DESIGN AND DEVELOPMENT OF A TACTILE JACKET TOWARDS IMMERSIVE EXPERIENCE

Project Report

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THESIS CERTIFICATE

This is to certify that the thesis titled **DESIGN AND DEVELOPMENT OF TACTILE JACKET TOWARDS IMMERSIVE EXPERIENCE**, submitted by **S.KAUSHIK (EE10B061)**, to the Indian Institute of Technology Madras, Chennai for the award of the degree of **MASTER OF TECHNOLOGY**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS:

Tactile Stimulation, Tactile Perception, Vibrotactile actuators

Tactile stimulation involves the sensation of touch and texture. It offers an extra modality for user interaction. This kind of stimulation can be optimally used in consumer products, particularly in multimedia. In order to study tactile stimulation and its application towards immersive experience we have designed a jacket containing an array of vibrotactile actuators.

The goal of this study is to use this jacket as a tactile display upon which various tactile patterns can be rendered. To achieve this firstly the various factors affecting tactile perception were studied. Some of these factors like sensory saltation were used to reduce the number of actuators that were needed in the design of the jacket.

To create these tactile patterns various basic shapes were created and tested using a tactile kit. These shapes serve as the building blocks from which various effects can be generated. These patterns offer an alternate channel in which to present information and this when integrated with audiovisual content enhances the immersive experience.

Since we are mainly looking at using these various effects in a viewing scenario (multimedia or user space) we break down the possible ways in which a person can be touched into the type of touch and the type of hand-manipulation causing the touch. Using this classification a suitable taxonomy of suitable taxonomy was developed to create a set of guidelines that can be used to design a library of patterns.

Finally a user test was carried with the prototype of the tactile jacket that was developed. The experimental results of a user test indicate that the jacket is highly reliable and that the participants were able to identify correctly the various patterns rendered by the device most of the time.

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CHAPTER 1

INTRODUCTION

“Immersive” is a frequently-used term in applications such as virtual reality, computer games, and human-computer interaction. The goal of immersive systems is to artificially create all stimuli that would be experienced in that environment in reality. Recently with the introduction of new 3D video representations and formats, new modalities of interaction with video for truly immersive media applications are becoming feasible.

Touch is a powerful sense for humans and the sense of touch (haptics) in interactive systems has been particularly studied and appears to be a key factor in user immersion. Many haptic interfaces that enable the physical interaction with virtual or remote objects have been developed and evaluated in the past decades. They were first used in virtual reality or tele-operation systems. Nowadays haptic technologies are used in various applications in medical, robotics and artistic settings.

In contrast, the use of haptics in a multimedia context, in which haptic feedback is combined with one or more media such as audio, video and text, seems surprisingly underexploited. Yet, in 1962, Heilig introduced the Sensorama, a system where one could watch a 3D movie, sense vibrations, feel the wind and smell odours. Although the potential industrial impact of haptics for audiovisual entertainment seems to be important, research and technology remains essentially focused on improving image and sound. Only a few systems, known as “4D cinemas”, currently exploit this technology.

The combination of haptics and audiovisual content becomes the complete medium of haptic-audiovisual (HAV) content. The young field of study of HAV introduces new scientific issues. What kind of device is suitable for rendering haptic feedback in a viewing scenario? To what extent can haptics influence the video viewing experience? and how can the resulting quality of experience be evaluated?

In this study we look at the design and development of one possible device, a wearable jacket and the possible tactile patterns that can be rendered using it to enhance video viewing experience.

1.1. Tactile Feedback

Touch is the most primal and the basic form of communication. Tactile communication refers to what we communicate through the sense of touch. Tactile feedback is technology which recreates the sense of touch by applying forces, vibrations, or motions to the user. This mechanical stimulation can be used to assist in the creation of virtual objects in a computer simulation, to control such virtual objects, and to enhance the remote control of machines and devices.

O'Modhrain et al(2003) have demonstrated that the benefits of haptic feedback observed in virtual reality, video games or tele presence are applicable to multimedia applications. Haptic feedback increases user's feeling of presence, of realism and user's engagement in the application. Haptic feedback may also open new ways to experience audiovisual content.

1.2. Tactile Perception

Tactile Perception (sometimes referred to as touch perception) is the brain's ability to understand (perceive) what the hands are feeling. Although touch (also called tactile perception) is considered one of the five traditional senses, the impression of touch is formed from several modalities including pressure, skin stretch, vibration and temperature.

The human sense of touch can be divided into two separate channels. Kinesthetic perception refers to the sensations of positions, velocities, forces and constraints that arise from the muscles and tendons. Force-feedback devices appeal to the kinaesthetic senses by presenting computer-controlled forces to create the illusion of contact with a rigid surface. The cutaneous class of sensations arise through direct contact with the skin surface. Cutaneous stimulation can be further separated into the sensations of pressure, stretch, vibration, and temperature. Pain is sometimes also referred to as a separate sensation, though excessive stimulation of the other parameters will lead to a feeling of pain. Tactile devices generally appeal to the cutaneous senses by skin indentation, vibration, skin stretch and electrical stimulation.

1.3.Problem Definition

The goal is to design a wearable tactile jacket with multiple actuators and to create a library of tactile patterns to be rendered on this jacket which acts as a tactile display.

1.4. Objective

Designing a jacket with multiple actuators allows us to create a large variety and number of tactile patterns. The objective was

- to come up with a suitable taxonomy to build a framework that would enable us to generate a library of patterns.
- to study factors affecting the tactile perception and use them in the design and development of the jacket.
- to design a software library of tactile patterns which could be used to program different effects easily.

1.5.Thesis Organization

This thesis is divided into six chapters how they can be improved in the future. Chapter 1 (this one), explains the problem statement, objective and scope of the project. Chapter 2 explores the literature and previous work done in the field of tactile perception, tactile stimulation and other wearable haptic devices developed before. Chapter 3 explains the pilot work done before designing the jacket, experiments of sensory saltation, characterization of the vibrotactile actuators used and the creation of a small tactile kit to study the various shapes that can be used to develop the tactile patterns. Chapter 4 has details of the design of jacket, the electronics and the software design, the taxonomy and the classification of the library of tactile patterns and the strategy behind it. Chapter 5 discusses about this prototype's workings and the results on user testing. Chapter 6 summarizes the entire thesis and looks at possible limitations and future works.

CHAPTER 2

LITERATURE REVIEW

2.1. Cutaneous Perception

Before the designing of the tactile jacket it is imperative to know the capabilities and the limits of the sense of touch. This section gives an overview of the most important aspects of cutaneous perception.

Amplitude: Discrimination capacity for amplitude, is largely dependant on the location of stimulation, being finer at those points of the body with lower detection thresholds (Geldard, 1957). As with vision and audition, discrimination capacity is not constant throughout the stimulation amplitude range. Amplitude discrimination is lower at low intensities, becomes more sensitive in the range 200-700 microns, progressively degrading with increasing stimulus amplitude (Werner and Mountcastle, 1968). Discrimination capacity for amplitudes is reported to be roughly independent of the frequency of stimulation (Tan, 1996). The highest thresholds for detection occur at low frequencies of stimulation (Lofvenberg and Johansson, 1984) and the minimum thresholds occur in the region of 250 Hz.

Frequency: While humans can hear sound in the range 20-20,000Hz, the practical frequency of the skin is much smaller, ranging from 10Hz to 400Hz, with maximum sensitivity (Summers, 1992) and finer spatial discrimination at around 250 Hz. The resolution of temporal frequency discrimination is finer at lower frequencies. Measures for discrimination threshold for frequency are problematic, as perception of vibratory pitch is dependant not just on frequency, but also on the amplitude of stimulation. Geldard (1957) found that subjects reported a change in pitch when frequency was fixed, but amplitude of stimulation was changed. Sherrick (1985) found that people could distinguish three to five different levels of frequency, but that this range could be increased to eight by adding amplitude as a redundant parameter. The perceptual interaction between frequency and amplitude is another important factor that needed to be taken into account while designing the tactile display.

Waveform: Different waveforms can be generated and used to create different tactile sensations. Brown *et al.* (2005) have looked at the effects of amplitude modulation to create stimuli of different ‘roughness’. A study showed that participants felt the modulation as varying levels of roughness, and that roughness increased as modulation frequency decreased (with the exception of a pure sinusoid which was perceived as smooth). They suggest that up to 3 roughnesses, with a study showing that participants could recognize them with 80% accuracy.

Duration: Geldard (1957) reports that the temporal duration just noticeable difference (JND) increased from 50 to 150 ms, with increasing stimulus duration from 0.1 to 2.0 sec. When using duration in the design of the tactile interface it is important to ensure that the stimuli are detectable, but not so long as to make information transfer too slow. Interactions between duration and perceived amplitude is another important factor to consider. Stimuli lasting less than 0.1 sec may be perceived as taps or jabs, whereas longer stimuli may be perceived as smoothly flowing tactile phrases (Gunther 2002). Craig and Sherrick (1982) warn that durations which are too short may result in sensations such as pokes or jabs.

Location on the Body: Different locations on the body have different levels of sensitivity and spatial acuity. The two point of contact discrimination threshold is 0.9mm in the absence of any movement lateral to the skin’s surface. Two points of contact closer than this cannot be resolved in to distinct stimuli. Another important factor to consider is whether the stimuli are presented to glabrous (non-hairy) or hairy skin as sensitivity differs greatly between them and might require more discriminable stimuli (Summers, 1992). But since the tactile jacket is worn over a piece of thin clothing we take that the sensitivity does not differ that greatly due to the differences between hairy and non-hairy skin. Craig and Sherrick (1982) suggest the back , abdomen and thigh as suitable body locations. They report that once subjects have been trained on vibrotactile pattern recognition on the back, they can immediately recognize the same patterns when presented to the thigh or the abdomen.

2.1.1. Anatomical, Neurophysiological and Perceptual issues of Tactile Perception

The skin is a complex receptive organ, made more difficult to analyze because the receptor structures are buried deep in a multi-layered tissue matrix. The rapidly adapting mechanoreceptors present in the skin are Meissner's and Pacinian corpuscles. They are velocity-sensitive, discharging an impulse only during movement in the indentation of the skin. Meissner's corpuscles are encapsulated nerve endings that are located in the grooved projections of the skin surface formed by epidermal ridges. They can be found in abundance in the hand, the foot, the nipple, the lips and the tip of the tongue. They are sensitive to vibrotactile stimuli in the range of 10 – 100 Hz.

Pacinian corpuscles are elliptical encapsulated endings, located in the deeper skin layers of both glabrous and hairy skin, which respond to rapid mechanical displacement of the skin. The Pacinian corpuscle is a layered structure, the mechanical characteristics of which limit the stimulus energy transmitted to the nerve endings to relatively high frequencies over the range of 40 – 600 Hz with optimal sensitivity around 250 Hz.

The slowly adapting mechanoreceptors include Merkel's disks and Ruffini's endings. They also discharge impulses in response to displacement of the skin; however, they can maintain a discharge of impulses in response to sustained deformation of the skin. These slowly adapting mechanoreceptors are sensitive to vibrotactile stimulation in the range of 0.4 – 400 Hz with varying characteristics and points of maximal sensitivity. Merkel's disks are found in the fingertips, the lips and mouth, with basket like terminations that surround hair follicles. Ruffini's endings are situated in the dermis of both glabrous and hairy skin, deeper than Meissner's endings. It is believed that these receptors can provide continuous indication of the intensity of steady pressure or tension within the skin (e.g., lateral stretching).

Skin sensitivity is a function of receptor density, with the fingers, lips, and genitals having the greatest thermal and spatial acuity. Furthermore, the areas of cortex devoted to their representation are proportional to innervations density (Merzenich and Kaas, 1980). These facts lead us to several design principles that will be relevant to any real-world tactile display technology.

First, stimulation at a site will activate, to one degree or another, all tactile receptors – not just one specific type. Second, the active driving element (the "actuator") has to be of sufficient size to ensure activating at least some of these receptors, particularly on somewhat insensitive body sites like the abdomen or back.

