INDUCING VIBRO-TACTILE SENSATION AT MESOSCALE

by

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ABSTRACT

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Haptics, the feeling of touch, has primarily been used to provide a person a general sensation such as vibration using a joystick or cellphone. But haptics has gradually developed to a stage where it is investigated for virtual and augmented reality environments. Vibro-tactile based feedback is a modality employed to provide a more realistic and localized sensation. This research focuses primarily on providing vibro-tactile feedback at the mesoscale level on the fingertips. A research platform for mesoscale vibro-tactile feedback has been investigated and developed. The software is based on LabVIEW and could generate a number of different and distinct waveform patterns to control and actuate a set of shaft-less actuators on a wearable glove. This platform has been used to study and determine the parameters that affect the vibro-tactile sensation for a set of volunteers. The results of the initial study indicate that with proper training the waveform characteristics of frequency and amplitude, and the combination of waveform patterns could be employed for controlled vibro-tactile sensation associated with a specific action or task.

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CHAPTER 1

Introduction

1.1 Haptics overview

Haptics is the science of applying tactile sensation and control to applications on computer-based systems related to virtual and augmented reality or human robot interaction. It provides a perspective on an object shape, size, and form factor. Such a technology enables a user to feel various tactile feedback types such as clicks, vibrations, pressure, and slippage.[13] The field of haptics is divided into 3 major categories:

- Human haptics,
- Machine haptics,
- Computer haptics.

In human haptics, the environment consists of only a human and an object to be assessed and identified. The human is responsible for collecting information from the object surface and transfer the information to the sensory system in the body to generate a tactile understanding. In machine haptics, a mechanical system is responsible for generating a tactile feedback or to collect the information from the object surface. In computer haptics, software is used to process the collected information using neural networks or other algorithms to generate an output for a specific data set.[14][15]

The most recent developments in the field of haptics have been focusing and commonly found on developing haptic technology in diverse areas such as patient rehabilitation programs, gaming interface, cellular phone notification systems, graphical interface, and human robot interaction.

Recent applications for haptic technology increase the quality of tactile sensation by combining visual representations with the feedback being provided. Some systems rely on a 2D system which projects corresponding visual information on a screen. There are also systems which use virtual reality or augmented reality to provide information; where a system using virtual reality provides a replacement to the real world by using a display technology to provide a 3D view of the graphical representation and a system using augmented reality provides a textual, symbolic or graphical information that represents a real time relationship with a situation or the surroundings. Such systems increase the level of immersiveness for a person's interaction with the information.[16]

Haptic technology concentrates on providing feedback for two types of haptics: kinesthesia and tactile feedback. As defined by Kendra Cherry "Kinesthesis is the perception of the body movements where a person is able to detect changes in the body position and movements without relying on information from vision, smell, touch, taste and hearing." [17]

The body perceives the movements by computing position, orientation, force and torque of the body parts. For example, in figure 1.1 two postures A and B are represented. While changing the posture from A to B, the body computes the collected information for the position, orientation, force and torque inputs provided by the receptors. On processing this information, the body is able to plan the change in motion that it has to undergo to be able to transition from posture A to B. This type of haptic is applied as the logic behind force feedback systems. In force feedback systems, the devices translate the forces which are generated due to body movements using mechanical movements of a system and the visual representations on a screen.

Generally, these types of feedback are provided by applying varying pressure at a specific site on the body or by restricting the motion of the hand or body parts which would lead a person to think that they are holding a real object.[18]

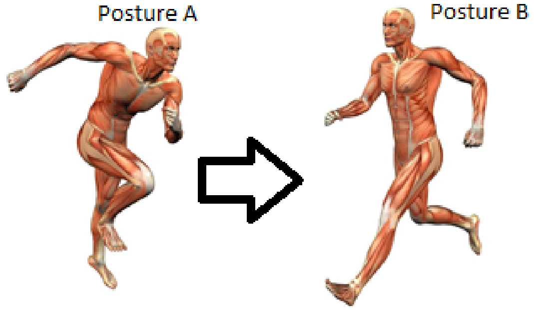


Figure 1.1. Kinesthesia body movements [1].

Tactile feedback concentrates on the information from the receptors which are responsible for touch based exploration. These receptors provide informational cues using contact location, pressure shear, slip, vibration, and temperature. For example, in figure 1.2, a person is moving a hand over a trunk of a tree to sense and understand the texture of the trunk. While performing this motion, vibrations are generated due to the friction between the skin on the inner side of the fingers and the surface of the trunk. Due to these vibrations, the person is able to collect informational cues to develop a tactile understanding which describes or corresponds to the texture being sensed.

1.2 Thesis statement

In this research, the focus is on inducing vibro-tactile sensation. The concept of inducing vibro-tactile based sensation is developed as a component of research

Figure 1.2. Tactile understanding [2].

performed at the Manufacturing Automation and Robotic Systems (MARS) lab at The University of Texas at Arlington in the field of Human Robot Interaction and interaction with prosthetic devices.[19][20][21][22] The existing modules such as Flex sensor control, voice control and brain computer interface concentrate on establishing a uni-directional channel for information transfer to the developed robotic prosthetic arm. In order to receive feedback from the prosthetic device, a bi-directional information transfer system needs to be established. To convert the existing system into a bi-directional system, the present research focuses on developing a tactile feedback glove as the research platform to induce vibro-tactile feedback.

During this research, a platform consisting of hardware and software modules were developed to study, investigate and understand the sensation corresponding to tactile feedback. The research platform was used to evaluate the induced sensation to volunteers for a set of waveform patterns which were identified based on distinguishable pattern features. During this evaluation, the volunteers were required to provide feedback corresponding to their sensitivity to the actuation they felt by identifying graphical representations from an existing database. The analysis of the collected experimental data concluded that small amplitude variations in a large pattern are better recognized as compared to large variations in a pattern.

1.3 Research activities

The scope of this research includes the following topics:

1. Study of existing haptic technology
    - (a) Study the open literature to better understand existing research activities and challenges
    - (b) Compare hardware options
2. Study the process involved in developing a haptic waveform
    - (a) Develop a viable process for waveform pattern development
    - (b) Determine factors which affect the induced sensation to a human or the sensation by a human
3. Develop a research platform to provide tactile sensation
    - (a) Design and implement hardware and software modules
    - (b) Determine factors or waveform properties which affect the sensation by a person
4. Investigate characteristics which affect the sensation by a person

1.4 Chapter summary

Chapter 1 briefly introduced the concept and types of haptics, the thesis statement and the research activities. Chapter 2 introduces information on haptic technology applications, literature survey, tactile receptors, and investigated actuators and sensors for research platform development. Chapter 3 discusses the research platform development followed by Chapter 4 focusing on the experimental and evaluation procedures and the results of the volunteer based study. Chapter 5 summarizes and concludes this research and provides recommendations for future research.

CHAPTER 2

Background information

This chapter focuses on the background information and literature survey that is investigated to develop a foundation for the research and is divided into 6 sections. Section 2.1 discusses the investigation performed on haptic data collection and processing systems where the sensors for haptic data acquisition devices are discussed in section 2.2. Section 2.4 discusses haptic feedback devices and actuators for haptic feedback devices. Section 2.5 discusses the human sensory system and receptors which act as biological sensors. Section 2.6 discusses the factors that affect the development of a research platform.

Haptics has become a major part of existing technology due to the need for feedback. This feedback allows a person to understand the quality of an action being performed. The application of haptics is concentrated to provide feedback for a number of applications including but not limited to gaming platforms, medical training, rehabilitation, cell phone notification systems and graphical user interface systems.

In gaming, force feedback systems allow a person to sense a structure of an object in a virtual environment and understand the extent of a force they are applying to improve their control while interacting in the game. A system by Dextra Robotics produces force feedback.[23] They have developed a wearable exoskeleton glove which comprises of a variable stiffness force feedback mechanism to limit the movement of the fingers, and track the movements of the hand with corresponding visuals in a virtual environment so that the user has a reference to the restrictions on the movement of the fingers.

In order to increase the immersiveness in a gaming experience, a player must be able to feel the fine textures of the objects held in the game. For this sensation, the system would need to include a module for tactile feedback. Such a system is under development by HaptX; a wearable glove-based system which uses actuators having the capability to inflate and deflate to provide a specific vibro-tactile feedback.[24] The actuators use fluid to inflate and deflate and work with a virtual interface. While providing a vibro-tactile feedback the system also provides feedback on the magnitude of the force being applied by limiting the movements of the hand.

Other than force and tactile feedback there are devices widely used to provide visual and auditory feedback to the users. The Da Vinci series is one of the extensively used robotic surgical systems which uses visual feedback to guide a surgeon while performing a medical procedure.[25] The robotic system allows the surgeon to perform minimally invasive procedures by translating the motions of the surgeon's fingers to the robotic wrists and provides feedback using visual and auditory cues.

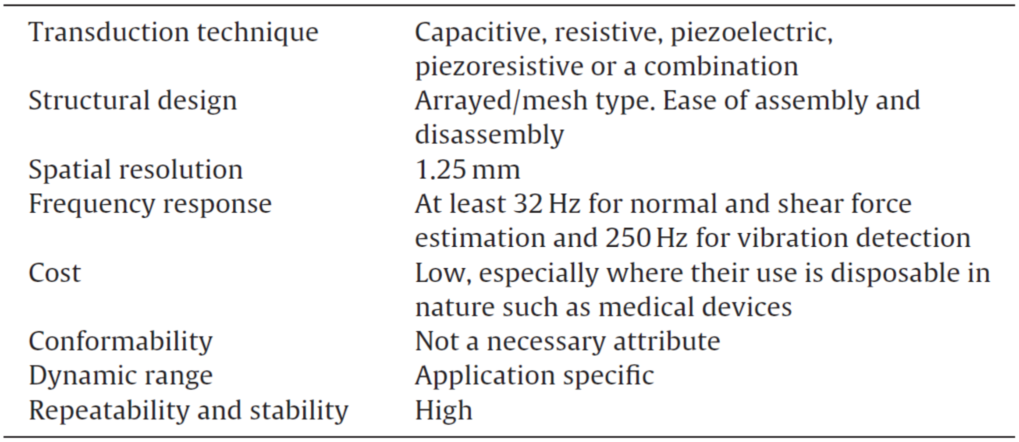
2.1 Literature survey on haptic data collection and processing systems

The aspect of sensory data collection concentrates on haptic information processing systems and sensors which collect information related to vibration, force, pressure, and temperature. This section briefly discusses existing literature related to haptic data collection and processing systems.

Haptic data collection systems utilize input from sensors for vibration, pressure and force generated during an interaction and classify them based on the type of interaction and texture. This type of information processing system can be found in the work performed by Gao et al.[26] They developed a deep learning model which made predictions on tactile understanding and described the texture of the surfaces of the object using haptic adjectives. In their work, they evaluated the performance of visual and physical models separately and combined the results using training data collected with a Biotac sensor on a PR2 robot system. They found that a combined visual and physical model performs better when compared to the models working individually. While evaluating the performance of the developed models, they compared convolutional neural networks (CNN) and long-short-term-memory (LSTM) neural networks and found that the performance of CNN improved after the model learnt all the weights whereas in LSTM the performance degraded when multiple LSTMs were stacked. Chu et al.[27] worked on expanding the ability of a robot to communicate with humans by creating a system using a machine learning model based on support vector machines (SVMs) that would allow them to learn haptic adjectives by interacting with objects. In their work, they proposed a machine learning model to relate haptic adjectives to a specific set of pre-defined movements of the robot such as tap, squeeze, static hold, slow slide and fast slide. These movements allow a robot to collect object related information. The information collected using a Biotac sensor was related to a set of adjectives derived using a volunteer based study to describe the surface with adjectives which work as a training data set. Based on their evaluation and results, machine learning models using dynamic feature based learning approach performed better when compared to static feature based learning models.

The sensory input provided to information processing models include applied pressure, generated force, frequency of vibration, and temperature captured by sensors such as Biotac, force and piezoelectric sensors (see section 2.2). Tiwana et al.[12] discussed and categorized previous expectations for tactile transduction techniques such as capacitive, piezoresistive, inductive, piezoelectric, magnetic and optical methods and the reasons for their failures. Based on their analysis, they proposed a set of design criteria presented in table 2.1 regarding mechanoreceptors in glabrous human skin.

Table 2.1. Proposed design criteria for mechanoreceptor based sensors [12]



Transduction technique	Capacitive, resistive, piezoelectric, piezoresistive or a combination
Structural design	Arrayed/mesh type. Ease of assembly and disassembly
Spatial resolution	1.25 mm
Frequency response	At least 32 Hz for normal and shear force estimation and 250 Hz for vibration detection
Cost	Low, especially where their use is disposable in nature such as medical devices
Conformability	Not a necessary attribute
Dynamic range	Application specific
Repeatability and stability	High

The application of force and pressure sensors is critical for developing tactile understanding as they directly affect the interaction a person has with an object. When a person interacts with an object in order to understand the tactile interaction, he/she collects information from the surface of the object, however the extent of information collected depends on the force generated at the surface, pressure being applied, speed of interaction and duration of interaction. Due to variable factors, the information collected during interaction is critical and needs a well-controlled area for information collection. Work performed by Wang et al.[28] focuses on design and performance of a haptic data acquisition glove which uses a grip sensor to provide a localized force map between the hand and the object or the environment. They showed that the main constraint in a glove for haptic data acquisition is a well controlled contact area for force measurement. While preforming their evaluation, they compared force sensitive resistors (FSR) and a grip sensor by Tekscan.[29] Their findings indicated that the forces were not distributed evenly on an FSR sensor but the distribution was better for a grip systems. This was due to the large coverage and high density of sensors in the grip system. A similar system was investigated by Martin et al.[30] to increase the dexterity of a robot hand. They researched the development of a haptic data acquisition glove which would provide sensor information for finger and palm coverage considering spatial resolution, sensitivity, wire minimization and robustness for every touch a robot performs. During their investigation, they found that Quantum tunnelling composite (QTC) sensors provided better results compared to FSR sensors and developed a glove using QTC sensors in order to increase the dexterity of the robot hand.

To provide tactile feedback corresponding to the sensation from the environment, an actuation waveform pattern can be used which is a function of the waveform frequency and amplitude. These waveform patterns are modelled based on the information captured using sensors and data acquisition devices. Kandee et al.[31] investigated the ability of using mathematical models to develop waveform patterns which could be deployed using a haptic device. They proposed a mathematical model which could generate pulse patterns for an abnormal arterial pulse waves. In their work, they developed waveform patterns by deriving abnormal pulse patterns and superimposing them on a sinusoidal wave. They successfully modelled waveform patterns representing irregularities in the human artery.

2.2 Sensors for Haptic data acquisition devices

Based on the literature discussed in section 2.1, sensors that could be used to develop haptic data acquisition devices are identified and discussed.

