Qatar University
College of Engineering
Department of Computer Science and Engineering

Senior Project Report

Tactile Footwear Interface to Simulate the Illusion of Walking on Different Surfaces

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This project report is submitted to the Department of Computer Science and Engineering of Qatar University in partial fulfillment of the requirements of the Senior Project course.

Declaration

This report has not been submitted for any other degree at this or any other University. It is solely the work of us except where cited in the text or the Acknowledgements page. It describes work carried out by us for the capstone design project. We are aware of the university's policy on plagiarism and the associated penalties and we declare that this report is the product of our own work.

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Abstract

This project aims to design and develop an integrated system of feet-haptic insole and MR environment to create the illusion of walking on virtual textures. This system contributes to the enhancement of the realism provided by virtual and augmented reality. Based on literature found in recent studies, the vibration tactile approach is implemented to create the perception of physical properties of textures. The majority of applications that simulate the texture sensations considered the tactile communication through hand. However, this project customizes the mechanisms and techniques of creating texture perception to fit feet sensation taking in consideration the nature and the distribution of mechanoreceptors in the foot's sole skin. Two main parameters are used to control the tactile vibrators: PWM frequency, and motor activation time. Well-designed virtual/augmented environments are used with several scenarios to examine the realism provided by the system. In addition, the system deploys an algorithm to detect and analyze the user movement behavior in order to provide more realistic experience. Therefore, this project provides a fully immersing virtual/augmented experience to the user utilizing visual, auditory, and tactile means. In this project, several experiments are conducted to investigate the texture recognition rate among different users, as well as the satisfaction rate for the enhancement added by the haptic technology. The applications of the system that will be developed in this project are very wide including rehabilitation, gamifications, training, and entertainment.

Acknowledgment

All the thanks to Allah for giving us the strength and the knowledge to work on this project. As we sincerely convey our appreciation and gratitude to our supervisor, Dr. Osama Halabi, for his support and guidance that helped us to complete all the tasks and the objectives of this part of the project. We would like also to thank all Computer Science and Engineering Department faculty and staff members for their support since our first year at the department. As well as we would like to thank our colleagues for their support and collaboration. Finally, we would like to thank our families and friends for their understanding, encouragement and support towards the completion of this part of the project.

Table of Contents

List of Figures

List of tables

List of Abbreviations

AR	Augmented Reality
VR	Virtual Reality
MR	Mixed Reality (Virtual & Augmented)
FSR	Force Sensing Resistor

1. Introduction and Motivation

1.1. Problem statement

The field of haptic feedback has been rapidly expanding for the last decade and it is used in many areas such as the medical filed, education, and military. Trainings on sensitive surgery operations [1], rehabilitation applications [2] and many other applications in education and entrainment used haptic feedback. In addition, many haptic feedback applications were developed to provide simulations of several properties of tangible environments [3]. In similar context, virtual reality and augmented reality environment field is expanding in the same areas. The integration of haptic technology and AR/VR can increase the realism of virtual and augmented environments which can lead to better results and performance of the related application.
The majority of haptic applications are limited to hands and fingers communication. On the other hand, other parts of the human body had much less attention. The human foot is essential for walking and moving around, therefore it is critical to provide haptic sensation if we want to reach higher level of realism. Recently, several studies and experiments have been conducted to find out the possible applications of haptic insole in order to communicate through the human feet. These studies depended on the feet sensation to provide directional guidance, emotion recognition, walking illusion and some other applications [4][5]. Consequently, there are few work that address this type of research and there is mainly lack of research in studies related to simulate the feeling of different surface textures such as: sand, sponge, wood, etc. Nowadays, VR and AR environments are lacking the ability to provide advanced full feet-feeling experience to the user.

1.2. Project significance

The communication with different parts of the human body using haptic technology has always helped in delivering more realistic virtual and augmented environments. Yet, there is still a need that is not met in previous literature to provide a full foot-feeling experience to the user. Designing a haptic insole that is able to provide the illusion of walking on different surfaces contributes to the creation of more realistic virtual or augmented environments. This project will enlarge the range of applications that can be implemented through the integration of both AR/VR and haptic technologies.

Furthermore, having the ability of creating the feeling of different surface textures through a haptic insole will significantly impact several important areas that include: education, rehabilitation, and entertainment. For instance, it can be used in classrooms to educate children about how it feels to walk in a specific environment such as walking on sand in desert. In addition, one of the potential application is to help recovering people who cannot leave the rehabilitation center to take a walk in a virtual garden or on a virtual beach sand. This feet-haptic feedback contributes in creating advanced virtual and augmented training environments that can be deployed in security training for police, firemen, and military as well.

