Haptic Socks

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Abstract

Smart phones have been spreading faster than any other technologies and with them, the research for finding different alternate interaction techniques that will be quick and efficiently responsive. The best feedback response in terms of mobile usage has been a long debate and is actually not possible, so it is difficult to conclude which feedback will be effective in all environments.

In navigation applications, two modalities are used as feedback; visual and auditory. This thesis presents work, experiments and results on implementing the third modality i.e. haptic feedback.

The basic purpose of this work is to find out how effective wearable haptic feedback can be, than visual or auditory feedback in terms of navigation. Using hand-held GPS navigation while walking or driving a car can sometimes be dangerous if the user is focusing more on the device than on the roads.

The concept of Haptic Socks can be used as a secondary interaction technique for navigation so that user can use other interaction techniques to perform their primary tasks or perform their daily life routine work. Haptic socks will consist of actuators embedded in a certain position of human foot that will give tactile feedback, helping the user in turn by turn navigation. The device can most probably be the user's smartphone. Haptic Socks will use wireless connection with the device which in this research study will be Bluetooth.

Furthermore, if the feedback results are positive then it will be easier to discuss how effective it can be made for people who are deaf-blind.

Keywords:
Haptic Feedback, Sense of touch, Tactons, Vibration Parameters, Force Feedback, Vibration alert, Somatosensation

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1. Introduction

The sense of touch is the foremost sense that develops during the early stages of human life [Berk, 2008] and is also an effective medium of communication. One of the problems faced by dual-sensory impaired people is their slow response or complete inability to interpret gestures of other people which can make them insecure. Consequently, they are unable to trust people around them. Therefore, touch serves as a fundamental tool of support and trust and plays a pivotal role in the life of blind-deaf people. It is also an intuitive way for a human user to interact with a computer or other haptic systems. This sense is capable enough to acquire sufficient data for carrying out routine tasks and it is why the design and implementation of tactile based assistive devices have emerged in recent years. In short, we can say that haptics has opened a new channel of communication with smart devices using sense of touch.

Interaction with such devices can involve vibrations, motion or application of force. For example, while using haptic gaming controls, a resistance force is felt by the user during speed bumps or some other events giving him complete synchronization with the game environment. This resistance makes use of vibratory motion or pressure to let the user actually experience that event. The phenomenon that is used in this scenario is called 'Haptic Feedback'. Haptic feedback can be classified into two types, *Kinesthetic Feedback* and *Tactile Feedback* [Heller and Schiff, 1991].

Kinesthetic feedback can be classified as the "feel" that is recognized by the brain when a person holds any object or touches it through the joint angles. The brain identifies different properties of that object such as weight, shape or size. On the other hand, *tactile feedback* is the type of feedback measured by the fingers or surface of the skin (through tissues). In this case, the brain will identify it as high/low vibrations, pressure or the texture of the surface a person touches [Heller and Schiff, 1991]. Taking an example of a bag, if a person holds it through the joint angles then he/she gains the knowledge of the properties of the bag such as weight, shape and size but touching it with their finger or skin surface will help them recognize the texture of the material used.

A description of Haptic Feedback would be incomplete without shedding some light on vibration. Vibration is a periodic response of an object in a mechanical system. If the response cycle is low but regular then is it termed as "oscillation", on the other hand if the repetitive motion is high with irregularity, then it falls under the category of vibration [Silva, 2007]. Vibration can occur naturally as "Free Vibration" or can be forced by any internal mechanism or external source as "Forced Vibration" [Silva, 2007].

Haptic Feedback is mostly used in environments where wireless or optical communication is not possible or in environments that do not involve long distance communication or indirect contact between the interacting surfaces. To provide a link of the haptic sensations with the human skin, special sensory channels are present to transmit and receive information. The different types of modalities used in the above context include visual, auditory, tactile/kinesthetic, smell and taste [Johansen-Berg and Lloyd, 2000].

People use their phones for many purposes, sending text messages, receiving calls, listening to music and using GPS navigation while they are walking. However, multi-tasking on phones means that human brain has its attention divided between both, roads and the navigation device. Sometimes, taking a quick look at the device can be risky. Recently there has been quite a lot of research done in implementing haptics for using GPS navigation or for guidance as a substitute for audio-visual information. Studies have been done both on wearable and non-wearable technologies. Prototypes have been made that include haptic navigational bots that sit on user's palm and show them the directions as a tour guide [MOMO]. Other studies have been done to develop a navigation system that can assist visually impaired people during walking. As described in the research, users can walk safely in their living room and the system will also provide vibrotactile hints of navigation and free directions for outdoor walking [Ni et al., 2013]. Vibrotactile belts have been introduced for location-aware information services [Tsukada and Yasumura]. These navigation belts enable user to intuitively obtain directional information in the real world simply by activating [Tsukada and Yasumura]. They are easy to adjust and have been designed to suit mobile environments. Another study has been done that is not limited to location information, but is also for training purposes, such as learning dance moves in which user learns simple dance steps using vibrotactile feedback [Rosenthal et al., 2011]. A much broader spectrum can lead to studies done to achieve directional information in three dimensions that is sensed through the vibrations via an array of the vibrotactors placed around the torso [Logan and Perez, 2012].

The above mentioned studies clearly have some very innovative ideas and motivation for further investigation in haptic navigation but after going through the experiment and result section, it is evident that they lack in usability aspects. Taking the example of MOMO [MOMO], the bot that is designed for the purpose of the tour guide; it will be difficult for the user to hold 0.5 kg device with the same gesture on their palm for a long distance especially when they are carrying their personal possessions as well. A walking assistant system [Ni et al., 2013] on the other hand, can be expensive, as it uses Kinect and other sensors to recognize obstacles in the environment and then 15 motors to guide the user. With regards to haptic belts, some users mentioned in the study that taking out the belt or adjusting the vibrator locations was difficult and also the noise of the motors was irritating. At one point the belt was not of the size of the user, so he could not feel the vibrations at all.

We live in an era where multi-tasking has become the norm of the day; using haptics in a navigation system will certainly provide a solution in many cases. This thesis focuses on using haptic feedback on foot for navigation. For example, if users want to listen to music or keep a check on road signs and bill boards while walking then this system will direct them toward their destination while they focus on different road advertisements.

The main purpose of this study is to develop a system which will not only retain the advantages of haptic feedback for navigation, but also overcome the portability issues encountered in the systems proposed so far. Designing a prototype that will be wireless, easy to wear, plug and play and smaller in size can be a big challenge for this research. Discussion on sensitive sensory receptors on foot and locating intriguing area where haptic feedback can be more effective will be carried out. In addition, comparison and study of user's behaviour on haptic feedback in three different scenarios, i.e. user walking while *focusing on environment*, *listening to music* or *listening to audio conversation* will also be investigated. For this purpose, real time experiment will be conducted with participants, which might also highlight other areas for future research.

This thesis has eight chapters. In chapter 2, discussion on sensory level on human body and possibility of using haptics on foot is present. Chapter 3 summarizes the motivation for this research and tests conducted to locate effective point on human foot where actuators can be placed. Chapter 4 describes the design and development of the prototype. Chapter 5 gives details of the method of the experiment conducted, whose results are described in chapter 6. Chapter 7 presents a discussion of the results obtained in relation with the existing knowledge of the literature. Chapter 8 summarizes the work and presents some of the future research opportunities in this field.

2. Human Touch

Every human being possesses a natural urge to touch and to be touched whether the feeling encompasses his fellow human, a non-living object, an animal or any other thing that is a part of his surroundings [Hertenstein, 2002]. The curious minds of humans play an important role to empower this urge to touch. Moreover, it is this same sense of touch that forms the basis of inter-communication. The feeling of touch gives a person a sense of belonging and protection because it bears immense importance in social, emotional and mental health of the human beings [Hertenstein, 2002].

Human touch is one of the foremost senses that form the fundamentals of communication. It is also the basic source of interaction between the infants and their care-takers. The study of different tactile patterns is a complex area of research because several degrees of freedom are involved in a particular touch pattern e.g. stroking, rubbing and tapping [Hertenstein, 2002].

Amongst all the other senses, touch is the sense that develops during the early stages of reproduction system and responds to stimulation in the uterus (around 8-14 weeks). So it will be fair to say that the sensation of touch initiates from the womb [Raisamo and Raisamo, 2009]. The human skin is composed of innumerable cells thereby, turning itself into a useful tool to acquire information about the environment even before the birth. Touch provides us assistance in learning the world around us and adopting different behaviours. It also plays a crucial part in biological, cognitive and social development [Raisamo and Raisamo, 2009]. Touch is a type of proximal sense that makes one feel whether a particular object is in close proximity or not i.e. if the objects are in direct contact with the skin surface then the subject will have the feeling of something touching that particular part of his body [Raisamo and Raisamo, 2009].

Touch is an important human sense because it is the fundamental key to evaluate the surroundings, to understand what might be happening at the surface of any body and to perform simple functions. It plays a key role in interpersonal communication as well. Although much work has been carried out to analyse the strengths and weaknesses of the rest of the four senses but the sense of touch is one of those areas that need to be explored because of its immense advantages in communication systems.

2.1. The Sense of Touch

The human body forms a field that has infinite scope of research. Among the possible areas of the human body that can be focused are the five senses; sight, hear, taste, touch and smell, that have emerged as an interesting dimension because they help the human brain to form a perception about the surroundings and to take immediate action accordingly.

Compared to the other senses, the sense of touch is the foremost sense that develops during the early stages of human life. It forms a gateway to acquire the environmental parameters and to evaluate this information. The consequences of the loss of sight or sense of hearing are naturally more apparent to the human mind than what follows if a person loses his sense of touch. Losing sense of touch is far more terrible than losing any other sense because the human capability to control the body motion is completely lost. Among many other drawbacks, it becomes difficult to perform those activities that involve cognitive loads and motor skill [Torre, 2006].

Unlike other human senses i.e. sight, hear, taste and smell, touch is the sense that covers all the major parts of the human body because the above mentioned senses are just associated with a certain human organ like eyes, ears, tongue and nose respectively. Figure 1 shows the sensory homunculus for touch that visually represents the proportional sensory perception mapping of the body surfaces in the brain [Raisamo and Raisamo, 2009]. As shown in the figure, lips, tongue, hands, feet and genitals are comparatively more sensitive to the sense of touch than other parts of the human body [Raisamo and Raisamo, 2009].

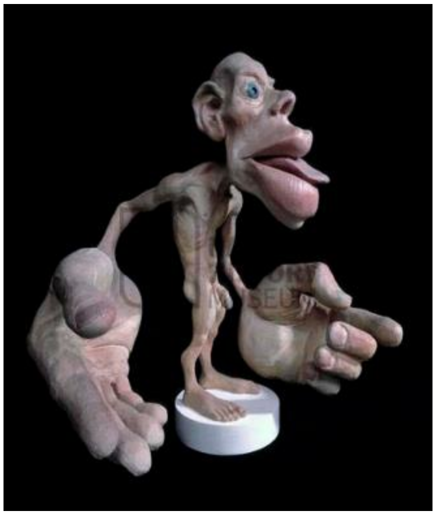


Figure 1. Sensory Homunculus for Touch

Sense of touch is utilised by the humans to attain the various properties of an object or environment like temperature, material, texture etc. The sense of touch greatly influences a customer's decision to buy a certain product whose weight, texture; material and hardness tend to differ [Peck and Childers, 2003]. Haptic feedback is an efficient way to extract these 'material properties' of an object and hence, the buyer is tempted to make his decision via the sense of touch instead of just being satisfied by the appearance or the written description of the product [Peck and Childers, 2003].

2. 2. Anatomy of Touch

Somatosensation is the controlling system in the human body that is responsible for the tactile sensations caused on the skin due to mechanical vibrations. Pressure, temperature, pain and proprioception are the main components of somatosensation [Johansen-Berg and Lloyd, 2000]. Skin is the hub of all the somatosensory information. Various types of skin surfaces include hairy skin, glabrous skin and mucocutaneous skin. Most of the part of the skin comprises of hairy skin while the glabrous skin has to go through all the stress and pressure that a human goes through during his life cycle. The palms of the hands and the soles of the feet are made up of glabrous skin. The mucocutaneous skin is the skin type found on entrances of the human body like nose, mouth and body mucous. The skin in turn is multi-layered that has two broad divisions: dermis and epidermis. The dermis is composed of all of the skin sensory receptors while the epidermis protects the body externally [Krantz, 2012]. The mechanical vibrations on the skin surface activate the mechanoreceptors that are located on different areas of the skin surface [Johansen-Berg and Lloyd, 2000]. The mechanoreceptors and thermoreceptors are located throughout the skin and they work together with the mechanoreceptors found in muscles and joints to provide the sensory information [Lederman and Klatzky, 2009].

Figure 2 shows the cross section of the skin showing some of several somatosensory receptors found there [Krantz, 2012]. The receptors can be classified into three categories [Krantz, 2012]: Mechanoreceptors (which sense deformation of skin), Thermoreceptors (which sense change in temperature) and Noiciceptors (which sense pain). This research study we will be focused on Mechanoreceptors.

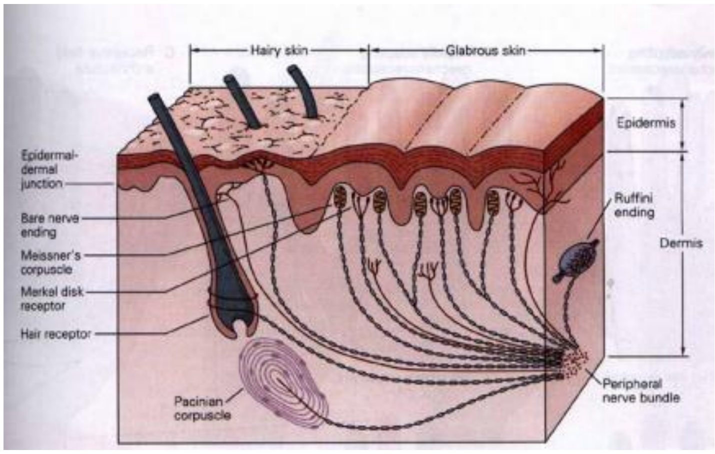


Figure 2. Cross section of the skin showing some skin receptors

Any tactile activity is the combined effort of all the four types of mechanoreceptor channels namely; *slowly adapting with small receptive fields* (SAIs), *slowly adapting with large receptive fields* (SAIIs), *fast adapting with small receptive fields* (FAIs) and *fast adapting with large receptive fields* (FAIIs) [Johansen-Berg and Lloyd, 2000]. Johansen and Lloyd explain the anatomy in the following words;

> "Peripheral nerves project from mechanoreceptors to the dorsal root ganglia. Fibres from the dorsal root ganglia project along the dorsal columns of the spinal cord to the dorsal column nuclei in the medulla. Fibres from these nuclei project to the ventroposterior thalamus (VP) which projects to somatosensory areas in the parietal cortex [Johansen-Berg and Lloyd, 2000]."

A somatosensory homunculus is a complete map of body surface on primary somatosensory cortex (SI). Different portions of the SI sketch out different body parts, the area represented does not reflect the size of that particular body part but it represents the sensitivity of the tactile stimuli in that area. Figure 3 shows that a larger portion of the somatosensory cortex represents hands and lips [Gallace and Spence], as it was also explained in section 2.1 figure 1.

The different modalities of somatosensation work in collaboration to provide an interface with the environment. It is the combined activity of all the processes that creates the sensation for haptic utilisation. Haptics is used to interact with the external world and to gather data that might be helpful in depicting the properties of the object under consideration. The creation of the tactile perception is greatly determined by the body posture and position [Rincon-Gonzalez et al., 2011].