1. Biotac Sensor: This sensor replicates the sensory aspects of a human fingertip. It provides an advanced human-like tactile sensing. The design consists of a rigid core surrounded by an elastic liquid filled-skin to give a compliance similar to that of the human fingertip. The sensor can sense force, vibration, and temperature similar to human touch capabilities. A cross-section view of Biotac sensor is presented in figure 2.1.[3]

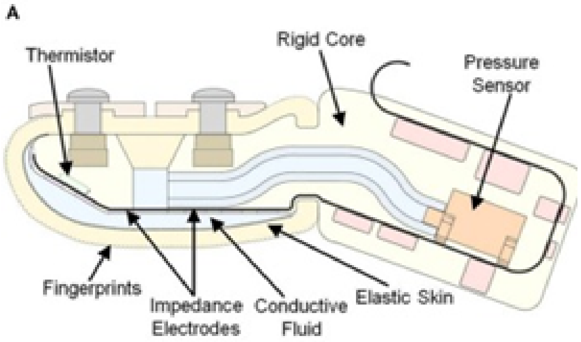


Figure 2.1. Cross-sectional view of a Biotac sensor [3].

2. Force Sensors: Two types of force sensors, force sensitive resistors and load cells, are generally used. Force sensitive resistors (FSR) vary their resistance depending on how much pressure is applied on the sensing area.[32] The larger the force the lower the resistance. They consist of two conductive layers separated by a thin insulating layer. When pressure is applied, the conductive layers come in contact causing resistance decrease. FSRs are not the most accurate when used for assessing pressure but they provide a sense of pressure being applied. The layer by layer view of an FSR sensor is presented in figure 2.2.[4]

   Load cells are more accurate compared to FSRs and are categorized according to the type of method used for generating the output signal. There are three

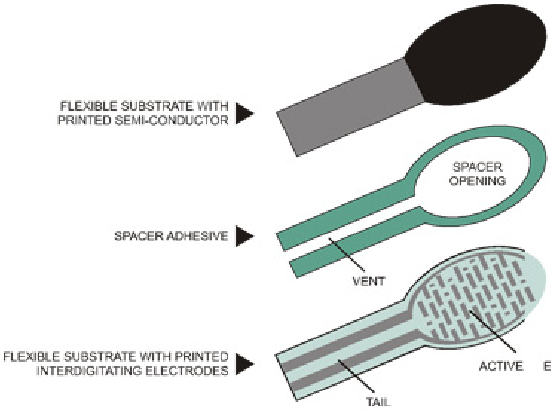


Figure 2.2. Force sensitive resistors [4].

major types pneumatic, hydraulic and electric. The high accuracy of this force balancing technique (inertial force is compensated with an electrically generated force, the voltage applied to generate this force proportionally represents the mechanical input) allows it to be used for haptic applications. For example, load cells are used on automotive user interface devices by placing them behind the touchscreen to measure contact force to enable the on-board computer to confirm correct and incorrect input and in return provide varying vibrations to the user to acknowledge the input.[33][34]

3. Piezoelectric Sensor: This sensor generates electrical charge as a response to change in pressure, acceleration or force. When a piezoelectric material is deformed by applying it against a surface, a voltage resembling the properties of the vibration between the surface of the object and the sensor is generated. A piezoelectric vibration sensor is presented in figure 2.3.[5][35][36]

2.3 Survey on haptic feedback systems

Haptic feedback is divided into two parts; force feedback systems which aim at providing kinesthetic cues, and tactile feedback systems which generate vibro-tactile

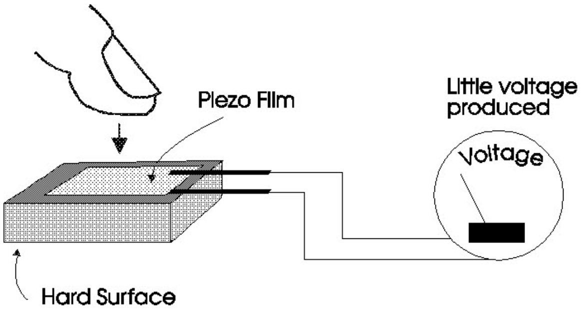


Figure 2.3. Piezoelectric sensor [5].

effects or skin stretch. This section discusses literature related to haptic feedback systems.

Force feedback systems restrict the movements of a specific body part such as fingers, arm and legs corresponding to actions in a virtual environment in order to replicate motion effects from a real action. Xue et al.[37] researched a haptic force feedback system to replicate the forces generated during a tele-operation procedure. They concentrated on the design of a 2 degree of freedom (DOF) robot to provide straight and rotational force feedback corresponding to the force produced during needle insertion. Their system comprised a slave robot and a master robot which collected the information regarding the generated force and simultaneously provided the corresponding actuation. In their work, a force control framework was proposed based on current force closed loop to reflect the feedback force captured during needle insertion. Arata et al.[38] research the development of DELTA-4, a haptic device using parallel link mechanism to overcome a problem of area constraint. Their device could provide 3 DOF translational and rotational motion. They showed that characteristics such as position resolution, force resolution, rigidity, output force and backward drivability and weight of an end effector are important for a display of force.

Force feedback systems provide a sense of the structure corresponding to an object in a virtual environment but these systems cannot convey scalable information attained using tactile understanding such as the amount of pressure applied at the finger pads, softness of an object, texture of an object, and temperature of interaction.

Tactile understanding is generated when a person establishes contact with an object and performs a motion over the object to understand the properties of the surface. During this motion, the hand receptors collect information from the vibrations generated between the finger pads and the object (see chapter 1). Tactile feedback devices are constructed as a wearable device to provide high flexibility to the fingers for independent movements and localized sensation. Localized tactile feedback could be accomplished by using actuators such as linear resonating actuators, piezoelectric actuators, shape memory alloy and fluid based inflatable tactors. Hoda et al.[39] worked on developing a haptic rehabilitation glove with FSR sensors on the finger pads and shaft-less mini vibrating motors to convey the sensed pressure by the sensors. This system was connected to a game which provided a visual representation to correlate the forces applied on the hand. Lim et al.[40] proposed a 5 DOF finger-wearable cutaneous haptic device which could provide a sensation of touch or pressure when manipulating objects in a virtual environment. Their setup uses shape memory alloy (SMA) actuators which contract and expand with a suitable input. This actuator allows a more concentrated sensation at the finger tips with a high number of DOF. The use of SMA actuators was aimed at high force to volume and power to weight ratio. Schorr et al.[41] worked on developing a sensory feedback device which induces skin stretch as a sensory substitution for tele-operation. They compared various types of feedback modalities such as vibratory, graphical and auditory, and force. Using a volunteer-based study, they found that skin stretch could be a viable replacement to vibratory feedback and reduced force feedback. They also showed that visual and auditory feedback provided a better angular feedback as compared to skin stretch.

The waveform patterns used for actuation represent a specific characteristic or feature for feedback. These waveform patterns can be used to replicate a sense of push or pull or help a person navigate in 3D space. Lehtinen et al.[42] explored the effects of a vibro-tactile glove supporting visual search tasks while pointing. In their work, they placed four shaft-less actuators to assist users in 3D space navigation. A method of frequency manipulation was used to show if the motion of the hand was towards or away from the object. Two actuators placed in the palm were spread out and due to their sequence of actuation, the users could sense the direction. The actuation of the shaft-less actuator is described using the adjectives, pull and push. A limitation in communicating 3D position was overcome by Gunther et al.[43] They worked on assistive spatial guidance in 3D space through vibro-tactile navigation. They increased the actuator density on the dorsum of the hand and placed a single actuator on the palm of the hand. Their system followed a method similar to that by Lehtinen et al. for frequency manipulation and achieved better results in 3D position description due to the higher density of actuators.

2.4 Actuators for Haptic feedback devices

A wide variety of hand-held communication devices provide tactile and force feedback to the user. They aim to enhance the level of immersive experience when interfacing with a virtual environment. To provide vibro-tactile feedback, the devices use special actuators which cater to a specific sensation property. Such devices are called tactors or actuators. In this section, actuators that could be used for developing haptic feedback devices are discussed.

1. Eccentric rotating mass actuator: As stated by Michael Greene “They are the simplest and cheapest of the actuators used. They are a basic DC motor with an attached off-center mass. When activated by the DC voltage produced by the

driver board, the motor spins the off-center mass and the centripetal force produced causes a bi-directional vibration throughout the unit."[44] An exploded view of a ERM actuator is presented in figure 2.4.[45]

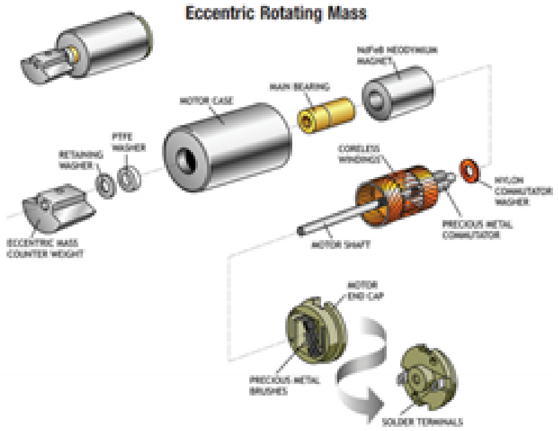


Figure 2.4. Exploded view of eccentric rotating mass actuator [6].

2. Linear resonant actuator (LRA): As stated by Michael Greene "It is the most popular actuator due to its quick response time and long-life span. A linear resonating actuator is created through a moving magnetic mass connected to a spring. Applied current produces an electromagnetic field within the voice coil of the linear resonating actuator that axially and bi-directionally drives the magnetic mass and spring assembly, causing it to vibrate in a single direction at a fixed resonant frequency."[44] An exploded view of a LRA is presented in figure 2.5.[46]
3. Piezoelectric actuator: As stated by Michael Greene "It consists of thin layers of piezoelectric material that bend back and forth quickly when a voltage is applied, causing vibration. In order to produce bending, piezo actuators require a relatively high voltage input using a driver board, usually between 50 and

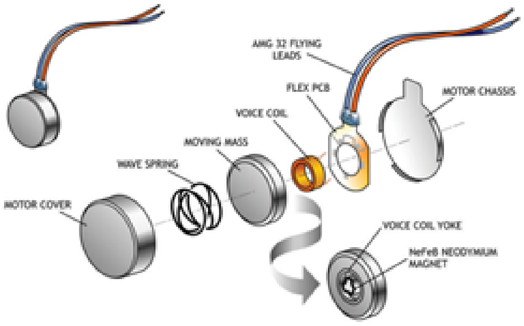


Figure 2.5. Exploded view of linear resonating actuator [6].

150 volts. The main advantages for this actuator type are size, reduced noise, reduced start-up and breaking time and rate of reaction."[44] A side view of the layers of piezoelectric actuator is presented in figure 2.6.[7]

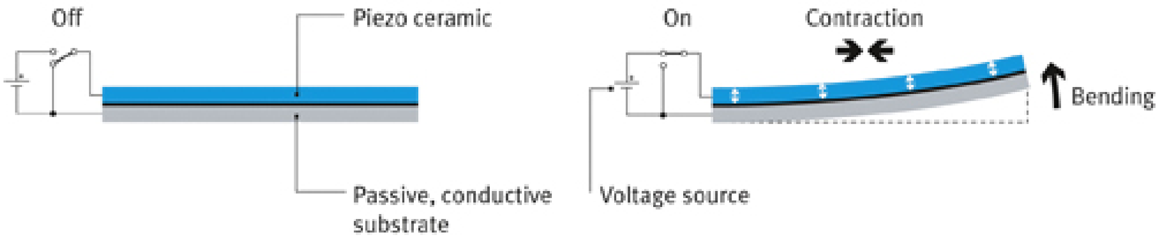


Figure 2.6. Piezoelectric actuator [7].

4. Electrostatic haptic technology: Electroactive polymers (EAP) deform in the presence of an applied electric field, much like piezoelectric actuators. However, unlike piezoelectric actuators, EAPs operate on force, strain, and deflection similar to biological muscles. The ionic polymer-metal composite cations are randomly oriented in the absence of an electric field. Once a field is applied, the cations gather to the side of the polymer in contact with the anode causing the

polymer to bend. An EAP actuator is presented in figure 2.7 in idle condition when power is provide.[8]

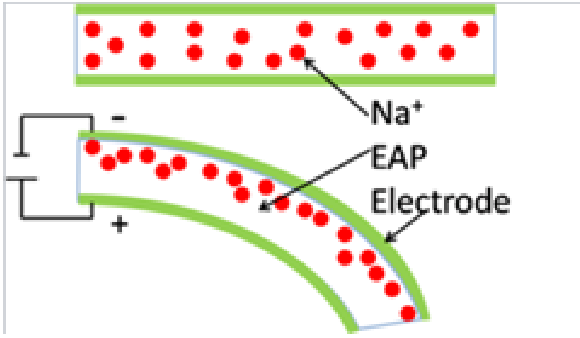


Figure 2.7. Electro active polymer [8].

5. Ultrasonic transducers: They are devices used to convert electrical energy into an ultrasonic vibration. For haptic feedback, they are used to create a disturbance in the air that users can feel when they pass their fingertips across it. These transducers are used to create interfaces that do not require direct interaction with a surface. Multiple transducers could be used to direct vibrations at a single focal point which would allow a user to feel the boundary of an object. A mid-air feedback due to ultrasonic actuators is presented in figure 2.8.[47][48]

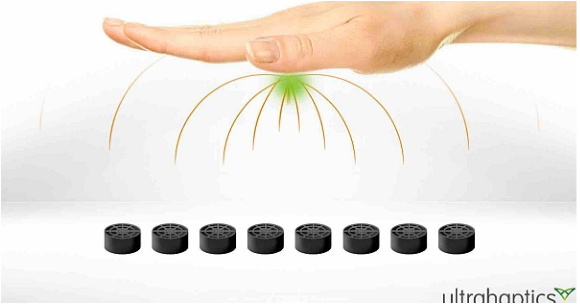


Figure 2.8. Ultrasonic transducer [9].

6. Servo motor (Brushless DC Servo motor): They are a rotary or linear actuator that allows for precise control of angular or linear position, velocity, and acceleration. It consists of a suitable motor coupled to a sensor for position feedback. Such motors are used for developing force feedback mechanisms that can be used to restrict the motion of the fingers, limbs or other parts of the body to aid in rehabilitation and to increase the immresiveness of a person in the digital environment.[49]
7. Mckibben Muscle: These muscles are contractile or extensional devices operated by pressurized air filling a pneumatic bladder.[50]
8. Pressurized fluid based tactors: They use inflatable balloons to provide feedback to a person. These balloons are connected to tubes filled with fluid and the applied pressure causes the balloon to inflate and deflate at the required frequency.[24]

2.5 Human sensory system

Our senses of sight, hearing, smell, taste, and touch help us perceive the environment around us. This research concentrates on the sensation corresponding to touch. The sensation of touch allows a person to understand specific properties of an object such as shape, surface texture, hardness, and temperature. This section discusses the human sensory system and the receptors which capture the information required for processing tactile information.