1.3. Project objectives

This project aims to advance the integration of both feet-haptic communication and MR environment through achieving the following objectives:

1. To design and implement a haptic insole that deploys vibrators to simulate the texture of several surfaces such as: sand, leaves, rocks, etc.

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2. To study and optimize the design and layout of vibrators used to implement haptic insole.
3. To design and develop MR environment that is integrated with the haptic insole for an entertainment application.
4. To design and develop an intelligent algorithm for feet activity recognition that can make decisions about the feet statues including speed and direction of movement.

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2. Background

2.1. Haptic Technology

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Humans communicate with the outer world through their five senses. In computer interaction, it is usually limited to visual and auditory means only. Recently, the sense of touch was more involved in human-computer interaction, and this filed of communication is called “Haptic”. The human’s body perceives the physical properties of different materials and shapes through touching [6]. Haptic technology aims to recreate the sense of tactile interaction without actually touching the real object or surface. Instead, different means such as vibrations, force, pressure, temperature and motion are used to simulate the perception of touching a virtual object or surface texture [6].

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The word haptic comes from a Greek origin “haptikos” which means to touch [7]. The sense of touch is considered one of the essential channels for human interaction with the outer world. Nowadays, there are two types of haptic: kinesthetic and tactile perceptions [7]. We will mainly focus on tactile feedback which depends mainly on vibrations to deliver the perception of touching virtual objects or surfaces.

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There are four types of mechanoreceptors in the human skin which are responsible for creating the sense of touch as can be seen in Figure 1 [8]. Each type corresponds to a specific range of frequencies and communicates a different type of tactile sensation. Both Merkel’s receptor and Ruffini’s corpuscle are sensitive for very low frequencies and pressure, while Meissner’s corpuscle is activated by relatively high frequencies, and Pacinian corpuscle is sensitive to very high frequencies vibrations [8][9]. If each type of those cells is activated selectively as a combination or individually, the feeling of touch can be recreated.

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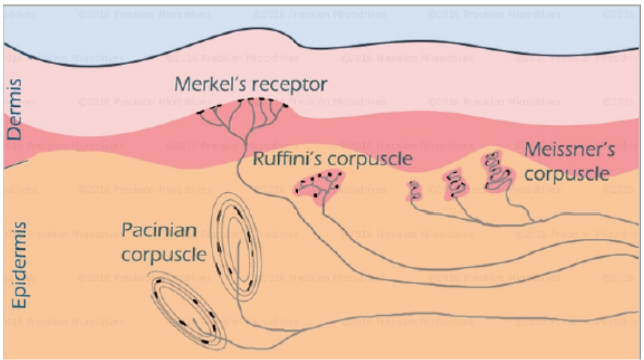

Figure 1: Four types of mechanoreceptors in the skin as described in [8][9]

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Haptic technology is used to communicate information with human using tactile sensation. Many studies and applications deployed the haptic technology to serve the communication propose such as directional guidance and providing assistance in driving simulator [5][10]. However, the human perception of different surfaces texture is more complicated than limited normal communication, and it involves simulating several physical properties that describe different materials. Previous studies assumed that the tactile perception of textures has five psychophysical dimensions [6]. Those dimensions were stated as follows: fine roughness (rough/smooth), macro roughness (uneven/relief), friction (moist/dry, sticky/slippery), hardness (hard/soft), and warmness (cold/warm). Another study [3] suggested that each one of the first four psychophysical dimensions are simulated through activating a specific type of mechanoreceptors as presented in Figure 2. Thus, simulating the tactile feeling of a texture depends on knowing the psychophysical dimensions of this material.

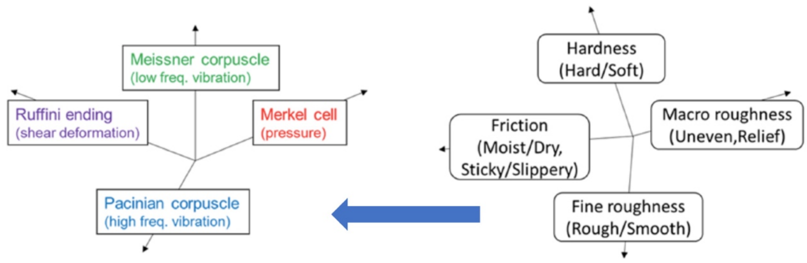

Figure 2: Transformation of four psychophysical dimensions to four mechanoreceptors [3]

- **Foot-Haptic**

Pacinian and Meissner corpuscles are heavily existed in the foot sole skin and both of them are very sensitive to vibrations [11]. In fact the threshold of both vibrations and pressure in the feet sole are many times greater than the threshold in hands as illustrated in Figure 3 [12]. Thus, the feet are very suitable for establishing haptic communication. Yet, the majority of haptic researches and studies are limited to hands and fingers. However, the field of feet haptic has been growing up especially for the last few years. Several advanced applications were developed to enhance walking experience and to create the illusion of self-motion through haptic feedback [13][14].

