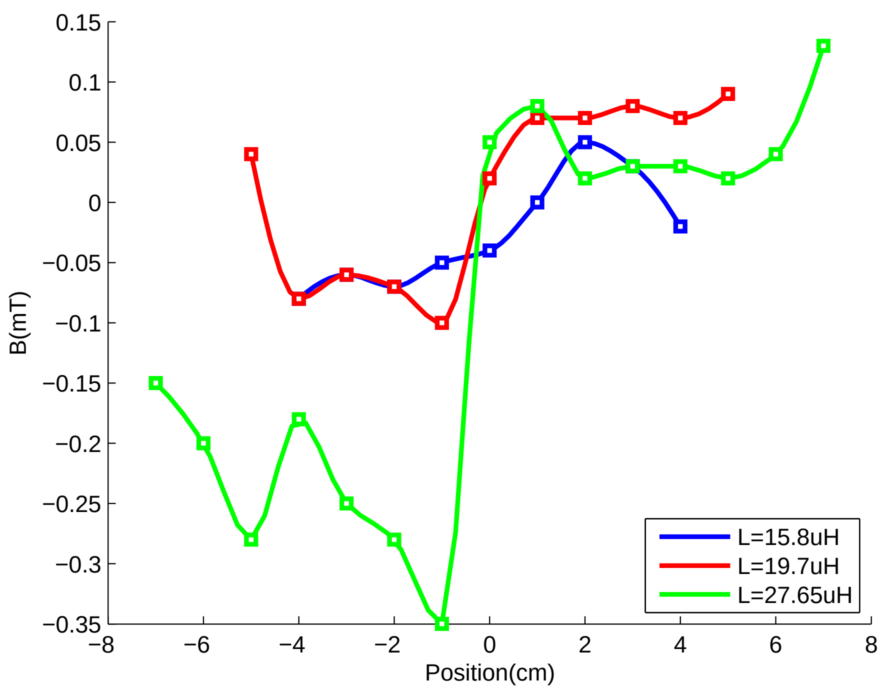

Figure 5.20: Distribution of magnetic field for four-leaf coils with 10V supply

The magnetic fields of the four-leaf coils are measured across the coil diagonally. The results show an opposite direction of field patterns for the left and right circle. However for the four-leaf coils, the magnetic fields are unstable and specific flux patterns are obtained.

5.2.3 Discussion of magnetic flux experiment

The designs of the coils are not uniform, i.e. different sizes. To obtain better results, other than using the same kind of coils, it is learned that the sizes (external diameter and internal diameter) of the coils should be as close as possible. A desirable result could be obtained by improving the coil designs. The multilayer cylinder coil design has been adopted for the use of the experiment for the human fingers as the fields are evenly distribution around the coil and it would be suitable for the human fingers to be placed surrounding the circular coil to expose steady fields to the fingers.

5.3 Experiment on the effect of pulsed electromagnetic fields on human fingers

5.3.1 Experiment on the suitable parameters for user study based on research a) Methodology

The experiments are done by first setting up the power pulse modulator, shown in the figure on the left to a power supply, and to the coil followed by a diode as reference to the schematic shown in the right figure. The frequency and pulse value can be adjusted by turning the knobs on the power pulse modulator. An oscillator is used to measure the frequency and the waveforms.

5.3.2 Data Analysis and Results

Before proceeding with the user studies, a variety of parameters is tested on the coils to select the suitable parameters. New circular coils of different inductances with small center holes have been developed for the user study. The set of data above is taken when the frequencies are varied from 10Hz, increasing until 25Hz. When the values of the frequency change, the voltage output and current output change as well. For a coil of inductance 400uH, the magnetic fields are very small, in the range of less 1mT. The preset voltage is set at its maximum, 30V and the output voltage and current output varies simultaneously. Values in the tables, voltage output, current output and the magnetic fields shown are approximate values obtained during the experiment as these values changed simultaneously. For the 400uH, there wasn't any change of feelings that could be obtained while placing the fingers on the coils surface.

For the 570uH coil, the fields have become larger but still there wasn't any difference in the change of neither the feelings nor heat of the coils. Again, the values shown are approximate values.

When magnetic fields obtained from the coils became much larger, at least 2 times for the same frequency; some heartbeat pulses or slight vibration could also be felt on fingers. It is observed that the vibration is much more noticeable and the heat of the coil is best suited for human fingers at 20Hz. Though larger fields can be obtained with higher frequency, the heat is not comfortable for subjects. The frequency value of 20Hz also matches the value of the findings Bouzarjomehri et al [20]. where 20 Hz pulse rate worked best at decreasing wound healing time and increasing the tensile strength of scar tissue. The parameters set for user studies are 30V preset voltage supply and frequency of approximately 20Hz. A metal screw has been placed in the middle of the coil to enhance the magnetic field and the magnetic field value obtained is around 3 to 3.6mT. The same parameters are used for the rest of the user experiments.

The table above shows the data of the coils when the frequency was kept as a constant at 20Hz and the voltage was being increased. The current was being put as a constant without changing its value, while the voltage was adjusted, the output current changed as well. The results have shown that when the voltage and current increase, the magnetic fields increase as well. The maximum preset voltage of 30V is selected for all the user studies for maximum magnetic fields.

5.4 User Study Experiments

5.4.1 Technical Section Methodology

The responses of 40 healthy subjects in the age range of 21 to 35 years old are studied. Two coils, one which was connected to the pulse and power supply (with the parameters of 30V preset supply, 20 Hz frequency and magnetic field range of 3-3.6mT) while the other coil is not connected were placed next to each other on the table. Subjects are asked to place their fingers, the thumb and the index fingers around the coils one with each hand to feel the differences. In the process, the subjects are asked to switch the coils so that they could feel the same coils with different sides of their hands. Each subject is exposed to the magnetic fields for 15 minutes. During and after exposure the subjects are interviewed on how they feel on their hands and their inputs are recorded. In the experiments, an assumption has been made, that the magnetic fields are the same (range of 3-3.6mT) for all subjects even though the exact position where they touch the surface of the coils may differ and that affects the exposed fields. The subjects are asked to physically touch the surface of the coils because subjects can effectively be exposed to the fields steadily for 15 minutes. In addition, since the fields are weak, the exposed field needed to be as close as possible.