The first step a person performs in order to understand and capture tactile information is to move a specific part of the body to establish contact between the surface of the object and the skin of the body. After establishing contact, the person moves the hand over the surface to assess the properties of the object. While performing this motion, the vibration generated between the skin and the surface of the object is received by the receptors located below the skin. When these vibrations are captured, the information generated by the receptors responding to specific stimuli provide input to the sensory system for processing and classifying the tactile sensation recently encountered. The receptors aid the sensory system to understand and identify the texture of an object by providing information consisting of location, modality, intensity, and duration of each sensation. For tactile understanding, there are four receptor sets which are classified based on their frequency range for sensitivity, response stimuli and the rate of adaptation and are classified in figure 2.9.

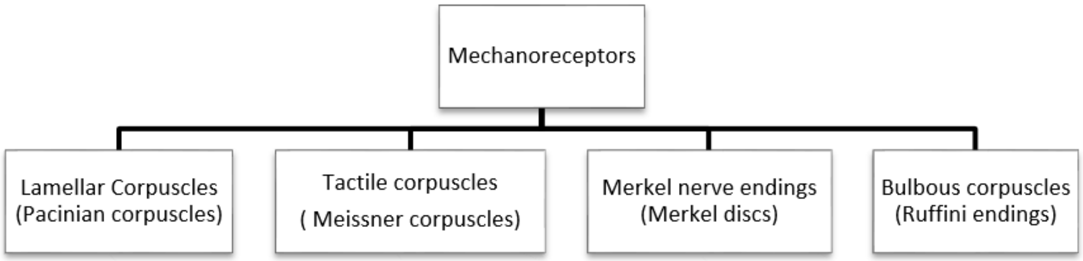
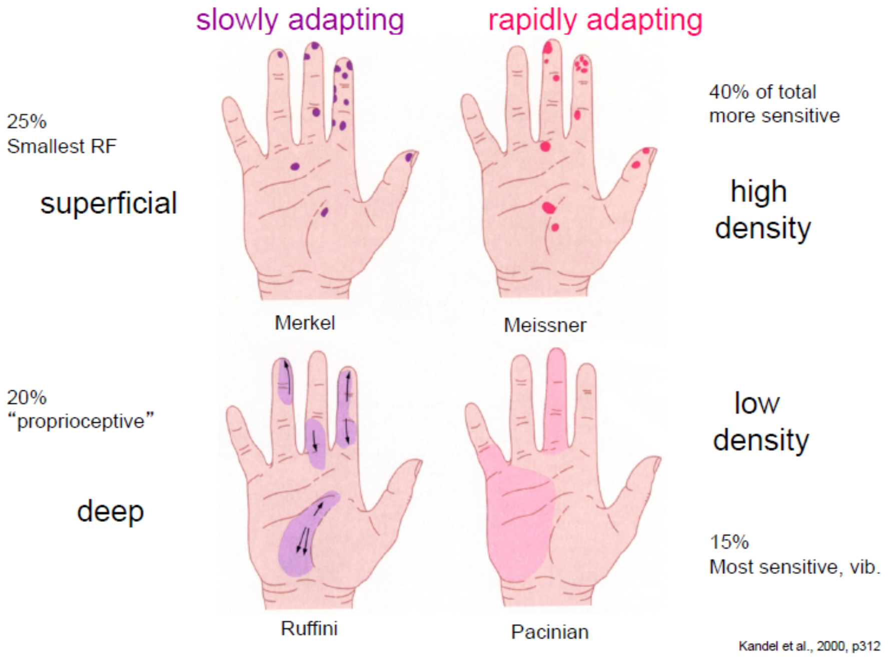


Figure 2.9. Receptors for tactile sensing.

The Pacinian corpuscles are rapidly-adapting, deep receptors that respond to stimuli such as pressure and vibration. They have a sensitivity range of 200 to 300 Hz. The Meissner corpuscles are rapidly adapting, encapsulated neurons that respond to stimuli such as touch, pressure and slippage. They are located in the glabrous skin on fingertips and eyelids and have a sensitivity range of 30 to 50 Hz. The Merkel disk are slow-adapting, un-encapsulated nerve endings that respond to stimuli such as touch and vibration. They are present in the upper layers of skin that has hair or is glabrous and have a sensitivity range of 0 to 15 Hz. The Ruffini endings are slow adapting, encapsulated receptors that respond to stimuli such as skin stretch, pressure and slippage. They are present in both the glabrous and hairy skin and have a sensitivity range of 3 to 400 Hz. A schematic with details of the four receptor sets is shown in figure 2.10.[10][51][52]



Kandel et al., 2000, p312

Figure 2.10. Characteristics of human receptors for tactile sensing [10].

Receptors work by responding to specific response stimuli by generating an action potential. This action potential is referred to as threshold stimuli. At low energy levels, this stimulus is denoted as adequate stimuli which represent the most sensitive range for the receptors. Receptors are classified based on their rate of adaptation as slowly adapting and rapidly adapting receptors. Slowly adapting receptors are referred to as tonic since they are able to sense a touch for a longer time duration as compared to rapidly adapting receptors that take time to adjust to the changes of the threshold potential. Rapidly adapting receptors are referred to as phasic as they

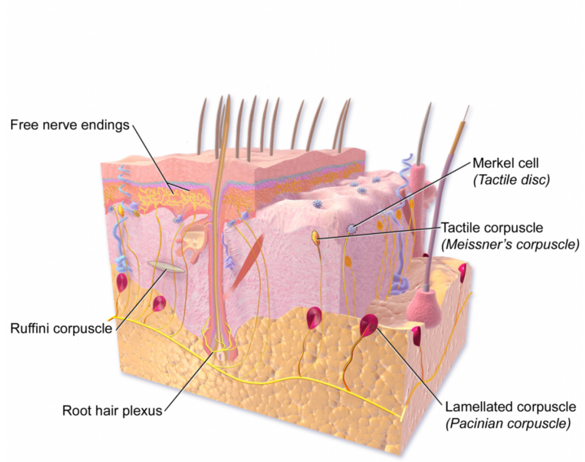


Figure 2.11. Placement of receptors for tactile sensing [11].

can feel a set of vibrations for a lower duration of time due to their ability to quickly adjust themselves. A cross-sectional view of the skin is presented in figures 2.11. [53]

2.6 Factors that influence research platform and evaluation process

The discussion in sections 2.1 - 2.5 provided an overview on applications of haptic devices and critical components in developing a haptic device. It is observed that haptic devices are built considering the type of feedback to be provided. This section is divided into two subsections to categorize the actuators based on the type of feedback that they can generate and the hardware requirements for this research.

2.6.1 Force and tactile feedback

Force feedback systems are mechanisms which restrict or manipulate the movements of a body part. These mechanisms, are constructed using actuators such as servo motors, stepper motors, EPAs and McKibben muscles to restrict the motion of the hand or fingers. Force feedback systems are accompanied by a visual representation that provides a reference to the shape of an object as a person depends on multiple sensory inputs to form a single sensation. The quality of force feedback provided by haptic devices depends on factors such as position and force resolution, rigidity and output force, back drivability, and weight of an end effector.

Tactile feedback devices provide feedback in the form of vibration, skin stretch, temperature, and site of interaction. Actuators such as ERM, LRA, piezoelectric, SMA and ultrasonic transducers are used to build tactile devices. The quality of tactile sensation directly depends on the speed, duration, and force of interaction. These interactions provide information to the receptors in the hand which is transmitted to the sensory systems for generating or determining a tactile understanding. The process of understanding surface generated vibrations can be replicated using haptic feedback devices to recreate or induce an equivalent sensation or provide feedback to an action performed and is called tactile cueing.

2.6.2 Types of feedback and factors affecting research platform

To perform tactile cueing as a part of this work a research platform has been developed to establish a bi-directional channel for information transfer for human robot interaction. To develop an effective platform the following aspects relating to the human biology should be considered: location, sensitivity range, and stimuli of sensory receptors, 2-point threshold, and site for feedback. Merkel disk, Meissners corpuscles, Ruffini endings, and Pacinian corpuscle are the sensory receptors (see section 2.5) which collect information about location, modality, intensity, and duration of interaction for tactile assessment and provide them as input to the sensory system. The 2-point threshold is a measure of tactile acuity defined as the smallest separation at which sensation can be clearly distinguished at two points simultaneously. It varies from 1 or 2 millimeters in the finger pads and tongue to more than 60 millimeters on the upper arm, upper thigh, and back. The site for feedback refers to the location on the body where the feedback is concentrated. Tactile feedback is generated on the body as a result of the vibrations due to actuators as discussed in section 2.6.1.

Actuators for generating haptic feedback are selected based on factors such as reaction time (acceleration), force generation capacity, frequency range and size of the actuator. Reaction time determines the rate at which an actuator rises towards the target value for actuation. Force generation capacity is related to the strength of actuation. Frequency range determines the number of actuations repeating per unit time. Size of the actuator is important as it affects the dimensions of a haptic feedback device and establishes constraints over the possible mounting surfaces that can be used and vice-versa. Based on the factors identified for actuator selection and the focus of this reserach, LRA and piezoelectric actuators were identified as candidate hardware options for further investigation. LRA actuators were selected over ERM actuators since a precise waveform of varying intensity over time can be reproduced in an LRA with a fixed frequency, whereas a waveform of varying intensity in an ERM will also produce a varying vibration frequency. SMA actuators were not a viable actuation source as they are slow to respond compared to piezoelectric and LRA actuators in operation.

Based on the preliminary research and literature survey, sinusoidal, square, triangular and sawtooth waves were selected for developing the haptic waveform patterns and they are characterized by three controllable features of amplitude, frequency, and type of waveform travel which represents the structure of the actuation pattern. These patterns are selected to model waveform patterns using the method identified during the preliminary investigation and is the foundation for investigating the effect on sensation induced by a waveform pattern. In the work by Kandee et al.[31] a mathematical model was proposed to generate irregularities corresponding to arterial pulses and then superimposed on a sinusoidal wave for recreating the patterns to produce a continuous actuation. Also, during investigations on haptic data acquisition devices and information processing systems, it was identified that every effect that is captured using sensors represents a unique waveform pattern feature that corresponds to an interaction. Waveform patterns for haptic application and the process of developing these patterns are discussed in detail in chapter 4.

2.7 Chapter summary

This chapter discussed the applications of haptic technology and research activities towards developing data acquisition devices and feedback systems for haptic applications. Haptic feedback systems have been divided into two types; force feedback and tactile feedback systems. This chapter also discussed actuators which are capable of generating tactile feedback and the reasons for selecting them. The development of the proposed research platform and the justification for selecting the hardware and software components will be discussed in chapter 3.

CHAPTER 3

Research platform development

The development of the proposed research platform is discussed in this chapter. The research platform is based on the preliminary investigations discussed in chapter 2 and expanded for the purpose of studying and understanding the haptic sensation experienced by a person related to a number of haptic waveform patterns.

3.1 Hardware selection

Based on the preliminary investigation discussed in chapter 2, linear resonating actuator (LRA) and piezoelectric actuator were selected for further research. These two actuators were preferred since the research focuses on inducing vibro-tactile sensation on the hand. The hardware components selected for developing the research platform and their performance characteristics are discussed in this section.

For comparing the performance of a LRA and a piezoelectric actuator, a test bed was prepared by connecting the actuator to a myRIO micro-controller using an actuator driver. The actuation was controlled by generating pulse width modulation (PWM) signals using a program developed in LabVIEW. The program produced PWM signals as actuation output by varying the amplitude from 0 to 100% duty cycle range and frequency from 1 to 500 Hz. This frequency range was selected based on the sensitivity range of the sensory receptors discussed in chapter 2. Figure 3.1 presents the connection flow diagram for the two actuators.

The performance comparison of the actuators was based on acceleration, actuation resolution and size of actuators. Acceleration of an actuator is the rate of

Figure 3.1. Connection flow diagram for actuators.

change of velocity which affects the amount of time it takes for an actuator to reach a desired actuation. Due to a low acceleration there can be instances where an actuator could skip an actuation as it could fail to reach the required speed on time. Actuation resolution is the smallest possible movement, also known as the step size of an actuator. A smaller step size results in a smoother actuation. The size of an actuator is important as a size limitation is set based on the mounting platform selected, so that the dimensions of the actuator do not exceed the dimensions of the mounting platform. The evaluation of LRA and piezoelectric actuator is performed by assessing the sensation an actuator induces on a human finger and is not measured using a device in this research. The comparison of the induced sensation was assessed by placing a finger over the surface of the actuator.

It was found that a piezoelectric actuator has faster acceleration as compared to a LRA. The actuation resolution of a piezoelectric actuator was found to be better when compared to LRA. The size of a LRA actuator and a peizoelectric actuator are measured to be 3/8 in and 1 in respectively. The size limitation for the research platform was approximately 1/2 in, the width of the finger. Due to the size limitation, the LRA actuator was selected for research platform development. Figure 3.2 presents a piezoelectric actuator and a LRA being compared to the size of a finger.

To mount the selected LRA on the research platform, three wearable mounting surface alternatives are compared; cotton, dishwashing rubber, and mechanics glove

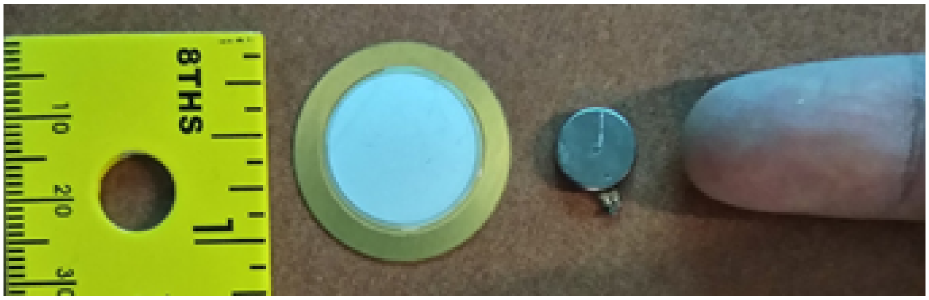


Figure 3.2. Size comparison of Piezoelectric (left) and LRA (right) actuators.

shown in figure 3.3. While comparing the sensation through the gloves produced by actuation of LRA, the gloves were assessed based on freedom for finger movements and the ability of the glove to maintain position during actuation. Freedom for finger movements refer to the ability of moving a finger without affecting the other fingers on the hand. Evaluation of each glove was performed by the researcher by wearing each glove and assessing the performance. Figure 3.3 presents the gloves being compared.

On the assessment of the cotton glove, fit and feel was found to be loose and did not restrict the freedom of finger movement. It did not maintain position when LRAs were actuated. On the assessment of dishwashing rubber glove, fit and feel was found to be tight but restricted the freedom of finger movement. It maintained position when LRAs were actuated. On the assessment of mechanics glove, the fit and feel was found to be comfortable and did not restrict the freedom of finger movement. It maintained the position when the LRAs were actuated. The mechanics glove was found to be the most advantageous amongst all the gloves compared and was selected as the wearable glove for the research platform.