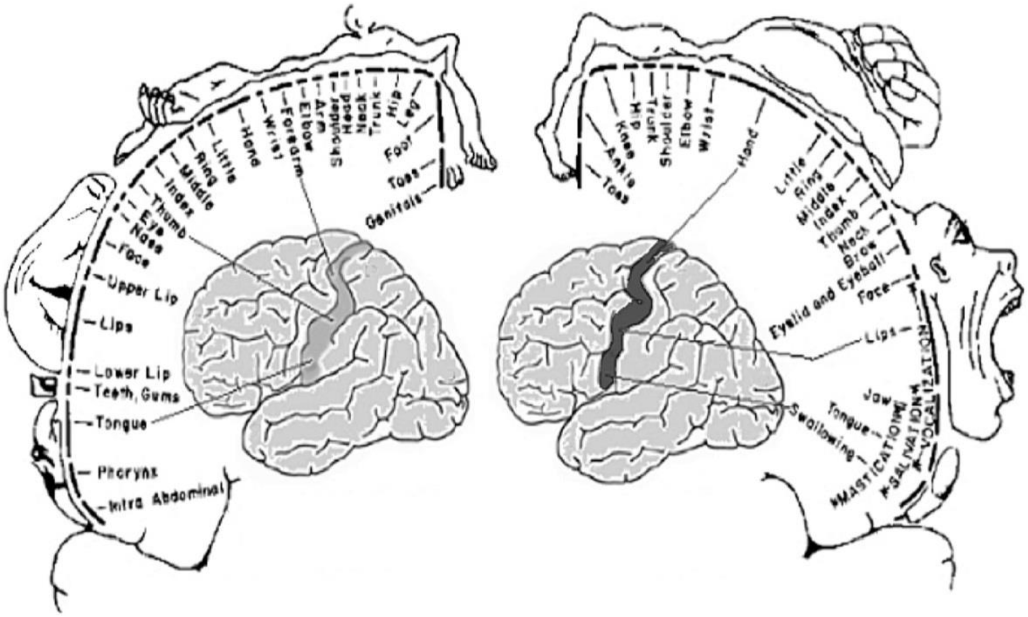


Figure 3. Somatosensory Homunculus

Any damage to the nerves carrying the sensory information may cause drastic damage to the nervous system as a result of which a person may lose his sense of touch [Torre, 2006].

Losing sense of touch can turn one's life into a living challenge. However, this case equally implies to all other senses too because in reality all the human senses work together to form the perception of the environment. When a stimulus is experienced then all the sense modalities activate to process the information [Johansen-Berg and Lloyd, 2000].

2.3. The Limitations of Human Touch

Spatial and temporal activity of the human body can be studied through the different human motion. Every part of the human body moves in a pre-defined pattern and angle when the human body makes any motion. But in order to differentiate between different types of human motion, the relevant details are the relative angles, directions, phases and timings [Das et al., 2005].

Cutaneous receptors are located throughout the body surface and their information is used for several haptic functions. However, certain limitations faced by the cutaneous system to discriminate spatial and temporal activities of the skin results in an inaccurate haptic perception [Lederman and Klatzky, 2009]. To determine the skin's spatial activity, two classical approaches are implemented, *Two-point touch threshold* and *Point-localization threshold*.

In the Two-point touch threshold, two similar stimuli are applied on closely related areas of the skin of the subject and they are asked to point the area where the stimulus is felt. The drawback of this experiment is that the result is based on the participant's response [Lederman and Klatzky, 2009]. Unlike Two-point touch threshold, Point-localisation threshold makes use of a stimulus applied to the skin which is followed by another stimulus that may be applied to the same spot or elsewhere. The subject is required to tell whether the stimuli were felt on the same location of the skin or on different locations. Comparatively, the latter approach is more sensitive than the former one. Figure 4 represents both the classical approaches for a female body. The male body also works in a similar manner.

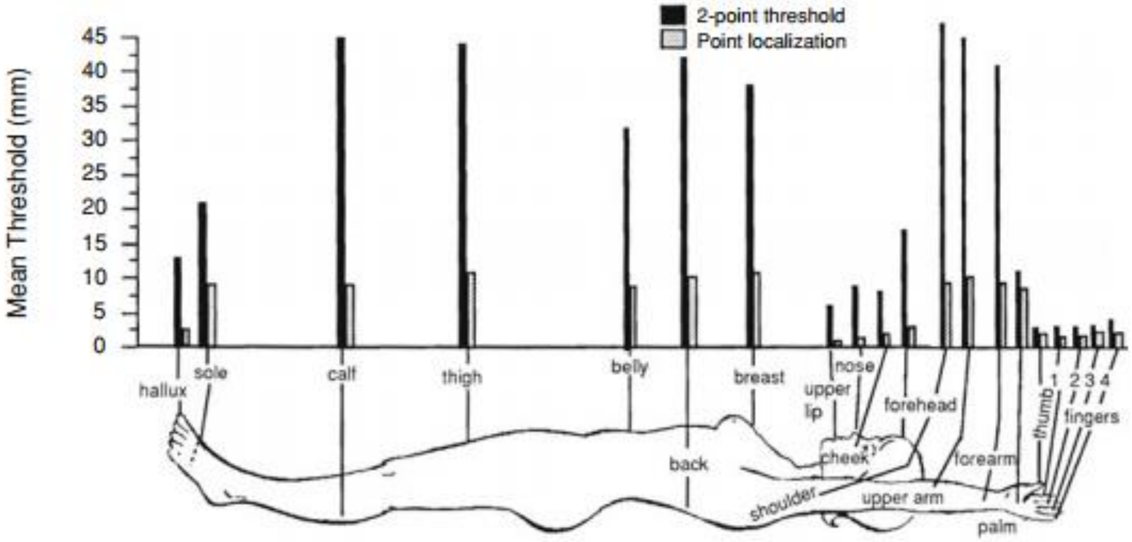


Figure 4. Two-point touch and point-localisation thresholds for different female body parts

It is observed that the tactile spatial acuity is highest on the fingertips and lowest on the back. However, this tactile activity on the fingertips rapidly decline in old age for normal and blind people. But the temporal resolving capacity of the skin is more effective and accurate than that of the vision [Lederman and Klatzky, 2009].

The somatosensory system has recently remained the topic of debate by scientists and researchers based on its comparison with the vision and auditory system [Lederman and Klatzky, 2009]. The reason that touch has been one of the most discussed topics lately is due to the question mark that whether this system is composed of the typical two subsystems: the 'what' system that deals with the perceptual function and the 'why' system that focuses on perceptual guidance of the action. The 'what' system is used to process surface, objects and their various characteristics in the touch phenomenon. Similar and identical objects are easier to spot with touch in an accurate manner. The object properties that can be haptically obtained are *Material* and *Geometric* [Lederman and Klatzky, 2009]. Material properties are independent of the object under consideration while the Geometric properties are used to define the framework of the object [Lederman and Klatzky, 2009].

2.4. Active and Passive Touch

It is important to have a clear vision of active and passive touch when dealing with haptics. Active touch is the action 'touching' through which the information about the environment and object is obtained. It is the voluntary motion of the perceiver to observe the surrounding [Heller and Schiff, 1991]. Passive touch is the sensation of 'being touched' through which the information of just the outer levels of the surface can be accessed. Passive touch mainly focuses on the events that take place at the surface of the object [Gibson, 1962].

When a person undergoes variations in his motor activities then this causes variations in skin stimulations which in turn determine his course of action to touch an object. Active touch is widely used to gather information about the environment hence, it can be fairly termed as 'tactile scanning' [Gibson, 1962]. This can also partially compensate for vision for the blind population.

Passive touch is utilised in experiments to study the tactile sensory system. Passively generated stimuli have been created to be applied on the skin in order to reveal the basic characteristics of touch [Bolanowski et al., 1999]. The active/passive issue is highly controversial and will take some time to settle down. Visual and auditory impaired people use passive touch as a means of communication [Heller and Schiff, 1991].

As the human body brushes over a surface or an object then the receptors located over the skin, joints and tendons are activated through stimulations provided by active touch. Passive touch only stimulates the receptors of the skin only. The difference between active and passive touch exists when perceiving the motion of objects. When a hand or finger is moved through the edges and surfaces of the object then it is not termed as moving although the object possesses some motion relative to the skin. This is the case of active touch. In the case of passive touch when the object is moved through the skin, it is perceived to be moving [Koskinen, 2008].

The Cookie-cutter experiment was performed by Gibson to evaluate the importance of active and passive touch. In this experiment, the forms of the objects were pressed against the palm of the hand and were also traced through fingertips by placing them over the palm. The objective was to match the tactual forms with the actual shape. As shown in figure 5, the stimulation sources were in the form of small cookie cutters. A total of six forms were used that were composed of unique number of corners and that had to be identified by the subjects via touch [Gibson, 1962].

Figure 5. Six forms of cookie cutters to be identified through touch

The subject was shown the images of the cookie cutters and was then instructed to guess the number that represented the stimulator behind a curtain. In the first method, the subject was allowed to relax his hands while in the second method he had to cup his fingers in order to feel the edges of the form. In the active condition, the subject was given the freedom to feel the stimulator in any way he wanted like using all the fingertips or just any one fingertip. In the passive condition, the stimulator was pressed on the palm of the subject manually. The experimental results revealed that 95% of accurate matches were obtained through active method while only 49% of accurate guesses were made through passive method [Gibson, 1962].

2.5 Haptics on Foot

Artificial sensory feedback has been a popular area of research previously and in this regard, many methods have been implemented to provide sensory feedback including piezoelectric actuators, motor driven actuators etc. All of these systems follow a similar working principle; the systems cause mechanical depressions on the skin surface which are detected by the sensory receptors. Although numerous applications have been found for haptic feedback but some of the limitations associated with this area reduces the system's overall efficiency.

The mechanoreceptors present on the foot and muscles detect force and other navigation details during motion which is then transmitted to the central nervous system [Fan et al., 2008]. Compared to the other human haptic parts like chest, upper limb etc, the sole of the human feet has glabrous skin just like the human palms. This opens up avenues for greater sensory perception. Due to the large surface area and the presence of the more sensitive sensory receptors, the foot forms an intriguing area for haptic feedback system [Gurari et al., 2009]. Both types of slow adapting nerves (SA-I and SA-II) and fast adapting mechanoreceptors (FA-I and FA-II) that are present on the hands are also found on the foot [Rovers and Essen, 2005].

The human foot experiences a force range of 0 – 900 N while walking normally. However, this range and contact area of foot varies from one person to another and also for the same person during different posture and walking situations. Hallux, central heel, and the first and the second metatarsal head form the most important points to transmit contact information [Fan et al., 2008]. Even the human foot has varied points of effectiveness. The sole of the feet forms a less effective area for haptic feedback because the skin of the sole is usually thick and the density of the spatial distribution of sensors is low. Figure 6 shows the location and size of the mechanoreceptor fields for slowly adapting (SA) and fast adapting (FA) units [Rovers and Essen, 2005].

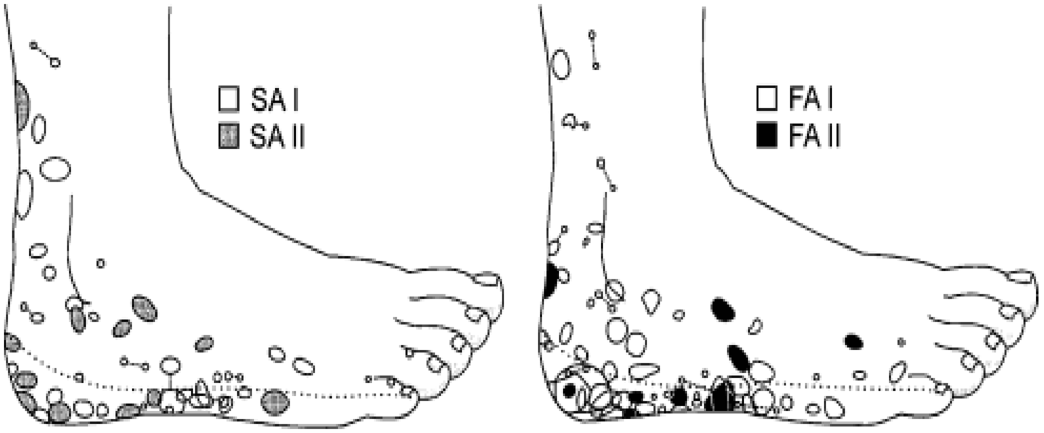


Figure 6. Location and size of SA and FA mechanoreceptor fields on the foot

Fingers and hands have been popular amongst researchers as topics of exploration because the skin surface of fingers and hands has a higher density of touch receptors. But this does not imply that the remaining body parts should not be investigated for tactile perception. Human feet is the core element to attain motion stability and for walking and other motion styles. Abnormal touch receptors on the human feet will result in gait disability [Kikuchi].

An experiment to investigate the input of the foot senses for plantar pressure applied on the foot sole, ankle motion and vibration was conducted by Kikuchi [Kikuchi]. In this investigation as shown in figure 7, various samples having different elasticity, shape and tilt angle were lifted via a load control plate while the subjects had to sit on a smooth surface. Sensor inhibitors were worn by the subjects to inhibit foot senses. The results of the experiment concluded that plantar pressure can be used to identify shape, tilt angle and elasticity of the ground. However, the method carried out above to verify the three different foot sensations is for passive contacts only.

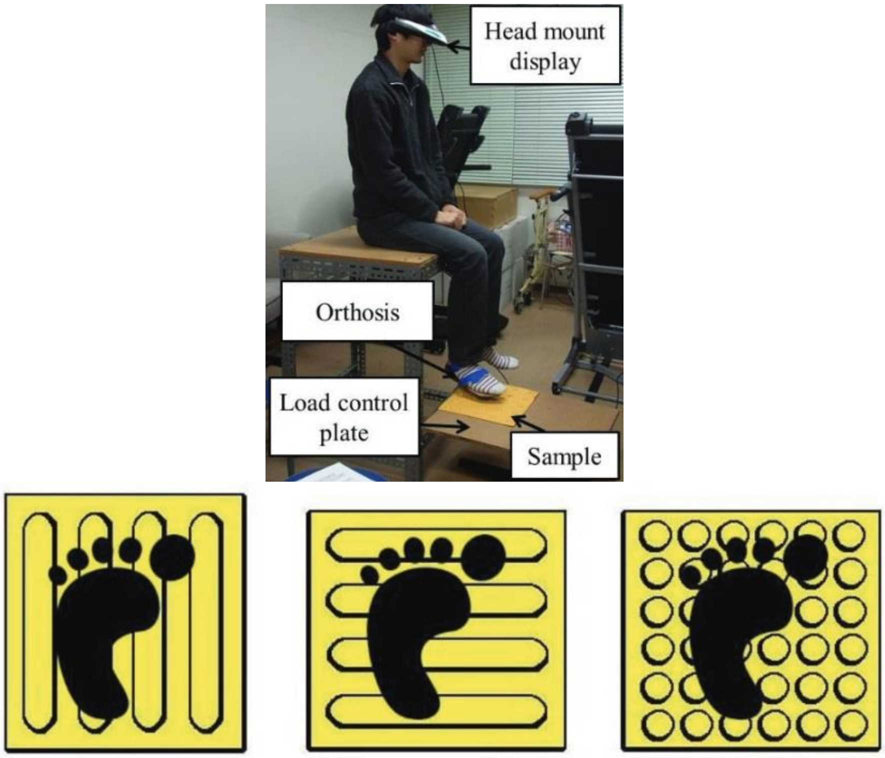


Figure 7. Experimental method to measure plantar pressures

The approaches to investigate haptic devices on foot follow a similar pattern as that utilised for haptic devices in hands; the forced feedback option considering rolling or ground referenced devices and the vibro-tactile option. The former is more challenging and costly than the latter [Nordahl et al., 2010].