The following are some of the important factors related to the conditions under which touch sensation and perception arise.

Difference Threshold: The difference threshold is the amount of indentation that is related to the minimal required change in amplitude to be detected.

Subjective magnitude: The intensity of a stimulus is often indicated with reference to the absolute threshold of the stimulus (dB SL). However, stimuli with the same objective intensity level are not necessarily perceived to be equal in subjective intensity, and doubling the objective intensity or amount or energy does not necessarily result in a doubled subjective intensity (Verrilo , Fraioli and Smith, 1969).

Spatial Summation: Sherrick and Cholewiak (1986) concluded that the sense of touch exhibits spatial summation (change in threshold as a function of the area of stimulation), but that it is small and probably a central and not a peripheral process.

Psychophysics of Localization: Issues relevant to the perception of stimulus location are: how well one can determine the location of a stimulus (absolute localisation), how well can one distinguish different locations from each other (relative localisation or the spatial resolution of the skin), and how can spatially separated stimuli influence each other (spatial masking).

Temporal Summation: The relationship that exists between the duration of a stimulus and the threshold required for detection is known as temporal summation (Verillo,1965).

Adaptation: Adaptation corresponds to a change in the percept of a stimulus after prolonged stimulation. The absolute threshold increases and the magnitude of sensation decreases with increasing adaptation. The time constant of the adaptation process is approximately 2 min (Hollins et al , 1990).

Apparent Motion: Apparent motion is a perceptual illusion in which two or more non-moving stimuli activated in a specific spatiotemporal pattern evoke a percept of continuous motion. This percept is not always stable though.

2.2. Sensory Saltation

One major concept that helps us in designing the jacket is Sensory Saltation Effect. It is an illusion of perceiving stimuli at places other than place of contact or point at which a stimulus is issued. It occurs across the senses resulting in the perception of apparent motion.

When two equally intense taps, separated in both time and space are delivered to the skin, with the contactors delivering the taps located 5 or 10 cms apart and the second tap following the first by say a tenth of a second, it is found that the location of the first tap is attracted to the locus of the second tap, about halfway in this particular case (Frank A. Geldard , 1982).

Using variation in these parameters different spatio-temporal patterns can be perceived differently through the tactile sense. For example, a single point can be perceived as a direction (van Erp, 2001). Tactors arranged spatially on the body can create a relationship akin to vision where the ego centre is perceived as one point and the stimulus at another, thus creating direction. Taking advantage of sensory saltation, lines can be perceived, as can their length, straightness, spatial distribution and smoothness (Cholewiak,2000).

An important feature of this illusion is that it is able to stimulate higher spatial resolution than the actual number of stimulators, creating the impression of a dense stimulator array, thus potentially reducing the overall weight and power consumption needs of a wearable device. The image below (Fig 2.1) is a graphical representation of the perception of saltation by a user. As seen from the graph three pulses each given at three different locations is being perceived as one continuous pulse from the first to the last point. The shaded dots indicate the exact locations on the body where the stimuli was delivered and the non-shaded circles are the locations where the sensation was felt.

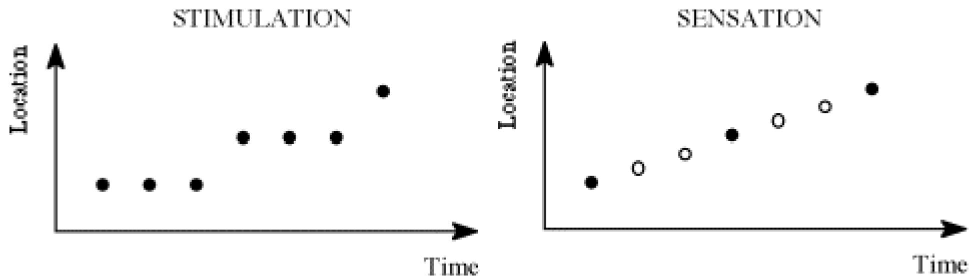

Fig 2.1: Perception of Saltation Effect

2.2.1. Psychophysics of Saltation

The cutaneous rabbit illusion (or the saltation effect) was first described in 1972 by psychologists Frank Geldard and Carl Sherrick. The underlying mechanisms however remained unkown for years afterwards. Some researchers initially attributed the illusion to some activity in the primary somatosensory cortex , which is the main sensory receptive area for the sense of touch. Here the tactile representation is orderly arranged from the toe to the mouth. This was confirmed by a neuroimaging study which showed that the tactile sensations perceived during the illusion are associated with activity in the corresponding regions of the somatosensory cortex (Blankenburg et al , 2006).

According to Goldreich.D (2007) , the brain circuitry encodes the expectation, acquired over a lifetime of sensory experience, that tactile stimuli tend to move slowly. The expectation that stimuli tend to move slowly results in the perceptual conclusion that rapidly successive stimuli are more likely to be closer together on the skin. This is explained by the Bayesian perceptual model which reaches an optimal probabilistic inference by combining uncertain spatial sensory information with a prior expectation for low-speed movement.

An illusion which can be closely related to the rabbit illusion is the tau effect. The tau effect arises when an observer judges the distance between consecutive stimuli in a sequence. If the distance from one stimulus to the next is constant, but the time elapsed from one stimulus to the next is not constant, then subjects tend to inaccurately perceive the interval that is shorter in time as also being,. Thus, like the rabbit illusion, the tau effect reveals that stimulus timing affects the perception of stimulus spacing shorter in distance.

2.3. Vibrotactile Sensitivity

The tactile sensitivity varies across different parts of the human body. For instance , the finger tips and the facial skin are particularly receptive to touch (Weinstein, 1968). Differences in tactile sensitivity can be related to the underlying neurophysiology of the skin. Skin can be divided into three main categories: glabrous skin (e.g., the thicker, non-hairy skin on the palms), hairy skin (e.g., the vast majority of the skin on the body, which contains different types of hairs), and mucocutaneous skin (e.g., the lips).

The human skin contains *mechanoreceptors*, or receptors that are sensitive to mechanical pressure or deformation of the skin. However, the concentration of mechanoreceptors within the skin is not uniform. Rather, the highly sensitive areas of skin, such as the lips and fingertips, contain densely packed mechanoreceptors, while insensitive areas, such as the stomach and back, contain lower concentrations of mechanoreceptors. More sensitive areas of the skin also project to a larger proportion of the somatosensory cortex than less sensitive areas. Thus, the area of the brain which receives touch sensations (for example, from the fingertip) is proportional to the actual sensitivity of the skin area.

Different regions of the somatosensory cortex process tactile information from different parts of the body, with these regions forming a "map" of the body surface on the cortical surface (Fig 2.2). In general, the more cortex dedicated to a body surface, the greater the sensitivity of that region (Blake & Sekuler, 2006). A disproportionately large volume of the cortical tissue is devoted to certain parts of the body such as the hands and the mouth.

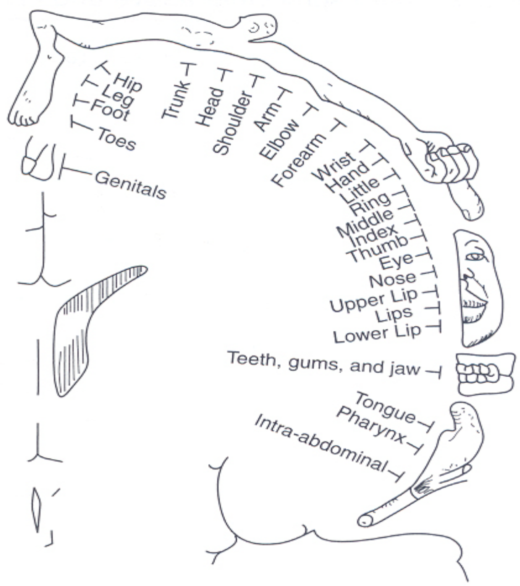

Fig 2.2. Map of amount of cortex dedicated to different body parts (Blake&Sekuler,2006)

This fact is further supported by the two point discrimination threshold for different parts of the human body (Fig 2.3) which is the ability to discern that two nearby objects touching the skin are truly two distinct points and not one.

Site	Threshold Distance
Fingers	2-3 mm
Upper Lip	5 mm
Cheek	6 mm
Nose	7 mm
Palm	10 mm
Forehead	15 mm
Foot	20 mm
Belly	30 mm
Forearm	35 mm
Upper arm	39 mm
Back	39 mm
Shoulder	41 mm
Thigh	42 mm
Calf	45 mm

Fig 2.3: Two point threshold distance for different body parts (Image from io9)

2.3. Wearable Tactile Devices

Over the course of time various wearable tactile devices have been created and tested for various applications. In this section we review the various wearable devices that are designed to be worn by as the user experiences audio visual content. Typically these are composed of several vibrotactile actuators embedded into clothes as detailed by Rahman *et al* (2010) (Fig 2.4). In their study using actuator hardware off the shelf they add haptic features to Youtube videos so that the users can experience different tactile sensations while watching them.

Fig 2.4. Vibrotactile jacket and armband (Rahman et al, 2010)

Lee *et al* (2005) proposed a device with vibrotactile sensations through an assembly of 7x10 vibrotactors attached to the user's forearm (Fig 2.5). The array of actuators is 60 mm by 120 mm. A Vibrotactile device can be easily used to detect the motion of a specific object and using that idea this prototype was used to render movements of the ball on the field during a soccer game. The tactile array was mapped to the field and vibrations were triggered at ball locations. A tactile display method was also proposed to trace the path of the ball in a two dimensional space. According to the authors this device allows the user to better understand ambiguous game situations.

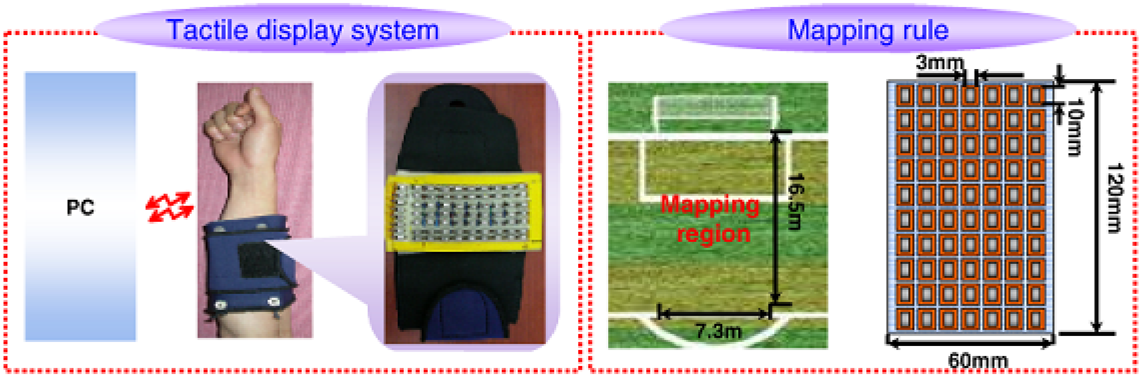

Fig 2.5: System Configuration to render a football game (Lee et al, 2005)

Kim et al (2011) designed a tactile glove for immersive multimedia that contains 20 tactile actuators per glove (4 per finger). The gloves are wireless-controlled and produce vibrotactile patterns as the user watches a movie (see Figure 2.6). Firstly each frame of the tactile video is mapped to the different actuators which are activated with different intensities by using a tactile display. These four tactile actuators are attached to the front part of each digit of the inner glove.

A sequence of such frames is mapped to a sequence video in the tactile device which is then matched with the full movie scenes. However there is a diverse range of options available in the process of adding tactile feedback to movie scenes and there is little criteria to act as guidelines.

Fig 2.6 Vibrotactile Glove (Kim et al, 2011)

A vibrotactile belt has been designed by Ooshima et al (2008) to provide a feeling of being slashed. They have used small speakers to generate vibrations that propagate inside the user's abdomen. These speakers function as tactors to produce a strong perception which acts as a stimulus to the body. The aim is to create tactile apparent movement which is comparable with auditory motion, focusing on position and speed. The device is made up of four vibrators placed in a row inside a waist band and sixteen speakers placed in a row outside the waist band (see Fig 2.7 and Fig 2.8).