An external power source is required for the LRA which is provided using DRV2605L driver board. This driver board follows I2C communication protocol for accessing pre-loaded waveform patterns (to be discussed in chapter 4) and accepted custom PWM signals for actuation. The DRV2667 driver[54] was used to actuate a

Figure 3.3. Types of gloves: cotton (left), dishwashing rubber (middle) and mechanics (right).

piezoelectric element when comparing with LRA, as the piezoelectric elements require a high voltage to operate this driver amplified a 5V signal to 105V to generate actuation. To communicate with DRV2605L, NI myRIO micro-controller was selected due to its ability to communicate using I2C protocol and generate PWM signals. NI myRIO is a portable re-configurable input output (I/O) micro-controller, that includes analog inputs, analog outputs, digital I/O lines, LEDs, a push button, an onboard accelerometer, a Xilinx FPGA, and a dualcore ARM CortexA9 processor.[55]

3.2 Software development

LabVIEW is selected as the software development platform, since it provides a common integration environment platform for all the modules introduced in chapter 1 for research in the field of human robot interaction in the MARS Lab. LabVIEW uses graphical language for visual programming where different types of pre-programmed function blocks are used to develop graphical flow diagrams and provides the ability to develop custom graphical user interface.

Two programs were developed in LabVIEW to control the hardware; a waveform pattern generation and a waveform pattern selection and retrieval.

1. Program 1: Waveform pattern generation

   Waveform pattern generation is performed by using the arithmetic operators; addition, multiplication, subtraction and division on two types of trigonometric functions (to be discussed in chapter 4). The program to generate waveform patterns is developed in LabVIEW using I2C protocol to establish communication with DRV2605L using NI myRIO and generate PWM signals for actuation. The signals for actuation in LabVIEW were generated as analog signals using the pre-built signal generation functions and were converted into digital signals for the actuator drivers.

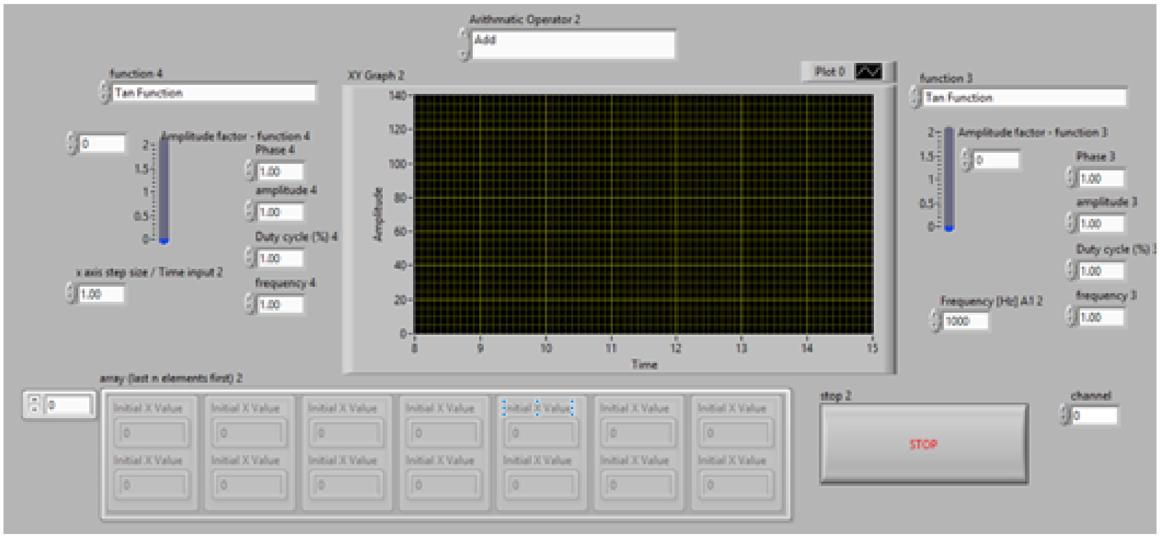
   The graphical user interface for waveform pattern generation presented in figure 3.4 allows the user to observe a graphical representation of the actuation signal and select and modify parameters in real time. The controllable parameters are:

   (a) Waveform pattern / trigonometric function,
   (b) Arithmetic operators,
   (c) Manual control of waveform parameters.

   Figure 3.5 presents a section of the graphical flow diagram developed to generate various types of actuation based on the parameters selected and defined in the interface presented in figure 3.4.

2. Program 2: Waveform pattern selection and retrieval

   The program developed for waveform pattern selection and retrieval is created as two components sharing the waveform pattern data. One component is



Arithmatic Operator 2: Add

function 4: Tan Function

Amplitude factor - function 4: 0

Phase 4: 1.00

amplitude 4: 1.00

Duty cycle (%) 4: 1.00

frequency 4: 1.00

x axis step size / Time input 2: 1.00

function 3: Tan Function

Amplitude factor - function 3: 0

Phase 3: 1.00

amplitude 3: 1.00

Duty cycle (%) 3: 1.00

frequency 3: 1.00

Frequency [Hz] AI 2: 1000

channel: 0

array (last n elements first) 2: 0

Figure 3.4. Waveform generation GUI.

processed on the computer to access the database with the waveform patterns in a shared variable and the other component is processed on NI myRIO to use the data from the shared variable to generate the actuation signals. The graphical user interface for waveform pattern retrieval presented in figure 3.6 allows the user to observe a graphical representation of the actuation signal and select control parameters in real time. The parameters are:

(a) Factor of increment which affects the strength of actuation,

(b) Time delay between each data-point of the selected waveform pattern,

(c) Selection of actuator.

Figure 3.7 presents a section of the graphical flow diagram developed to retrieve waveform patterns for actuation from the database available on the host computer.

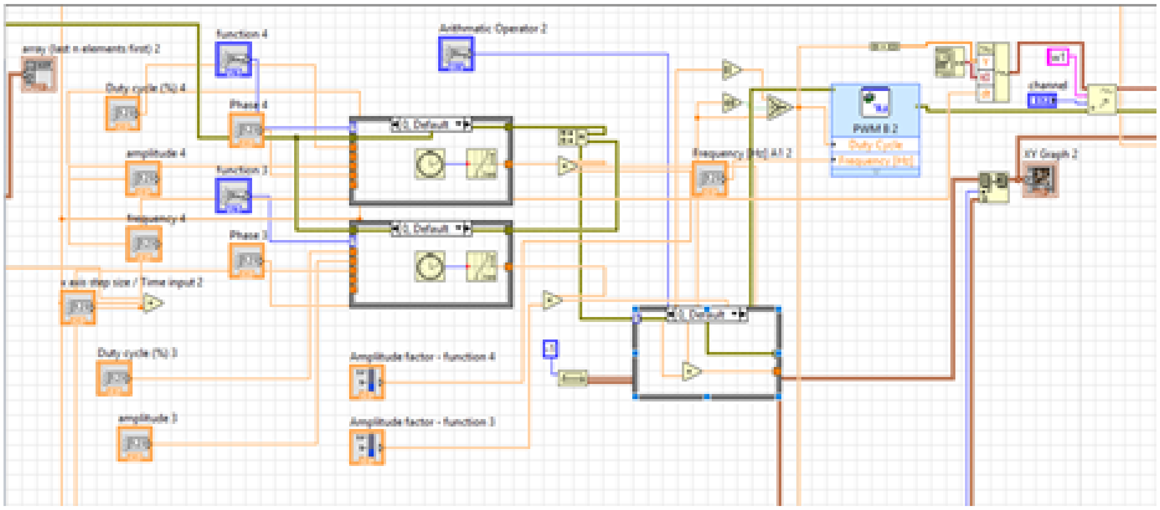


Figure 3.5. Waveform generation flow diagram.

3.3 Platform construction

This section discusses the construction of the developed research platform and highlights challenges encountered and resolved in the process. The developed research platform consists of LRA, mechanics glove, DRV2605L actuator driver, myRIO microcontroller and finger clips.

A mechanics glove is used as the mounting platform for placing and aligning the LRAs to the finger pads. Each actuator is connected to a corresponding DRV2605L board. These actuator boards are connected to an I2C port on NI myRIO using an I2C multiplexer. The LabVIEW host computer is connected to the myRIO to generate the signals for actuation. Figure 3.8 presents the connection flow diagram for a single actuator.

A number of challenges were encountered while developing the hardware platform.

- The research platform has 5 driver boards to actuate 5 LRAs independently. NI myRIO having only 3 I2C ports limits the number of driver boards that can be

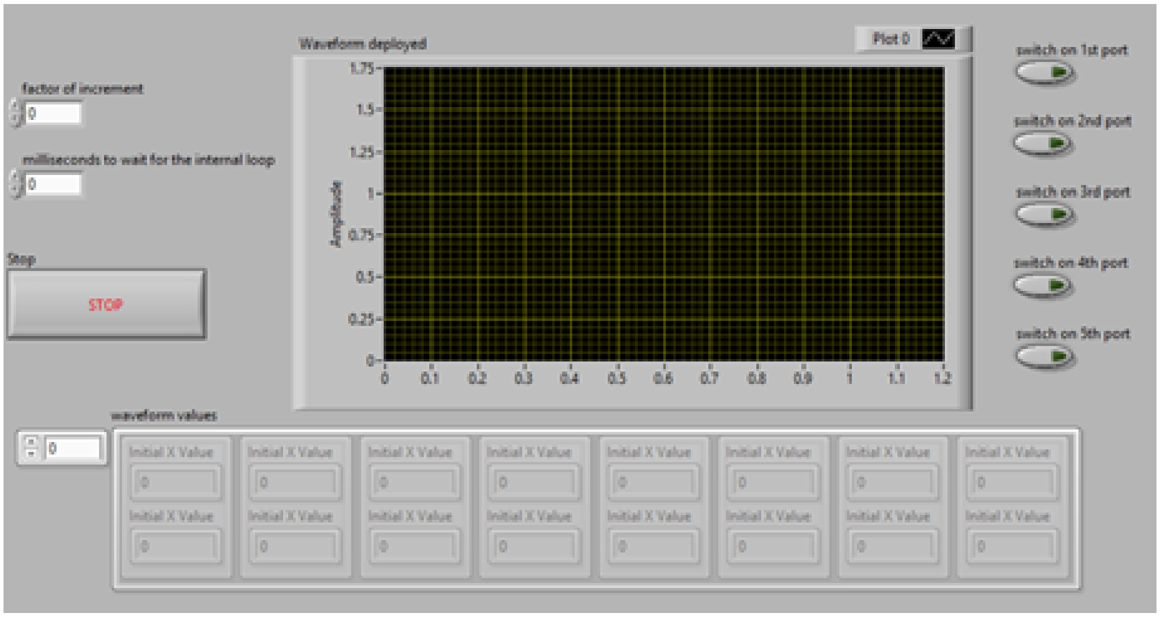


Figure 3.6. Waveform selection and retrieval GUI.

connected to the platform with the same fixed hardware address. Therefore, an I2C multiplexer was added to expand the number of possible I2C protocol based connections. The I2C multiplexer selected, TCA9548A, allocated additional address to all the boards and provided separate communication channels.

- During the preliminary evaluation procedure, an actuator shutdown was observed at low duty cycles when the actuator relied on the myRIO for power. This was identified to be a result of limited current supply from the myRIO. Therefore, an external 5V power source was used to supply power to the driver boards, I2C multiplexer and actuators.
- Due to lack of information on the data types for addressing and data entry codes, the communication between the driver boards and the myRIO was not successful. This was overcome using the information available in the open source programs available for DRV2605L which are developed on Arduino IDE.

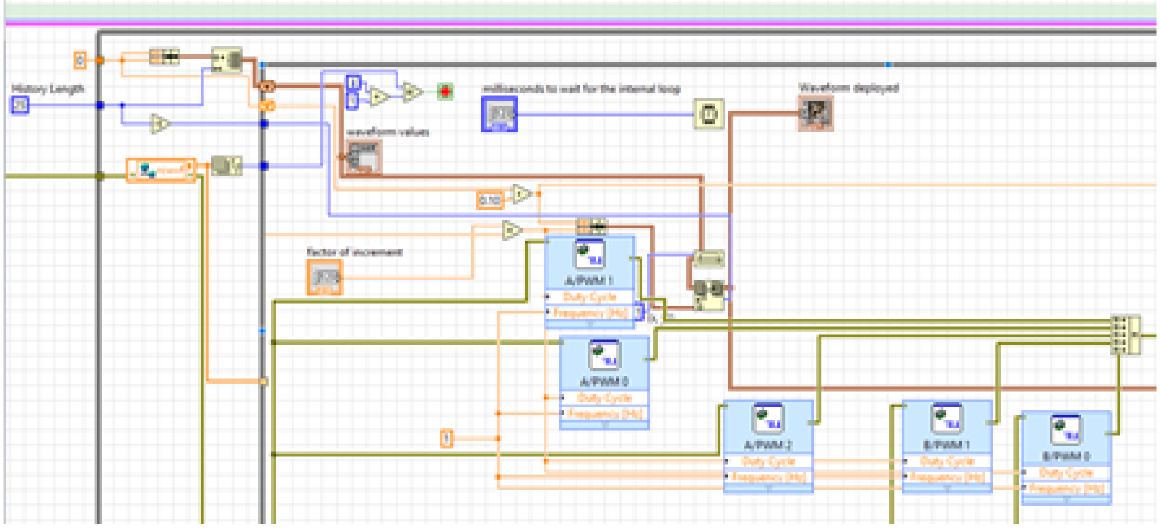


Figure 3.7. Waveform selection and retrieval flow diagram.

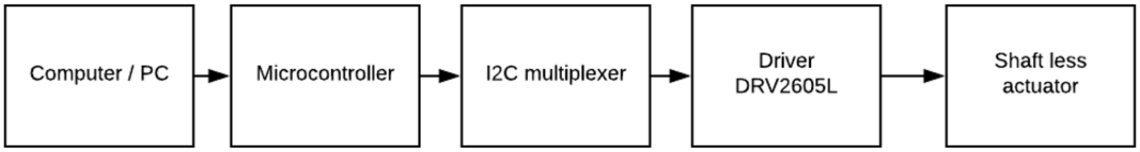


Figure 3.8. Connection flow diagram for a single actuator.

Figure 3.8 presents the connection flow of a single actuator for the developed hardware platform. Figures 3.9 and 3.10 present the ventral side of the glove where the actuators have been mounted and Figures 3.11 and 3.12 present the Dorsal side of the glove. Figure 3.13 presents the setup developed on a breadboard. Figures 3.9 and 3.12 present the finger clip placement location on the developed research platform. These clips are 3D printed on a Polyprinter-229 using NinjaFlex material. Finger clips have open areas on the slides to make them adjustable and flexible and also, have two slots on the upper and lower side to insert a velcro band. The velcro bands allow adjustment to the finger clips to increase the quality of contact between the actuator mounted on the glove and fingers.

Figure 3.9. Wearable glove Ventral side.

Figure 3.10. Wearable glove Ventral side.

Figure 3.11. Wearable glove Dorsal side.

Figure 3.12. Wearable glove Dorsal side.