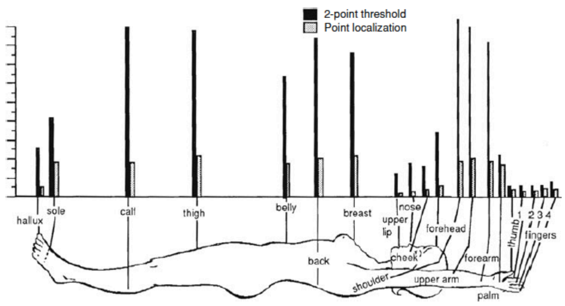

Figure 3: Vibration and pressure threshold among the human body [11]

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To understand how haptic feedback would work on human feet, it is important to understand the different parts of the foot and what frequencies can stimulate a specific feeling of a specific material like sand, leaves or rocks. There are our types of mechanoreceptors can be found in human foot as shown in Figure 4: fast adapting I (FA I), fast adapting II (FA II), slow adapting I (SA I), slow adapting II (SA II). The FA I and FA II receptors are sensitive for vibration within different frequency ranges. FA I are mainly aroused between 10 Hz and 100 Hz, while the FA II mechanoreceptors are most sensitive in the range of 100 Hz–300 Hz [15].

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Figure 4: Mechanoreceptors distribution among the human foot [15]

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On the other hand, there is a shortage in developing applications that deploys haptic technology to simulate different textures for feet. In reality, the need of texture simulation for feet is associated with the rapidly developing field of virtual and augmented reality. It is much more realistic to support the virtual environments with three means: visual, auditory, and tactile as suggested in Figure 5 [7].

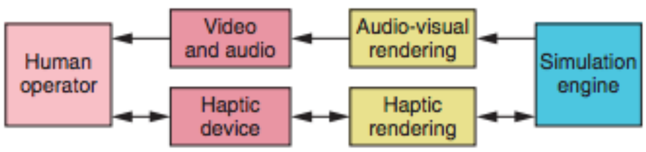

Figure 5: Basic architecture for a VR application incorporating visual, auditory, & haptic feedback

2.2. Virtual Reality & Augmented Reality

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- **Virtual Reality**

Virtual Reality refers to the technology of using specialized headsets, multi-projected environment, or a combination of both to generate a virtual, realistic environment through combining images and sounds to immerse the user. The user can look around freely and interact with virtual objects, and moves through either a game controller, or physically walking, depending on the setup [16]. We believe virtual reality can be an ideal framing device to introduce the haptic insole technology, with the right hardware, it can provide a realistic environment with multiple object of different type of textures for the user to interact with.

The virtual environment is displayed to the user through the head mounted display (HMD) like the one shown in Figure 6. The HMD provides two displays, one for each eye, both views merge together to gives an immersive view to the user to mimic reality in way that makes the simulated environment appear as real as possible. The HMD will be connected to the PC through an HDMI or a DisplayPort.

Figure 6: Virtual reality and augmented reality headsets

- **Augmented Reality**

Augmented reality is a technology that provides an indirect view to the real world augmented through a computer and a specialized headset. Since the augmented reality allows the user to preserve the real world, it can allow mixing real and virtual objects at the same time instead of the full isolation provided by the VR. Moreover, it also allows for a portability aspect that VR cannot safely provide. A higher level of integration with the augmented reality environment can be accomplished by using location sensors, height sensors, pressures sensors [17].

In the light of the above-mentioned facts, virtual and augmented based reality trainings are beneficial for cutting cost of trainings and for saving time, the fact that they can involve many fields, be performed in a confined area and are easily reproducible should be enough of a reason for organization to start adopting these as a training method. Virtual and augmented trainings are used in various fields like police and army simulations, education, rehabilitation, etc.

For our project, we chose the Occipital's Bridge headset, which offers a unique take on both the virtual and augmented reality concepts by scanning the real-world surroundings into a mesh and using the structural sensor to provide texture for this mesh, offering the augmented reality experience but in a completely virtual environment. Occipital call this technology Mixed Reality, and we believe the fluidity it offers in switching between real world and virtual environments is a perfect fit for our objectives in this project.