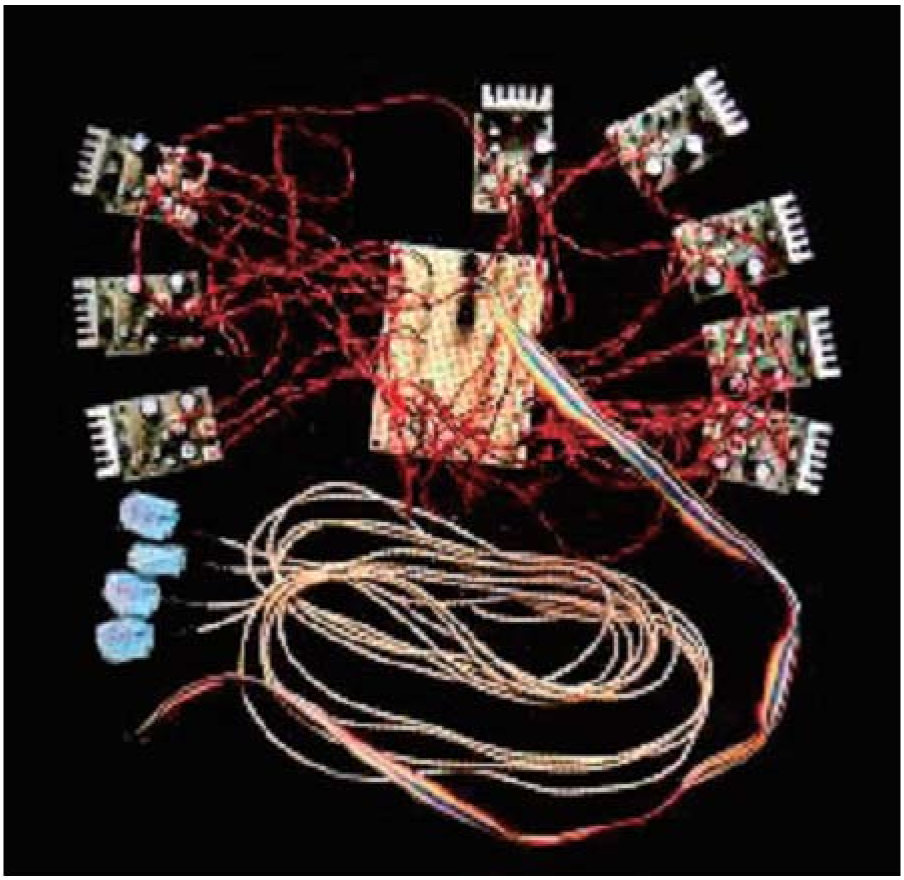

Fig 2.7 : Position of vibrators in vibrotactile belt (Ooshima et al , 2008)

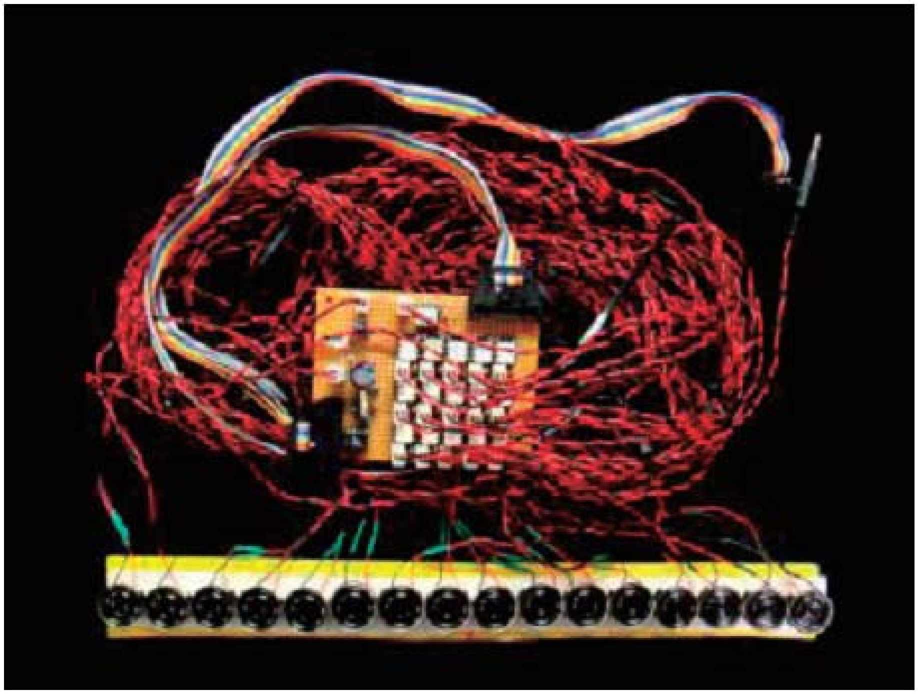

Fig 2.8 : Position of speakers in Vibrotactile belt (Ooshima et al, 2008)

A tactile jacket has also been developed by Lemmens et al (2009).They explored the influence of tactile devices on spectators' emotional responses, and designed a tactile jacket with 16 segments of 4 vibration motors covering the torso and the arms. Motors are activated following patterns related to specific emotions. For example, the feeling of love is enhanced by activating motors overlying the abdomen in a circular manner.

Palan et al (2010) presented a vest (fig 2.9) with embedded vibration motors, solenoids and Peltier elements. The vest was designed to display three haptic effects as realistically as possible: gunshots, slashing and blood flow, with the motivation of improving video games experience. Similarly, a commercially available jacket manufactured by TNGames produces effects such as explosions, gunshots or accelerations using 8 aircells.

Fig 2.9 : Tactile Gaming vest (Palan et al, 2010)

Device	Actuator	Haptic effect
Vibrotactile Armband	7*10 vibration motors	Vibrations(related to position of a ball during a soccer game)
Vibrotactile glove	20 vibration motors (4 per finger)	Vibrations
Vibrotactile armband or jacket	Array of vibration motors(variable size)	Vibrations
Vibrotactile jacket	16*4 vibration motors	Vibrations (related to users emotions
Vibrotactile vest	Vibration Motors + Solenoids + Peltier elements	Pressure(gunshot) ,temperature (blood flow), vibrations (slashing)
Vibrotactile vest	8 air cells	Vibrations and pressure (gunshots, acceleration, explosion)

Table 2.1: Overview of existing wearable devices

CHAPTER 3

DESIGN OF TACTILE KIT

As a precursor to designing the tactile jacket, a tactile kit was developed consisting of a few simple experiments to lay the groundwork for the development of the jacket

3.1. Saltation Effect

As discussed in Section 2.2 Saltation effect or cutaneous rabbit illusion is a tactile illusion evoked by tapping two or more separate regions of the skin in rapid succession. The illusion is most readily evoked on regions of the body surface that have relatively poor spatial acuity, such as the forearm. A rapid sequence of taps delivered first near the wrist and then near the elbow creates the sensation of sequential taps hopping up the arm from the wrist towards the elbow, although no physical stimulus was applied between the two actual stimulus locations. Similarly, stimuli delivered first near the elbow then near the wrist evoke the illusory perception of taps hopping from elbow towards wrist.

3.1.1 Experimental Setup

In a simple experimental setup three vibrotactile actuators are placed equidistant from each other on the forearm (Fig 3.1). The actuators are tightly fitted into small packets which are stitched onto Velcro strips (Fig 3.2). These strips are then tightly wound at three places on the forearm at equal distances from each other. The actuator closest to the wrist delivers three short pulses, followed by three more at the middle actuator and finally three more pulses by the last actuator. They receive short duration pulses (PWM signals) from a custom made motor driver.

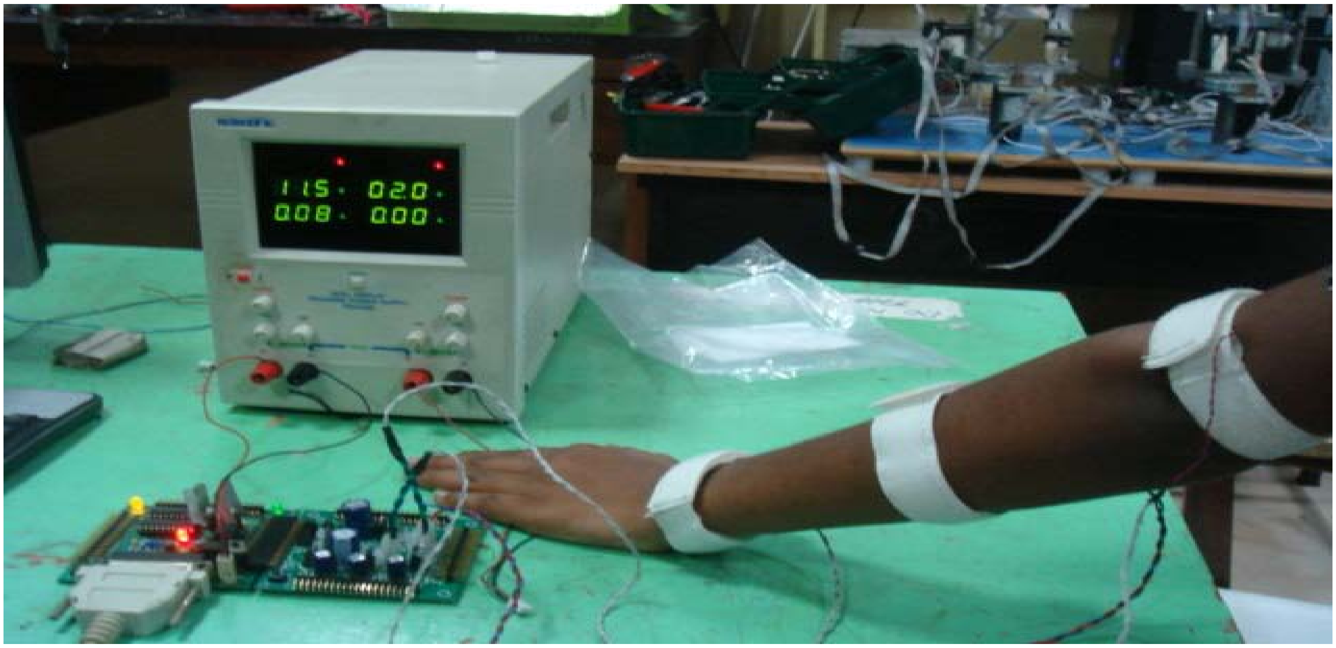

Fig 3.1: Experimental Setup of Saltation Effect

Fig 3.2: Actuator fitted into the strip

3.1.2. Vibrotactile Actuators

Coin- type eccentric rotating mass (ERM) type motors are used for this experiment. They are also called shaft less or pancake vibrator motors with 10mm diameter. They are compact and convenient to use. They have no permanent moving parts and can be affixed in place with a strong permanent self-adhesive mounting system.

Fig 3.3: ERM actuator

Mechanical Structure: The ERM is basically a DC motor with an offset (non-symmetric) mass attached to the shaft (Fig 3.3.1). As the ERM rotates, the centripetal force of the offset mass is asymmetric, resulting in a net centrifugal force, and this causes a displacement of the motor. The ERM used is 310-103 (10mm).

Fig 3.3.1 Mechanical Structure of ERM

Construction of the ERM: A Neodymium ring magnet is present on the base. In the centre of this magnet, are two brushes aligned at an angle lesser than 180^o. On top of this the rotating mass is present in the form of a PCB with the mass at one end. This PCB contains the commutator and the coil. The operation of the commutator is as follows.

The operation of the commutator is as follows:

	COIL I	COIL II
STAGE I	Forward Direction	Not Connected
STAGE II	Forward Direction	Forward Direction
STAGE III	Not Connected	Forward Direction
STAGE IV	Forward Direction	Not Connected
STAGE V	Reverse Direction	Reverse Direction
STAGE VI	Not Connected	Forward Direction

Table 3.1: Working of ERM

In order to characterize the ERM, a piezoelectric disc was selected. This was coupled with the motor using an adhesive and copper foil for conduction. This was then coupled with a heavy metal block using double sided tape. When applied with sinusoidal signals, the tactor vibrates with an amplitude and frequency corresponding to the applied input voltage. The results of this characterization were seen to match with the characteristics that were given in the specifications sheet (Fig 3.4).