The work carried out by Giordano is an important step to investigate the effect of planter vibration feedback on the perception of the ground surface. The conclusion drawn from this experiment was that the vibro-tactile sensory channels bears significance to the perception of surface compliance and highlights that human locomotion is greatly dependent upon correlations that exists between vibro-tactile sensory information and motor activity [Visell et al., 2011].

3. Haptics in Navigation

Though the word navigation can have several meanings, theoretically used for describing course of a ship or aircraft, but literal meaning can be understood as 'manage' or ‘guidance' of one’s position or planning. The general idea of haptic navigation implies that the user will have a device that will direct him to certain position through touch based feedback, so sense of touch will be used as a medium for input and output channel [Venesvirta, 2008]. In general haptic navigation is a one-way communication between system and the user. The system gives haptic feedback for next course of action but user does not have any haptic interaction with the system. The interaction by the user in this scenario can be input of location plan.

Research and experiments in the field of haptics have opened up ventures for it to have vast applications in navigation techniques. Many products and devices are found in the market, which use haptics as a basic tool for navigation in the real world. Some devices are developed for visually impaired people or people in special situations [Venesvirta, 2008] or in an environment where our auditory and visual modalities are taken for performing other tasks like, driving a car, crossing a road or best example can be war situations where military soldiers have to stay alert of the environment all the time with a need of having exact location of new areas [Krausman and White, 2006]. There can be other various basic needs as well. Some devices are built for learning purpose like basic dance moves [McDaniel et al., 2010] or other various common uses.

The products that are made for either commercial purpose or for research will be discussed in detail in section 3.4.

3.1. Haptic Terminologies

As mentioned in Chapter 1; haptic feedback is a way of communicating with a user through sense of touch. Generally, it means communication through vibrations depending on the device. The sense of touch can be classified into two types, *Cutaneous touch* and *Kinesthetic touch* [Paananen, 2010].

Cutaneous feedback is also termed as ‘Tactile Feedback’ which gives information of just the sensation of the skin. On the other hand, kinaesthetic feedback involves information obtained from different joints, tendons and muscles and so it is also termed as ‘Forced Feedback’ [Paananen, 2010].

Figure 8 describes the relationship between these terminologies in the case of human and hand-held devices [Paananen, 2010].

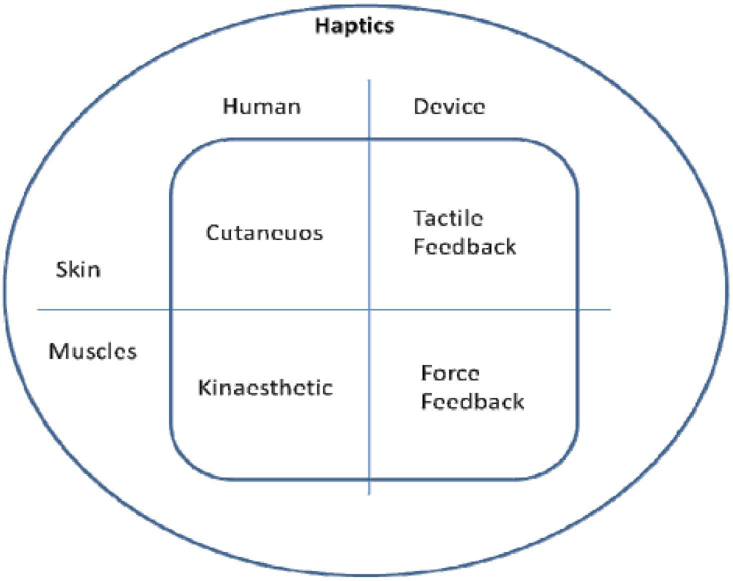


Figure 8. Relationship between Haptic terminologies

Cutaneous or tactile feedback is mainly responsible for the detection of roughness, temperature and vibrations. In this work, usage of vibrotactile cues is of primary concern. Research and experiments will be conducted on how effective vibrotactile feedback can be in terms of navigation.

3.2. Vibrotactile Feedback Parameters

Vibrotactile feedback has been introduced as a way of receiving information without distracting or notifying anyone around the user or for a situation where both hearing and vision senses are taken for performing other tasks [Kohli et al., 2006].

The term vibrotactile feedback and vibration alert is commonly confused and is considered same, but in real they are quite different. Vibrotactile feedback is all about conveying information through sense of touch unlike simple vibration alerts that are just used to capture user’s attention [Precision Microdrive]. Taking an example of a smart phones with touch screen, vibrations generated by pressing key on the screen can be termed as vibrotactile feedback while vibrations generated through incoming call can be specified as vibration alert.

Vibro-tactile feedback for haptics has immense applications and its implementation in hand-held devices has gained momentum. Not only mobile phone industries have taken advantage of this way of communication but several other companies have used this feedback as an effective means of communication. Some common examples are vibrating barcode reader, applications having touch panels with vibrotactile feedback or game controllers giving user the feeling of immersion within the environment figure 9.

Figure 9. Barcode reader, game controllers, & touch screen with vibrotactile feedback.

Vibrotactile messages generated by applications are basically non-visual transfer of information to the user and are generated by using tactile words or "tactons" [Brewster and Brown, 2004]. Each tactile word or tactons are designed using different parameters. Mojtaba Azadi, and Lynette A. Jones have discussed in their paper about the approach used to design tatctons.

> *"The process of designing tactons by varying stimulus parameters has often been conducted in an ad hoc manner and not based on a conceptual framework derived from psychophysical studies of tactile perception. One systematic approach that has been explored is multidimensional scaling (MDS) in which all possible combinations of stimuli used in an experiment are presented in pairs to participants who judge the degree of similarity (or dissimilarity). The objective of this approach is to understand how people perceptually organize a set of vibrotactile stimuli and then determine which stimulus dimensions are most salient for creating tactons* [Azadi and Jones, 2014]*."*

While designing tactons, there are some parameters to be considered during the process. These parameters depend on product, type of feedback, type of use, skin surface and the environment they will be used in. Some common parameters include; Frequency, Amplitude, Waveform and Duration. Under some environment more complex parameters also need to be considered; Roughness (rhythm) [Brown et al.].

Frequency:
It cannot be said for sure whether frequency can be useful or not while designing tactons messages. Compared to human hearing range i.e. 20-20,000Hz, skin frequency has much lower range and can be defined as 10-400Hz. Under limited bandwidth it might be unusable if other parameters are not considered in tacton design. In the light of some experiments conducted frequency can still play some significant role, depending on tactile texture [Brown et al.] & [Hoggan and Brewster, 2007].

Amplitude
Adjustable amplitude is more convenient than a fixed one because if the value of amplitude is too low then the detection of perception might become difficult because the amplitude will further decrease due to noise and other attenuation. On the other extreme, increasing amplitude may cause irritation [Brown et al.].

Waveform
Waveform can't be considered as a useful tacton parameter because of the difficulty in measuring differences in waveforms on the skin for perception. Moreover, the device's limited bandwidth is a drawback too and because of it, differences in the waveforms are lost [Brown et al.]. Since waveform plays an important role in earcon, so it might be used as an important parameter in cross model applications [Hoggan and Brewster, 2007].

Duration
By managing duration of the pulse, feedback or information can be encoded so it can be termed as an important parameter in tacton design process. Creating pulses using above mentioned parameters and managing their duration creates rhythm that can provide more flexibility in tacton messages [Brown et al.].

Rhythm
Rhythm is an important parameter in tacton design process. Experiments have been conducted in which users recognized the information sent through them using timely patterns rather than other parameters like frequency or amplitude [Brown et al.]. It is estimated that approximately 5ms are required by a human to detect two tactile stimuli.

3.3. Vibrotactile Actuators

In a haptic system, an actuator plays a very important role in creating sense of feel for skin surface. Usually these actuators are mounted in the device in such positions that maximum vibrations could be sensed by the user. There are basically three main types of actuators.

Each type has different working process and is designed to be used for a specific product [Immersion].

The most commonly used actuators are Eccentric Rotating Mass (ERM) Actuators and Linear Resonant Actuators (LRAs) which can also be referred to as inertial haptic actuators. The third type, Piezo Electric Actuator can be classified as high definition haptic actuator as its buzz has significant difference with ERMs or LRAs and is more effective comparatively [Rao, 2012].

Eccentric Rotating Mass (ERM) Actuators

Being cost-effective, ERM provides a preferable option as vibrotactile actuators. However, their weak response at lower frequencies and high mechanical time constant can prove to be a constraint in some of the applications [Immersion]. ERM actuators may also involve noise of rotating motor inside [Rao, 2012].

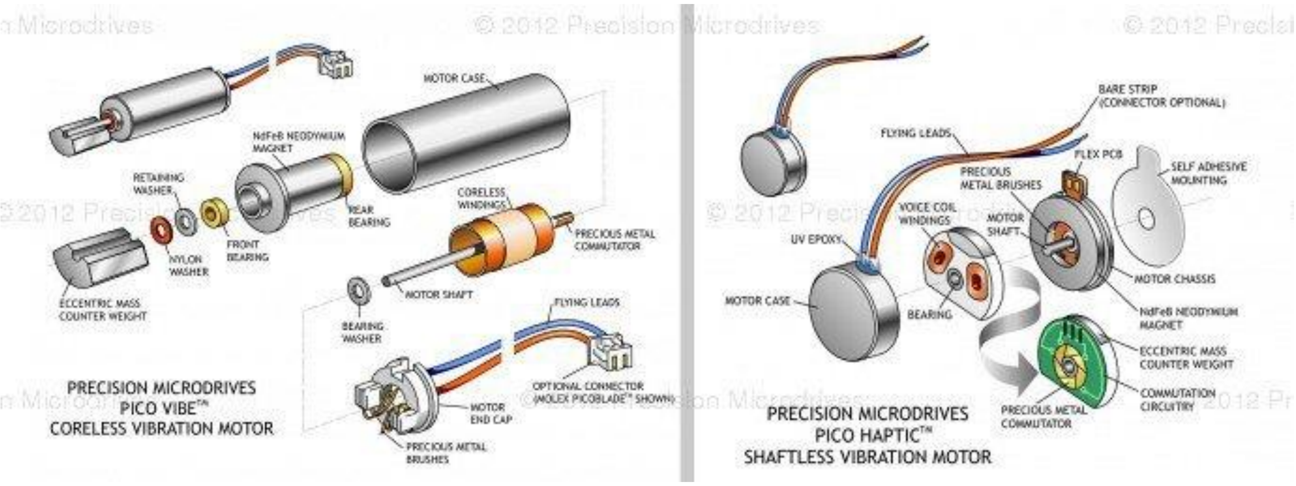


Figure 10. Inside the eccentric rotating mass vibration motors

Linear Resonant Actuators (LRAs)

Another preferable option for haptics is LRA because of their slim structure and more durability and they are more expensive than ERM and also require complex techniques for controlling resonant ringing [Immersion]. The spring mounted inside vibrates in linear motion [Rao, 2012].

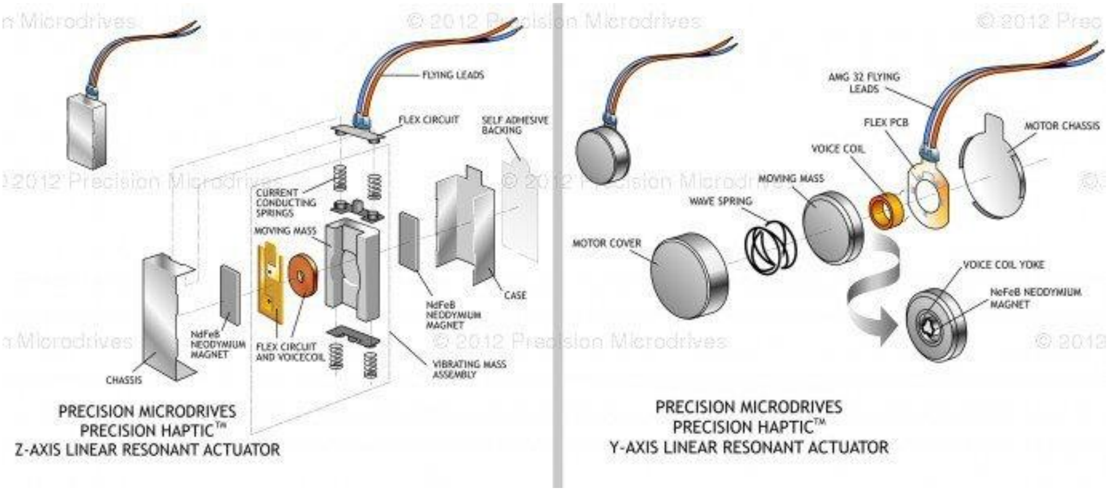


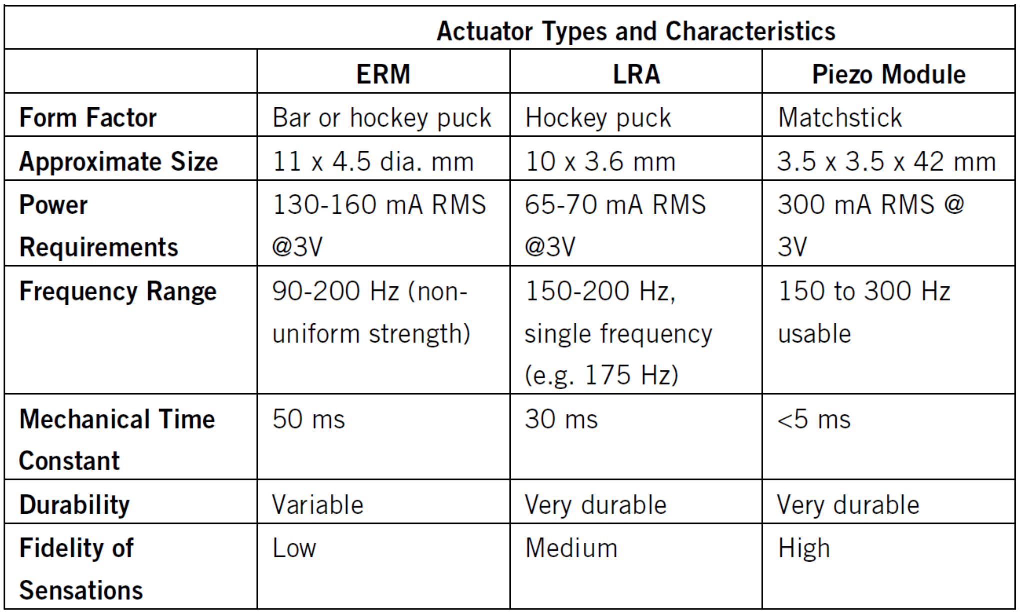
Figure 11. Inside the linear resonant actuators

Piezo Modules

Piezo modules are utilised in applications that require high-fidelity haptic effects. These actuators bend, when current is provided at both ends. They are available as disks form (for z-axis vibrations), or rectangular strips (called as benders). Benders are used for touch screen vibrations [Rao, 2012]. Some of the benefits of this actuator type include lesser mechanical time constant and faster haptic effects [Immersion].

Figure 12. Piezoelectric Actuators

Figure 13 below provides a comparison study of the features of the above mentioned actuators. We can see that Piezoelectric actuators are comparatively smaller in size, durable with high sensations.



Actuator Types and Characteristics			
	ERM	**LRA**	**Piezo Module**
Form Factor	Bar or hockey puck	Hockey puck	Matchstick
Approximate Size	11 x 4.5 dia. mm	10 x 3.6 mm	3.5 x 3.5 x 42 mm
Power Requirements	130-160 mA RMS @3V	65-70 mA RMS @3V	300 mA RMS @ 3V
Frequency Range	90-200 Hz (non-uniform strength)	150-200 Hz, single frequency (e.g. 175 Hz)	150 to 300 Hz usable
Mechanical Time Constant	50 ms	30 ms	<5 ms
Durability	Variable	Very durable	Very durable
Fidelity of Sensations	Low	Medium	High

Figure 13. Types of actuators and their characteristics

3.4. Related Research

In this section products that have been developed using haptic technology are described. The products include both wearable and non-wearable devices. The idea is to research how haptic actuators have been used for navigation feedback.