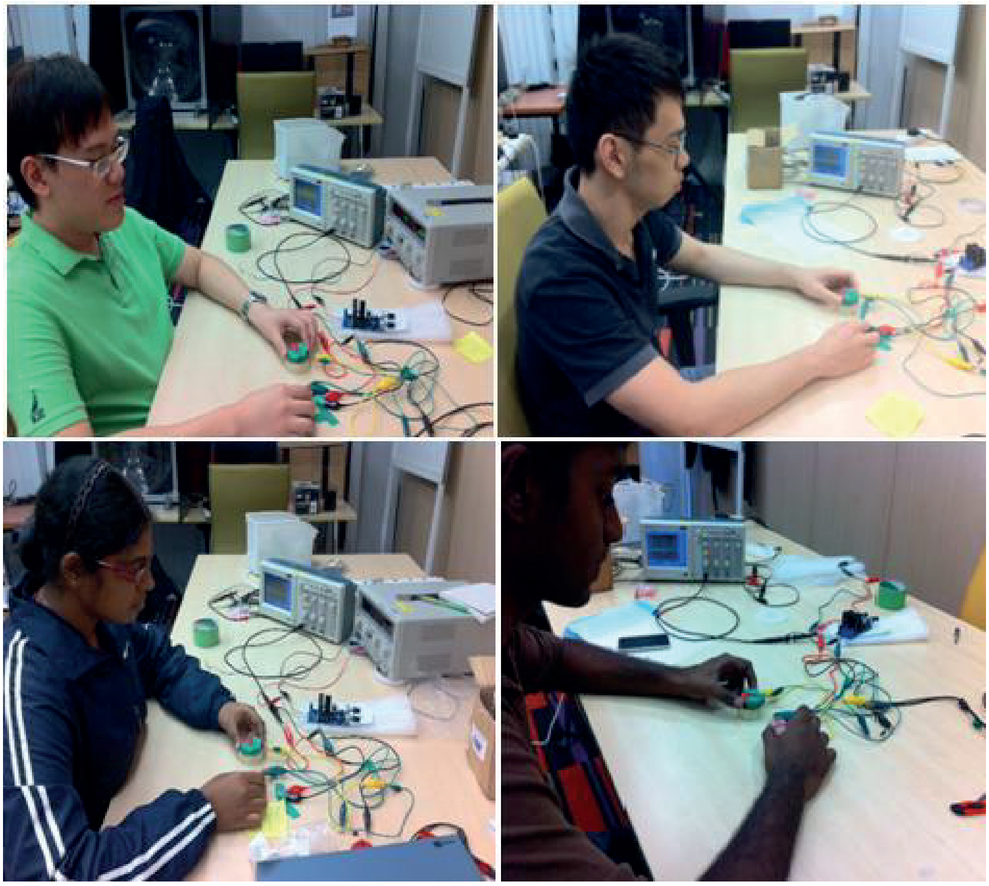

Figure 5.21: Snapshots of few subjects during the experiments

The findings have shown that the majority of the subjects can feel pins and needles running through their fingers. Through observation, these pins and needles feelings generally get more intense as exposure went on longer and may result in slight numbness or stiffness in some subjects in the hands or fingers. The data and results will be discussed in details in the next section.

5.4.2 Results and Data Analysis

The previous section describes the experiments, i.e, the investigation of magnetic flux patterns of different design of coils and the user study experiments in detail, together with the parameters and variables selected. In this section, the results and observations will be discussed thoroughly. According to our findings, the 20Hz electromagnetic fields exposure on the human fingers caused slight pins and needles feelings through the fingers and longer exposure may cause slight numbness in the hands or fingers. The results will be elaborated below.

When there are pulses of current going through the coil, the wire of the coil vibrates at its frequency and it is natural that subjects may feel slight pulses like heartbeats when they placed their fingers on the coil. From the experiments, 8 out of 40 (20%) of the subjects could not tell which coil was supplied with current.

It is observed that out of 8 subjects, only 1 of them is a female subject. Those who can not sense that the coil is vibrating has lesser sensitivity in the sense of touch on their fingertips. It has been found that people who have smaller fingers have a finer sense of touch, which may explain why women tend to have better tactile acuity than men [90]. It should be highlighted that not all of the subjects can feel the pulses in the coil, most of the subjects that can not sense the pulses; still get pins and needles going through their fingers. It is observed that pins and needles sensations induced by the coil do not have connections with the pulses

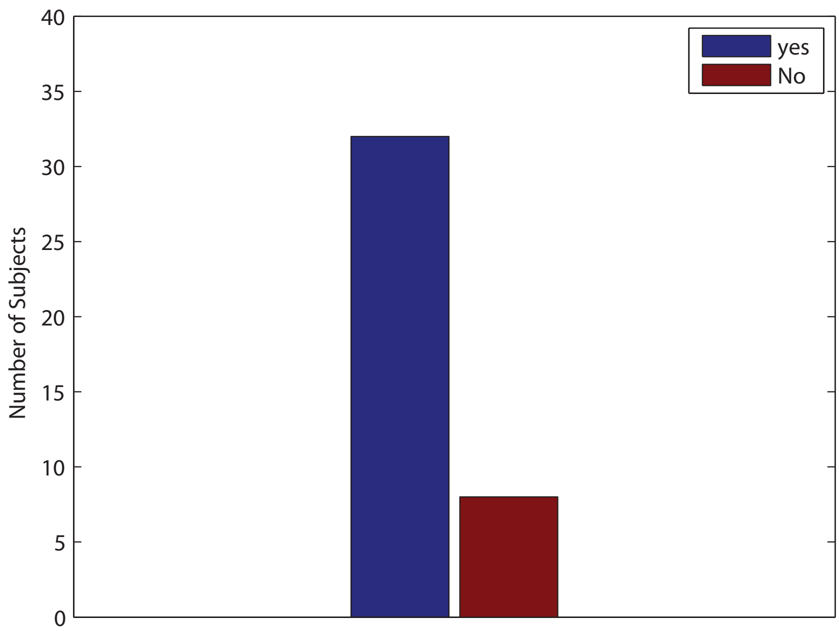

Figure 5.22: Graph of the number of subjects that could feel pulses in the coils

sense, meaning that subjects may still be able to feel pins and needles through fingers though they do not feel the pulses in the coil.