3.4 Chapter summary

The research platform discussed in chapter 3 consists of LRA, mechanics glove, DRV2605L actuator driver, myRIO micro-controller and finger clips. Section 3.1 discussed the basis for selecting LRA instead of piezoelectric actuator, and mechanics

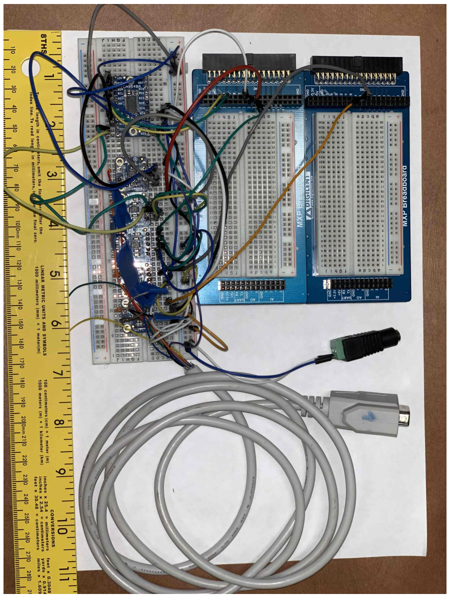


Figure 3.13. Electrical hardware setup.

glove instead of cotton and rubber glove. Section 3.2 discussed the software platform used for development of waveform generation, and waveform selection and retrieval programs. Section 3.3 focused on the construction of the platform and the challenges faced during platform development. Chapter 4 will discuss the evaluation and experimentation procedures followed in this research and the results based on the feedback collected from a set of volunteers during the evaluation process.

CHAPTER 4

Experimentation and results evaluation

The study design, evaluation procedures followed and results inferred based on the feedback collected from the volunteers are discussed in this chapter. The study design for the process of evaluation is discussed in section 4.1. The evaluation process steps of preliminary study, waveform parameter evaluation, waveform pattern combination, and investigation of effects of the waveform patterns on sensation by conducting a volunteer based study are discussed in sections 4.2 to 4.5. The results from the analysis performed on the feedback collected from the volunteers is discussed in section 4.6.

4.1 Study design

The study design discussed in this section describes the strategy for performing the evaluation process. A volunteer based study is conducted to evaluate the methods for generating waveform patterns using the research platform discussed in chapter 3. Volunteers participating in this study were graduate students and university staff members of varying ethnic and cultural background and age. They were not provided with any type of incentive which would result in a biased feedback and were asked to describe the sensation as a feedback using adjectives, drawing graphical representation and identifying the graphical representation of the waveform patterns retrieved from an existing database corresponding to their sensation. Waveform patterns were generated as analog signals based on the input parameters; frequency, amplitude, DC offset, phase offset and resolution and were converted to digital signals for actuation.

The frequency defines the number of occurrences of a repeating event per unit time, the amplitude is the extent of vibration (a measure of the changes in vibration over a single period), the DC offset is a mean of the amplitude displacement from zero, the phase offset is the position of a point in time in a waveform cycle and the actuation resolution is the quality of the actuation corresponding to the step size for discretization of a waveform pattern. Figure 4.1 presents the changes that would occur due to input parameters on a sinusoidal wave.

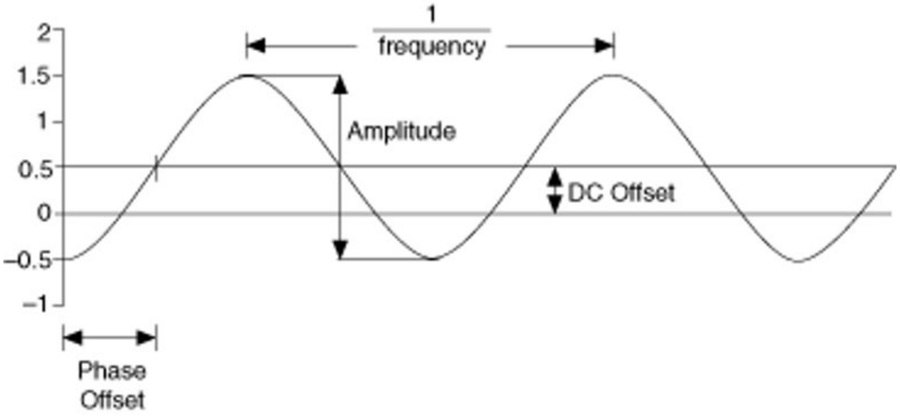


Figure 4.1. Waveform input parameters.

4.2 Stage 1: Preliminary evaluation

This section discusses the preliminary evaluation performed to test the operation of the developed research platform, evaluate preloaded waveform patterns on DRV2605L and determine the use and effect of changing parameters with respect to human sensation. Based on the literature investigated, a software environment was developed to generate waveform patterns using sinusoidal, square, triangular and sawtooth waves. These patterns were used since they differ from each other based on the waveform travel and can be varied by changing the input parameters. A manual control is provided through the graphical interface to vary the input parameters. The function blocks used in LabVIEW generate a complete signal based on the input parameters and have sampling set at a default 1 kHz sample frequency and generate 1000 samples. Three volunteers participated in this stage and provided feedback by using adjectives and drawing graphical representation corresponding to their sensation. A list of adjectives is provided in the DRV2605L driver board manual.[56]

The procedure followed for this stage is divided into two parts. First, pre-built waveform patterns available on the DRV2605L driver were explored and the sensation was related to the adjectives listed in the DRV2605L manual.[56] Arduino is used as a micro-controller to establish a communication link to access these pre-built waveform patterns. Second, waveform patterns were generated in LabVIEW which varied in amplitude and frequency from 0 to 100% duty cycle and 1 to 500Hz respectively, while the phase angle and DC offset were set to 0. Figure 4.2 graphically presents the first part of the procedure and figure 4.3 graphically presents the second part of the procedure.

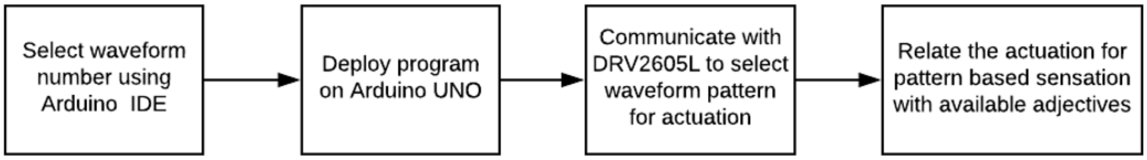


Figure 4.2. First part of the procedure with built-in DRV2605L patterns.

While recording the sensations of the volunteers it was observed that the actuators in the research platform failed to provide a clear distinguishable sensation for actuation below 0.65 and above 2 which were the raw duty cycles. The quality of the actuation was observed to deteriorate with increase in frequency and vice-versa.

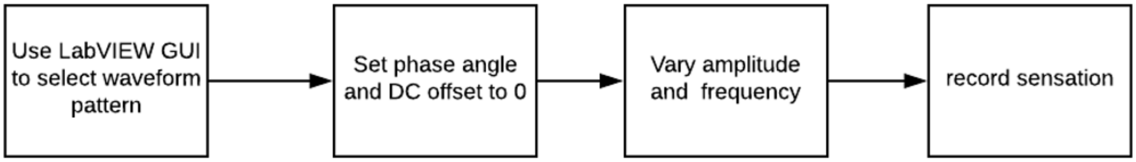


Figure 4.3. Second part of the procedure with waveform patterns generated in LabVIEW.

This was due to the low acceleration of the LRA which led to all data points used for actuation not being processed on time. During the assessment of the feedback provided by the volunteers it was observed that the sensation was distinguished based on the waveform travel and the strength of vibration. The concentration of a person was observed to be reduced when 5 actuators were operated at the same time and this deteriorated the quality of identification.

4.3 Stage 2: Waveform parameter evaluation

This section discusses the procedure followed to evaluate the effects of waveform patterns generated during the second stage and to assess the effects of two of the waveform control parameters phase angle and DC offset. Based on the observations from stage 1, the arithmetic operators of addition, subtraction, multiplication and division were used to combine two different types of waveform patterns to alter the waveform feature. A manual control is provided through the graphical interface to modify the input parameters in real time. The frequency parameter was set at 1 Hz in order to attain the maximum actuation resolution. Two volunteers were part of this stage who provided feedback using adjectives and drawing graphical representations corresponding to their sensation. Volunteers were also asked to share the location where they sensed the beginning and end for a waveform pattern.

Two waveform patterns were selected and combined using an arithmetic operator for signal generation. The input parameters phase angle and DC offset were initially set to 0 and the frequency was set to 1 Hz for evaluating the effects of the new set of waveform patterns only by varying the amplitude. The phase angle was varied from 0 to 360 degrees and DC offset was varied from 0 to 100% duty cycle to evaluate the effects of the input parameters. The feedback from the volunteers corresponding to their sensation produced by these waveform patterns was recorded. Figure 4.4 presents the procedure flow for stage 2.

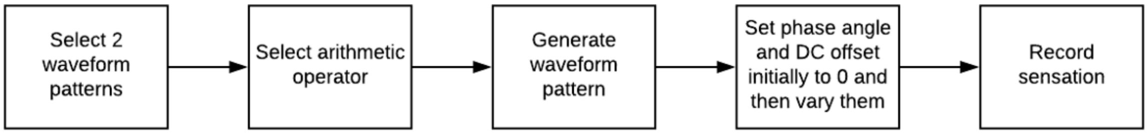


Figure 4.4. Procedure flowchart for second stage for waveform patterns generated in LabVIEW.

Based on the feedback recorded, it was observed that the actuation corresponding to the waveform patterns was distinguished based on the features of waveform travel, location of peaks and valleys, and amplitude differences that were created by merging two waveform patterns. While varying phase angle and DC offset a change in the actuation location with respect to waveform pattern was observed but this did not result in a change of overall sensation for a volunteer.

4.4 Stage 3: Waveform pattern combination

This section discusses the procedure followed to identify waveform patterns with distinct features and assess the quality of sensation by varying the X-step value from 0 to 1. Based on the observations from stage 2 (section 4.3) trigonometric functions tan, sin, cos, sec, csc, atan, sin(x)/x, acos, asec, acsc, sin cos, atan2, and asin were used to create augmented sets of waveform patterns.

A resolution factor called X-step was added to control the quality of the actuation using an internal clock of NI myRIO. Since the new set of trigonometric functions only accepted a single input of radians from the clock, factor X-step controlled the duration of the interval between each radian value provided to the system. Motor selection option was added to the developed program in LabVIEW for selecting a single actuator on a specific finger and evaluating the sensation caused by its actuation. Five volunteers were part of this stage, providing their feedback using adjectives and drawing graphical representations corresponding to their sensation. During this stage, either two types of waveform patterns were merged or listed trigonometric functions were merged with each other using an arithmetic operator to generate a waveform pattern for assessment. During this process only two input parameters amplitude and frequency were varied to assess the performance of the X-step and identify the features that helped a volunteer to identify a waveform pattern. The feedback of the volunteers for their sensation based on the actuation produced by these waveform patterns was recorded.

While recording the sensation of the volunteers it was observed that the quality of actuation was high when X-step was set at 0.25 ms. After analyzing the user feedback it was found that the waveform patterns were distinguished based on waveform travel, sequence of features, waveform travel maneuvers and amplitude variations. As the number of volunteers increased, it was observed that due to the varying size of fingers it was difficult to maintain constant contact between the glove inner surface and the fingers. To overcome this issue, a set of finger clips were designed to secure the placement of the fingers and maintain a steady contact between the glove and the fingers. A technical communication gap was observed as volunteers were unable to describe their sensation using the adjectives listed in the DRV2605L Driver manual[56]. Figure 4.5 presents the procedure for stage 3.

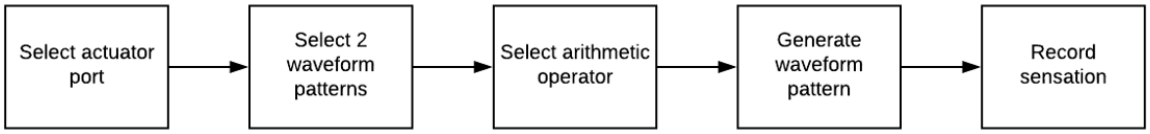


Figure 4.5. Procedure flowchart for third stage for waveform generation using LabVIEW.

4.5 Stage 4: Investigation of effects of waveform on sensation

This section discusses the procedure followed to investigate the effectiveness of the proposed procedure for waveform generation and training of waveform identification and analyze the characteristics that allow a person to sense a pattern. Based on the features identified during stage 3, 28 patterns were identified and stored in a database built using a CSV file. Each identified waveform pattern, consisted of 12 data-points which were generated by LabVIEW and recorded using LabVIEW. These patterns were a result of merging two different types of trigonometric functions using an arithmetic operator. To access this database a new waveform pattern selection and retrieval program (discussed in chapter 3) replaced the waveform pattern generation program. This program allows for manual control over the waveform pattern, actuation amplitude and frequency of actuation. Seven volunteers were part of this stage and provided feedback corresponding to their sensation. Before beginning the evaluation in stage 4, feedback methods used by the volunteers were evaluated as a technical communication gap was observed during stage 3.

Evaluation of methods for volunteer feedback:

1. Method 1: Adjectives to describe the sensation

   Volunteers were asked to describe their sensation corresponding to a waveform pattern using adjectives such as buzz, ramp up, clicks, and bump. The volunteers were trained on the patterns available on TI's DRV2605L driver where they were asked to correlate their sensation with the list of adjectives provided in the manual for DRV2605L[56]. While following this procedure, it was observed that the volunteers found it difficult to communicate their sensation completely as the adjectives did not describe each and every feature. This method was also tried without training and it was observed that the feedback for the patterns identified by the volunteers was less descriptive as compared to when they were trained.

2. Method 2: Drawing graphical representation of pattern

   Volunteers were required to draw a graphical representation corresponding to their sensation due to the actuation. For these methods no type of training was possible since it depends on the person's tactile understanding and the quality of sensation. While following this method, it was observed that the volunteers were able to draw the overall structure but missed the small pattern variations. Also, the scale of the graphical representations drawn by the volunteers were not an accurate representation. This method was also observed to be time consuming.

3. Method 3: Identifying graphical representation of waveform patterns from a database

   Volunteers were required to identify sensation related to the actuation produced by the waveform patterns by identifying their representations from the graphical record of the database provided. For this method, the volunteers were trained by helping them correlate their sensation due to actuation to an available graphical record for each waveform. It was observed that the accuracy of identification improved and the ambiguity in pattern description was reduced.

The evaluation procedure followed in this stage was divided into two parts; training and evaluation. During the evaluation of the waveform patterns identification procedure, it was observed that volunteers performed better when trained and provided feedback by identifying graphical representation of waveform patterns from a database.

4.5.1 Training procedure

The set of figures 4.6 - 4.11 present the patterns utilized for the training process. These patterns were selected based on the different characteristics such as amplitude variations, varied waveform travels, and sequence of features such as peaks and valleys. Figures 4.6 and 4.7 present patterns 1 and 3 which were selected to train the volunteers on amplitude variations between two patterns. Figure 4.8 presents pattern 9 which was used to train the volunteers on small maneuvers between two peaks. Figure 4.9 presents pattern 16 which was used to train the volunteers on waveform travel that involves a parabolic movement. Figure 4.10 presents pattern 17 which was used to train the volunteers on how to distinguish between parabolic and sharp motion produced as a combination of waveforms. Figure 4.11 presents pattern 22 which was used to train the volunteers on the waveform travel involving a ramp up movement.