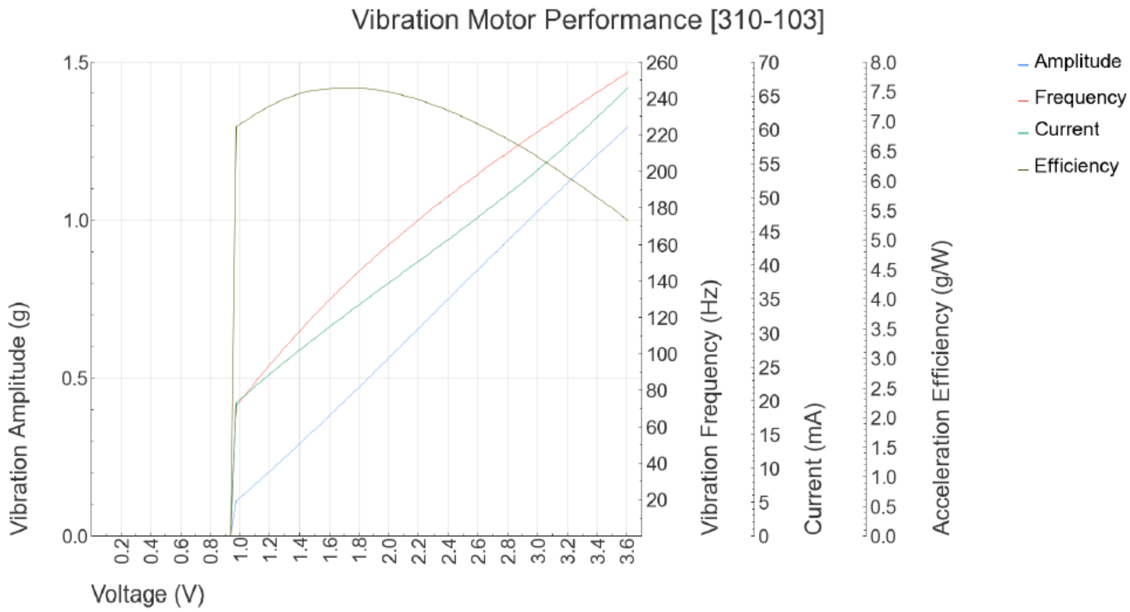

Fig 3.4 – Characteristics of the ERM (Precision Microdrives)

3.1.3 Observations

The saltation effect experiment was carried out on 10 participants. The pulses were first delivered from the wrist to the elbow and then from the elbow to the wrist. Nearly 8 out of the 10 participants didn't perceive the pulses at the points of actuation. Rather they said that they felt a continuous pulse as if it was moving from the wrist to the elbow on the first trial and back from the elbow to the wrist on the second trial. This basically verifies saltation effect and provides us a platform to create an array of actuators that can cover the entire human torso thereby paving the way for the vibrotactile jacket.

3.2. Characterization of Actuators

In the tactile jacket low cost mobile phone actuators were used. Three different types of these tactors similar in their characteristics were procured as shown in Fig 3.5. They are coin-type low cost vibration motors which vibrate at a minimum of 1V DC supply. For each section of the tactile jacket (see Fig 4.) similar type of motors were attached. The resistance of all the different types of motors is around 35 ohms.

The characterization of these actuators was done using a laser sensor – ILD 2300. The rated voltage of these motors is 3V. The typical rise times of these actuators (at rated voltage) are:

Type 1: 34 ms

Type 2: 68 ms

Type 3: 47 ms

The typical stop times of these actuators are:

Type 1: 30 ms

Type 2: 77 ms

Type 3: 54 ms

Fig 3.5: Actuator Types

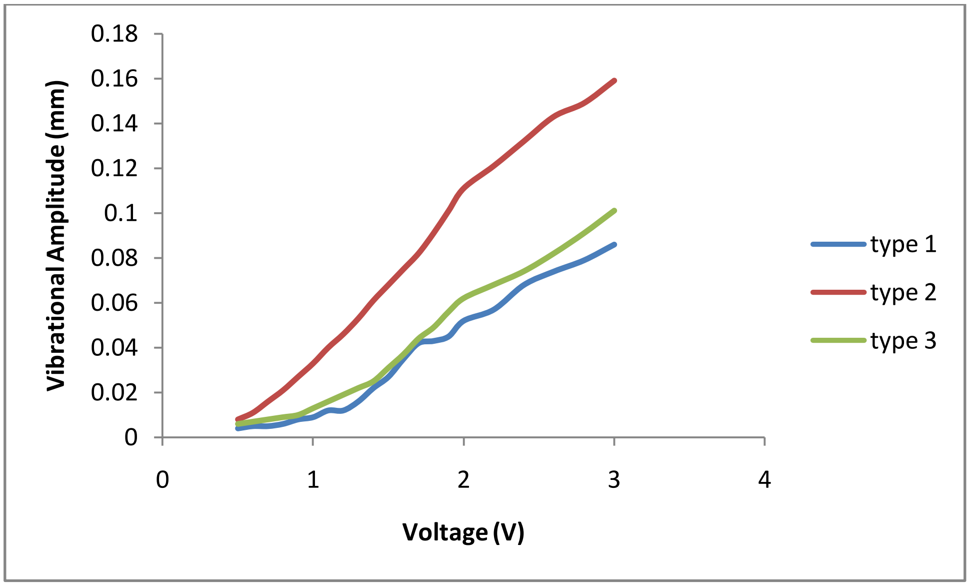

Fig 3.6.1 : Input Voltage vs Vibration Amplitude

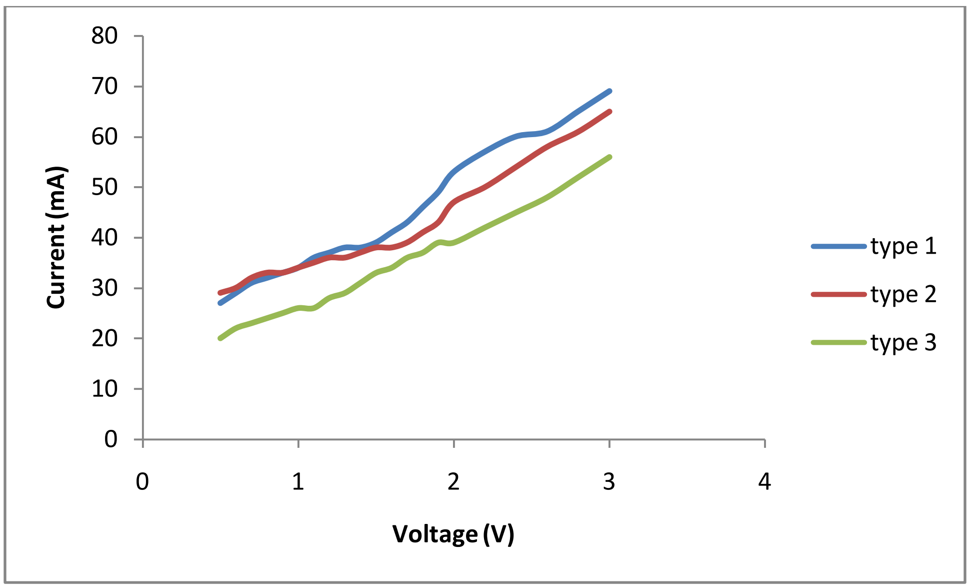

Fig 3.6.2: Input Voltage vs drawn Current

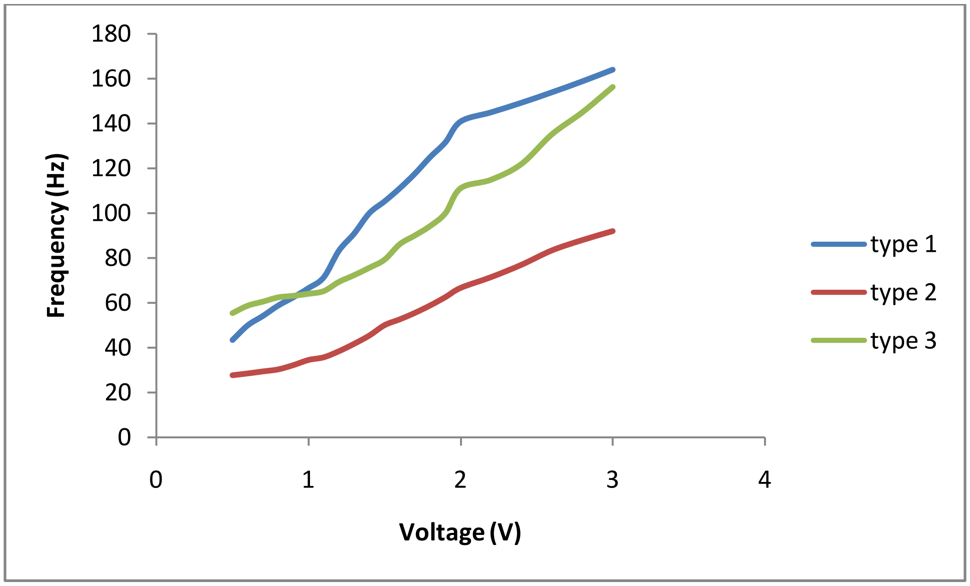

Fig 3. 6.3: Input Voltage vs Vibrating frequency

3.3 Tactile Kit

To create different vibrotactile patterns it is first important to generate and test the different shapes which are the basic building blocks of these patterns. So we created a tactile kit to generate different types of relating to Pulse Width Modulation (PWM) settings that are sent to the motors. Shapes define the vibration intensity over time. Patterns specify at what point in time a particular motor has to render the given shape. Patterns thus define the distribution of vibrations over the torso.

A computer mouse was used as a haptic grip (Fig 3.6) and the haptic controller was a custom made motor driver. The haptic mouse houses two ERM actuators and a wide range of shapes and effects are generated. The normal capabilities of the mouse were temporarily disabled for testing purposes. Another advantage of the tactile kit is that it can also help new users understand haptic feedback.

Fig 3.6 : Actuators in the Haptic Mouse

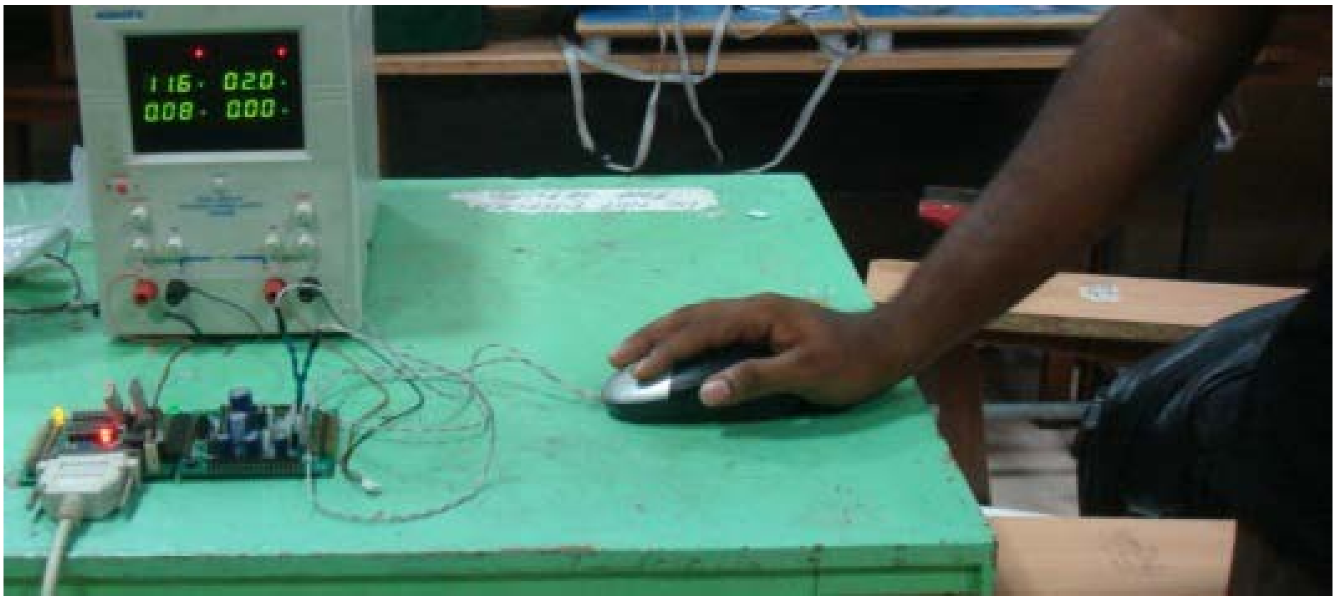

Fig 3.8 : Experimental setup of tactile kit

Some basic shapes that are created in the tactile kit are

DC Waveform : A continuous voltage of fixed value or the amplitude of vibration is fixed (Fig 3.8.1). Depending on the input voltage or the amplitude of vibration the haptic effect can be strong, medium or weak.