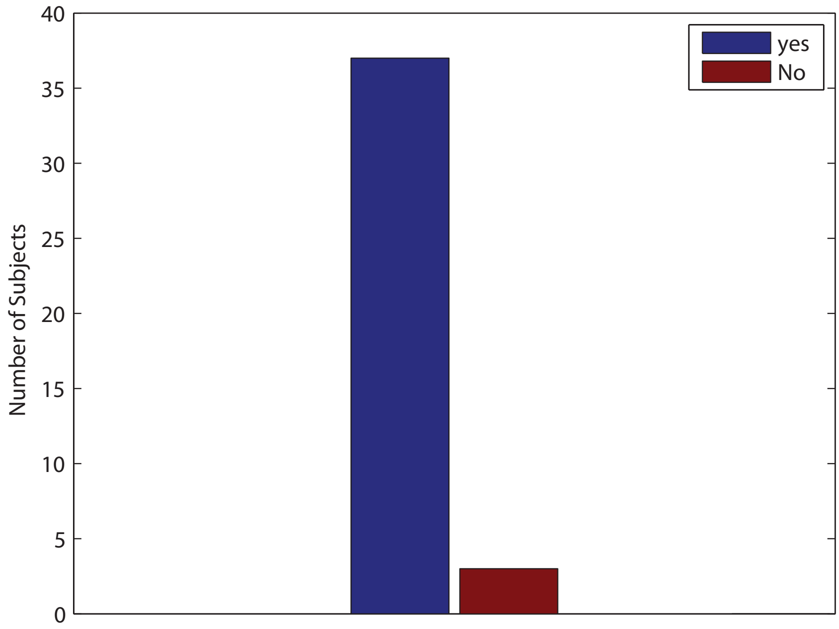

Figure 5.23: Graph shows the number of subjects who had mild paresthesia during experiments

During the user studies, 37 out of 40 of them (92.5%) felt pins and needles through their fingers on the coil that was connected to the supply during exposures. Out of that, 13 of them commented that the sensation got more intense after a while till the extent that the coil was pinching them. These signs of paresthesia may be cause of low-normal ionized calcium levels, which will be explained in more details later. A number of them felt slight numbness in the hands after sometime. It clearly shows that low frequency electromagnetic pulse can induce paresthesia effects in the human skin. However, more studies and explorations need to be done to have a better understanding on the effects and whether these effects can lead to significant numbness or whether in the long run, there are any undesirable side effects.

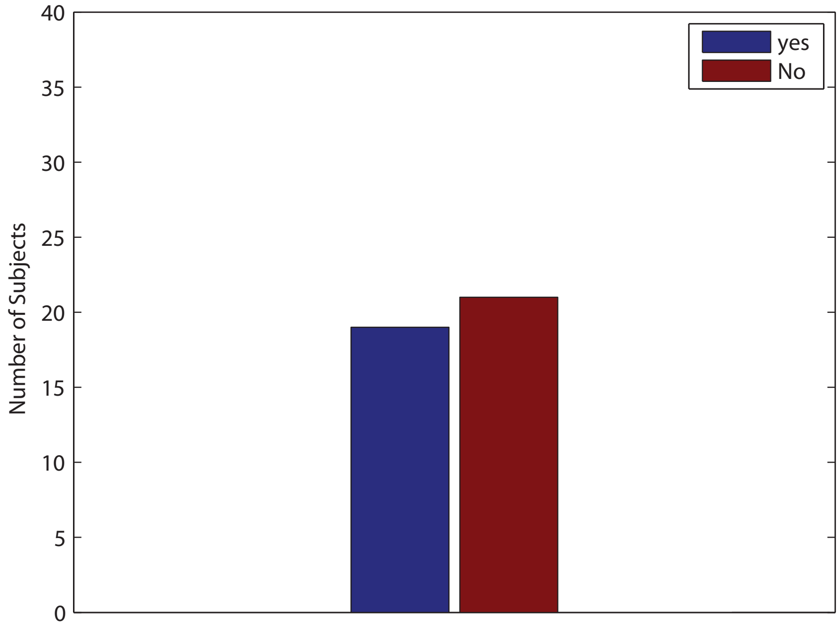

Figure 5.24: Graph shows the number of subjects who felt numb during the experiments

Out of 40, 19 subjects (47.5%) felt slight numbness on their fingers. It is observed that all 19 subjects who felt slight numbness have paresthesia sensations before that. In about 5 to 10 minutes of exposure after they felt pins and needles, the feelings led to slight numbness in their fingers. Hence, 19 of the subjects had both paresthesia and numbness. However 18 of 37 subjects who felt pins and needles did not feel numb in their fingers. In short, 92.5% of the total number of subjects had paresthesia and out of the 92.5% , longer exposure led to numbness in 19 out of 37 of them (51.35%). The results have shown that longer exposure in the pulse magnetic fields leads to slight numbness in the fingers of the subjects. However, it is still uncertain that the fields can induce numbness that is close to the effect of anesthesia. In addition, 18 of the subjects who could feel pins and needles at first did not feel numb at all. In this case, it is still an ambiguity whether the low frequency electromagnetic fields can really induce a significant numbness close to the effect of anesthetic drugs in the human skin.