3. Related work

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In this section, we will review several studies and the previous literature related to our project which will help in developing our design and implementation in further stages. Since our project aims to develop a haptic insole to simulate the illusion of walking on different surfaces, the related studies lay in several specialized areas including: foot-haptic communication, haptic simulation of self-movement, and haptic simulation of walking on textures.

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3.1. Foot-Haptic Communication

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Many involvements of the foot interaction in the haptic field were limited to basic communication and delivering of simple messages. However, it assisted in understanding the human foot perception of tactile vibrators. For example in [4], the researchers proposed a haptic feedback interface to help users adjust their focus and gait instantly during in exercising or daily life by using smart footwear. The haptic feedback in this project is achieved by using vibrators as shown Figure 7. The motors pause and reboot to give the user feedback to adjust his/her posture. This feedback allows the user to modify the position of the foot, such as changing distance between feet step width and strides, the other one is to adjust rotation angle of the foot. The paper uses information about the proper posture positions of the human body and the main pressure points on the foot. This information is used to help the user to quickly and intuitively adjust his/her gait and focus in real-time with accuracy of 79% and recognition time 2.6 seconds. The topic of this paper lays in the area of our study since both our project and this paper provide haptic feedback on human feet. However, the complexity of the vibration messages varies significantly. As the paper uses simple messages, simulating the feeling of material will need much more complex messages.

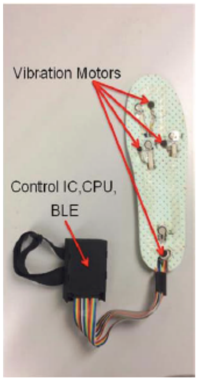

Figure 7: The vibration feedback insole [4]

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Another notable project in foot-haptic communication is shown in this paper [18] where the project aimed to provide a first attempt to evaluate the role of tactile perception by the human foot. The researchers proposed a wearable human-computer interface for the foot consisting of a shoe integrated vibrotactile display. To evaluate the role of tactile perception by the human foot and perceptual experiments, a device was built and conducted for this purpose with both healthy sighted and blind voluntary subjects. Results reported in show that some information is discriminable and

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that tactile-foot stimulation could be used for a wide number of applications in human-machine interaction.

In addition, this project provided different experiments to study the perception of the different parts of the human foot. In a first attempt, sixteen vibrators were installed in the bottom of the footwear. Based on the results achieved by experimenting on the subjects, the number of the vibrators was reduced from sixteen to four only to know if the same results can be reached. The four vibrators are arranged in a diamond-like shape with 35 mm side-length as presented in Figure 8.

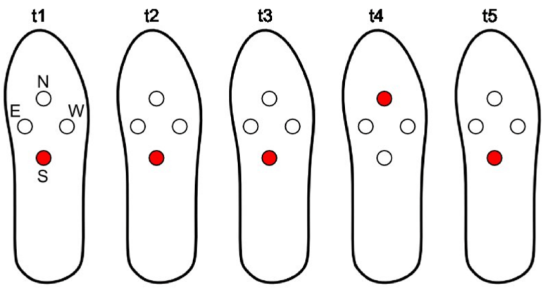

Figure 8: Schedule of activation of the vibrating actuators for the direction recognition task [18]

Foam was chosen from the beginning because it is easy to machine, and it is well known for absorbing vibrations, shock, and impact forces. Its absorbing material properties have a twofold purpose: to cushion the motors against the user's load and to prevent from having an expanding motor vibration effect throughout the insole. This study included four experiments: direction recognition, pattern recognition, emotion recognition, and language learning.

Results show that people understand easier directional information with patterns providing reference points rather than motion. Familiar patterns and emotions can also be easily recognized by the foot if information displayed is simple and encoded as short structured messages. New patterns abstractly representing information can also be understood, quickly learned, and retained in memory. To summarize, this paper provided great experiments that can save much time when it comes to optimizing the number of vibrators needed and knowing what parts of the bottom of the foot are more important to target.

3.2. Haptic simulation of self-movement

Many researchers investigated the possibility of providing the same illusion using haptic feedback. In the following, we present three studies which introduced three different approaches to create the illusion of self-movement and all of them were conducted in 2012: [13] a design by Masuda to create the illusion of walking through electromagnetic testbed, [19] a design by Ravikrishnan to create the illusion of walking using actuated plates, and [14] a design by Nordahl to create the illusion of vertical self-movement using tactile vibrators.