Fig 3.8.1 : DC Voltage

Pulse Waveform: The pulse waveform looks like in fig 3.8.2. By varying the amplitude and the time period (or the pulse width) the different effects that can be created are Strong, medium or weak and long, short. Different combinations of these two like a Long medium pulse or short strong pulse can also be created.

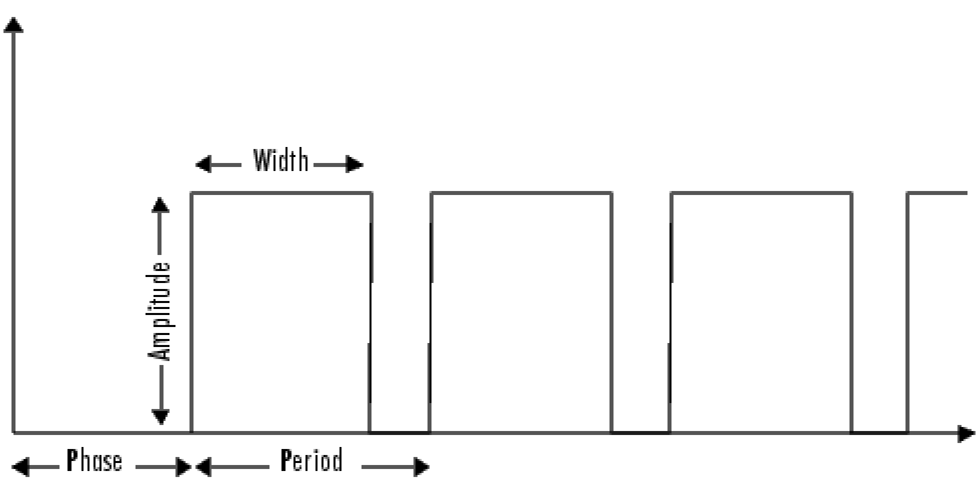

Fig 3.8.2 : Pulse waveform

Triangle Waveform: Again here depending on the time period (or width of the triangle) and the amplitude the different effect can be created.

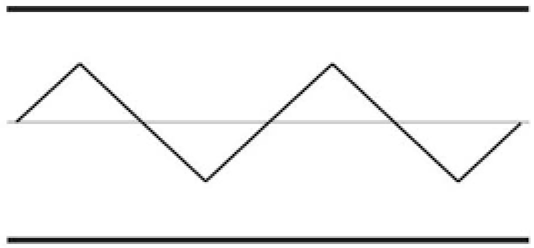

Fig 3.8.3 – Triangle Wave

Ramp Waveform : Ramp up and Ramp down (or positive and negative ramp) waveforms are shown in figure. Depending on the slope of the ramp they can be classified as sharp or smooth and long or short depending on the time period (width).

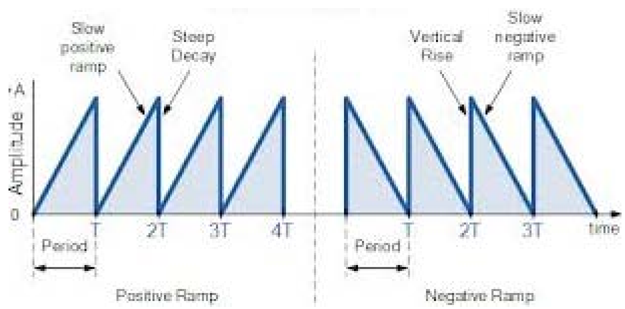

Fig 3.8.4 Ramp waveform

A few of the effects that can be created in the tactile kit are tabulated below.

S.No	Effect	Waveform
1.	Strong Click	One half cycle of a strong pulse
2.	Double Click	Two half cycles of a pulse
3.	Medium Click	One half cycle of a medium pulse
4.	Short Double Click	Two half cycles of a pulse with small width
5.	Long Double Click	Two half cycles of a pulse with large width
6	Strong Pulse	Pulse

7.	Medium Pulse	Pulse
8.	Ramp up short	Positive ramp of small width
9.	Ramp up long	Positive ramp of large width
10.	Ramp down short	Negative ramp of small width
11.	Ramp down long	Negative ramp of large width
12.	Ramp up smooth	Positive ramp of small slope
13.	Ramp up sharp	Positive ramp of large slope
14.	Ramp down smooth	Negative ramp of small slope
15.	Ramp down sharp	Negative ramp of large slope.

Table 3.1: Table of effects in the haptics kit

These are some of the basic shapes that can be created in the tactile kit. Now more complex shapes can be created by combining any of these shapes together. For instance Pulsed Ramp up short smooth can be one such complex shape. These effects generated serve as the building blocks of the patterns that can be generated using the tactile jacket.

CHAPTER 4

DESIGN OF TACTILE JACKET

4.1. Textile Integration

The main design criteria for the jacket were, ability to stimulate the back and front of the human torso and smooth integration of electronics with fabric (for good aesthetics), good accessibility of electronics, and light weight. The current design aims to enable projection of tactile patterns on the entire torso while keeping the electronic design low on complexity.

A stretchable fabric has been chosen to create a tight fit. This ensures that the actuators are close enough to the skin for the best tactile sensation possible.

This results in a jacket with 32 uniformly distributed actuators in a layout covering the entire torso with roughly 15 cm distance (Lemmens *et al*, 2009) between neighboring actuators. This ensures that the actuators are close enough to the skin for the best tactile sensation possible. As a prototype a large sized jacket was bought and small packets were stitched onto it to fit the actuator onto it (Fig 4.1).

Fig 4.1: Actuator fitted onto the jacket

4.2. Electronics and Software Design

For the actuators we have opted for pancake–shaped (coin type) generic mobile phone vibration motors because they are light weight, thin, and inexpensive compared to other offerings. A disadvantage is that we are limited to vibrotactile stimulation only.

The basic flow of control of the circuitry is show below:

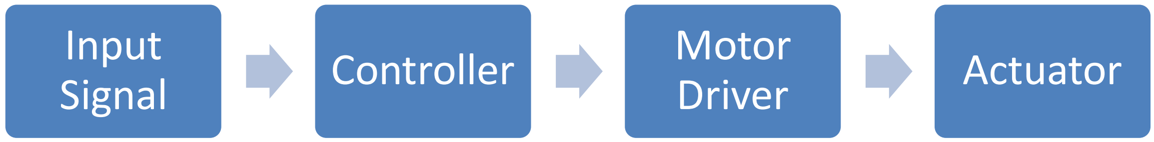

Fig 4.2: Basic flow of control

We use an Arduino Mega board for control which has an Atmega 2560 micrcontroller embedded in it. Now the arduino can't be used to directly run the actuators because the arduino can source up to only 40 mA current per I/O pin and since it has only 1 VCC pin it means that they can source of total of 200 mA. Each of these actuators draw a current of 50-60 mA and a spike current of nearly 100 mA. So to run these actuators we need a motor driver.

The motor driver being used is the IC L293D which has a dual H-bridge integrated motor driver circuit. It acts as a current amplifier by taking a low-current control signal and providing a higher-current signal which is used to drive the motors.

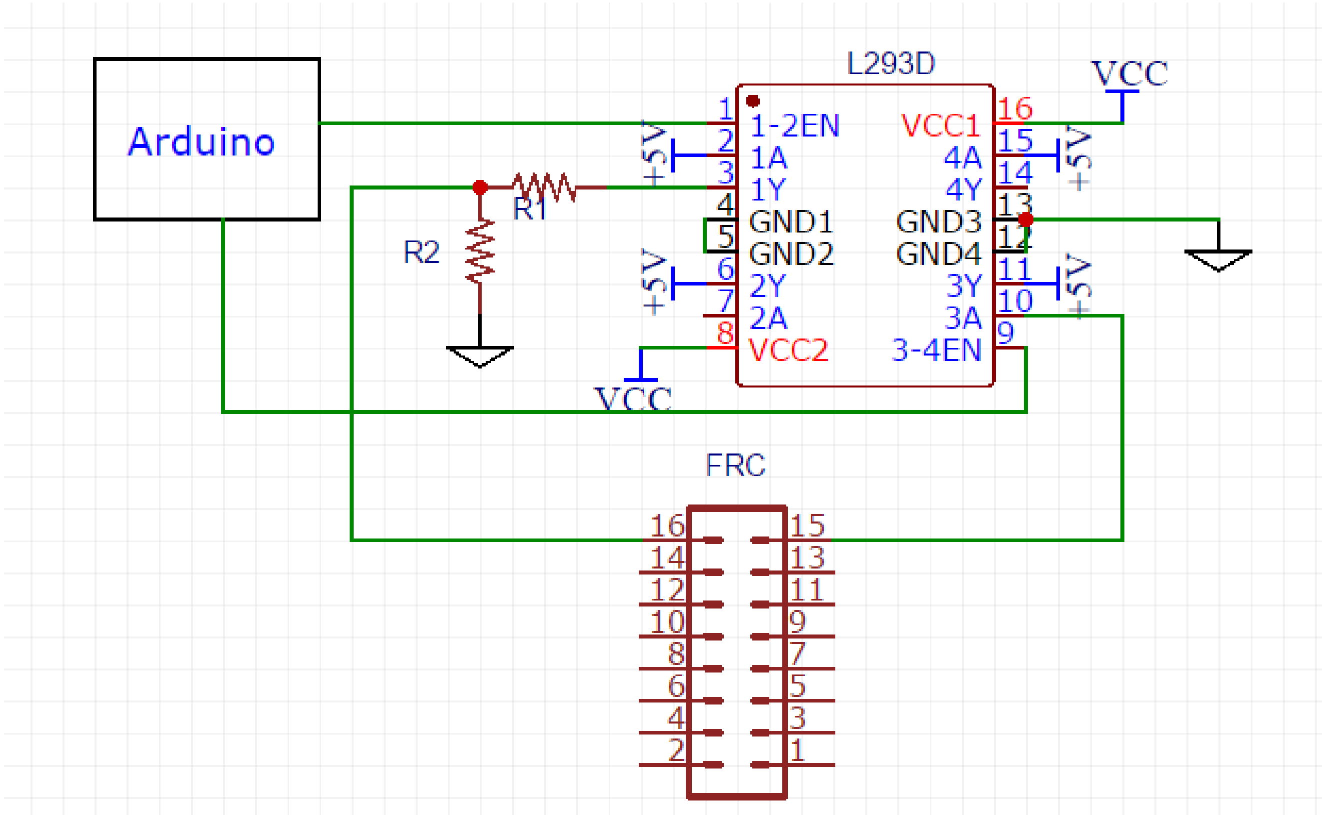

Fig 4.3 Circuit Diagram for running two motors (using L293D)