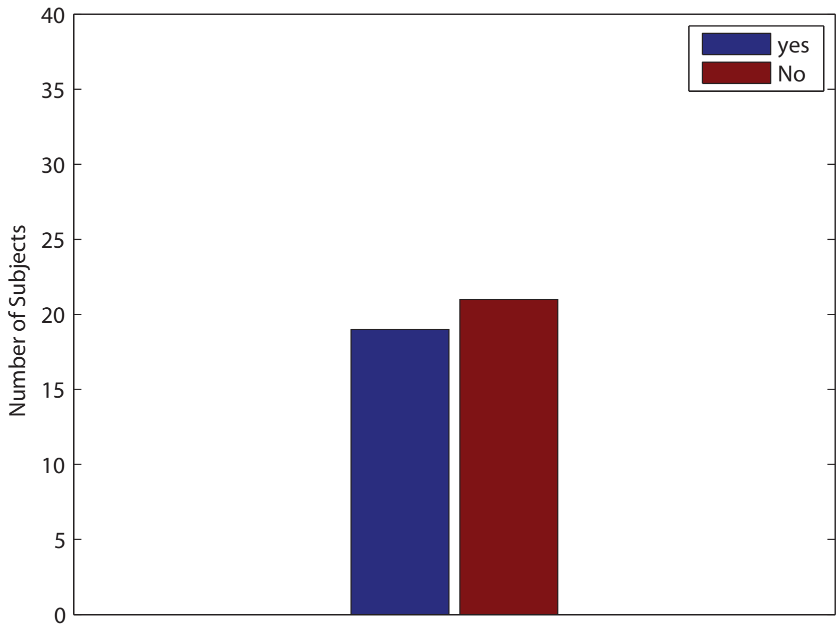

Figure 5.25: Graph shows the number of subjects who felt stiff after exposures

After exposure, the subjects were checked if there is any effect of the exposure to their hands or fingers. 19 out of 40 of them (47.5%) have responded that their fingers felt rigid. The stiffness feelings that have occurred on the subjects have no connections with numbness. This means that not all subjects that had numbness feelings earlier would feel stiff in their fingers. However, it is also noticed that all 19 of them had paresthesia during the experiment. Therefore, there may be a connection between paresthesia and stiffness in the situation.

The data of subjects showing the signs of paresthesia, numbness and stiffness has been extracted from the complete table and it shows that 11 subjects (27.5%) had all the three sensations during and after the exposure of the low frequency electromagnetic fields. Some other effects from this group include weakness, joint sore, and the feeling of blocking of blood pressure. Again, despite the fact that the percentage is very small, only 27.5%, but we still think that the results have been worthy enough to carry out further investigation on these effects.

There are reports on paresthesia caused by electromagnetic exposures and one of them stated the range of electromagnetically induced symptoms reported by electrosensitives, which includes skin disorders, various paresthesia (pins and needles, numbness, burning sensations) fatigue, muscle cramps, cardiac arrhythmia, and gastrointestinal problems are remarkably similar to those from hypocalcaemia (low blood calcium) and hypomagnesaemia (low blood magnesium). The affected cells may then not function properly and become incapable of protecting themselves fully from further damage. This could include an ever increasing loss of their ability to form adequate tight junction barriers, so making the victim progressively more sensitive to the radiation [38]. Although there is still no evidence stating electromagnetic fields could do harmful damages to the human skin, these areas should be investigated under safe parameters conditions. The parameters used for all the experiments are values that are extensively used commercially in the medical field.

5.5 Discussion

Different types of coils have been developed and have been experimented to investigate the flux patterns. The effects of low frequency (approximately 20Hz) pulsed magnetic fields (less than 0.005T) on the human skin have been explored to study on the possible applications in the future. The objective of the experiments is to study the effects, whether the field is capable of inducing numbness in the human skins. The application of numbness effect in the human body could be the substitution of painkillers and anesthesia that cause many side effects and even severe harm to humans. The findings from the user experiments have shown some positive effects, supporting our objective to cause the feeling of numbness, the results suggest signs of paresthesia (pins and needles, tingling or prickling sensation) in the inner part of the skin. Although this is still far compared to the feeling of anesthesia or loss of sense but it certainly merits further investigation on the parameters to cause better effects to block the feeling of pain in the human body.

For future work, studies on electromagnetic fields pulses and the capability of producing the effects of anesthesia or loss of responsiveness can be explored in depth for the application on substituting anesthetic drugs to reduce the risks of side effects. Careful considerations need to be done on the suitable parameters and exposures on electromagnetic fields to keep the environment safe for subjects or patients. Many researchers believe that long term exposures may cause side effects on the human skin and currently there are many reports on the investigations of the potential harm electromagnetic fields from systems such as wireless networks and cellular systems that could cause harm to the human body.

The studies on magnetic fields that can be applied to the medical field should also be done under careful considerations, considering the effectiveness or whether it is appropriate to use electromagnetic fields as a medium in this field. The experiments are done using parameters i.e. (low magnetic fields (3.6mT), low frequency (20Hz) and low current (1A)) that are used commercially by researches and the exposure time of the fields are relatively short (15 minutes) for each subjects to study the immediate effects in a safe environment. The parameters have to be worked on for more promising or positive outcomes that support the goal of inducing numbness in the human skin. On the contrary, if the parameters are to be changed to get major effects, it is an issue whether the parameters are suitable for human use and whether the procedures can produce bad effects. Over again, I feel that the results are worthy for further investigations but careful considerations need to be done in the process as there could be unwanted risks in the area of electromagnetic fields on the human body.

On the experiment methodology, progression could be done on the design. For the user study experiments, subjects are asked to touch on the surface of the coils while resting their hands on the table to maximize the exposure of the fields to the fingers and to fixate at a position. However, that way, the results obtained might not be accurate as there are many other factors involved when the subjects touch the surface of the coil on a fixed position. There are possible external factors that could affect the experimental results. I feel that if the design of the experiment can be improved in such a way that only the electromagnetic fields are exposed to the skin, without them essentially touching the surface, or fixate their hands position, the experimental results would be more favourable.