The volunteers were introduced to the waveform patterns described. While introducing the waveform pattern related actuation, the volunteers were shown the graphical records so that they could learn the types of features they would need to identify and distinguish to correctly interpret a waveform pattern. In a case where a volunteer was unable to understand the pattern related to the sensation, the frequency was reduced and the amplitude of actuation was increased to aid the training process and they were also assisted by the researcher to locate the corresponding actuation. Figure 4.12 presents the training procedure for this stage.

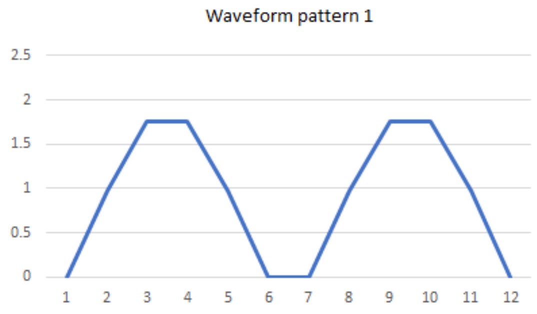


Figure 4.6. Waveform pattern 1.

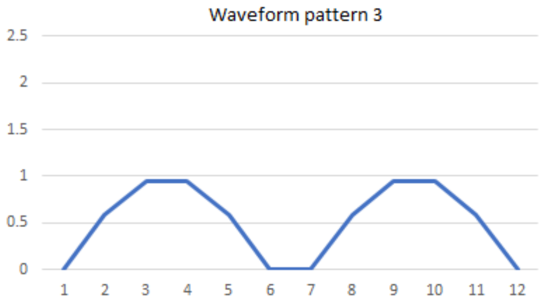


Figure 4.7. Waveform pattern 3.

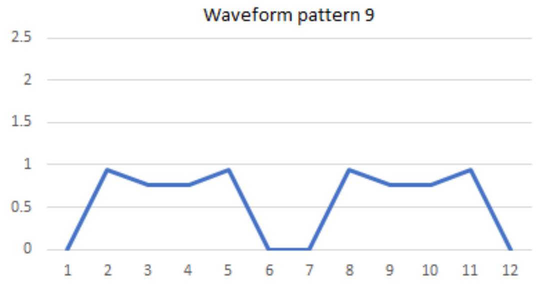


Figure 4.8. Waveform pattern 9.

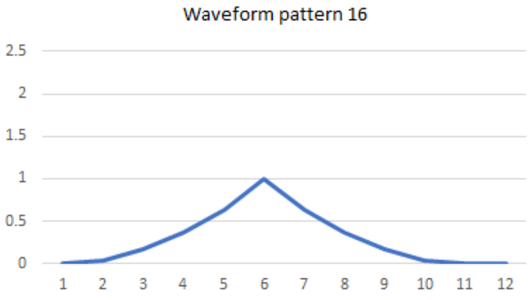


Figure 4.9. Waveform pattern 16.

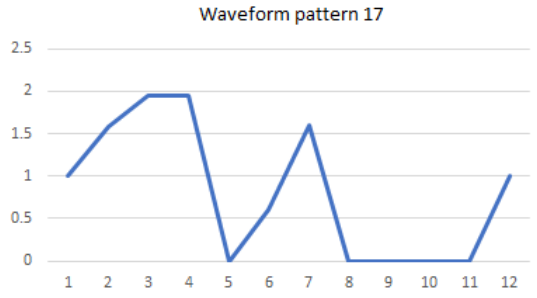


Figure 4.10. Waveform pattern 17.

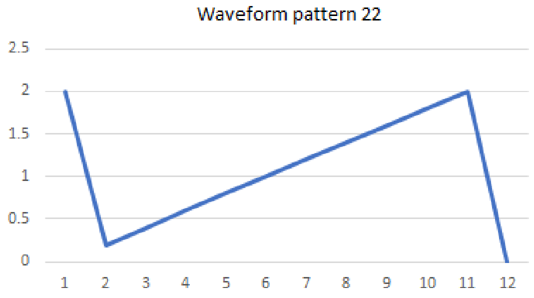


Figure 4.11. Waveform pattern 22.

4.5.2 Evaluation procedure

During the evaluation process the volunteers were informed about the set for waveform pattern identification. In a random sequence, four patterns in this set were used for actuation and the feedback due to each one of them was recorded. A waveform pattern from the set was provided as a reference to the volunteer in case the

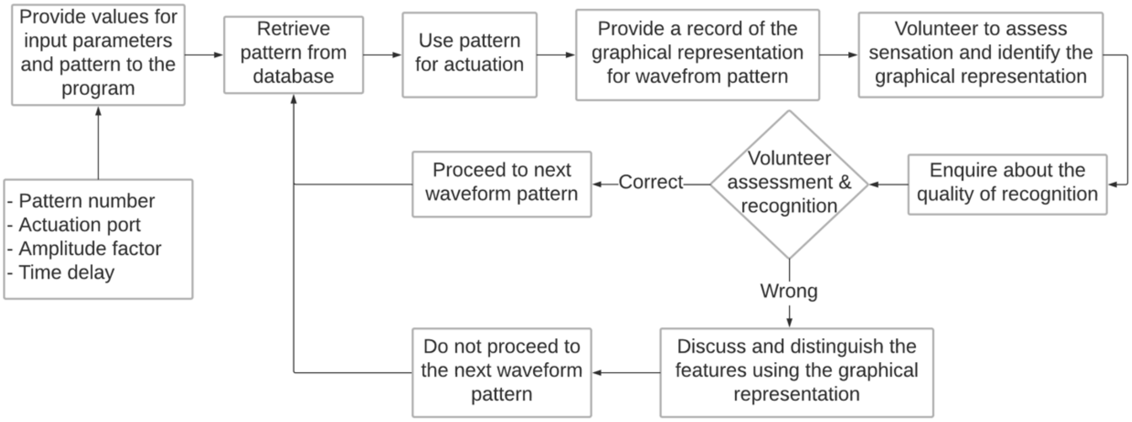


Figure 4.12. Training procedure flow diagram for stage 4.

volunteer is unable to correctly identify or describe either of the four patterns and the remaining three patterns from the set were then presented to the volunteer to record their feedback. This procedure was followed for all the sets which were evaluated in an ascending order from 1 to 7. Every volunteer was allowed to have 15 seconds as the maximum time for identifying a pattern. During this process, the volunteers were asked to describe the method they used for identifying the patterns. The evaluation procedure for stage 4 is presented in figure 4.13.

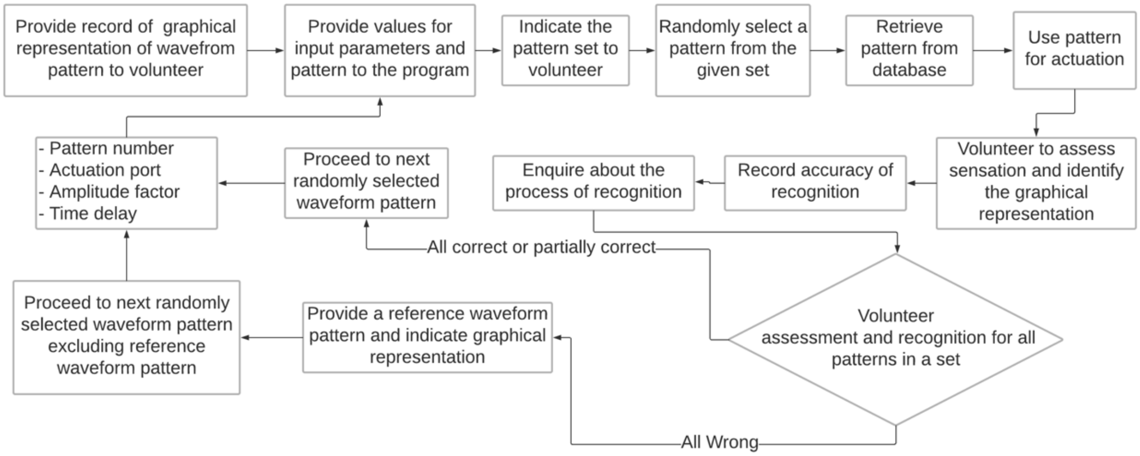


Figure 4.13. Evaluation procedure flow diagram for stage 4.

The sets used for the evaluation process concentrated on assessing the sensation related to a specific type of feature. Figure 4.14 presents the patterns which are part of set 1, this set intended to assess a volunteer's sensation of amplitude variation. Figure 4.15 presents the patterns which are part of set 2, this set intended to assess a volunteer's sensation of small amplitude variations in large patterns. Figure 4.16 presents the patterns which are part of set 3, this set is intended to assess a volunteer's sensation of small amplitude variations in small patterns with deep variations in between. Figure 4.17 presents the patterns which are part of set 4, this set is intended to assess a volunteer's sensation of patterns containing different waveform travel patterns - sharp rise and parabolic travel. Figure 4.18 presents the patterns which are part of set 5, this set is intended to assess a volunteers sensation of patterns with mixed features. Figure 4.19 presents the patterns which are part of set 6, this set is intended to assess a volunteer's sensation of patterns containing different waveform travel patterns - parabolic and ramp up travel. Figure 4.20 presents the patterns which are part of set 7, this set is intended to assess a volunteers sensation of untrained patterns having mixed features.

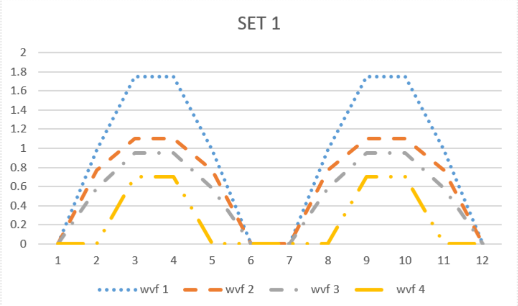


Figure 4.14. Pattern set 1 for whole pattern amplitude variation.

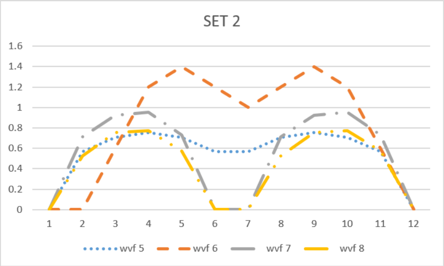


Figure 4.15. Pattern set 2 for small amplitude variations in large patterns.

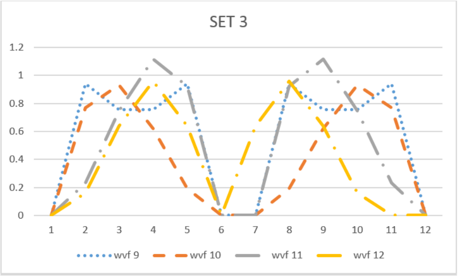


Figure 4.16. Pattern set 3 for small amplitude variations in small patterns with deep variations in between.

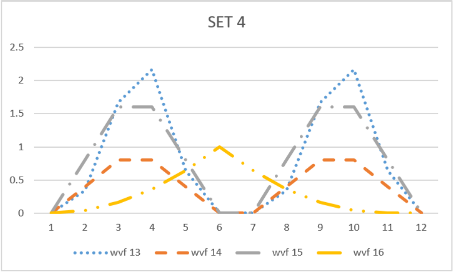


Figure 4.17. Pattern set 4 for identification of sharp and parabolic waveform travel.

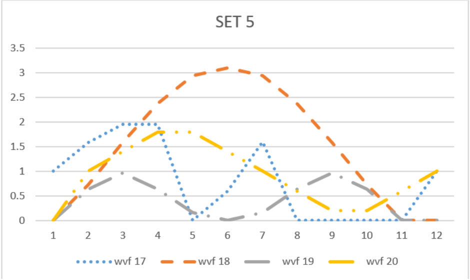


Figure 4.18. Pattern set 5 for identification of mixed patterns.

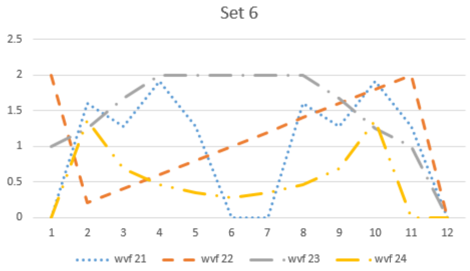


Figure 4.19. Pattern set 6 for identification of parabolic and ramp up travel.

4.5.3 Observations

Based on the feedback from the volunteers, it was observed that with training the quality of identification improved. When a reference pattern was provided to a volunteer, the quality of recognition improved due to the volunteer's ability to compare the reference pattern with the sensation for the remaining waveform patterns in that set. The volunteers mentioned that they were able to identify waveform patterns based on characteristics such as location of the peaks and valleys, the amount of time it took for a waveform pattern to reach a peak and amplitude variations between patterns.

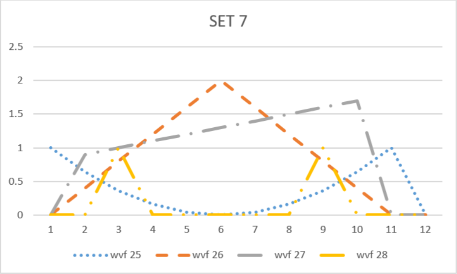


Figure 4.20. Pattern set 7 for untrained patterns having mixed features.

4.6 Test results

This section discusses the test results based on the volunteer feedback collected during the evaluation procedure. The test results represent the accuracy of recognition a volunteer had for all waveform pattern sets. While computing results the score assigned based on the volunteer's recognition of a waveform pattern is presented in table 4.1.

Table 4.1. Assigned score for recognition

Type of recognition	Score
Correct	1
Incorrect	0
Correct with reference	0.5

The computed results presented in figure 4.21 indicate the accuracy of recognition for every volunteer who participated in the 4th stage for each waveform set evaluated. In some cases, the volunteers were not able to identify the waveform pattern in the first attempt but could identify it in the second attempt. A score of 0.5 was awarded to the volunteers provided they could identify the waveform pattern correctly in the second attempt. The average recognition accuracy was computed based on the accuracy of recognition presented in figure 4.21.