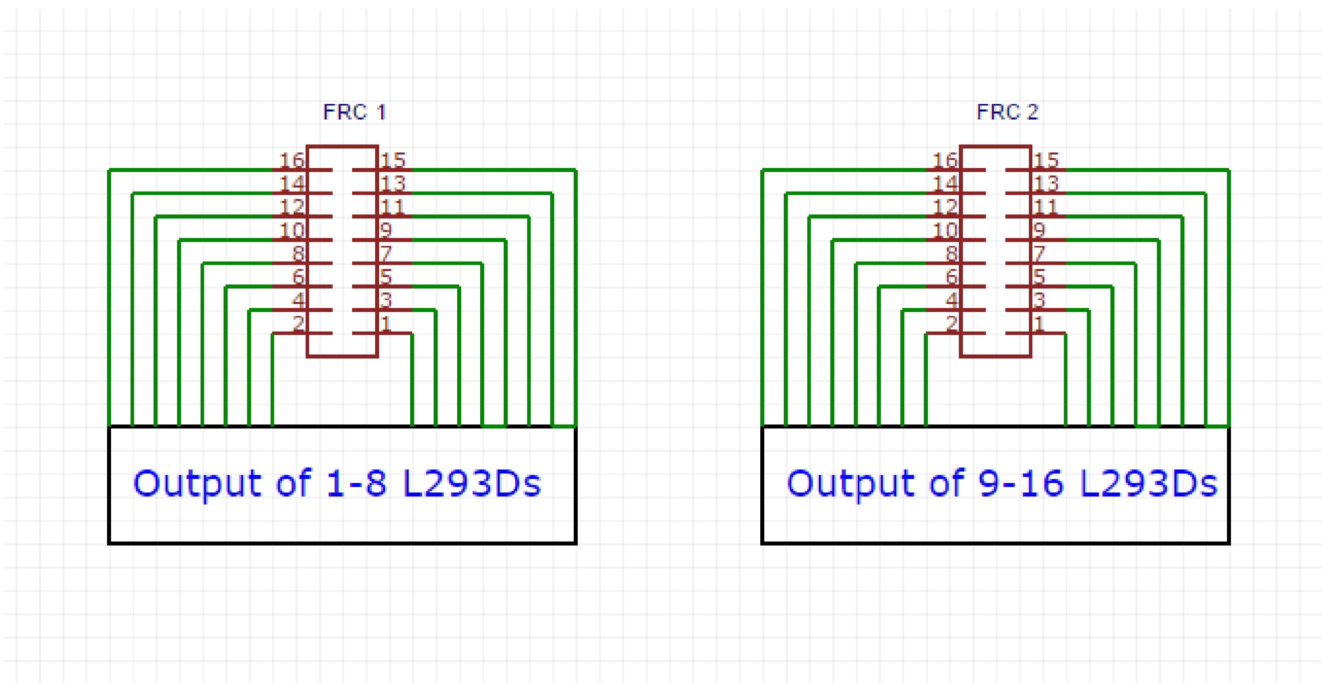

Fig 4.3.1 : Block Diagram for output to 32 motors

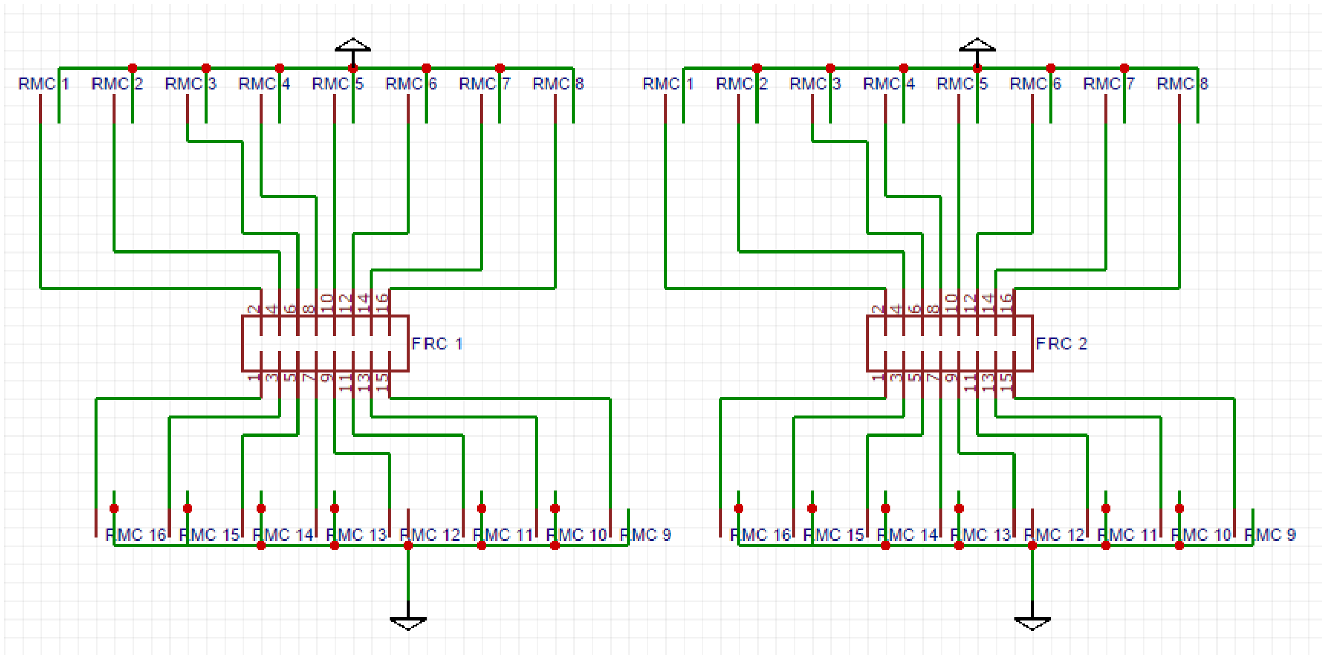

Fig 4.3.2 : Circuit Diagram of Connector Board

The input voltage to an L293D is a digital signal. It is either 0 or 5V. Any voltage above 3.3V is treated to be 5V and any voltage below is zero. In our design all input voltages are set at 5V.

In such a case the output voltage is given by: $V_{output} = (Enable/V_{ss})*V_s$

V_{ss} is always fixed at 5V.

In our design the output pin of the arduino is connected to the enable of the L293D.So the output voltage which drives the actuator is becomes

$V_{output} = (Enable/ 5)*V_s$

With V_s set it ensues that the output which drives the motor is directly proportional to the PWM signal given to the Enable by the output pin of the arduino. So each side of the L293D can run one actuator thereby enabling one IC to run two motors. A simple resistive divider circuit is used to make sure that the base voltage at which the actuators are run is set at 2V.

Now the arduino has only 13 PWM pins but since we have to run 32 actuators even the digital pins were used to run the actuators by software PWM. Below we take a brief look at what actually Pulse Width Modulation is.

4.2.1. Pulse Width Modulation

A Pulse Width Modulated signal is a type of digital waveform. It alternates between bursts of ‘On’ and ‘Off’, also known as high and low respectively, at a fixed frequency. The PWM signal differs from other digital signals (e.g. square waves) because the time that the signal is high and low can be varied (Fig 3.4). This is useful because when the PWM signal is averaged with a simple analog filter, a DC voltage is produced that is proportional to the duty cycle (which is the percentage of time that the PWM signal is high). Since a vibration motor's speed and frequency of vibration is directly proportional to the voltage applied to the motor, we can use PWM to control precisely how the motor runs.

The specified frequency of the signal needs to be sufficiently high so that the load, in our case a vibration motor, does not see 'bursts' of high and low (the switching digital signal). Instead we want the PWM signal to appear as a smooth averaged signal, which is proportional to the duty cycle of the digital signal (Fig 3.5).

Luckily, because of the inductive and resistive nature of a DC motor's windings, it effectively has its own low pass analog filter built in. If the load was purely resistive then the PWM waveform would still be visible. With the motor as a load, the PWM signal is clearly averaged (though still a little spiky / noisy, but we can improve on that later).

The width of the on burst can be adjusted by the microcontroller which is complimented by the inverse change in the off pulse width, thereby maintaining the same frequency. Changing the pulse widths results in a change of the average voltage after filtering, allowing any value between zero and the maximum voltage to be represented by increasing or decreasing the on pulse width. Hence the term Pulse Width Modulation.

This enables analogue control of the motor using digital signaling, making it very useful to control the actuator. The PWM signal has three separate components:

- A Voltage, V_{PWM}, the value of the 'on' or high voltage level (typically between 2 ~ 5V if PWM signal is produced by a microcontroller / CMOS logic).
- A Frequency - the period of one clock cycle, i.e. one high pulse and one low pulse.
- A Duty Cycle - the ratio of the on-time to the off-time, which controls the resulting voltage, explained in detail below.

The Duty Cycle represents the length of the On pulse compared to one period cycle. It is expressed as a percentage. The resulting voltage, which is seen by the motor, is the average voltage over the period. It is calculated using the following formula: $V_{AVG} = V_{PWM} * \text{Duty Cycle}$.

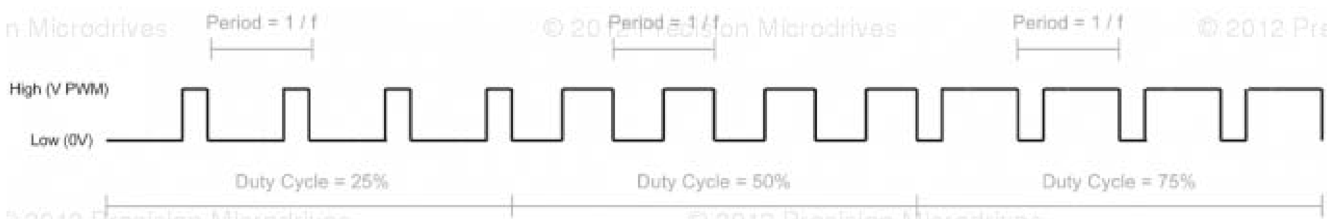

Fig 4.4: PWM example waveform (Precision Microdrives)

The output voltage, which is the voltage seen by the motor, of the above waveform is shown below:

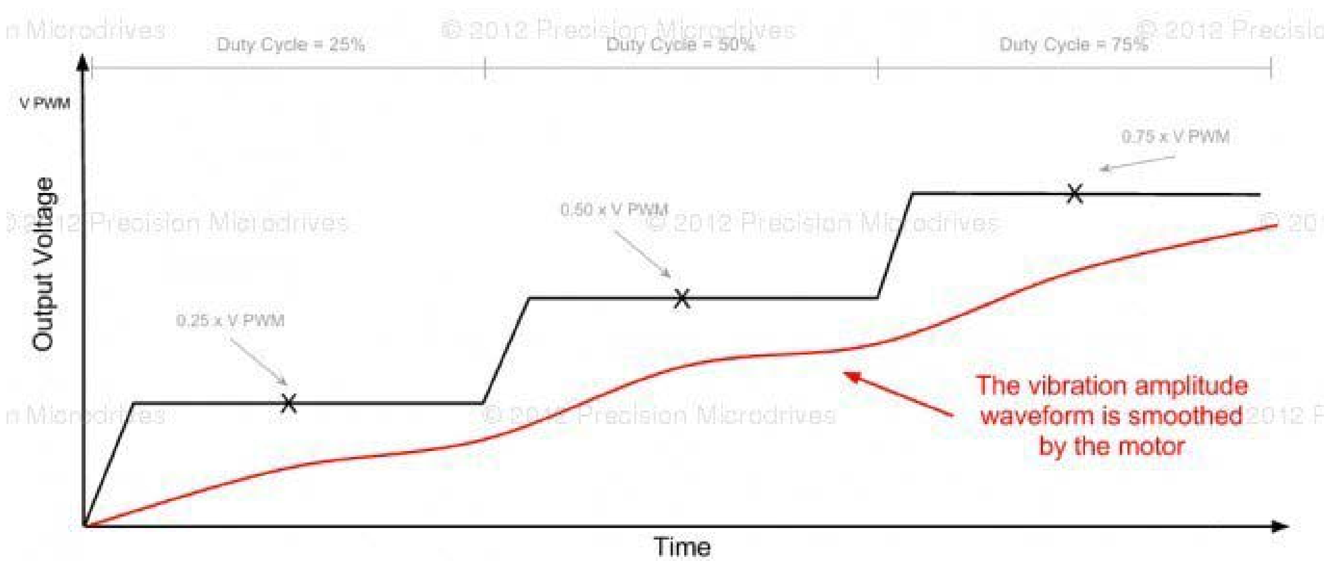

Fig 4.5: Output voltage of different duty cycles (Precision Microdrives)

4.2.2. PCB Design

PCB design in EAGLE is a two-step process. First the schematic is designed and then we lay out a PCB based on that schematic. Schematic helps us catch errors before the board is fabricated, and it also helps us to debug a board when something doesn't work.