Through the user study experiment that has carried out using the parameters of 20Hz frequency, current of 1A and fields of 3.6mT, it can be concluded that low frequency pulsed electromagnetic fields can induce paresthesia in the human fingers; other possible effects that can occur include slight numbness and stiffness in the human fingers. This answers the main research question, What are the visible immediate effects of low frequency pulsed electromagnetic fields on the human skins? The results have been encouraging enough to merit further investigation in the field, using principle of Transcranial Magnetic Stimulation to generate sensations on the human skin.

Chapter 6

Conclusion

This thesis discusses about developing unconventional human computer interfaces using some of the selected magnetic materials and properties. Three research works has been presented in the thesis and they are Liquid Interfaces, Haptic Mouse and Pulse. These interfaces offers features like shape changeability of surface, tactile feedback, higher degree of freedom, gestures, and visual changes to achieve meaningful manipulations for digital information. Theoretical contributions, technical and user experiments were discussed in detail throughout the chapters.

In Summary, this thesis addresses three limitations of the conventional human computer interfaces; constrained interaction with limited metaphors and physical objects in Tangible User Interfaces, absent of near surface haptic sensations in pointing interfaces for touch-less interaction, and create and reproduce perceptions are limited by factors such as sensors of the human body.

The three Unconventional User Interfaces solve the above mentioned limitations them by providing the organic user interactions with their rich metaphors and physical objects, enabling near surface sensing and actuation for the effective touchless-interaction in the pointing interfaces and allowing to create or reproduce the feelings and sensations on the skin of the fingertip such as numbness, stiffness, and parasthesia.

The results have been encouraging and they merit further investigation by enhancing the prototypes to be used in the fields of mixed reality, human computer interaction, new media and medicine.

Appendix A : Reproduction and Creation of Perceptions by Electrically Modifying Neural Firing

With a novel mechanism of pulse magnetic flux nozzle, a magnetically induced deep brain electrical stimulation system (Figure 6.1) for enhancing brain functions or modifying brain perceptions with physical means is under research and development, in which the design of electrical stimulation mechanisms for effectively enhancing brain functions or modifying perceptions is bringing up a new issue to Neurosciences: can brain perceptions be modified, reproduced or created with electrical stimulation that modifies neural firing in the brain?

The brain works by firing electrical impulses in certain functional units of neurons. For an event of specific brain function or perception, the brain registers it in a form of neural firing in certain units of neurons at specific locations, which is the physical equivalent of the brain function or perception.

In education, when learners practice something, the units of neurons that

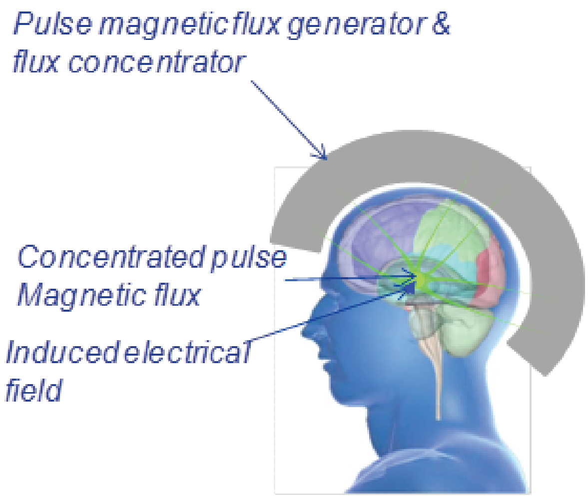

Figure 6.1: Magnetically induced deep brain electrical stimulation system

control and drive that action fire repeatedly. When the neurons fire frequently, they grow and extend themselves out to other neurons. These electrical signaling connections are with their axons and synapses. These firings are the physical equivalent of knowledge in the learners brain. For example, it takes a fraction of a second to recognize a person or an object that you previously known, even when seen under strikingly different conditions [93].

Via the same mechanism, there are firings in the brain for various brain perceptions, such as pain, taste, smell, and satiety. Understanding the firing in the brain for each of the brain perceptions could potentially provide the basis for modifying, reproducing or creating the perception by modifying the neural firing with an electrical means.

For example, it is known from EEG studies that during pain perception, there tends to be a decrease in the slow wave (e.g. theta and alpha rhythm) and an increase in the fast wave (e.g. beta activity) in the brain areas including somatosensory cortices, anterior cingulate cortex and Insula. Therefore, the physical equivalent of pain in the brain could be the neural firing in these brain regions. In the same brain regions and in the same units of neurons, if the neural firing for no-pain perception is recorded and then is loaded back overwriting the neural firing for pain perception, the pain perception may be replaced by no-pain perception. Physically such a reproduction of neural firing can be achieved by applying electrical stimulation at the local field [78]. In this way pain perception can be alleviated by modifying the neural firing with a physical means. In achieving this, the following three neuroscience questions may have to be answered:

1. What are the units of neurons in the brain that fire for a brain perception?
2. What are the dynamic behaviours of the neural firing for a brain perception?
3. What are the critical physical conditions associated with the neural firing of a brain perception, changing which changes the brain perception?

By answering the first question the brain regions of the neural firing for a brain perception are known. By answering the second question a physical model for a brain perception is established. By answering the third question the physical essentials for reproduction and creation of a brain perception by modifying neural firing is established.

This research is proposed to study the neural firing of a few brain perceptions, including pain, taste, smell, and satiety, for purposes of medically needed modification, reproduction or creation of these perceptions by electrically modifying the neural firings, with the following objectives to be achieved:

1. To locate the neural firing in the brain for each of the concerned brain perceptions
2. To investigate and model the dynamic behaviours of the neural firing for each of the concerned brain perceptions
3. To identify and validate the critical conditions of the neural firing and accompanying local field potentials for each of the concerned brain perceptions, changing which changes the brain perception

The proposed research has 4 phases for a period of 5 years, with Phase 1 for developing engineering tools and establishing intracranial test facilities, Phase 2 for investigating and modelling the locations and dynamic behaviours of the neural firings of the concerned brain perceptions, Phase 3 for identifying and validating the critical conditions the neural firing of each of the concerned brain perceptions for modification, reproduction, or creation of the brain perception by modifying the neural firing with electrical means, and Phase 4 for studying the neural firing for a range of higher brain functions, including learning.