3.4.1. Vibrotactile Belt

A vibro-tactile belt is designed to be worn around the waist by the dancers. The belt provides vibrations and the users learn simple dance steps based on the pre-defined vibro-tactile patterns. Light-weight, easier implementation and providing no hindrance during motion are some of the features that makes this product user friendly. The belt is highly flexible and can be adjusted on various waistlines. Figure 14 shows haptic belt and its basic system architecture [Rosenthal et al., 2011].

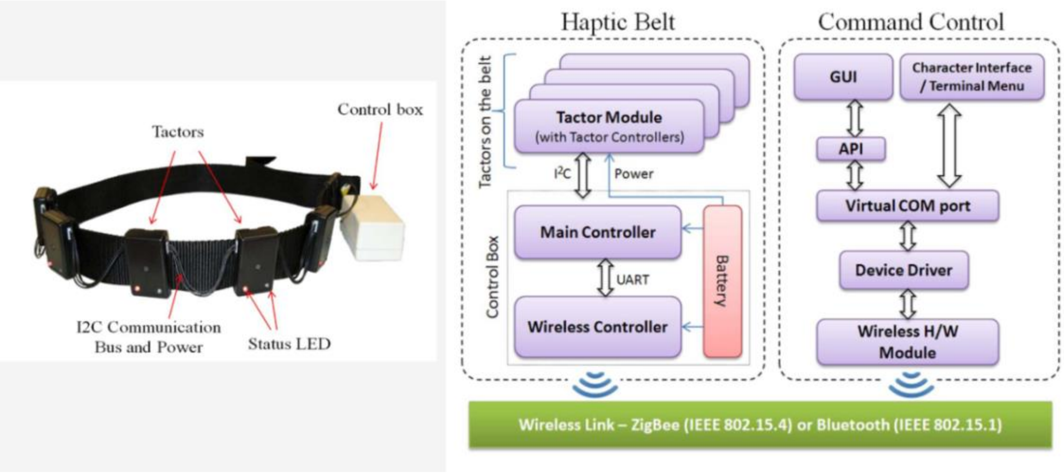


Figure 14. Haptic belt and system architecture

Haptic belt consists of two sub-systems; one for the haptic belt and other for the command control. The control box contains microcontroller, power module, wireless modules, and communication bus. The tactor controller which is present inside the tactor module manages the haptic vibrations produced by the motors. The main controller provides connectivity with the wireless controllers which are actually the haptic belt controllers. Both the sub-systems are independent of each other and any data that is to be shared is stored in the main controller. Thus, this system functions efficiently without much data transmission and less software usage [Rosenthal et al., 2011].

3.4.2. ActiveBelt

ActiveBelt is a device that employs tactile sensations to provide navigational information and is very much related to our research study. The product is designed to provide usability during motion in the form of a belt structure that uses a display to show directional information. Figure 15 shows ActiveBelt prototype and its basic architecture [Tsukada and Yasumura].

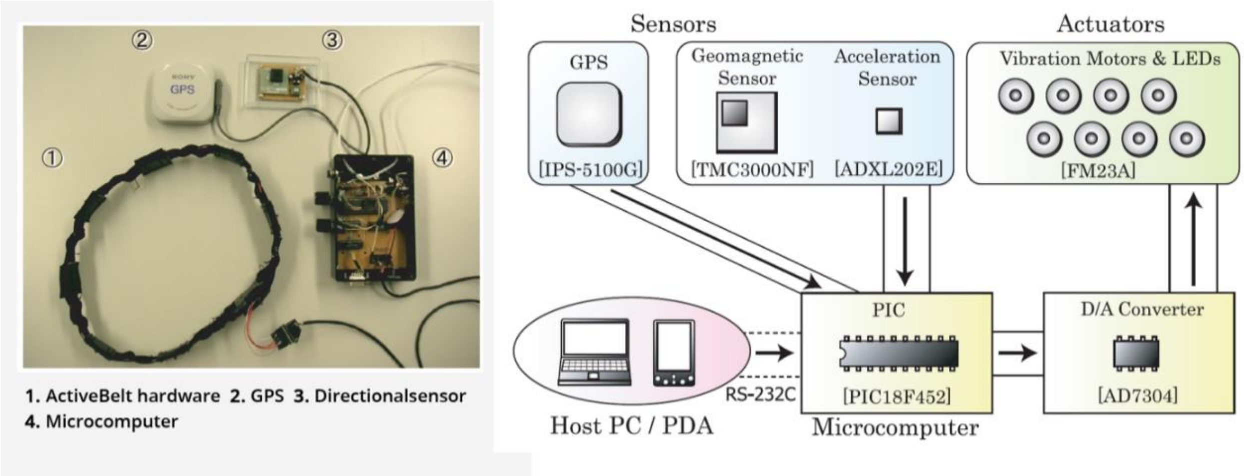


Figure 15. ActiveBelt prototype and its system architecture

As visible from the above figure, the active belt consists of GPS, direction sensors, microcontroller and vibration motors. GPS and directional sensors function together to obtain the location information for the user and based on that, microcontroller transmits tactile information to vibrators on the belt. ActiveBelt has the following applications [Tsukada and Yasumura]:

FeelNavi
In this application, the user inputs the latitude and the longitude of the destination and is then able to walk towards the destination through the guidance of vibrators.

FeelSense
Visual display is used that can transmit location-aware information for the users so that direction of a particular area of interest can be known.

FeelSeek
Due to the growing applications of RFID tags, FeelSeek makes use of RFID tags to make the user aware about important objects left behind or forgotten. The RFID reader located on the belt searches for the RFID tagged objects and alerts the user about its location and guides him towards its position.

FeelWave
This is an entertainment application of the ActiveBelt in which the user feels the rhythmic vibrations to perform steps and dance to any music.

3.4.3. Vibro-Vest

Like previous research on haptic technology, Vibro-Vest uses 16 actuators placed in an array on a vest to acquire three-dimensional directional information for the user that is essential or navigational purposes. It is capable of encoding 66 angular regions on the vibrotactors. The design architecture of the Vibro-Vest involves the usage of an elastic material to fix the positions of the vibrators and to provide contact with the user. Figure 16 shows the Vibro-Vest that was used by Logan and Perez to perform the experiment [Logan and Perez, 2012].

Figure 16. Vibro-vest prototype

3.4.4. KOR-FX

The KOR-FX is a gaming vest that transforms the audio and media of games into a feedback which creates a virtual environment for the user to feel the action effects of the game as if they were occurring in real time. The unique feature of KOR-FX is that it can be customized according to the level of actions that the user wants to experience. The key features of this vest includes complete customization according to the requirements of the user, experiencing actions and forces of the game in a virtual environment using accousto-haptics and plug and play feature. Figure 17 shows the KOR-FX vest that the users wear before playing games [KOR-FX].

Figure 17. Vibro-vest prototype

3.4.5. Walking Assistant System

Walking Assistant System focuses on assisting the visually impaired in walking by providing information about any hindrances present in their path. Kinect camera and ultrasonic sensors placed in the device acquire information of the environment which is then converted into vibrotactile sensations to guide the user in walking. A speech recognition system is used to communicate the destination of the user while GPS provides the current location [Ni et al., 2013]. A visually impaired person will study environment only through audio and touch. Therefore, this system is designed to integrate these properties in order to obtain the environment's information automatically. The system is composed of six components which include a GPS navigation, information prompt and obstacle detection functionaries. Kinect cameras and ultrasonic sensors extract the information about the surrounding that includes details about any obstacle like surface type. Voice GPS navigation is used by users to walk in their living vicinity. The wireless headset is worn by the user on the head while the belt is tied around the waist under the clothing. The vibrotactile belt provides directions of the destination and contains a voice prompt device for navigation as well.

In this research study authors mentioned some of the benefits of the Walking Assistant System such as higher sensitivity of the visually impaired people, possibility of voice communication and improved performance by integrating ultrasonic sensors and Kinect cameras.

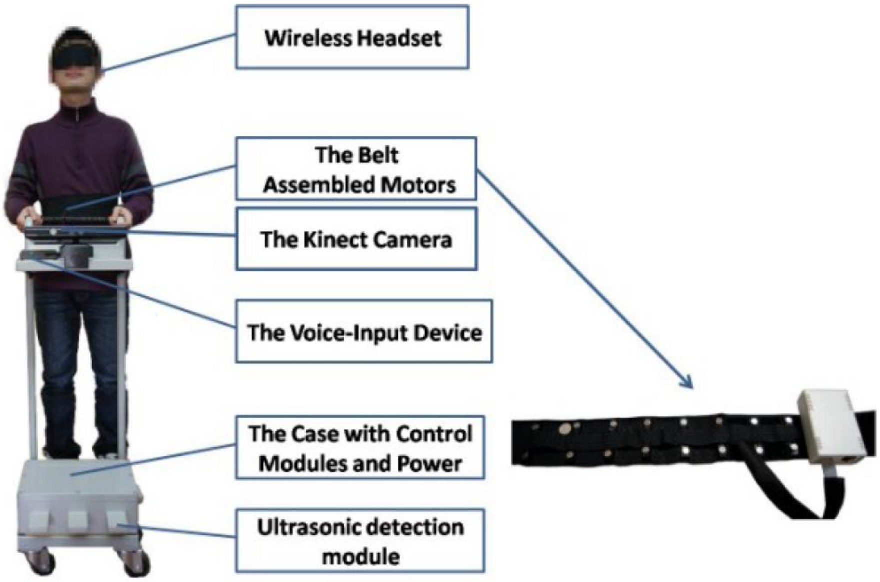


Figure 18. Walking Assistant System Prototype

3.4.6. Lechal

Lechal is a Hindi word that literally means 'take me along' which justifies the function of the foot-ware. With an in-build haptic technology on the heels of the shoes, the product is built for applications in navigation systems, fitness and monitoring daily routine activities. The Lechal Shoes comes with an embedded app that is integrated with Google Map to provide route and location guidance to the users. The foot-ware is designed to keep a record of the user's defined targets. User controls the shoes through simple foot movement and gestures while the shoes respond through vibratory motion [Lechal].

Figure 19 below shows the Lechal application (supported by Windows, iOS and Android), shoes and insoles that are now commercially available.

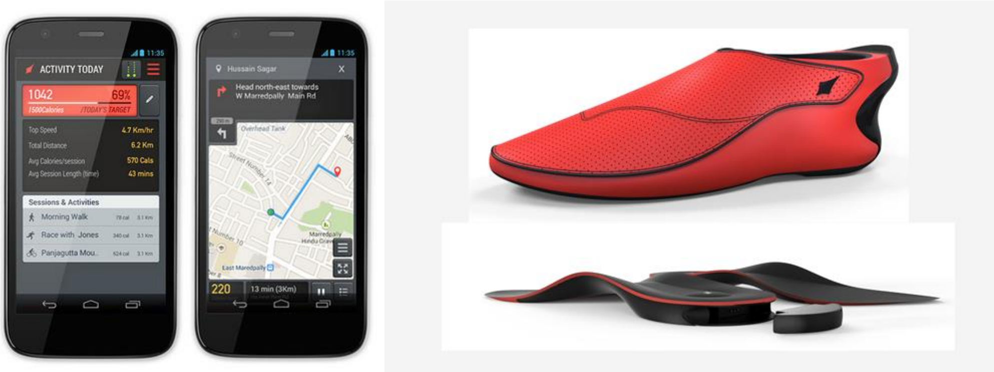


Figure 19. Lechal Mobile Application, Shoes and Insoles

3.4.7. Smart Shoe

Smart Shoe is a novel approach to haptic terrain display in virtual environments. Its portability and compactness can display the terrain features of the environment apart from maintaining ankle balance on uneven surfaces [Wang and Minor, 2014]. Unlike a standard shoe, the Smart Shoes has a multi-layered sole that is made up of a bladder structure. The mechatronics plate controls the force and displacement of the bladder system during compression process. Microcontrollers are embedded in the pneumatic valves for controlling pressure in the chambers. The shoe is made of elastic material with embedded proximity sensors to provide height feedback. When the power module is switched on then the microchip present in the Smart Shoe reads the data and acquires information of height and pressure in each chamber on the shoe sole[Wang and Minor, 2014]. The structure and design of the Smart Shoe is shown in the figure 20.

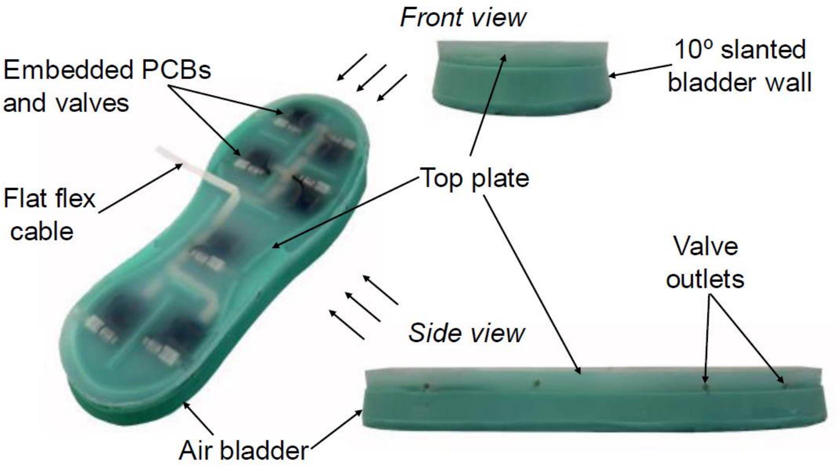


Figure 20. Smart Shoe sole design

3.4.8. Momo

Momo uses the sense of touch to provide navigation assistance to the user unlike a typical a haptic device that integrates maps to navigate. It sits on the palm of the user and leans towards the destination so that the user may follow its pointed directions. It can be used as a tour guide and by people who are novice to a particular place and keep on forgetting directions. Users can discover new places and wonder in unknown areas with directional information provided by Momo [MOMO]. This device consists of a GPS module, digital compass, an arduino board, two servo motors and a vibration motor. The structure is designed to allow 360 degrees rotation of the device. The microcontroller present calculates the angle of the user's destination with reference to the North direction in order to control the rotation of the servo motor. Figure 21 shows the design and structure of the prototype.

Figure 21. Momo prototype

3.5. Why Haptic Socks?

From the previous chapter it is evident that a lot of research has been carried out in the field of haptic technology in relation to navigation or for learning/guiding purpose. With the growth in the number of research, numerous products have been made to assist people in different ways by using tactile sensation. Most of these prototypes are still in the making and need some improvement before the users can actually implement them in their daily lives.

The idea of using haptics in navigation raises the question that how easily and quickly, people can sense tactile feedback and recognize the pattern while they are walking. As discussed in section 3.4 some prototypes that are made use multiple actuators for navigation [Tsukada and Yasumura], [Rosenthal et al., 2011], [Logan and Perez, 2012], which can create complex directional scenarios, and might also lead the user towards a wrong move.

The reason for using haptics on foot is that it implies splitting all the direction moves into two simple categories, i.e. Left and Right. All the directions towards left side should be sensed on user's left foot and directions towards right side should be sensed on right foot. This will help the user to recognize the feedback more quickly and respond accordingly.

The presence and size of both, slowly adapting (SA) and fast adapting (FA) mechanoreceptor fields on human foot have already been discussed in section 2.5. According to the study conducted by [Rovers and Essen, 2005], Figure 24 shows some areas where the actuators have been tested for their sensitivity i.e. by placing actuators under the foot (ankles), right above the foot near fingers and by placing it on the skin surface on the foot side.