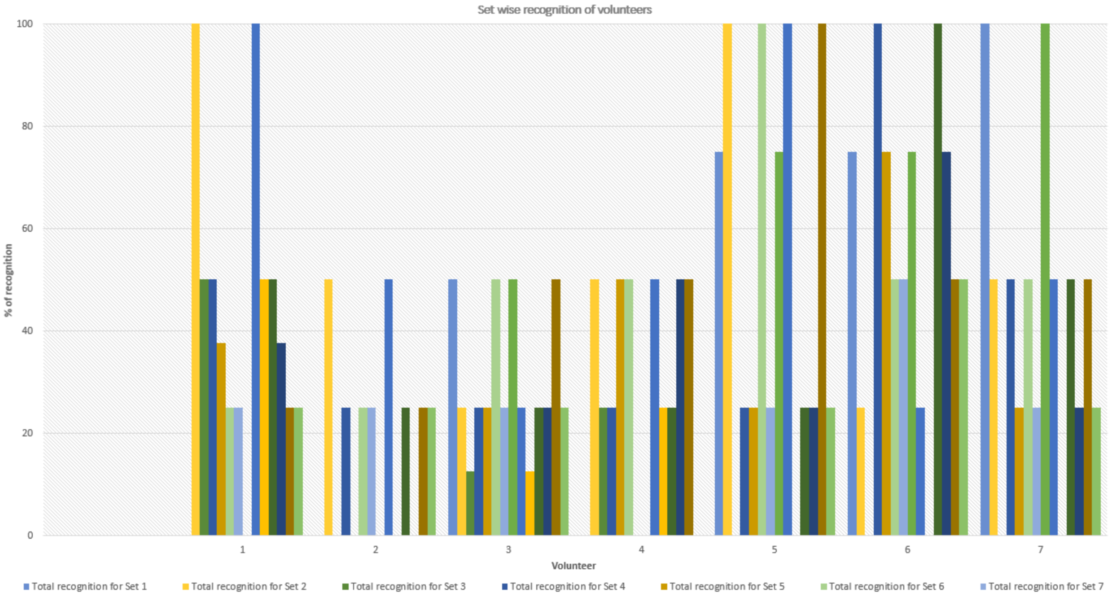


Figure 4.21. Set wise recognition by volunteers.

The average recognition for every set for all volunteers was computed and presented in figure 4.22. It is observed that the volunteers'recognition for sets 1 and 3 was poor, for sets 5 and 7 was better as compared to sets 1 and 3, and for sets 2, 4, 6 was the best compared to all other waveform sets.

While assessing the computed information, the volunteers' identification of an amplitude change is better for small variations that occur between a large pattern as compared to a whole pattern changing in amplitude consisting of the same features. Distinct features like a peak or a valley assisted the volunteers in identifying the sequence of features in a pattern. The volunteers were able to distinguish the travel for a waveform pattern based on the amount of time it took for a waveform to accelerate to the peak or decelerate to the bottom of a valley. In addition, it is observed that it was easier for a volunteer to identify and understand a waveform pattern efficiently as compared to understanding a change in amplitude of a waveform pattern. A detailed

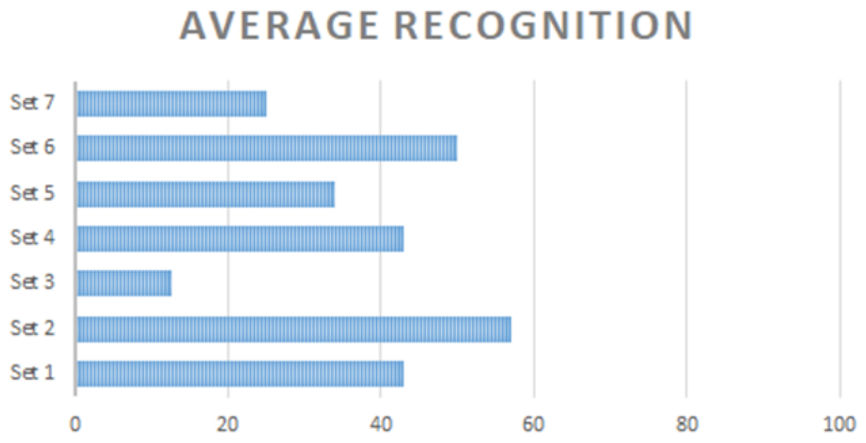


Figure 4.22. Average recognition for sets 1 to 7.

chart consisting of the scores related to the responses of the volunteers is available in appendix A.

Based on the feedback from the volunteers the important parameters for a waveform pattern were found to be the

(a) Amplitude of waveform pattern that relates to the strength of sensation,

(b) Frequency of the waveform pattern that controls the speed of actuation,

(c) Resolution of the waveform pattern that controls the quality of actuation and sensation.

4.7 Chapter summary

The study design, evaluation procedures followed and results inferred based on the feedback collected from the volunteers are discussed in this chapter. The study design elaborates the strategy that was followed for evaluating the process developed for generating haptic waveform patterns. The methodology used for the volunteer feedback is discussed and it is observed that identifying graphical representation for waveform patterns from the database is a better way for volunteers to indicate their sensation as compared to using adjectives and drawing graphical representation. During the evaluation process the change in sensation due to the input parameters and the waveform pattern generation procedure was evaluated. The recognition of waveform patterns was analyzed to evaluate the test results discussed in section 4.6. Based on these test results it was easier for a volunteer to identify and understand a waveform pattern efficiently as compared to understanding a change in amplitude of a waveform pattern. Chapter 5 discusses the evaluation and experimentation procedures followed in the research, highlights the challenges addressed, and the results based on the feedback collected during the evaluation process.

CHAPTER 5

Conclusions and recommendations for future research

5.1 Conclusions

The foundation of this research was developed based on the existing literature survey which included information on types of actuators used for haptics, the process involved in developing haptic waveform patterns, sensor technology being utilized for collecting haptics data, the computer algorithms which are being used for tactile processing, and the biological aspects of the human body which work towards understanding the tactile aspect of a sensation.

Based on the background information linear resonating actuator was used due to size constraints of the research platform and LabVIEW was utilized for developing the programming environment to control the actuators. While developing the platform two major issues were faced relating to I2C communication between the myRIO and the DRV2605L and the power delivered by myRIO to the driver boards. These issues were successfully resolved using an I2C multiplexer and an external power supply. The waveform pattern generation program built was modified to provide point by point output using the internal clock of the NI myRIO. In this program, the resolution of the pattern being generated was controlled by introducing a factor called X step.

During evaluation of a volunteer based study it was found that identifying the graphical representation of waveform patterns from a database was a better method as compared to other methods such as using adjectives to describe sensation or drawing graphical representations corresponding to the sensation of a person as it reduced the ambiguity due to a technical communication gap with the volunteers.

Based on the evaluation it was assessed that waveform properties that affect a volunteer's sensation are the waveform parameters amplitude, frequency, and resolution, and the waveform pattern characteristics waveform travel (parabolic rise, sharp rise, ramp up), amplitude variations and placement of features.

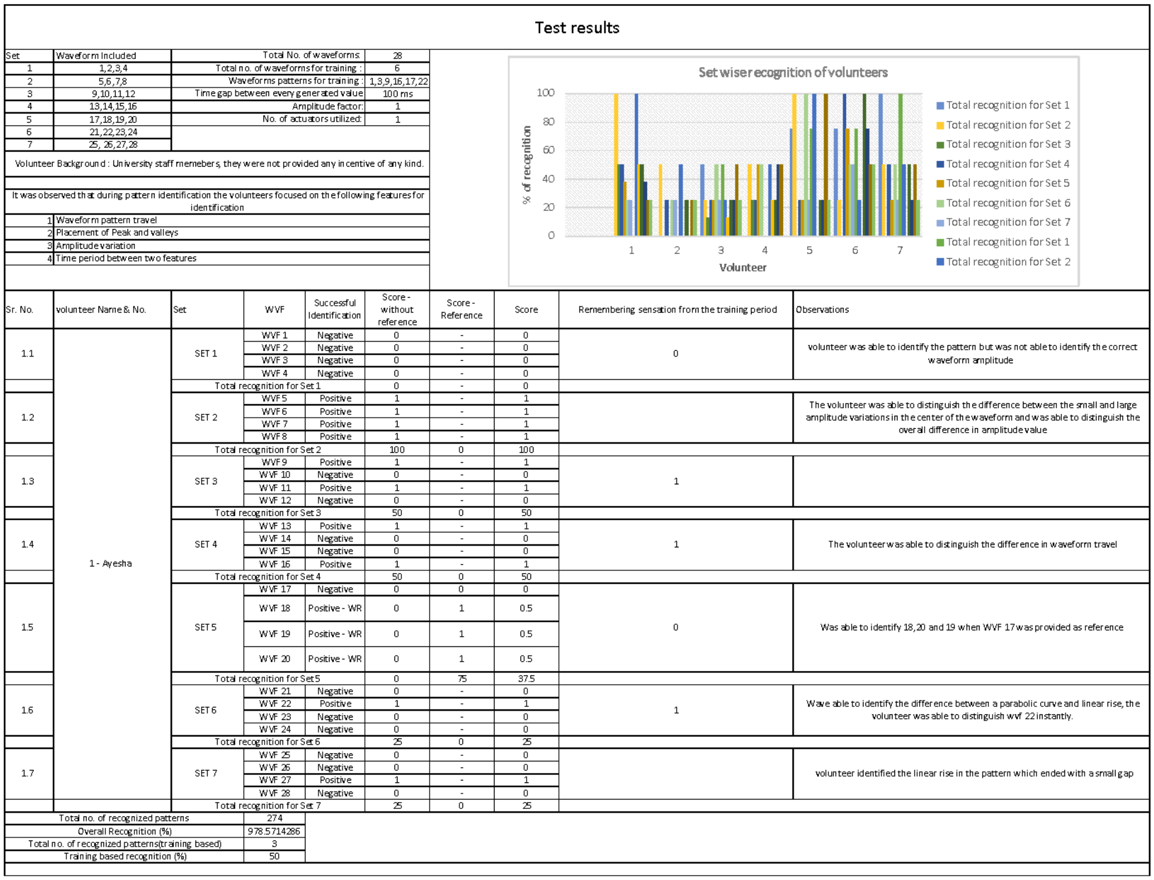
Based on the analysis of results it was concluded that identification of amplitude changes is better when the variation is in-between a waveform pattern as compared to the whole pattern amplitude changing. The location of peaks (high points) helped the volunteers to identify a sequence and variations in waveform travel were distinguished based on the amount of time it takes to reach a peak. The volunteers could identify a change in travel when they were separately provided or occurred at a small time away from other variations.

5.2 Recommendations for future research

Based on the primary objective of development in the field of human robot interaction at MARS Lab, the scope of this research can be further extended to establish a bi-directional channel for information transfer. This could be achieved by linking tactile feedback glove to the prosthetic arm and adding a force feedback module. To develop the interface to integrate the glove with the prosthetic arm, researchers would need to study the forces generated on the human fingers and the vibrations to be produced at the finger pads to provide the correct sensation. Further, a virtual platform which uses 2D or 3D visual system can be added to aid the haptic feedback by providing visuals corresponding to the type of interaction represented by the feedback.

APPENDIX A

Evaluation scores



Test results

Set	Waveform Included
1	1,2,3,4
2	5,6,7,8
3	9,10,11,12
4	13,14,15,16
5	17,18,19,20
6	21,22,23,24
7	25, 26,27,28

Total No. of waveforms:	28
Total no. of waveforms for training :	6
Waveforms patterns for training :	1,3,9,16,17,22
Time gap between every generated value	100 ms
Amplitude factor:	1
No. of actuators utilized:	1

Volunteer Background : University staff memebers, they were not provided any incentive of any kind.

It was observed that during pattern identification the volunteers focused on the following features for identification

1	Waveform pattern travel
2	Placement of Peak and valleys
3	Amplitude variation
4	Time period between two features

Sr. No.	volunteer Name & No.	Set	WVF	Successful Identification	Score - without reference	Score - Reference	Score	Remembering sensation from the training period	Observations
1.1	1 - Ayesha	SET 1	WVF 1	Negative	0	-	0	0	volunteer was able to identify the pattern but was not able to identify the correct waveform amplitude
			WVF 2	Negative	0	-	0		
			WVF 3	Negative	0	-	0		
			WVF 4	Negative	0	-	0		
		Total recognition for Set 1			0	-	0		
1.2		SET 2	WVF 5	Positive	1	-	1		The volunteer was able to distinguish the difference between the small and large amplitude variations in the center of the waveform and was able to distinguish the overall difference in amplitude value
			WVF 6	Positive	1	-	1		
			WVF 7	Positive	1	-	1		
			WVF 8	Positive	1	-	1		
		Total recognition for Set 2			100	0	100		
1.3		SET 3	WVF 9	Positive	1	-	1	1	
			WVF 10	Negative	0	-	0		
			WVF 11	Positive	1	-	1		
			WVF 12	Negative	0	-	0		
		Total recognition for Set 3			50	0	50		
1.4		SET 4	WVF 13	Positive	1	-	1	1	The volunteer was able to distinguish the difference in waveform travel
			WVF 14	Negative	0	-	0		
			WVF 15	Negative	0	-	0		
			WVF 16	Positive	1	-	1		
		Total recognition for Set 4			50	0	50		
1.5		SET 5	WVF 17	Negative	0	0	0	0	Was able to identify 18,20 and 19 when WVF 17 was provided as reference
			WVF 18	Positive - WR	0	1	0.5		
			WVF 19	Positive - WR	0	1	0.5		
			WVF 20	Positive - WR	0	1	0.5		
		Total recognition for Set 5			0	75	37.5		
1.6		SET 6	WVF 21	Negative	0	-	0	1	Wave able to identify the difference between a parabolic curve and linear rise, the volunteer was able to distinguish wvf 22 instantly.
			WVF 22	Positive	1	-	1		
			WVF 23	Negative	0	-	0		
			WVF 24	Negative	0	-	0		
		Total recognition for Set 6			25	0	25		
1.7		SET 7	WVF 25	Negative	0	-	0		volunteer identified the linear rise in the pattern which ended with a small gap
			WVF 26	Negative	0	-	0		
			WVF 27	Positive	1	-	1		
			WVF 28	Negative	0	-	0		
		Total recognition for Set 7			25	0	25		

Total no. of recognized patterns	274
Overall Recognition (%)	978.5714286
Total no. of recognized patterns(training based)	3
Training based recognition (%)	50