Phase 1 (from Month 1 to Month 12):

- A super high density 1024 channel scalp EEG system using novel dry EEG sensors [81] together with a novel EEG source localization imaging system will be developed for 3D localization of the electrical dipole sources in the brain in equivalent to a cluster of neural firings of a brain perception.
- A novel single shank multichannel 3D micro intracranial electrode array for deep brain depth local field potential measurement will be designed and developed.

- A novel super precision device for implanting an array of single shank multichannel 3D micro intracranial electrodes one by one deep into the brain at the targeted local field without damaging the neurons and their connections, will be designed and developed.

- Animal facilities for intracranial measurement of the neural firing of each of the concerned brain perceptions will be established.

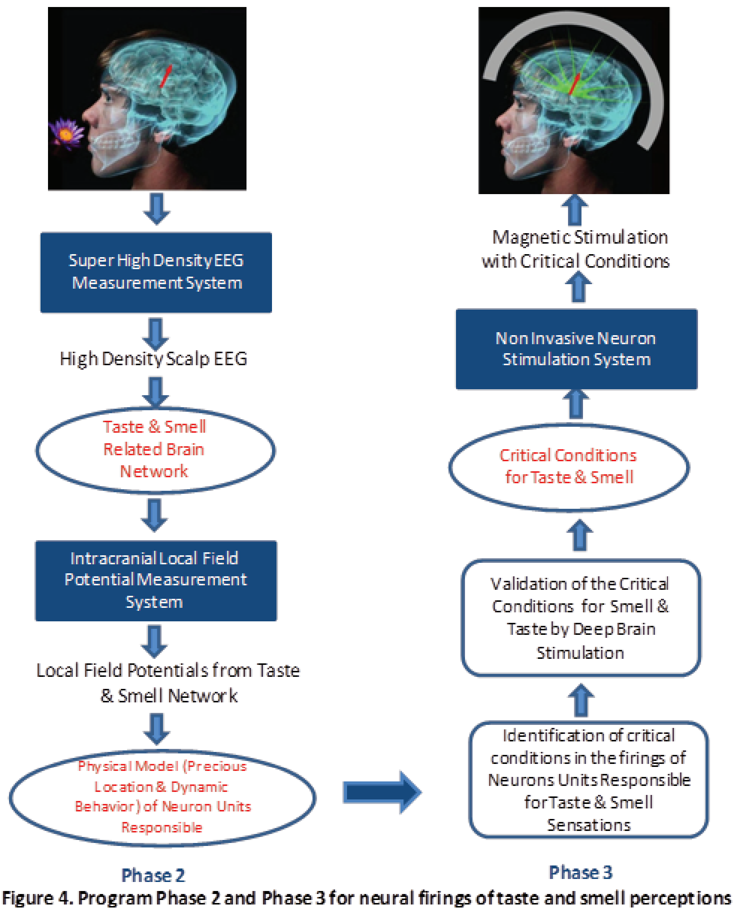

Figure 6.2: Program phase 3 and phase 3 for neural firings of smell perception

Phase 2 (from Month 13 to Month 36):

For each of the concerned brain perceptions, including pain, taste, smell, and satiety:

- the neural firing will be localized using the super high density 1024 channel scalp EEG system and the EEG source localization imaging system
- the dynamic behaviour of the neural firing will be investigated by measuring and monitoring the accompany local field potentials using an array of single shank multichannel 3D micro intracranial electrodes precisely placed across the neuron units of the neural firing
- A comprehensive physical model for the neural firing will be developed

Phase 3 (from Month 37 to Month 54):

For each of the concerned brain perceptions, including pain, taste, smell, and satiety:

- the critical conditions of the neural firing and accompanying local field potentials will identified through analyzing the developed physical models from Phase 2, and then;
- the identified critical conditions will be validated by modification, reproduction, or creation of the brain perception with an electrical means applying the critical conditions.

As examples for illustration, the program Phase 2 and Phase 3 for neural firings of smell is shown in Figure6.2, respectively.

Phase 4 (from Month 55 to Month 60):

The results from Phases 2 and 3 will be fully summarized and concluded, based on which a comprehensive research plan will be established in preparing for the next 5 year program targeting at higher brain functions.

Deliverables

- Engineering tools for studying the neural firing of brain functions and perceptions;
- Animal facilities for studying the neural firing of brain functions and perceptions
- Comprehensive knowledge and physical models about the brain regions and dynamic behaviours of the neural firings for a range of brain perceptions, including pain, taste, smell, and satiety
- Validated critical conditions for modification, reproduction or creation of each of the brain perceptions by modifying the neural firing with an electrical means

Future Applications

There are many application possibilities that can be implemented through the presented system, related to education, communication, virtual reality, medical, and gaming fields. In particular, the digitization of taste and smell senses allows for richer multi-sensory remote communication possibilities, which are harder to achieve with analogue chemical stimulations.

Furthermore, chemical based smell interfaces has the difficulty of controlling the flow of the odor molecules. They spread through the air and becomes difficult to control within the personal space. Therefore, the proposed methodology will be useful for developing applications to deliver personal experiences. For example, the proposed magnetic stimulation device would be used to provide rich experiences for movies or theatres. When there is a party on the screen or in the stage there is a possibility of experiencing smells of food and wine. Similarly, it is also possible to simulate the smells of natural flowers on the screen such as lavender and jasmine.

This system could also use in family communication, specifically sharing of taste and smell sensations with loved ones who live in distant locations. Therefore, this system may help people to share their experiences, enjoyment, and emotions which are blended with taste and smell sensations. This will re-combine the isolated nature of humans in the modern world and gives positive thinking of remote co-presence and co-living experience through digital taste and smell communication.

Furthermore, medical field will be one of the fields that would be benefited immensely through this system. For example, the taste actuation device has the potentiality of treating both diabetic patients and people with taste disorders. If a patient could not smell due to cranial nerve failure, he will be able to use the deep brain magnetic flux stimulation device and experience the missing sensations, the smell.