Then we work on the board designer editor to create the PCB. The board designer has layers just like an actual PCB. A palette of colours is used to represent the different layers. Here are some of the layers used in the designer :

Color	Layer Name	Layer Number	Layer Purpose
	Top	1	Top layer of **copper**
	Bottom	16	Bottom layer of **copper**
	Pads	17	Through-hole pads. Any part of the green circle is exposed **copper** on *both* top and bottom sides of the board.
	Vias	18	Vias. Smaller copper-filled drill holes used to route a signal from top to bottom side. These are usually covered over by soldermask. Also indicates **copper** on both layers.
	Unrouted	19	Airwires. Rubber-band-like lines that show which pads need to be connected.
	Dimension	20	Outline of the board.
	tPlace	21	**Silkscreen** printed on the top side of the board.
	bPlace	22	**Silkscreen** printed on the bottom side of the board.
	tOrigins	23	Top origins, which you click to move and manipulate an individual part.
	bOrigins	24	Origins for parts on the bottom side of the board.
/ / Hatch	tStop	29	Top stopmask. These define where **soldermask** should *not* be applied.
\ \ Hatch	bStop	30	Absent **soldermask** on the bottom side of the board.
	Holes	45	Non-conducting (not via or pad) holes. These are usually drill

			holes for stand-offs or for special part requirements.
	tDocu	51	Top documentation layer. Just for reference. This might show the outline of a part, or other useful information.

Table 4.1: Different layers in Eagle (Image from Sparkfun)

While arranging the different components in the board we need to make sure that the parts don't overlap and that the intersecting air wires are minimized. Then we route the components to minimize the size of the board. After routing, gerber files are generated and the boards are given for printing. The motors are divided into 8 segments of 4 motors, with every 4 segments being controlled by their own connector board shown in figure 4.3.2 where the motor outputs go to the rmc connector.

4.3. Taxonomy of Tactile Patterns

Once the hardware and the software were built we needed to come up with a framework for the library of patterns that we intended to create. Since we were looking at using these patterns in a viewing scenario (cinema or user living space) we studied the typical human–to–human touch behaviors, for instance, a tap on the forearm to call a person. Such a touch behavior can be broken down into two, one – the kind of hand manipulation used for the touch and second - the type of touch. For example a tap on the forearm can be broken down into, tapping (which is the type of touch) with one (or many fingers) and motion at the point of contact of the second person.

4.3.1. Touch-based Classification

There are a multitude of ways in which humans can touch external objects. For this study we look at the following four common types of touch and how they are stimulated by the vibrotactile actuators. One important factor to note here is that these different touch types are not discrete but rather continuous with one type being able to easily flow into the other

Passive touch: Touch without any movement of the hand at the point of contact stimulated by continuous vibration of the actuators.

Pat or Tap: Stimulated by continuous on and off of the motors.

Stroke: Continuous movement of a segment of actuators.

Rub: Sequentially firing a set of four motors in a circular manner.

4.3. Hand Manipulation

To understand and classify hand-based manipulation, it is important to define what is meant by a "hand." We define hand as the parts below the wrist and we are not looking at the whole arm because the most common ways in which people touch another person is through the hand (MTA Sin , 2013).So for instance, we are not looking at a pattern aimed at achieving a suggestion like a comforting arm around a shoulder.Below we look at the definitions of some of the terms used in the classification:

Contact: Hand is touching an external object or the environment (another human body in our case).

Prehensile: Action of hand on object is described with more than one finger.

Sender: The person who touches the other body.

Receiver: The person who is being touched.

Motion: Any part of the sender's hand moves in relative to his body (which is like a fixed frame).

Within Hand: Points on the sender's hand are moving relative to his hand base frame.

Motion at contact: Sender's hand moves relative to the receiver's body.

4.3.3. Our Classification

The following is a detailed classification. For our purpose we only need certain branches in the classification where some examples of tactile patterns which can be generated are listed.

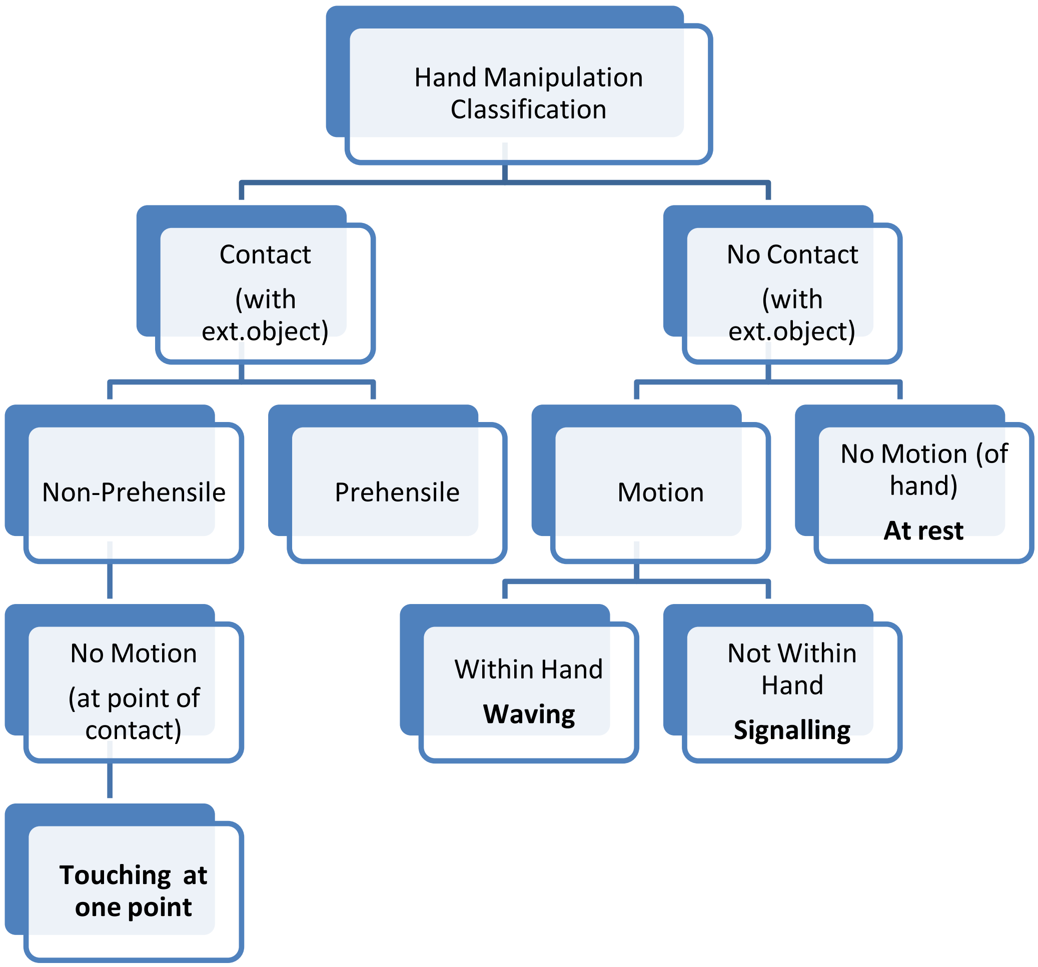

Fig 4.6 : Classification of Hand Manipulation

The classification is continued below but the different kinds of non-prehensile and prehensile motion are done separately. The parts in bold highlight some of the examples that fall under the particular category of classification

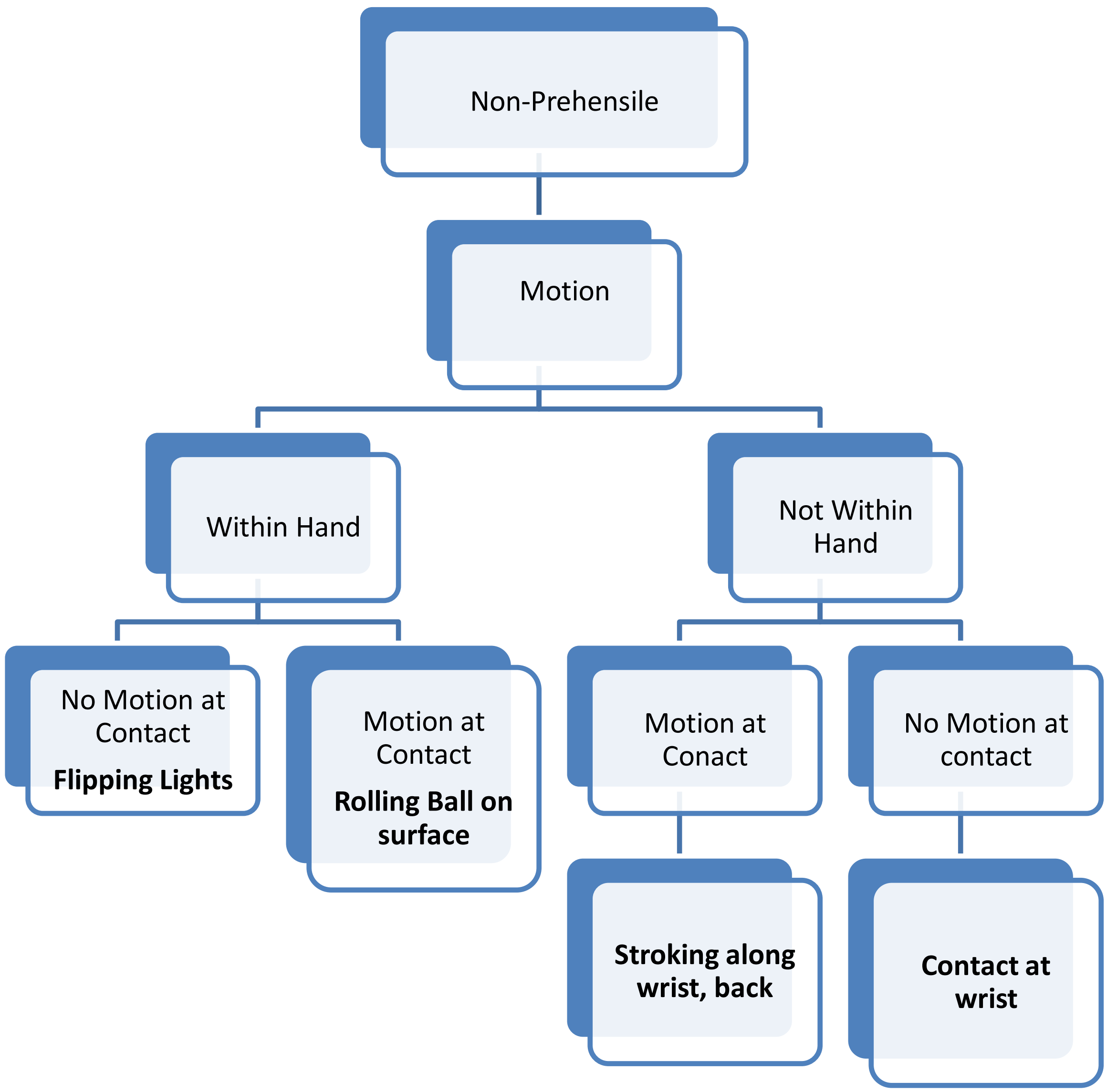

Fig 4.6.1 : Classification - Contact → Non-Prehensile

The tactile patterns that can be generated using the jacket fall under the category :

Contact → Non-Prehensile → Motion → Not Within Hand → Motion at contact.