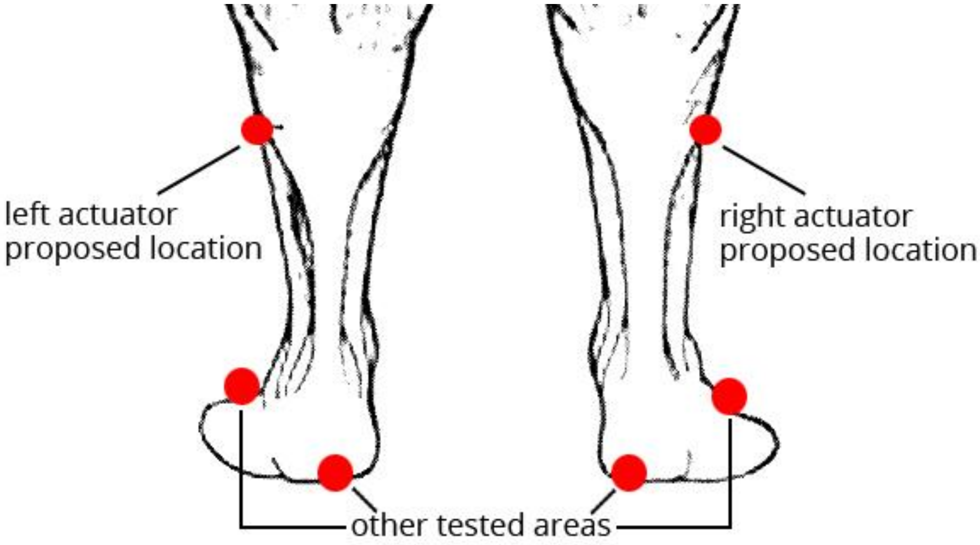


Figure 24. Testing locations for haptic actuators on foot

During the test process, it was found that actuators placed under the foot (ankles) have very low or no sensitivity. The sensation was almost non-detectable. This was because of the force that is exerted directly above the actuators while user is walking. The feedback was also very much dependant on user's weight as it will make a significant difference on the force exerted. Similarly actuators placed right above the foot, near fingers also had dependencies w.r.t the style of the user's shoes. Tighten or loosen shoes can create major variances in haptic feedback while walking.

The proposed area after this research is the skin surface on user's foot side as shown in figure 24. This location has high sensitivity and also less chances of getting effected by perspiration.

In the coming chapters, the concept of Haptic Socks and research on how an effective prototype can be made with actuators placed on user's socks at proposed location shown in figure 24 will be discussed. Once the prototype is finalized, experiments with real participants will be conducted which will help to achieve some concrete results.

4. Haptic Socks – Concept & Prototype

This chapter covers the concept of Haptic Socks and its prototype design & development process, to further analyse our research study.

4.1. Concept

The concept of Haptic Socks is to overcome the usability issues of previously built devices, discussed in chapter 1 and section 3.5, and make it a simple yet effective wearable device. Ideally with this device, the users will be able to focus more on the environment and perform other tasks while being guided towards their destination. It is this multi-tasking benefit that will gain the attraction of the users. Figure 25 shows an idea of commercial haptic socks.

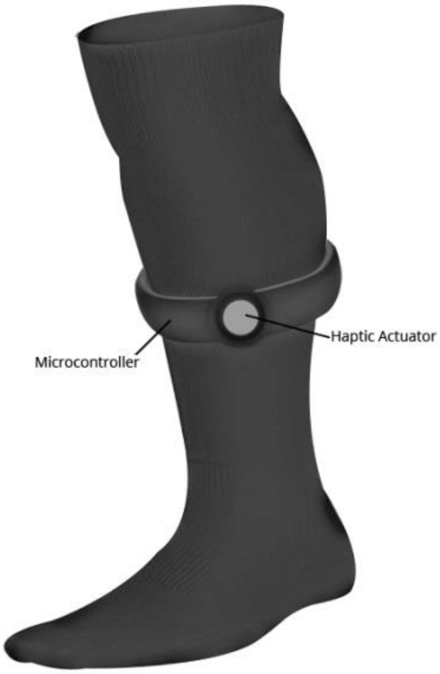


Figure 25. Commercial design for Haptic Socks

The main concepts of Haptic Socks are:

- To enable users to obtain directional information through tactile sensation
- To be used as a wearable device for mobility
- To be used for multipurpose, but mainly for location-aware information services

The ideal product should be light in weight, affordable, with less complex circuitry and detachable.

4.2. System Architecture

Haptic Socks consist of two haptic actuators and a navigation application device. The navigation application device can be user's mobile phone with Google map installed in it or any other similar map application. The device will be connected to actuators wirelessly via Bluetooth. Actuators will receive navigation commands from the device and will transfer a tactile message on user's foot. Each navigation command will have its own specific pattern so that the user can understand the feedback. Figure 26 shows how the actuator will display tactile messages.

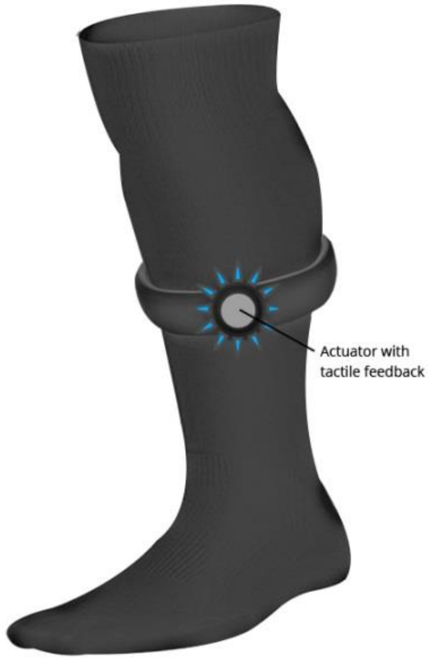


Figure 26. Actuator with tactile feedback (similar feedback will be on the other foot)

4.3. Development - Prototype

In order to get concrete results, a prototype of Haptic Socks is developed. In the coming sections, starting with the workflow model of the prototype, the software that is used to develop navigation commands and the hardware components for haptic feedback are discussed in detail. During the workflow design, one major challenge that occurred has also been discussed with the proposed solution.

Workflow Model

Figure 27 shows the initial workflow of haptic socks. In this scenario user's phone is acting as a server and the receiver on user's right foot is acting as a client. Navigation commands will be transferred via Bluetooth from the phone *(server)* to the receiver *(client)* on the right foot. The receiver *(client)* is then connected to both the actuators that will be embedded on right and left foot respectively.

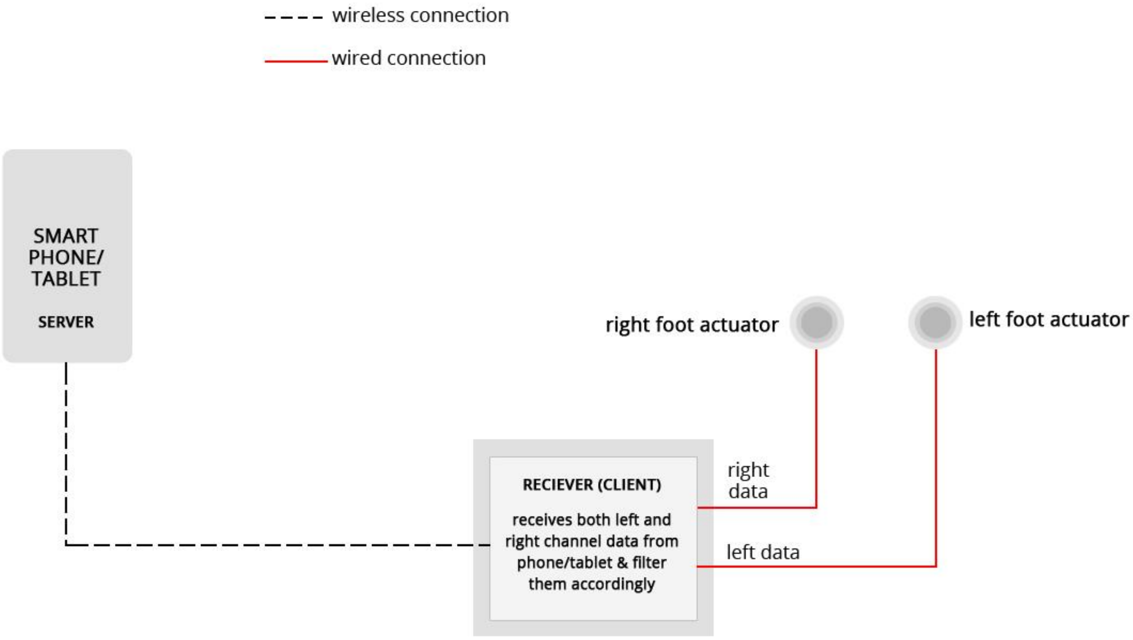


Figure 27. Initial workflow of the prototype

In an ideal case the system should be connected to any map application such as google map on phone that would have guided the user, but implementing this, would have opened another research area with more challenges. The purpose of this study is to measure the effectiveness of haptic sensations while the user is walking. So in this research, some pre built commands installed in phone will be used to find out user's response. Integrating the device with maps can be an interesting area of research with respect to future work.

Challenge

Consider figure 27, both actuators are connected with the receiver (client) through wired connection. In real time it means both of the user's leg will have a wired connection in between that will obviously create problem for them while walking hence, it becomes a major usability issue.

By default mobile Bluetooth adaptor protocol allows to pair with only one Bluetooth receiver for data transmission i.e. one server client connection at a time, which means in this case user can receive commands from the mobile device (server) wirelessly on right foot (client) but commands for the left foot should be transferred through wired connection, as installation of another Bluetooth receiver (client) to work simultaneously with the mobile device is not possible.

Proposed Solution

A new work flow is designed, adding one more server-client relationship as shown in figure 28. In this scenario the mobile *(server A)* sends navigation commands (both left and right data) to the receiver *(client A)*, where only data for right channel is collected and sent to the right actuator. Data for left channel is then transferred to transmitter *(server B)*. The transmitter *(server B)* is wirelessly connected to receiver *(client B)* on the left foot, which receives left channel data and sends it to the left actuator. With this new workflow wireless connectivity between both the actuators was achieved.

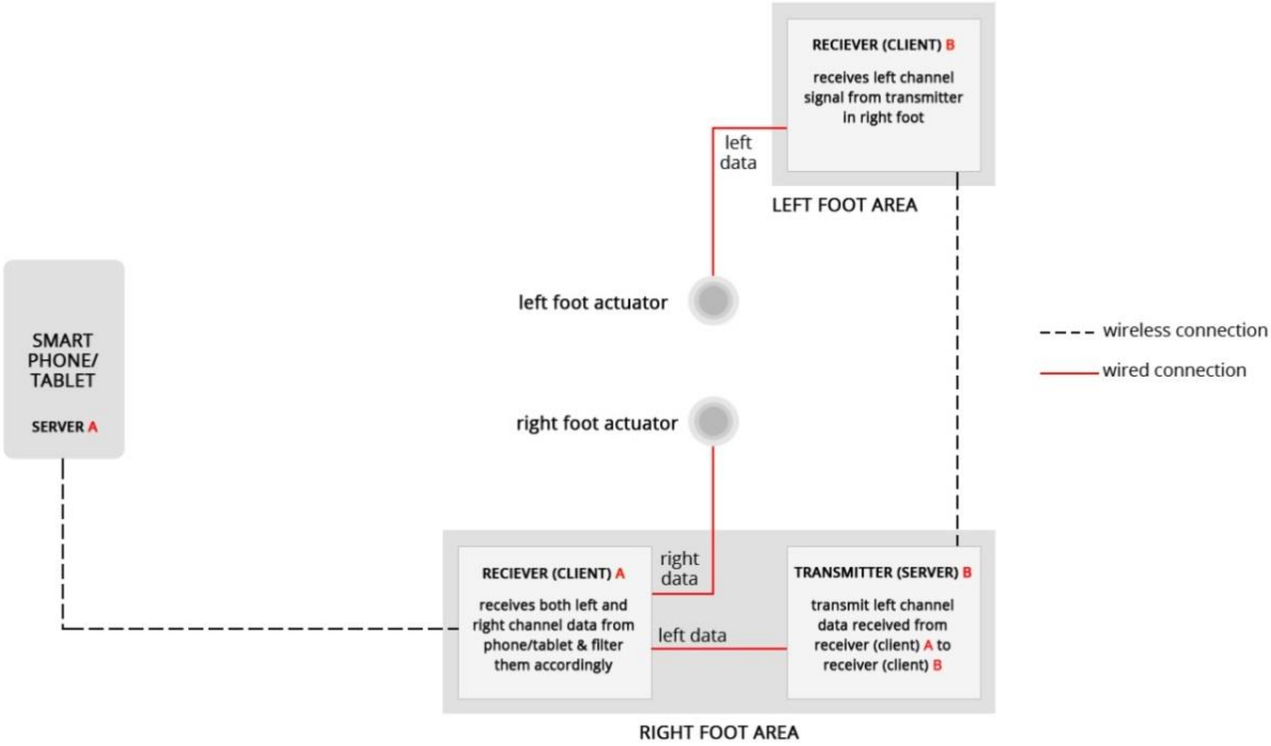


Figure 28. Final proposed workflow of the prototype

Issue:
After conducting some pilot experiments, it was found that a delay of 300ms-400ms was present on the left actuator that was displaying tactile data through receiver (client) B. This delay is due to adding one new server-client relationship and can be overcome through mobile programming. As this is a minor delay which is beyond the context of this research area so it will be ignored.

Figure 29 shows the actual prototype design of Haptic Socks. The main components includes Software (for navigation commands), Bluetooth Receivers, Bluetooth Transmitter and Haptic Actuators.