In addition, by integrating proposed system into virtual reality and gaming systems users may taste or smell virtual food or environment as if they are in a natural environment. For example, the system lets the player experience different smells when the player is travelling through a virtual jungle, which are part of a real life jungle experience. We believe, in the future, these new digitized experiences will stimulate novel and innovative applications into the existing digital world. Possible extension of this research includes amplifying the magnitude of taste and smell senses that are sensed by animals and plants but not by humans, thus increasing the human empathy for surroundings.

List of Publications

6.1 PhD Related Publications

Journals

- Kasun Karunanayaka, Sanath Siriwardana, Chamari Edirisinghe, Royohei Nakatsu, Ponnampalam Gopalakrishnakone, Magnetic Field Based Near Surface Haptic and Pointing Interface, World Academy of Science, Engineering and Technology, Isuue 72, December 2012
- Kasun Karunanayaka, Sanath Siriwardana, Chamari Edirisinghe, Royohei Nakatsu, Ponnampalam Gopalakrishnakone,Haptic Mouse : Magnetic Field Based Near Surface Haptic and Pointing Interface, International Journal in Interactive Digital Media (IJIDM),Issue 1, 2013
- Jeffrey Tzu Kwan Valino Koh, Kasun Karunanayaka, Jose Sepulveda, Mili John Tharakan, Manoj Krishnan, and Adrian David Cheok. 2011. Liquid interface: a malleable, transient, direct-touch interface. Comput. Entertain. 9, 2, Article 7 (July 2011), 8 pages.

Conference Papers

- Kasun Karunanayaka, Sanath Siriwardana, Chamari Edirisinghe, Royohei Nakatsu, Ponnampalam Gopalakrishnakone, Haptic Mouse - Enabling Near Surface Haptics in Pointing Interfaces, The Sixth International Conference on Advances in Computer-Human Interactions, ACHI 2013, Nice, France, 24th Feb- 1st March 2013. [Full Paper]

- Kasun Karunanayaka, Sanath Siriwardana, Chamari Edirisinghe, Royohei Nakatsu, Ponnampalam Gopalakrishnakone, Haptic Mouse A Magnetic Pointing Interface with Near Surface Haptics, 15th International Conference on Human-Computer Interaction, HCII 2013, Las Vegas, Nevada, USA, 21-26 July 2013. [Full Paper]

- Kasun Karunanayaka, Sanath Siriwardana, Chamari Edirisinghe, Royohei Nakatsu, Ponnampalam Gopalakrishnakone, Magnetic Field Based Near Surface Haptic and Pointing Interface, ICECECE 2012 : International Conference on Electrical, Computer, Electronics and Communication Engineering, Penang, Malaysia, 6-7 December 2012 [Full Paper]

- Kasun Karunanayaka, Sanath Siriwardana, Chamari Edirisinghe, Royohei Nakatsu, Ponnampalam Gopalakrishnakone,Haptic Mouse : Magnetic Field Based Near Surface Haptic and Pointing Interface, International Conference on Interactive Digital Media, Langkawi, Malaysia,3-4 December 2012 [Full Paper]

- Kasun Karunanayaka, Jerey Tzu Kwan ValinoKoh, Eishem Bilal Naik, and Adrian David Cheok, "Hall Effect Sensing Input and Like Polarity Haptic Feedback in the Liquid Interface System", in Proceedings of the international joint conference on Ambient Intelligence, AmI 11. Amsterdam, Netherlands, 2011 [Work in Progress Paper]

- Jeffrey Tzu Kwan ValinoKoh, Kasun Karunanayaka, Ryohei Nakatsu, Linetic: Technical, Usability and Aesthetic Implications of a Ferrofluid-based Organic User Interface. INTERACT 2013 Conference, Cape Town, South Africa, 2-6 September 2013. [Full Paper]

- Kasun Karunanayaka, Jeffrey Tzu Kwan ValinoKoh, Jose Sepulveda et al. (2010) Liquid Interfaces - A New Creative Entertainment Technology. In International Conference on Digital Interactive Media in Entertainment & Arts (ACE 2010). [Poster Abstract]

- Jeffrey Tzu Kwan Valino Koh, Kening Zhu, Kasun Karunanayaka, Doros Polydorou, Roshan Lalintha Peiris, and Ryohei Nakatsu. 2013. Characterizing the analog-like and digital-like attributes of interactive systems, Communication Design Quarterly Review 1, 2 (January 2013), 8-36. [Full Paper]

- Nimesha Ranasinghe, Kasun Karunanayaka, Adrian David Cheok, Owen Noel Newton Fernando, Hideaki Nii, and Ponnampalam Gopalakrishnakone. 2011. Digital taste and smell communication. In Proceedings of the 6th International Conference on Body Area Networks (BodyNets '11). ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), ICST, Brussels, Belgium, Belgium, pp. 78-84 [Full Paper]

- Nimesha Ranasinghe, Kasun Karunanayaka, Adrian David Cheok, Owen Noel Newton Fernando, Hideaki Nii, and Gopalakrishnakone Ponnampalam, Digital Taste & Smell for Remote Multisensory Interaction, BodyNets 2011, Beijing, China [Poster Abstract]

Awards prizes and nominations

- Creative Showcase Golden award - Liquid Interfaces - A New Creative Entertainment Technology. International Conference on Digital Interactive Media in Entertainment & Arts (ACE 2010).

- NUS faculty of engineering research and innovation award - Liquid Interfaces 2011(http://www.eng.nus.edu.sg/ugrad/awards/ira_2011.html)[Awarded for the FYP students of Liquid Interfaces]

Magazine Articles

- When sculptures 'sing' through new 3D liquid interface technology Featured article in Engineering Faculty website. (http://www.eng.nus.edu.sg/ero/announcemen liquid01-11-f%20inal.pdf)

- Liquid Interfaces A new creative entertainment technology. E-CONNECT, Bi annual publication of department of Electrical and Computer Engineering, July 2011

Demos and Exhibitions

- Haptic Mouse: Art Science Revealed, Art Science Museum, MarinaBay Sands, Singapore, October 06, 2013).