2.1	2 - Laine	SET 1	WVF 1	Negative	0	-	0	0	Amplitude difference was not noticed, all the patterns seemed to have the same sensation. But the Volunteer confirmed that the pattern of the graphical representation matched the sensation
			WVF 2	Negative	0	-	0		
			WVF 3	Negative	0	-	0		
			WVF 4	Negative	0	-	0		
		Total recognition for Set 1			0	0	0		
2.2		SET 2	WVF 5	Positive - WR	0	0	0		able to identify WVF 5,6 and 8 by identifying the Amplitude difference, and the compa
			WVF 6	Positive - WR	0	1	0.5		
			WVF 7	Positive - WR	0	1	0.5		
			WVF 8	Positive - WR	0	1	0.5		
		Total recognition for Set 2			0	75	37.5		
2.3		SET 3	WVF 9	Negative	0	-	0	0	The volunteer was not able to recognize any of the waveform patterns correctly
			WVF 10	Negative	0	-	0		
			WVF 11	Negative	0	-	0		
			WVF 12	Negative	0	-	0		
		Total recognition for set 3			0	0	0		
2.4		SET 4	WVF 13	Negative	0	-	0	1	Volunteer was able to recognize the parabolic curve travel of the waveform pattern
			WVF 14	Negative	0	-	0		
			WVF 15	Negative	0	-	0		
			WVF 16	Positive	1	-	1		
		Total recognition for set 4			25	0	25		
2.5		SET 5	WVF 17	Negative	0	-	0	0	The volunteer was confused between the 20 & 17 due to the long valley travel
			WVF 18	Negative	0	-	0		
			WVF 19	Negative	0	-	0		
			WVF 20	Negative	0	-	0		
		Total recognition for set 5			0	0	0		
2.6		SET 6	WVF 21	Negative	0	-	0	0	The volunteer was able to identify the parabolic pattern in WVF 23, but the volunteer did not identify the two peak structure in WVF 21 not the parbolic and linear pattern in WVF 24 and 22
			WVF 22	Negative	0	-	0		
			WVF 23	Positive	1	-	1		
			WVF 24	Negative	0	-	0		
		Total recognition for set 6			25	0	25		
2.7		SET 7	WVF 25	Negative	0	-	0		the volunteer identified the sharp bumps in WVF 28 but was not able to distinguish the pther patterns
			WVF 26	Negative	0	-	0		
			WVF 27	Negative	0	-	0		
			WVF 28	Positive	1	-	1		
		Total recogition for set 7			25	0	25		
Total no. of recognized patterns			53						
Overall Recognition (%)			189.2857143						
Total no. of recognized patterns(training based)			1						
Training based recognition (%)			16.66666667						
3.1	3- Danette	SET 1	WVF 1	Negative	0	-	0	1	The volunteer confirmed that the graphical representation matched the sensation but was only able to identify the WVF 3 and 4 distinctly
			WVF 2	Negative	0	-	0		
			WVF 3	Positive	1	-	1		
			WVF 4	Positive	1	-	1		
		Total recognition for Set 1			50	0	50		
3.2		SET 2	WVF 5	Positive	1	-	1		The volunteer was able to identify the small variation between the two peaks in WVF 5 but was not able to recognize WVF 6,7,8
			WVF 6	Negative	0	-	0		
			WVF 7	Negative	0	-	0		
			WVF 8	Negative	0	-	0		
		Total recognition for Set 2			25	0	25		
3.3		SET 3	WVF 9	Negative	0	0	0	0	The volunteer identified WVf 9 as 11 due to the similarity in the valley pattern and time period and location. When WVF 12 was provided for reference the volunteer identified WVF 10
			WVF 10	Positive - WR	0	1	0.5		
			WVF 11	Negative	0	0	0		
			WVF 12	Negative	0	0	0		
		Total recognition for set 3			0	25	12.5		
3.4		SET 4	WVF 13	Negative	0	-	0	1	Volunteer was able to recognize the parabolic curve in WVF 16
			WVF 14	Negative	0	-	0		
			WVF 15	Negative	0	-	0		
			WVF 16	Positive	1	-	1		
		Total recognition for set 4			25	-	25		
3.5		SET 5	WVF 17	Negative	0	-	0	0	The volunteer identified WVF 19 on the basis of peak placements and valleys between them. Volunteer was confused between WVF 17 and 20 due to the similarity in the pattern
			WVF 18	Negative	0	-	0		
			WVF 19	Positive	1	-	1		
			WVF 20	Negative	0	-	0		
		Total recognition for set 5			25	-	25		
3.6		SET 6	WVF 21	Positive	1	-	1	1	the volunteer identified the shallow valley between the peaks in WVF 21 and the linear rise in WVF 22. Also the volunteer was confused due to the parabolic curve placement in WVF 23 and 24
			WVF 22	Positive	1	-	1		
			WVF 23	Negative	0	-	0		
			WVF 24	Negative	0	-	0		
		Total recognition for set 6			50	-	50		
3.7		SET 7	WVF 25	Negative	0	-	0		the volunteer distinctly identified the sharp structure of WVF 28 but was confused in the rise pattern in the WVF 25,26 and 27
			WVF 26	Negative	0	-	0		
			WVF 27	Negative	0	-	0		
			WVF 28	Positive	1	-	1		
		Total recognition for set 7			25	-	25		
Total no. of recognized patterns			183						
Overall Recognition (%)			653.5714286						
Total no. of recognized patterns(training based)			3						
Training based recognition (%)			50						

4.1	4- Katherine	SET 1	WVF 1	Negative	0	-	0	0	The volunteer confirmed the sensation of the waveform matched the graphical representation of the pattern but was unable to understand the amplitude variation
			WVF 2	Negative	0	-	0		
			WVF 3	Negative	0	-	0		
			WVF 4	Negative	0	-	0		
		Total recognition for Set 1			0	-	0		
4.2		SET 2	WVF 5	Positive	1	-	1		The volunteer was able to understand the variations in shallow valleys in WVF 5 and 6 and identified them correctly. But in WVF 7 & 8 the volunteer understood the pattern but was not able to distinguish them based on amplitude.
			WVF 6	Positive	1	-	1		
			WVF 7	Negative	0	-	0		
			WVF 8	Negative	0	-	0		
		Total recognition for Set 2			50	-	50		
4.3		SET 3	WVF 9	Negative	0	-	0	0	The volunteer identified WVF 9 as WVF 12, both the patterns have similar patterns. But the volunteer identified WVF 11 based on the travel
			WVF 10	Negative	0	-	0		
			WVF 11	Positive	1	-	1		
			WVF 12	Negative	0	-	0		
		Total recognition for set 3			25	-	25		
4.4		SET 4	WVF 13	Negative	0	-	0	1	The volunteer identified the parabolic curve in WVF 16. In WVF 14 and 15 the voluntee got confused between the amplitude but I dentified the pattern correctly.
			WVF 14	Negative	0	-	0		
			WVF 15	Negative	0	-	0		
			WVF 16	Positive	1	-	1		
		Total recognition for set 4			25	-	25		
4.5		SET 5	WVF 17	Positive	1	-	1	1	the Volunteer identified WVF 20 as WVF 17 due to the similarity in structure.The volunteer was able to identify WVF 17 and 19 correctly.
			WVF 18	Negative	0	-	0		
			WVF 19	Positive	1	-	1		
			WVF 20	Negetive	0	-	0		
		Total recognition for set 5			50	-	50		
4.6		SET 6	WVF 21	Negative	0	-	0	1	the Volunteer identified the linear rise and parabolic rise in WVF 22 and 24 and identified them correctly but was not able to identify WVF 21 and 23
			WVF 22	Positive	1	-	1		
			WVF 23	Negative	0	-	0		
			WVF 24	Positive	1	-	1		
		Total recognition for set 6			50	-	50		
4.7		SET 7	WVF 25	Negative	0	-	0		Volunteer was not able to identify any of them correctly
			WVF 26	Negative	0	-	0		
			WVF 27	Negative	0	-	0		
			WVF 28	Negative	0	-	0		
		Total recognition for set 7			0	-	0		
Total no. of recognized patterns			208						
Overall Recognition (%)			742.8571429						
Total no. of recognized patterns(training based)			3						
Training based recognition (%)			50						
5.1	5 - Flora	SET 1	WVF 1	Positive	1	-	1	2	The volunteer was not able to identify the sharp pattern in WVF 4 but understood the amplitude difference in all the others and identified WVF 1,2 and 3
			WVF 2	Positive	1	-	1		
			WVF 3	Positive	1	-	1		
			WVF 4	Negative	0	-	0		
		Total recognition for Set 1			75	0	75		
5.2		SET 2	WVF 5	Positive	1	-	1		The volunteer understood all the variations and identified them all coreectly
			WVF 6	Positive	1	-	1		
			WVF 7	Positive	1	-	1		
			WVF 8	Positive	1	-	1		
		Total recognition for Set 2			100	0	100		
5.3		SET 3	WVF 9	Negative	0	-	0	0	the volunteer was not able to recognize the features of the waveform patterns
			WVF 10	Negative	0	-	0		
			WVF 11	Negative	0	-	0		
			WVF 12	Negative	0	-	0		
		Total recognition for Set 3			0	0	0		
5.4		SET 4	WVF 13	Negative	0	-	0	1	the volunteer was able to retain the information for the parabolic pattern from the training
			WVF 14	Negative	0	-	0		
			WVF 15	Negative	0	-	0		
			WVF 16	Positive	1	-	1		
		Total recognition for Set 4			25	0	25		
5.5		SET 5	WVF 17	Negative	0	-	0	0	the volunteer identified WVF 18 correctly on the basis of the parabolic curve.
			WVF 18	Positive	1	-	1		
			WVF 19	Negative	0	-	0		
			WVF 20	Negative	0	-	0		
		Total recognition for Set 5			25	0	25		
5.6		SET 6	WVF 21	Positive	1	-	1	1	the volunteer was able to distinguish between shallow patterns and linear rise and parabolic rise
			WVF 22	Positive	1	-	1		
			WVF 23	Positive	1	-	1		
			WVF 24	Positive	1	-	1		
		Total recognition for Set 6			100	0	100		
5.7		SET 7	WVF 25	Negative	0	-	0		the volunteer identified the sharp patternin WVF 28 but was not able to identify the patterns of the other waveforms
			WVF 26	Negative	0	-	0		
			WVF 27	Negative	0	-	0		
			WVF 28	Positive	1	-	1		
		Recognition for set 7			25	0	25		
Total no. of recognized patterns			339						
Overall Recognition (%)			1210.714286						
Total no. of recognized patterns(training based)			4						
Training based recognition (%)			66.66666667						

6.1	6 - Janet	SET 1	WVF 1	Positive	1	-	1	2	The volunteer was able to identify the pattern and the amplitude difference in WVF 1,3 and 4.
			WVF 2	Negative	0	-	0		
			WVF 3	Positive	1	-	1		
			WVF 4	Positive	1	-	1		
		Total recognition for Set 1			75	-	75		
6.2		SET 2	WVF 5	Positive	1	-	1		The volunteer understood the shallow pattern in WVF 5. The Volunteer was not able to identify the amplitude difference in WVF 7 and 8 but identified the patten correctly
			WVF 6	Negative	0	-	0		
			WVF 7	Negative	0	-	0		
			WVF 8	Negative	0	-	0		
		Total recognition for Set 2			25	-	25		
6.3		SET 3	WVF 9	Negative	0	-	0	0	The volunteer identified the waveform pattern 9 as 12 due to the similarity in the pattern
			WVF 10	Negative	0	-	0		
			WVF 11	Negative	0	-	0		
			WVF 12	Negative	0	-	0		
		Total recognition for set 3			0	-	0		
6.4		SET 4	WVF 13	Positive	1	-	1	1	the volunteer understood the shallow pattern variations, amplitude diffrences and parabolic rise
			WVF 14	Positive	1	-	1		
			WVF 15	Positive	1	-	1		
			WVF 16	Positive	1	-	1		
		Total recogition for set 4			100	-	100		
6.5		SET 5	WVF 17	Positive	1	-	1	1	The volunteer was able to identify WVF 17,18,19 correctly and WVF 20 was identified as 17 due to the similarity in pattern
			WVF 18	Positive	1	-	1		
			WVF 19	Positive	1	-	1		
			WVF 20	Negative	0	-	0		
		Total recognition for set 5			75	-	75		
6.6		SET 6	WVF 21	Negative	0	-	0	1	the volunteer understood the difference in a linear rise and parabolic rise but was not able to understand the shallow variation in patterns
			WVF 22	Positive	1	-	1		
			WVF 23	Negative	0	-	0		
			WVF 24	Positive	1	-	1		
		Total recognition for set 6			50	-	50		
6.7		SET 7	WVF 25	Negative	0	-	0		The volunteer understood the variations in WVF 27 and WVF 28
			WVF 26	Negative	0	-	0		
			WVF 27	Positive	1	-	1		
			WVF 28	Positive	1	-	1		
		Recognition for set 7			50	-	50		
Total no. of recognized patterns			340						
Overall Recognition (%)			1214.285714						
Total no. of recognized patterns(training based)			5						
Training based recognition (%)			83.33333333						
7.1	7 - Kathy	SET 1	WVF 1	Positive	1	-	1	2	The volunteer understood the variation in amplitude and the pattern
			WVF 2	Positive	1	-	1		
			WVF 3	Positive	1	-	1		
			WVF 4	Positive	1	-	1		
		Total recognition for Set 1			100	-	100		
7.2		SET 2	WVF 5	Positive	1	-	1		The volunteer understood the shallow pattern in WVF 5. The Volunteer was not able to identify the amplitude difference in WVF 7 and 8 but identified the patten correctly
			WVF 6	Positive	1	-	1		
			WVF 7	Negative	0	-	0		
			WVF 8	Negative	0	-	0		
		Total recognition for Set 2			50	-	50		
7.3		SET 3	WVF 9	Negative	0	-	0	0	The volunteer identified WVF 9 as WVF 12, both the patterns have similar patterns.
			WVF 10	Negative	0	-	0		
			WVF 11	Negative	0	-	0		
			WVF 12	Negative	0	-	0		
		Total recognition for Set 3			0	-	0		
7.4		SET 4	WVF 13	Positive	1	-	1	1	the volunteer understood the shallow pattern variations, and parabolic rise in WVF 13 and 16 but was not able to distinguish between amplitude diffrences and found WVF 14 and 15 to be the same
			WVF 14	Negative	0	-	0		
			WVF 15	Negative	0	-	0		
			WVF 16	Positive	1	-	1		
		Total recognition for Set 4			50	-	50		
7.5		SET 5	WVF 17	Negative	0	-	0	0	Based on the valley the volunteer identified WVF 19
			WVF 18	Negative	0	-	0		
			WVF 19	Positive	1	-	1		
			WVF 20	Negative	0	-	0		
		Total recognition for Set 5			25	-	25		
7.6		SET 6	WVF 21	Positive	1	-	1	1	The volunteer distinguished the shallow variation and Linear rise in the patterns 21 and 22. But in WVF 23 and 24 the volunteer was confused with the direction of parabolic rise
			WVF 22	Positive	1	-	1		
			WVF 23	Negative	0	-	0		
			WVF 24	Negative	0	-	0		
		Total recognition for Set 6			50	-	50		
7.7		SET 7	WVF 25	Negative	0	-	0		The volunteer identified the sharp feature in WVF 28
			WVF 26	Negative	0	-	0		
			WVF 27	Negative	0	-	0		
			WVF 28	Positive	1	-	1		
		Recognition for set 7			25	-	25		
Total no. of recognized patterns			287						
Overall Recognition (%)			1025						
Total no. of recognized patterns(training based)			4						
Training based recognition (%)			66.66666667						

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BIOGRAPHICAL STATEMENT

Sudip Hazra was born in Rajasthan, India, in 1992. He received his B.S. degree from Vellore Institute of Technology, Vellore, India in 2014 and a M.S. degree from The University of Texas at Arlington in 2018, all in Mechanical Engineering.

From 2014 to 2016, he worked in the field of cryogenics and metallurgy for developing equipment and process plant designs. During his professional tenure, he learnt the practical applications and the importance of control systems that are employed for automation. Intrigued by the scope of such systems, he further decided to pursue a M.S in Mechanical Engineering at The University of Texas at Arlington. During his masters, he researched on human robot interaction since his research interest lies in the field of control systems and human robot interactions. He researched on Haptics and would like to pursue research in the field of virtual reality systems for human robot interactions.