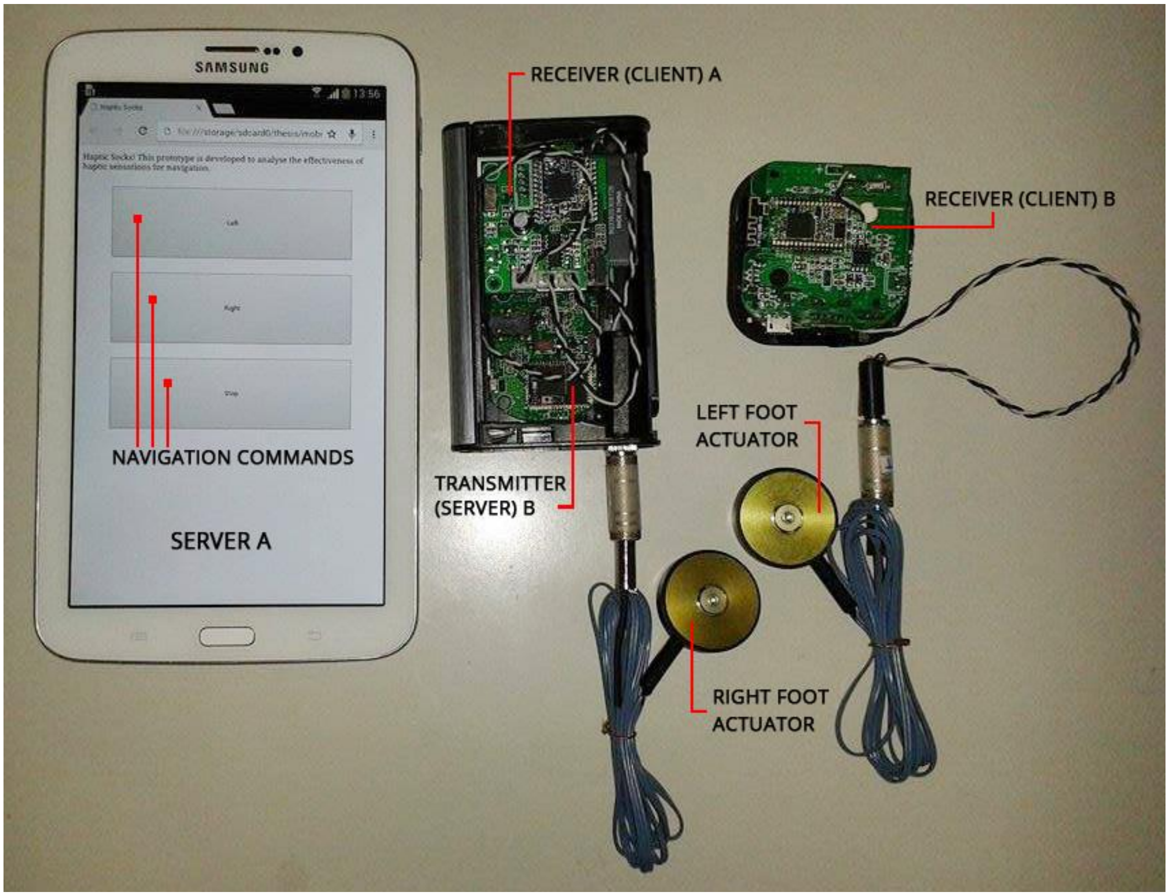


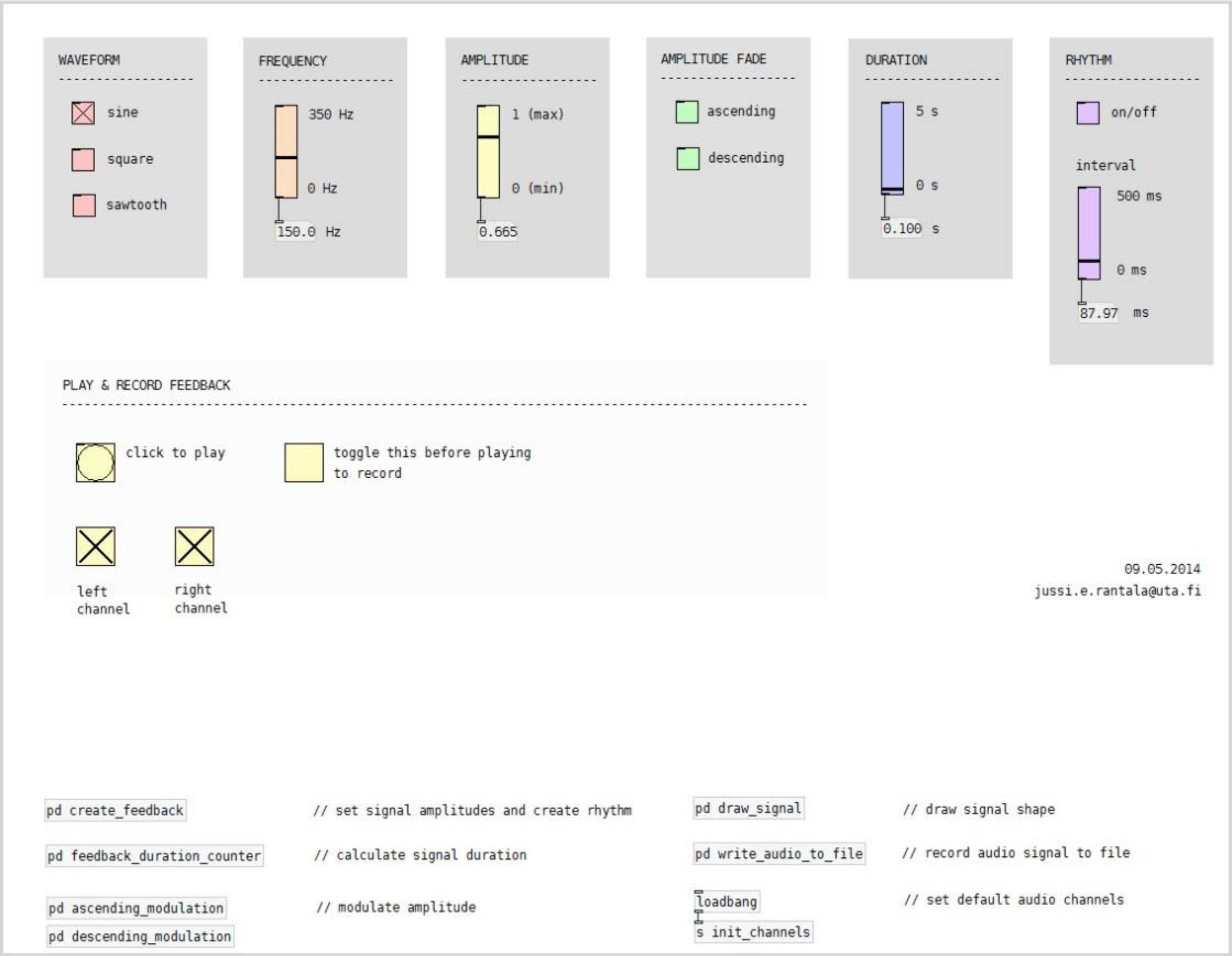
Figure 29. Prototype of Haptic Socks

Software Application

The software application is built using HTML5, CSS3 and JavaScript. Android tablet (Samsung Galaxy Tab 3) is used to execute the software with OS version of 4.1.2. When the participant clicks on left button, instruction pattern for left foot is executed and a tactile message is sent to left actuator. Similarly, when right button is clicked, instruction pattern for right foot is executed and a tactile message is sent to right actuator. For both, start and stop same instruction pattern is executed and a tactile message is sent to both actuators.

Pure Data - to create instruction patterns

To generate the instruction patterns *Tactile Pattern Editor* is used that is built using an open source visual programming language “Pure Data”. Tactile Pattern Editor is developed by Jussi Rantala. Figure 30 shows the layout of the editor.



```
pd create_feedback               // set signal amplitudes and create rhythm
pd feedback_duration_counter     // calculate signal duration
pd ascending_modulation          // modulate amplitude
pd descending_modulation
pd draw_signal                   // draw signal shape
pd write_audio_to_file           // record audio signal to file
loadbang                         // set default audio channels
s init_channels
```

Figure 30. Tactile Pattern Editor developed using Pure Data

As shown in figure, the editor has different parameters like *waveform, frequency, amplitude, duration and rhythm* that can be adjusted while creating a tactile pattern. Vibrotactile feedback parameters were discussed in detail in section 3.2.

Bluetooth Receivers

ISSC684S chip has been used as a Bluetooth receiver. It is a low power, single-chip RF and baseband SOC for Bluetooth v3.0+EDR audio applications. More information about it can be found at company's website [ISSC]. Figure 31 shows a descriptive diagram of the chip and actual Bluetooth receivers used in prototype.

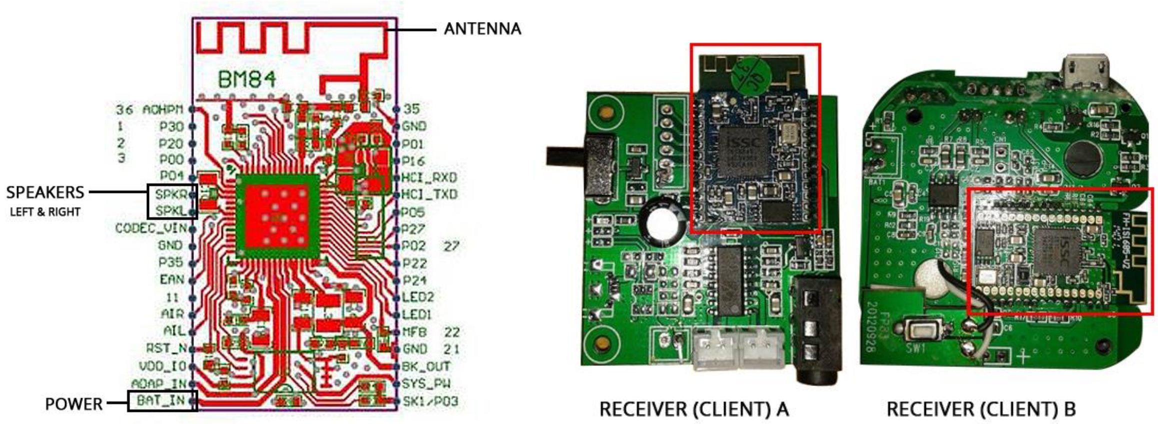


Figure 31. ISSC684S Bluetooth receiver used in prototype and its diagram

Bluetooth Transmitter

Avantree BTTC-200 has been used as Bluetooth transmitter in this prototype. It is a multipurpose chip that can be used both as Bluetooth transmitter and receiver figure 32. When it is switched to transmitter mode, it receives instruction patterns for left foot from receiver (client) A and transmits it to receiver (client) B on left foot wirelessly as explained in the workflow model previously (figure 28).

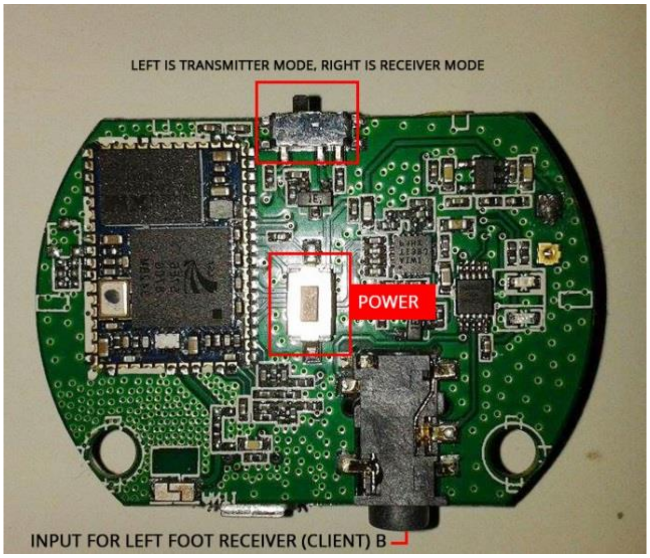


Figure 32. Avantree Bluetooth transmitter

Haptic Actuators

For this prototype, Linear Resonant Actuators (LRA) is used. They are also termed as Linear Vibrators. LRA motor have quite different working scenario than Eccentric Rotating Mass (ERM) vibration motors as discussed in section 3.3. Figure 34 shows the actuators used in the prototype. Figure 33 shows haptic actuator used in the prototype.

These actuators vibrate within Y-axis and use voice coil drive which makes the moving mass generate vibrations. The working scenario has been discussed in the previous section. Refer to section 3.3 for details.

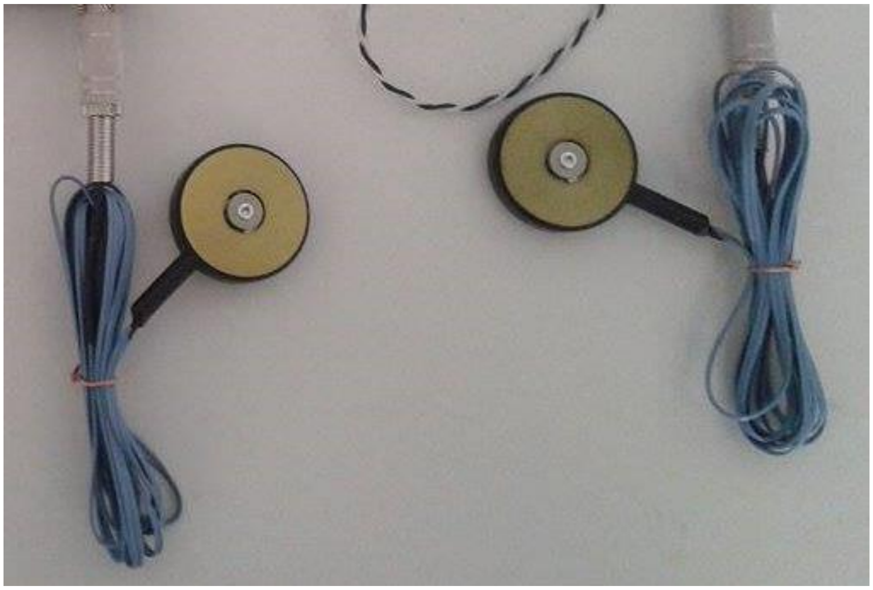


Figure 33. Haptic actuators

5. User Experiment

This chapter includes discussion and details about the testing of the prototype. The experiment was conducted with real participants and each experiment was performed under three different conditions discussed in section 5.3.

This chapter includes five sections. The first section provides necessary details of the participants. The second section highlights key arrangements made for the experiment. The third section describes methods of experiment following with the goals and hypothesis section. The last section describes the analysis procedure which will be continued in chapter 6.

5.1. Participants

A total of 9 participants were present aged between 20 to 36 years. Since the experiment involved listening to music and audio speech so it was investigated prior to the experiment whether any of the participants was suffering from any hearing problems. Five participants were aware of Haptics. One participant had participated in haptic experiment before but it was not related to haptic navigation; so his prior experience was not of any advantage for this experiment. The remaining participants did not have any experience with any kind of haptic research. Table 1 shows the demographics of the participants.

Gender	Age (years)	Familiarity with Haptics	Prior participation in experiment involving Haptics	Sense of Touch
Male	30	Yes	No	Normal
Male	29	Yes	No	Normal
Male	28	Yes	No	Normal
Female	20	No	No	Normal
Male	28	No	No	Normal
Male	24	No	No	Normal
Male	26	No	No	Normal
Male	36	Yes	No	Normal
Male	28	Yes	Yes	Normal

Table1. Participant Demographics

5.2. Arrangements

In order to ensure proper execution, some arrangements were made before the commencement of the experiment. Since it was an outdoor experiment, an empty parking area was selected with no obstruction in between. Weather forecast was checked to avoid rainy weather as it would have effected the prototype's circuits and participants would have felt uncomfortable. Seven participants appeared on the same day, while two appeared on different days. The weather on each day was a bit cold but it had insignificant effect on the walking pace of the participants because all of them were asked to walk normally. In addition, a technical cross–check list was used before each experiment to check if the software was running and was connected to the actuators and whether both the actuators are receiving feedback. Receivers, transmitters and mobile batteries were charged to avoid any inconvenience during the experiment. Audio speech and music was made ready with same volume level for each participant, and a significant vibration level of both the actuators was ensured. Figure 34 shows participant wearing the prototype.

Figure 34. Participant wearing prototype with controllers in hands

5.3. Parameters Investigated During Pilot Testing

Before the actual experiment was performed, the system was tested multiple times in order to find out the best parameter values for navigation commands. The main idea was to determine if users could sense the vibration, so it was decided to design a single tactile pattern for each command. The commands were LEFT, RIGHT, START and STOP. The participants had to turn according to the haptic feedback on their foot while walking i.e. Right turn if tactile message was felt on right foot and Left turn if tactile message was felt on left foot. If the tactile message was felt on both foot, then the participants had to either start or stop depending upon the condition they were facing during the experiment.

As explained in section 4.3 under Software Development, Pure Data was used to create instruction pattern considering parameters waveform, frequency, amplitude, duration and rhythm. These parameters were tested with different values and finally were set with waveform *(sine)*, frequency *(243.6 Hz)*, amplitude *(1)*, duration *(1.05 sec)* and rhythm *(107.5 ms)* in order to achieve maximum feedback. Figure 34 shows the visualization of the instruction pattern.