Contact → Non-Prehensile → Motion → Not Within Hand → No Motion at contact,

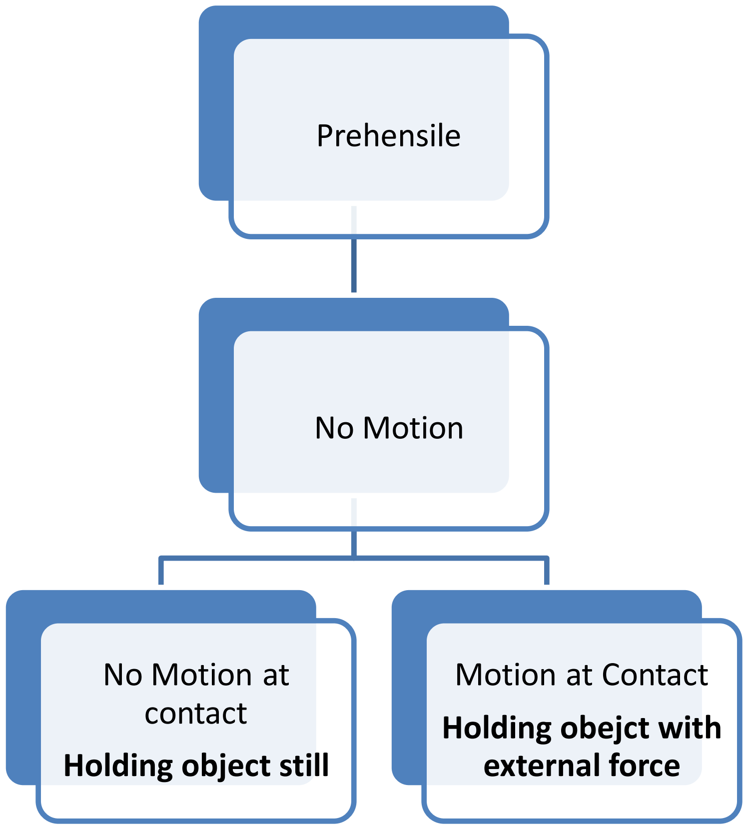

Fig 4.6.2: Classification - Contact → Prehensile → No Motion

The patterns that we can generate using the tactile jacket do not fall under any of this classification.

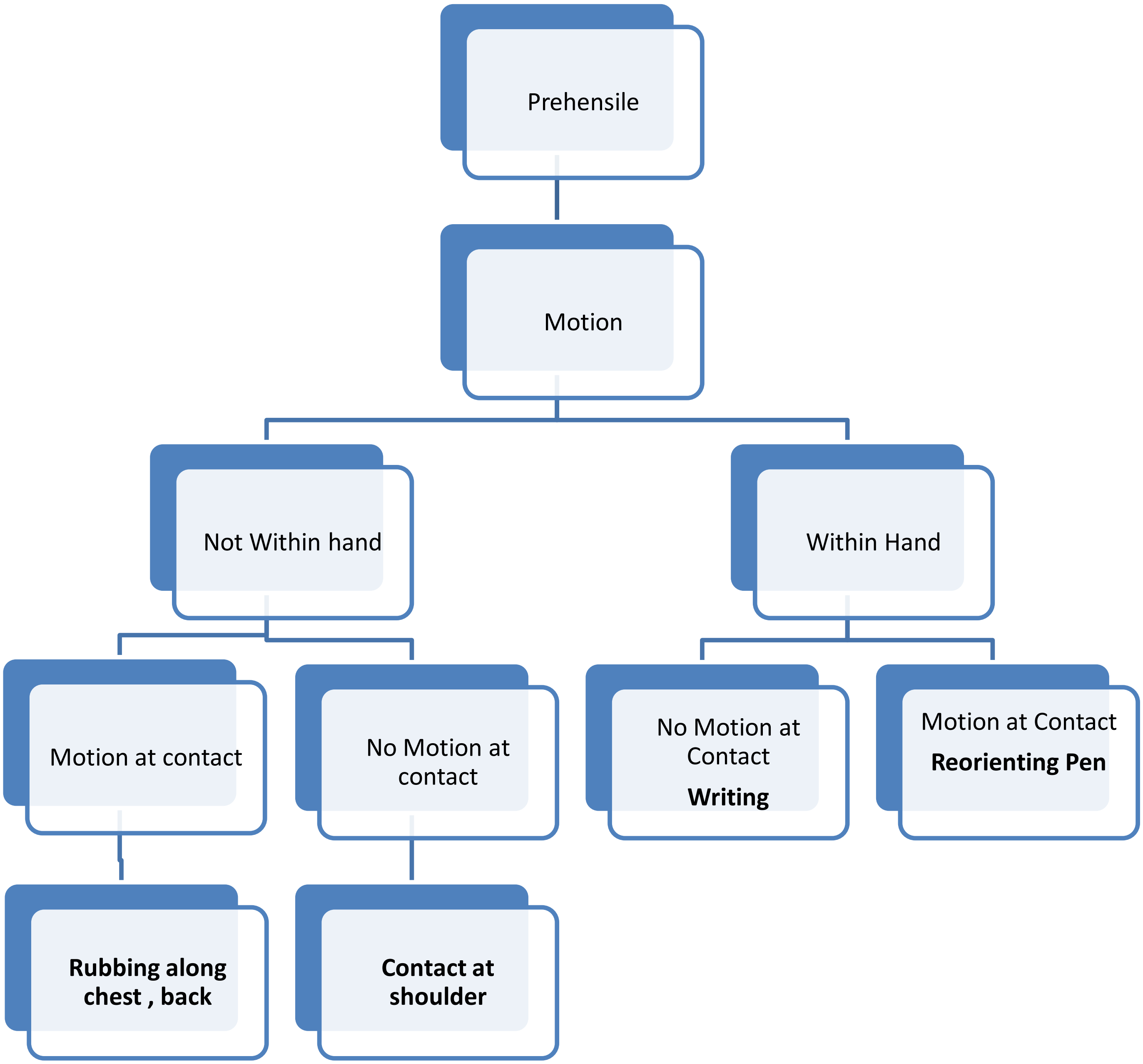

Fig 4.6.3: Classification - Contact → Prehensile → Motion

The tactile patterns that can be generated fall under the category :

Contact → Prehensile → Motion → Not Within Hand → Motion at contact.

Contact →Prehensile → Motion → Not Within Hand → No Motion at contact.

CHAPTER 5

RESULTS AND DISCUSSIONS

To assess whether the intended patterns were felt by the user a two pronged set of tests were taken. A group of 6 participants were asked to do the experiment. They consisted of four male and twp female participants in the ages 18-23.

They were asked to wear thin short sleeved shirts over which they could wear the jacket. Of the six, three were of large size and three of medium size. Small and extra large sized participants were not considered for the experiment as the jacket would either be too loose on them making them to not feel the vibrations and it would be too tight for the extra large people making it difficult for them to wear the jacket.

First each participant was asked to wear the jacket and at random an actuator was switched on to see if the participants could identify the correct actuator. This was repeated with three different actuators. Out of the 18 different trials it was observed that the participants could figure out the correct actuator every single time. This ensures that the actuators are fitted tightly onto the jacket.

Then the different patterns were played one by one and the participants were asked if they could identify the particular pattern. The results of this experiment are tabulated below:

S.No	Type of the Pattern	Number of participants saying		
		Yes	**No**	**Not Sure**
1.	Passive Touch on chest (both sides)	6	0	0
2.	Passive Touch on shoulder (both sides)	6	0	0
3.	Passive Touch on wrist (both hands)	6	0	0
4.	Pat on chest (both sides)	6	0	0
5.	Pat on shoulder (both sides)	6	0	0
6.	Pat on forearm (left hand)	5	0	1
7.	Pat on forearm (right hand)	6	0	0
8.	Stroke along the wrist (left hand)	3	1	2
9.	Stroke along wrist (right hand)	5	0	1
10.	Stroke along the back	6	0	0
11.	Rubbing along back (upper , middle, lower)	6	0	0
12.	Rubbing along chest (upper, middle)	6	0	0
13.	Rubbing along stomach	4	2	0

Table 5.1. Results of the user test

From the above table it is observed that the participants could identify the correct pattern about 92.3 % of the time. The only times when they couldn’t or were not sure if the said pattern was the one that was running it was majorly because of not a very tight fit of the jacket. It was also observed that the participants who couldn’t properly identify the exact pattern were all medium sized participants. However it should be noted that this was just a subjective evaluation and not a proper psychophysical experiment.

CHAPTER 6

SUMMARY

In this thesis, the various factors affecting tactile perception like amplitude, frequency, duration and location on the human body were studied and some tactile illusions like sensory saltation were made use of in building a prototype of a vibrotactile jacket.

An important feature of the saltation effect is that it stimulates higher spatial resolution than the actual number of actuators used thereby creating the impression of a dense actuator array. This minimizes the number of actuators to be used and reduces the overall weight and power consumption of the device. An experiment to test saltation effect was carried on 10 participants out using vibrotactile actuators and delivering short pulses at three different locations on the forearms. 8 out of the 10 participants said that the sensation that they perceived was not the points of stimulation but rather a continuous pulse from the first to the last point.

A tactile kit was developed to create basic shapes that could serve as the building blocks of the various patterns that were to be rendered using the tactile jacket. Some of these shapes were combined to create slightly complex shapes and patterns. The tactile kit can also be used to introduce people to haptics and basic haptic feedback.

As we were mainly interested in developing the jacket towards improving immersive experience we mainly focused on how these tactile patterns can be rendered in a viewing scenario – both multimedia and user space. So the idea was to mainly target the different ways in which human-human touch occurred in the torso. This target was broken down into two. Firstly we looked at the various types of touch and limited ourselves to four common ways in which human touch each other. Then we looked at the different ways of hand manipulation to cause this touch. We developed a suitable taxonomy based on hand-manipulation classification to come up with a set of guidelines under which the different tactile patterns can fall into.

Finally a user test was carried out to test the reliability of the jacket and also to understand if the participants could identify the various patterns being rendered by the haptic device. This was carried out in two stages, one to test the working of the jacket which was successful in all the trials. The next was to see if the participants could correctly identify the pattern being rendered on the jacket which was done about 92.3% of the time.

One major limitation was the size of the jacket. Since only for large sized people it creates a tight fit it becomes difficult to test the effectiveness for people of other sizes. Moreover in developing the taxonomy we limited ourselves to four common modes of touch and confined ourselves to creating the tactile patterns that was possible with these touch types.

Further studies using this vibrotactile jacket can involve carrying out more physiological tests to study the effects of these patterns on the users. A more detailed study needs to be carried out on the effects of individual tactile patterns and whether the equidistant distribution of actuators is the most optimal design. Another possible area of future work can be the integration of these tactile patterns with different audio visual content and to measure the extent to which it enhances the video viewing experience.

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APPENDIX

Terminology Used

1. Field of Haptics

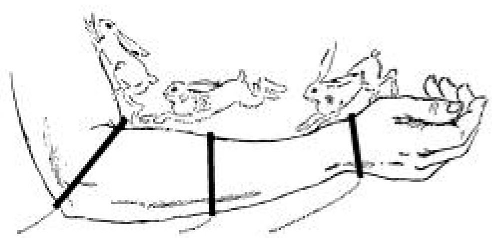
Study of or relating to the sense of touch

2. Haptic Interface

It comprises of hardware and software components which together generate sensations of mechanical nature – sense of touch using computer controlled program.

3. Cutaneous Rabbit Illusion

It is also known as sensory saltation or cutaneous saltation is the tactile illusion evoked by tapping two or more regions of the skin with low spatial acuity in rapid succession. It is likened to the perception of a rabbit hopping along the skin thereby giving it its name



Cutaneous Rabbit Illusion (Ikuta, Takeichi, & Namiki, 1999)

4. Just Noticeable Difference (JND)

In the branch of experimental psychology focused on sensation and perception, psychophysics, a just-noticeable difference or JND is the amount something must be changed in order for a difference to be noticeable, detectable at least half the time.

5. Tactation

Tactation is the sensation perceived by the sense of touch, and is based on the skin's receptors.