- Liquid Interfaces Prototype 4: 100% Design Singapore Exhibition 2012, MarinaBay Sands, Singapore, October 10 - 12, 2012).

- Liquid Interfaces Prototype 4: Mirai - The story of CUTE, Art House, Singapore, March 2 - 4, 2012).
- Liquid Interfaces Prototype 2: International Conference on Digital Interactive Media in Entertainment & Arts (ACE 2010).

6.2 Other Publications

Journals

- Dilrukshi Abeyrathne, Chamari Edirisinghe, Nimesha Ranasinghe, Kasun Karunanayaka, Kening Zhu, Roshan Lalintha Peiris, Owen Noel Newton Fernando, Adrian David Cheok, Lan Lan, and Yukihiro Morisawa. 2011. Connected online and offline safe social networking for children. Comput. Entertain. 9, 2, Article 9 (July 2011), 8 pages.

Conference Papers

- Remi Tache,Hunfuko Asanka Abeykoon, Kasun Karunanayaka, Janaka Prabhash Kumarasinghe, Sun Ying, Chamika Deshan,Gerhard Roth,Owen Newton Fernando, Adrian David Cheok : Command center: Authoring tool to supervise augmented reality session, IEEE Virtual Reality 2012 ; Orange County,USA ; 4-8 March 2012 [Short Paper]

- Cheok, A. D., Fernando, O. N., Fernando, C. L., Zhu, K., Ranasinghe, N., Narangoda, M., Godage, I. S., Peiris, R. L., Teh, J. K. S., Edirisinghe, C. P., Karunanayaka, K., Merritt, T., Abeyrathne, D., Hou, J., Thang, W., Morisawa, Y., Dayarathna, M., Withana, A.I., Ma, N. L., and Danjo, M. 2009. Petimo: safe social networking robot for children. In Proceedings of the 8th international Conference on interaction Design and Children (Como, Italy, June 03 - 05, 2009). IDC '09. ACM, New York, NY, 274-275.[Full Paper]

- Cheok, A. D., Abeyrathne, D., Edirisinghe, C. P., Fernando, O. N., Godage, I. S., Hoogendoorn, K., Hou, J., Karunanayaka, K., Narangoda, M., Peiris,

R. L., Ranasinghe, N., Teh, J. K., Thang, W. W., Zhu, K., Danjo, M., Dayarathna, M., Fernando, C. L., Ma, N. L., Morisawa, Y., and Withana, A. I. 2009. Petimo: children's companion for safe social networking. In ACM SIGGRAPH ASIA 2009 Art Gallery & Emerging Technologies: Adaptation (Yokohama, Japan, December 16 - 19, 2009). SIGGRAPH ASIA '09. ACM, New York, NY, 80-80. [Poster Abstract]

- Cheok, A. D., Fernando, O. N., Fernando, C. L., Zhu, K., Withana, A.I., Ranasinghe, N., Morisawa, Y., Karunanayaka, K., Danjo, M., Godage, I. S., Narangoda, M., Ma, N. L., Dayarathna, M., Peiris, R. L., Teh, J. K. S., Abeyrathne, D., Edirisinghe, C. P., Hoogendoorn, K., Hou, J., and Thang, W. 2009. Petimo: Childrens tangible social networking platform. In Proceedings of the 4th International Conference on Advances in Computer Entertainment Technology (Athens, Greece, October 29 - 31, 2009). ACE '09. [Full Paper]

- Cheok, A. D., Fernando, O. N., Fernando, C. L., Zhu, K., Withana, A.I., Ranasinghe, N., Morisawa, Y., Karunanayaka, K., Danjo, M., Godage, I. S., Narangoda, M., Ma, N. L., Dayarathna, M., Peiris, R. L., Teh, J. K. S., Abeyrathne, D., Edirisinghe, C. P., Hoogendoorn, K., Hou, J., and Thang, W. 2009. Petimo: Childrens tangible social networking platform. In Proceedings of the 4th International Conference on Advances in Computer Entertainment Technology (Athens, Greece, October 29 - 31, 2009). ACE '09. [Poster Abstract]

- Owen Noel Newton Fernando, Adrian David Cheok, Tim Merritt, Roshan-LalinthaPeiris, CharithLasantha Fernando, NimeshaRanasinghe, InoshaWickrama, KasunKarunanayaka (2009): Babbage Cabbage: Biological Empathetic Media, VRIC Laval Virtual Proceedings, April 22-26, 2009, Laval, France. pp. 363-366.[Poster Abstract]

Awards prizes and nominations

- Babbage Cabbage, nominated for the LAVAL VIRTUAL AWARDS 2009, in the Interfaces and Materials Catergory
- Babbage Cabbage, Winner of the Laval Virtual Revolution 2009 Competition which honors the world's finest virtual Reality projects, held in Laval, France April 2009
- Petimo: Safe Social Networking Robot for children short listed at the Como for Children (C4C) Competition at the 8th International Conference on Interaction design and children in Como, Italy, June 3 - 5, 2009. IDC '09.

Magazine Articles

- Babbage Cabbage - featured in the NUS Annual Report 2008 (pg. 45)
- Babbage Cabbage - featured in the NUS Website Research Gallery under title "Cabbages can warn us of danger"

Demos and Exhibitions

- Petimo: children's companion for safe social networking. In ACM SIGGRAPH ASIA 2009 Art Gallery & Emerging Technologies: Adaptation (Yokohama, Japan, December 16 - 19, 2009). SIGGRAPH ASIA '09

- Petimo: Childrens tangible social networking platform. At the International Conference on Advances in Computer Entertainment Technology (Athens, Greece, October 29 - 31, 2009). ACE '09. (Creative Showcase)

- Petimo: Safe Social Networking Robot for children at the 8th International Conference on Interaction design and children in Como, Italy, June 3 - 5, 2009. IDC '09.

- "Babbage Cabbage", demonstrated at the Laval Virtual Revolution 2009 under the "Welcome" catergory in Laval, France April 2009

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