Figure 35. Visualization of one instruction pattern

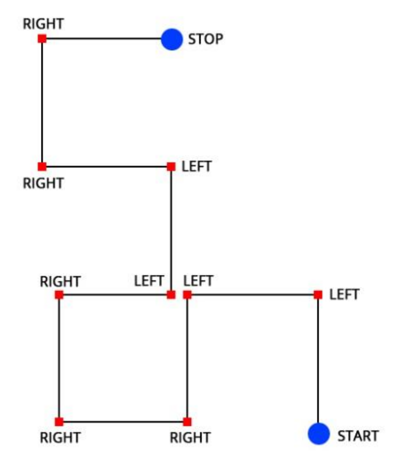
5.4. Methods

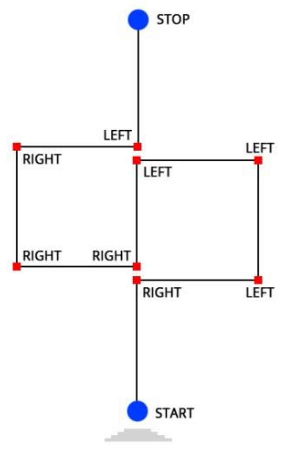
This section describes the experiment that was carried out to analyse the working principle and result of haptic socks as a navigation system. It was performed outdoor so that the environment resembled a real life scenario. Each participant had to wear a band with haptic actuators embedded on it on their feet. The actuators were wired with small hand-sized controllers that were placed in their pockets. The controllers were wirelessly connected to the android device in their hands which was playing a series of navigation commands after every five seconds. The participants had to walk under normal pace and take turn according to the actuator's feedback. The delay of five seconds was sufficient for the participants to react and make decision without any confusion.

The experiment was a single-subject design and each participant had to walk under three different conditions. In the first case, they had to walk normally without listening to anything. In the second case, they had to walk while listening to music and in the last case each participant had to walk while listening to an audio speech. The music and the audio speech were kept same for every participant. To avoid any variations caused by the learning behaviour of the participant, the conditions were balanced by three different routes. Total sets of conditions with balancing are as follows:

Participant #01:	**Participant #02:**	**Participant #03:**
Route A – No Music/Audio	Route B – Audio	Route C – Music
Route B – Music	Route C – No Music/Audio	Route A – Audio
Route C – Audio	Route A – Music	Route B – No Music/Audio

Table 2, 3 & 4 with figure 36, 37 & 38 below shows how the feedback was measured with different routes while the user was walking. The values shown are not the actual values.

Instruction Patterns	0=Mistakes, 1=No Mistakes	
Start	1	
Left	1	
Left	1	
Right	1	
Right	1	
Right	0	
Left	0	
Left	1	
Right	1	
Right	0	
Stop	0	

Instruction Patterns	0=Mistakes, 1=No Mistakes	
Start	1	
Right	0	
Left	0	
Left	1	
Left	1	
Right	0	
Right	0	
Right	1	
Left	1	
Stop	0	

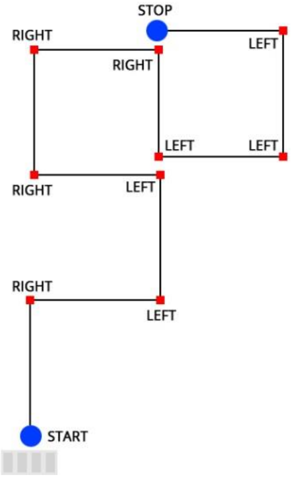
Instruction Patterns	0=Mistakes, 1=No Mistakes	
Start	1	
Right	1	
Left	0	
Left	1	
Right	1	
Right	1	
Right	1	
Left	1	
Left	1	
Left	0	
Stop	0	

Table 2, 3 & 4 with figure 36, 37, 38 Measuring response with route A, B, C

Every participant had to follow same experimental procedures which consisted of the following six steps.

1. Participants arrive and fill up the background information form (Appendix A).
2. Participants were given consent form, introduced to haptics and were briefed about the experiment instructions (Appendix B).
3. Prototype was setup and activated on participant's foot.
4. Participants familiarized themselves with the instruction patterns.
5. Actual experiment was performed under all three conditions.
6. After the experiment, an evaluation form was filled by each participant regarding the usage of this technique in real life (Appendix C&D).

5.5. Goals and Hypotheses

There were three research questions that had to be answered. The first question: Is haptic feedback effective on users' foot while they are walking? The second question: Does user behaviour (listening music, or audio speech) has any effect on navigation alert while walking? The third question: Regarding usability issues from previous research, can a prototype be developed that is less complex, easy to wear and portable? Answering these three questions will cover the major goals of this thesis.

The first question about effectiveness of haptic feedback is an important question that has to be measured. User making mistakes and taking wrong turns during experiment will help analyse the sufficient performance level of the user using this type of navigation. Furthermore, studying it under two different conditions (music and audio speech) and doing a comparative study of the mistakes made can be an optimal way to find out whether this technique can further be improved to develop an actual product. If the results are motivating, complex conditions such as jogging, running or driving can be used as analysis technique for future work.

Can people feel vibrations in foot while walking? Or can people feel vibrations while walking and listening to their favourite song or conversation? As an initial hypothesis, the answer can be in affirmative. It is expected that the subjects will detect haptic feedback and react accordingly. The reason is the presence of sensitive mechanoreceptors, the positive response that was shown when actuators were tested on foot for their sensitivity by placing it on the skin surface on the foot side, refer to section 3.5. Although chances of error occurrence will increase but as a trade-off, the higher effectiveness of vibration recognition will be obtained. With this expectation, the user performance goal was set between 90-95% with 10-5% of error rate. This goal was set for all the three conditions as performance below this range cannot be considered as effective.

The third question, about the simplicity of the product has its significance as well. People like smart design, and as this product will be used casually, it should be easy to wear, reliable and most importantly portable. While developing the prototype the workflow was kept simple with less circuitry, see section 4.3. The controllers designed were small in size and can fit in user’s pocket, but the circuits used were general purpose with other different functionalities and were not specifically designed for this prototype. It can be said that if the circuits are specially designed only for this workflow then they can be much smaller and can even fit with the actuators on user’s foot. Since the portability issue was emphasized during the development, so no extra effort will be required for handling it and in future, it can be much smaller in size.

6. Results

The results of the user experiment were analysed in two phases. In the first phase, the number of successful responses by the participants were noted during the experiment under all three conditions and compared with the expected user performance goal that was set in section 5.5. In the second phase, data gathered from user satisfaction form was reviewed and analysed to obtain results.

6.1. Statistical Analysis

In the first phase of the results three major terms were used to show the analysis. *Detected with no music / audio* indicates that the tactile message was recognized by the user successfully when the participant was not listening to any music or audio speech. *Detected with music* indicates that the tactile message was recognized by the user successfully when the participant was listening to music and *Detected with audio speech* indicates that the tactile message was recognized successfully when the participant was listening to audio speech. In the end overall performance was calculated by dividing total number of successfully decoded message with total number of messages sent. Table 5 shows the statistical representation of the data achieved in first phase.

Participants	Detected with no music / audio	Detected with music	Detected with audio speech
1	11/11	10/10	11/11
2	11/11	10/11	10/10
3	10/10	10/11	8/11
4	10/11	10/10	11/11
5	11/11	10/10	10/10
6	10/10	11/11	10/11
7	11/11	11/11	11/11
8	9/11	7/11	7/10
9	9/10	11/11	9/11
Overall	92/96 (95.8%)	90/96 (93.7%)	87/96 (90.6%)

Table 5 Statistical Analysis of data gathered in user experiment

User performance here as shown in table 5 is 95.8% in first condition which is quit motivating. As we move for the second condition with music, participants detected 93.7%

of the total feedback and similarly with third condition total detected feedback were 90.6%. The results are above our performance goal and suggests that with some minor improvements it can be used in real life. Figure 39 shows the graphical representation of user performance.

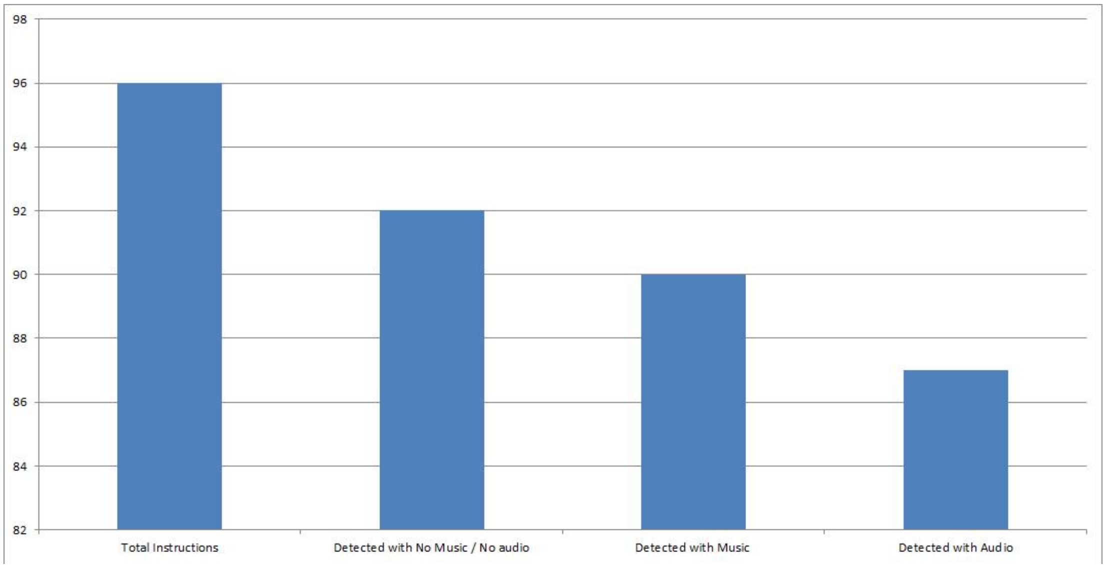


Figure 39. Graphical representation of user performance

6.2. Participants Analysis

After the user experiment was conducted, participants were required to fill the user satisfaction form in which they were asked to highlight the right value (according to them) within the range of -4 (negative) to +4 (positive). Since the analysis of the experiment was to be done under all three conditions therefore, the questions were answered after each condition was tested. The highlighted values are the nearest mean values of all the nine participants.

No Music, No Audio

1. I recognized all the navigation commands

Poorly	-4	-3	-2	-1	0	+1	+2	+3	[✓ +4]	Well

2. The technique was in my opinion

Impractical	-4	-3	-2	-1	0	+1	+2	+3	[✓ +4]	Practical

3. I experienced this navigation style

Disadvantageous	-4	-3	-2	-1	0	+1	+2	+3	[✓ +4]	Advantageous

4. If available, I will use this technique

Never	-4	-3	-2	-1	0	+1	+2	[✓ +3]	+4	Often

With Music

1. I recognized all the navigation commands

Poorly	-4	-3	-2	-1	0	+1	+2	[✓ +3]	+4	Well

2. The technique was in my opinion

Impractical	-4	-3	-2	-1	0	+1	+2	[✓ +3]	+4	Practical

3. I experienced this navigation style

Disadvantageous	-4	-3	-2	-1	0	+1	+2	[✓ +3]	+4	Advantageous

4. If available, I will use this technique

Never	-4	-3	-2	-1	0	+1	+2	[✓ +3]	+4	Often

With Audio

1. I recognized all the navigation commands

Poorly	-4	-3	-2	-1	0	+1	+2	[✓ +3]	+4	Well

2. The technique was in my opinion

Impractical	-4	-3	-2	-1	0	+1	+2	[✓ +3]	+4	Practical

3. I experienced this navigation style

Disadvantageous	-4	-3	-2	-1	0	+1	+2	[✓ +3]	+4	Advantageous

4. If available, I will use this technique

Never	-4	-3	-2	-1	0	+1	+2	[✓ +3]	+4	Often

All Conditions

1. I recognized all the navigation commands

Hard	-4	-3	-2	-1	0	+1	+2	[✓ +3]	+4	Easy

2. The technique was in my opinion

Unpleasant	-4	-3	-2	-1	0	+1	+2	[✓ +3]	+4	Pleasant

7. Discussion

In this section, results gathered from statistical analysis and participant analysis has been presented.

In section 5.5, user performance goal was set between 90-95% with 10-5% error rate. As shown in table 5, overall user performance with first condition is 95.8% which is higher than the expected hypothesis. The result shows that out of nine participants, six detected all the tactile messages that were sent and interestingly, this means that the users can detect vibrations while they are walking. The error rate is 4.2% which may be due to the participants' reaction time at the start of the experiment.

Performance under second condition i.e. while participant was listening to music is 93.7% which is a constructive finding because the result lies within the expected range. A total of six participants out of nine detected all the messages and responded accordingly. The remaining participants were not able to detect one or two messages. The overall error rate in this condition is 6.6% which may be due to lack of concentration of the participant on the experimental procedure while listening to song. With these results it can be said that music might affect user's sense of detecting vibrations but it can be overcome with certain parameter values.

Under the third condition, the participants were listening to same audio speech and the overall result is 90.6% which is near to the least expected value but still suggests that with proper settings in vibration patterns, it can be made more effective. Five participants out of nine detected all the values though they were listening to the same audio speech as others who made mistakes and the error rate is 9.4%. One reason may be that the conversation may have grabbed the attention of the participants.

The participants' analysis shows that under no audio/music condition, all the participants correctly recognized the navigation commands which seem logical because except for natural disturbance, no forced or external disturbance was present to divert the attention of the participants. Under audio and music conditions, the participants faced the same level of difficulty in understanding the navigation commands which can be explained by the fact that they might have concentrated more on the audio or music rather than the experimental procedures. The technique was labelled as 100% practical by the participants under no audio/music condition because it was the easiest and least challenging condition while the technique using audio and music during navigation scored +3 points because some might have found that there can be a chance of losing their focus of navigation. The navigation style was awarded a similar score as that of the technique used, sharing the same reason. Participants opined that they will use this technique often under no audio/music condition because they remained more focused under this condition while they would not use this technique as often in case while listening to music or audio because the probability of making wrong moves will increase. In this case we can further improve the prototype where participants can customize and accelerate vibration patterns according to their mood or volume of the audio.

The final survey form that was filled by the participants summarized the overall experience of using Haptic Socks as a means of navigation system.

The first question was regarding the preference of this device over normal audio and visual feedback. This question had a mixed review from the participants. Some thought that Haptic Socks was a useful navigation tool because it did not interrupt the thought processing even while walking and making motion and provided an accurate navigation route which is uncertain in normal cases. Some were of the opinion that the concentration required while using this technique might outweigh the benefits this technique offered.

The question about the usefulness of Haptic socks while listening to music or talking to a friend obtained affirmation from all the participants provided that the vibrations from the device were stronger because weak vibrations are hard to identify and also in case of any distracting activity occurring in background can also lead to missing any navigation commands.

The chances of error occurrence during the experiment was mainly because the audio or the speech had grabbed the attention of the participants who focused more on the music or speech which they found interesting rather than focusing on the navigation commands. Secondly, another problem that led participants to make mistakes was the weak vibrations which made it difficult for them to decipher whether they were actual vibrations or not.

The final feedback of the participants regarding this technique was interesting. Many of the responses catered to including various other testing conditions like cycling, driving and boating. Another opinion given by the participant involved variable vibration amplitude so that the user may vary the magnitude of vibrations according to his own needs and comfort.

8. Conclusion & Future Work

The research innovation brought by Haptic Socks in this field is interesting. Using haptic feedback as a navigation system will be an innovative addition for human beings by introducing multi-tasking in every walk of life.

Since the sense of touch is the foremost sense that develops during the early stages of human life [Berk, 2008] therefore, this idea has been used as the foundation of Haptic Socks. Haptic technology has seen much development in the past few decades and much work has been carried out to build prototypes that use tactile sensation as their working principle but most of these require some improvement. On one hand, some prototypes have a complex circuitry design using multiple actuators for navigation [Tsukada and Yasumura], [Rosenthal et al., 2011], [Logan and Perez, 2012]. On the other hand, some require a lot of effort for their working [MOMO]. Haptic Socks provided a solution to 'effectiveness combined with simplicity' that was much needed.

This thesis explores the possibility of designing a prototype that is simple, portable, wireless and plug and play. The results show that the problems faced by the users while using other navigation devices using haptic technology have been overcome and positive feedback is obtained regarding Haptic Socks.

As a future work, the size of Haptic Socks should be made smaller so that it becomes more comfortable for the users and they might get the feeling that they are wearing no additional piece of clothing. This can be done by using controllers specifically designed for the circuitry of Haptic Socks rather than general purpose controllers which are available in standard sizes. Secondly, the prototype can be tested under different conditions like jogging, running or driving and on difficult terrain like mountainous regions and harsh climatic conditions like rainfall and snowfall. Thirdly, instead of just left, right, start and stop commands, more commands can be interfaced like going back, climb or crossing roads so that the device becomes more sophisticated and enhanced. Lastly, another useful research area for Haptic Socks can be the development of a mobile application that can be easily downloaded on user's smart phone. This can be integrated with another health monitoring application that will store the health record of the user like pulse rate, heart rate and other activities and keeps a track of how much calories the user burns on a daily basis while navigating. The vibrating device can be further enhanced by interfacing varying magnitude vibrations so that the user gets the freedom to vary the magnitude of the vibrations according to his needs and desires.

References

[Amemiya et al., 2008] Tomohiro Amemiya, Taro Maeda and Hideyuki Ando, *Location-free haptic interaction for large-area social applications*, 2008.

[Azadi and Jones, 2014] Mojtaba Azadi and Lynette A. Jones, *Evaluating Vibrotactile Dimensions for the Design of Tactons*, IEEE Transactions on Haptics, Vol. 7, No. 1, January-March 2014.

[Berk, 2008] Laura E. Berk, *Infants and children: Prenatal through middle childhood*, 6th edition, Allyn & Bacon, 2008.

[Bolanowski et al., 1999] Stanley J. Bolanowski, Ronald T. Verrillo and Francis McGlone, *Passive, active and intra-active (self) touch*, Somatosensory & Motor Research, 1999.

[Brewster and Brown, 2004] Stephen Brewster and Lorna M. Brown, *Tactons: Structured Tactile Messages for Non-Visual Information Display*, University of Glasgow, Department of Computer Science, 2004.

[Brown et al.] Lorna M. Brown, Stephen A. Brewster and Helen C. Purchase*, A First Investigation into the Effectiveness of Tactons*, University of Glasgow, Department of Computer Science.

[Das et al., 2005] Sandhitsu Das, Maciej Lazarewicz, Leif H. Finkel, *Principal Component Analysis of Temporal and Spatial Information for Human Gait Recognition*, Department of Bioengineering, 2005.

[Fan et al., 2008] Richard E. Fan, Martin O. Culjat, Chih-Hung King, Miguel L. Franco, Richard Boryk, James W. Bisley, Erik Dutson and Warren S. Grundfest, *A Haptic Feedback System for Lower-Limb Prostheses*, In: 11th International Conference on Rehabilitation Robotics Kyoto International Conference Center, Japan, June 23-26, 2009.

[Gallace and Spence] Alberto Gallace and Charles Spence, *Touch and the Body: The Role of the Somatosensory Cortex in Tactile Awareness*, Psyche, Volume 16, number 1.

[Gibson, 1962] James J. Gibson, *Psychological Review: Observations on Active Touch*, Vol. 69, No. 6, Cornell University, 1962.

[Gurari et al., 2009] Netta Gurari, Kathryn Smith, Manu Madhav and Allison M. Okamura, *Environment Discrimination with Vibration Feedback to the Foot, Arm, and Fingertip*, 2009.

[Heller and Schiff, 1991] Morton A. Heller, William Schiff, *The Psychology of Touch*, Winston-Salem State University, 1991.

[Hertenstein, 2002] Matthew J. Hertenstein, *Touch: Its Communicative Functions in Infancy*. University of California, Human Development, 2002.

[Hoggan and Brewster, 2007] Eve Hoggan and Stephen Brewster, *New Parameters for Tacton Design*, University of Glasgow, Department of Computer Science, 2007.

[Immersion] Immersion, "Immersion – official webpage."[Online]. Available: http://www.immersion.com. [Accessed: 10-May-2015]

[ISSC] ISSC Technologies Corp., "ISSC – official webpage."[Online]. Avalaible: http://www.issc.com.tw. [Accessed: 10-May-2015].

[Johansen-Berg and Lloyd, 2000] Heidi Johansen-Berg and Donna M Lloyd, *The Physiology and Psychology of Selective Attention to Touch*, Oxford Centre for Functional Magnetic Resonance Imaging of the Brain, John Radcliffe Hospital, Oxford, 2000.

[Kikuchi] Takehito Kikuchi, *Design of Unit for Haptic Device on Foot*, Faculty of Engineering, Oita University.

[Kohli et al., 2006] Luv Kohli, Masataka Niwa, Haruo Noma, Kenji Susami, Yasuyuki Yanagida, Robert W. Lindeman, Kenichi Hosaka, Yuichiro Kume, *Towards Effective Information Display Using Vibrotactile Apparent Motion*, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2006.

[KOR-FX] KOR-FX, "KOR-FX, Haptic Gaming Vest – official webpage."[Online]. Available: http://korfx.com/. [Accessed: 10-May-2015].

[Koskinen 2008] Emilia Koskinen, *Optimizing Tactile Feedback for Virtual Buttons in Mobile Devices,* Master's Thesis, Helsinki University of Technology, 2008.

[Krantz, 2012] John H. Krantz, *Experiencing Sensation and Perception, The Skin Sense*, Hanover College, Psychology Department, 2012.

[Krausman and White, 2006] Andrea S. Krausman and Timothy L. White, *Tactile Displays and Detectability of Vibrotactile Patterns as Combat Assault Maneuvers are Being Performed*, Army Research Laboratory, 2006.

[Lechal] Lechal, "Lechal – official webpage."[Online]. Available: http://lechal.com. [Accessed: 10-May-2015].

[Lederman and Klatzky, 2009] S. J. Lederman, R. L. Klatzky, *Haptic perception: A tutorial,* Attention, Perception, & Psychophysics, The Psychonomic Society, Inc., 2009.

[Logan and Perez, 2012] Philip Logan and Daniel E. Perez*, Vibro-Vest: Directional Information in Three Dimensions*, Haptics Class Project Paper, University of South Florida, 2012.

[McDaniel et al., 2010] Troy McDaniel, Sreekar Krishna, Daniel Villanueva and Sethuraman Panchanathan, *A Haptic Belt for Vibrotactile Communication*, Arizona State University, Center for Cognitive Ubiquitous Computing, 2010.

[MOMO] MOMO, "MOMO – official webpage."[Online]. Avalaible: *http://momobots.com/*. [Accessed: 10-May-2015].

[Ni et al., 2013] Dejing Ni, Lu Wang, Yu Ding, Jun Zhang, Aiguo Song and Juan Wu, *The Design and Implementation of a Walking Assistant System with Vibrotactile Indication and Voice Prompt for the Visually Impaired*, Proceeding of the IEEE International Conference on Robotics and Biomimetics (ROBIO) Shenzhen, China, December 2013.

[Nordahl et al., 2010] Rolf Nordahl, Amir Berrezag, Smilen Dimitrov, Luca Turchet, Vincent Hayward, and Stefania Serafin, *Preliminary Experiment Combining Virtual Reality Haptic Shoes And Audio Synthesis*, 2010.

[Paananen, 2010] Maria Paananen, *Pick, Drag, Hit and Drop – Does Haptic Design matter?*, Master's Thesis, University of Tampere, Department of Computer Sciences, 2010*.*

[Peck and Childers, 2003] Joann Peck and Terry L. Childers, *To Have and To Hold: The Influence of Haptic Information on Product Judgments*, 2003.

[Precision Microdrive] Precision Microdrive, "Precision Microdrive – official webpage."[Online]. Available: *http://www.precisionmicrodrives.com*. [Accessed: 10-May-2015].

[Precision Microdrive] Precision Microdrive, "Precision Microdrive – official webpage."[Online]. Available: *http://www.precisionmicrodrives.com*. [Accessed: 10-May-2015].

[Raisamo and Raisamo, 2009] Roope Raisamo and Jukka Raisamo, *The Sense of Touch*, Haptic User Interfaces, 2009.

[Rao, 2012] ShreHarsha Rao, *High-definition haptics: Feel the difference*, 2012.

[Rincon-Gonzalez et al., 2011] Liliana Rincon-Gonzalez, Jay P. Warren, David M. Meller, and Stephen Helms Tillery, *Haptic Interaction of Touch and Proprioception: Implications for Neuroprosthetics,* 2011.

[Rosenthal et al., 2011] Jacob Rosenthal, Nathan Edwards, Daniel Villanueva, Sreekar Krishna, Troy McDaniel and Sethuraman Panchanathan, *Design, Implementation and Case Study of a Pragmatic Vibrotactile Belt,* IEEE Transactions on Instrumentation and Measurement, Vol. 60, No.1, January 2011.

[Rovers and Essen, 2005] A. F. Rovers and H. A. van Essen, *Guidelines for haptic interpersonal communication applications: an exploration of foot interaction styles*, 2005.

[Silva, 2007] Clarence W. de Silva, *Vibration – Fundamentals & Practice*, Vibration engineering, 2nd edition, 2007.

[Torre, 2006] Gabriel Robles-De-La-Torre, *The importance of the sense of touch in virtual and real environments*, Haptic User Interfaces for Multimedia Systems, International Society for Haptics, 2009.

[Tsukada and Yasumura]Koji Tsukada and Michiaki Yasumura, *ActiveBelt: Belt-type Wearable Tactile Display for Directional Navigation*, Keio University, Graduate School of Media and Governance.

[Venesvirta, 2008] Hanna Venesvirta, *Haptic Navigation in Mobile Context*, University of Tampere, Department of Computer Sciences, 2008.

[Visell et al., 2011] Yon Visell, Bruno L. Giordano, Guillaume Millet and Jeremy R. Cooperstock, *Vibration Influences Haptic Perception of Surface Compliance During Walking*, 2011.

[Wang and Minor, 2014] Yue Wang and Mark A. Minor*, Design of a Bladder Based Elastomeric Smart Shoe for Haptic Terrain Display*, IEEE/RSJ International Conference on Intelligent Robots and Systems September 14-18, 2014.

Appendix A: Background Information

Participant identification code (experimental fills): ____________________

With this form the background information for the analysis is collected. The information is stored and managed **anonymously** and **cannot be combined** with the participant.

Age __________ (in years)

Gender [ ] female [ ] male

Native Language [ ] Finnish [ ] English [ ] Other, ________________

Do you use navigation applications like google maps, while walking?
[ ] Yes [ ] No

Do you any problems with Headphones/ear phones?
[ ] Yes [ ] No

Do you listen to music while walking?
[ ] Yes [ ] No

Do you know what haptic interaction is?
[ ] Yes [ ] No

Have you ever acted as a participant in any haptic experiment before?
[ ] Yes [ ] I don't remember [ ] No

Do you use your mobile phone in vibration mode?
[ ] Yes, only vibration mode [ ] both, ringtone and vibration [ ] No, only ringtone or silent mode

Appendix B: Instruction for participants

Haptic Socks
An Experiment to measure accuracy of haptic feedback for navigation information services

General

While using navigation applications such as google maps we interact with two types of modalities; visual feedback or auditory feedback. This research study will present an experiment on implementing a third type of modality i.e. haptic feedback. This means user will get navigation guidance through tactile (sense of touch) feedback.

Being as a participant, you will be required to wear haptic actuators band on your feet (both left and right). Specific instructions such as **start**, **turn left**, **turn right** or **stop** will be given through the haptic actuators. We will conduct the experiment under three scenarios, i.e. participant walking while listening to **music**, **speech audio** or **nothing**. We will measure the accuracy of user feedback with all three mentioned conditions.

The aim of the study is not to examine the performance of a single user but to assess the usability of this interaction technique on a general level.

Description

Haptic socks will consist of vibrotactile actuators embedded on your feet at certain position. These actuators will guide you in turn by turn navigation through vibrations in response to the command received through the navigation device such as a smartphone. Haptic socks will use wireless connection with the device which in this case will be Bluetooth. After embedding actuators on your feet, the controller (android device) will be given to you. This controller will send navigation commands in a **specific pattern** and you will be asked to move accordingly. For example, vibration sensed in left foot should lead you to make a left turn and vice versa. One of our group members will be observing and noting down the mistakes. The experiment will be conducted in an empty hall without any obstacles in the area. Headphones, music playlist and audio speech will be same for each participant and will be provided by us.

Before experiment starts, you will be given proper demonstration of the prototype.

Risks and Benefits

There are no risks involved in participating in the study. The haptic sensors in this prototype used are non-intrusive and do not inflict any discomfort or pain, but you will experience physical feedback on your feet during the experiment. This feedback can be defined as very similar to your mobile vibration alerts. We will conduct the experiment in an open space with no obstacles, but there are potentially non-participants people present in the premises, so being cautious while moving is necessary. Navigating under the conditions of hearing music or audio speech may feel slightly disorienting.

We are unfortunately not able to provide any compensation for participating in the experiment. The results of this experiment will be used in conducting a course work for a university course, as well as a part of a Master's thesis project.

Duration

Conducting the experiment along with filling the required forms will take approximately 30-45 minutes.

Participation Rights

All the data collected during this experiment will be handled anonymously, and will be reported on a group level, and cannot be combined with a person. The participation is voluntary, including that you have the right to cancel your approval any time without any consequences.

By signing this consent form I agreed to participate in the experiment, and understood that there is no monetary compensation for participating. I also understood that my participation is voluntary and I am entitled to refuse to participate or stop the performance at any time without any consequences.

Name & Signature ________________________________

Date & Place ________________________________

Contact Information

If you have any questions, concerns or complaints about this experiment, its procedures, risks or benefits, you can me at: fahadahmed.x@student.uta.fi

Appendix C: Evaluation Questionnaire

Survey about the technique

Circle a number which best describes your sensations. Information provided here will be used for experiment evaluation on a general level.

Condition#1: No Music / No Audio

I recognized all the navigation commands
poorly -4 -3 -2 -1 0 +1 +2 +3 +4 well

Using this technique was in my opinion
difficult -4 -3 -2 -1 0 +1 +2 +3 +4 easy

I think using this technique was
unpleasant -4 -3 -2 -1 0 +1 +2 +3 +4 pleasant

The technique was in my opinion
impractical -4 -3 -2 -1 0 +1 +2 +3 +4 practical

I experienced this navigation style
disadvantageous -4 -3 -2 -1 0 +1 +2 +3 +4 advantageous

If available, I will use this technique
never -4 -3 -2 -1 0 +1 +2 +3 +4 often

Condition#2: Music

I recognized all the navigation commands
poorly -4 -3 -2 -1 0 +1 +2 +3 +4 well

The technique was in my opinion
impractical -4 -3 -2 -1 0 +1 +2 +3 +4 practical

I experienced this navigation style
disadvantageous -4 -3 -2 -1 0 +1 +2 +3 +4 advantageous

If available, I would use this technique
never -4 -3 -2 -1 0 +1 +2 +3 +4 often

Condition#3: No Audio

I recognized all the navigation commands
poorly -4 -3 -2 -1 0 +1 +2 +3 +4 well

The technique was in my opinion
impractical -4 -3 -2 -1 0 +1 +2 +3 +4 practical

I experienced this navigation style
disadvantageous -4 -3 -2 -1 0 +1 +2 +3 +4 advantageous

If available, I will use this technique
never -4 -3 -2 -1 0 +1 +2 +3 +4 often

Appendix D: Post Experiment Questionnaire

Final Survey

How did you experience this navigation style? Will you prefer this technique over audio or visual feedback that is used normally in maps?

Do you think this technique will be effective, while you are walking listening to music or talking to your friend?

If you think you made any mistake, was it because you did not sense the instruction or because of any other reason?

Do you have any other comments concerning this test?