Masuda's design which was presented in [13] deployed the magnetic field to generate the haptic feedback. The goal of the study was to provide walking and traveling experiences to the elderly in Japan who are suffering from physical and / or cognitive disorders and have a difficulty in going out

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and walking in real environments. Therefore, the project proposed a virtual walking system that consists of visual, auditory, and haptic devices to present various kinds of ambient information for users. In this paper, the use of magnetic field sensitive elastomers (MSEs) as working materials for the device was discussed and an electromagnet as a testbed of MSE was developed as shown in Figure 9. By applying magnetic field, different pressures on soles can be performed by this device. However, this approach is not recommended for our project since we are seeking to enhance the experience of walking on different textures by increasing the range of freedom and mobility through a haptic insole. The electromagnetic materials are heavy and hard to be integrated in an insole.

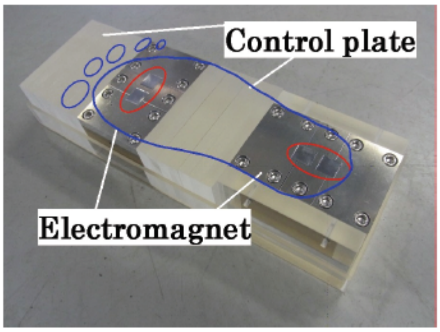

Figure 9: Testbed for foot haptic interface [13]

On the other hand, Ravikrishnan's project as shown in [19] developed a haptic device to provide a seated user with haptic feedback to create the illusion of walking. Their implementation deployed a set of actuated plates that move up and down, pressing on the soles of the feet to generate the required pattern of forces. Actual data of walking pressure distributions were used in the design process. Moreover, the system provides a virtual environment as well to create a more immersive experience to the user. Although the system uses vibrations to provide the haptic feedback, the approach of actuated plates restricts the mobility because it is heavy and requires huge space as shown in Figure 10. Therefore, the system assumes that the user is seated which in not the case in our project.

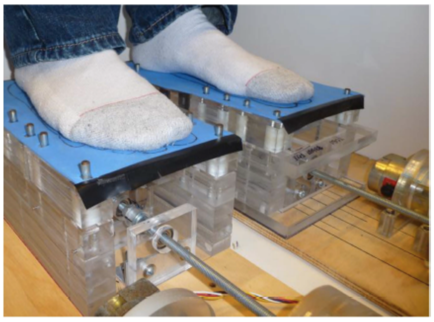

Figure 10: Haptic footstep display [19]

Lastly, Nordahl's work investigate the ability of using haptic stimulation of the feet to create the illusion of vertical self-motion as presented in [14]. The experiment introduces the user to a virtual environment where he/she experience being in an elevator. All the subjects were exposed to the identical visual and auditory effects. Analysis of self-reports were used to assess the participants' experience of illusory self-motion. The results indicate that such illusions are indeed possible. Significant differences were found between the configuration including no haptic feedback and the configurations that introduced haptic feedback to the user, where the majority of users proffered the haptic feedback overall. The researches implemented tactile vibrations using vibrators and pressure sensors that can be easily inserted in an insole as shown in Figure 11 unlike the previous discussed projects. Yet, the work in this project is limited to the creation of illusionary movement and do not get into the complexity of providing simulation of the different textures.

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Figure 11: Placement of a pressure sensor and two actuators in the heel of one sandal [14]

3.3. Haptic simulation of walking on textures

One remarkable project in [20] claimed that it is possible to provide both audio and haptic feedback at the same time to deliver a real experience of walking on different grounds. The aim of this project was to develop a physically based synthesis engine that is able to simulate the auditory and haptic sensation of walking on different surfaces. For that reason, they proposed a solution where they drew a primary distinction between solid and aggregate ground surfaces, the latter being assumed to possess a granular structure, such as that of gravel. As the human foot touches the ground while walking, the system needed to know what part of the foot touches the ground first and with what pressure. Therefore, haptic shoes enhanced with pressure sensors have been developed. In addition, the hardware needed to be installed in a footwear that allows the transfer of vibrations. Therefore, a pair of light-weight sandals was procured (Model Arpenaz-50, Decathlon, Villeneuve d'Ascq, France). This particular model has light, stiff foam soles that are easy to gouge and fashion.

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When it came to installing the hardware in the footwear, four cavities were made in the thickness of the sole to accommodate four vibrotactile actuators (Haptuator, Tactile Labs Inc., Deux-Montagnes, Qc, Canada). These electromagnetic recoil-type actuators have an operational, linear bandwidth of 50–500 Hz and can provide up to 3 G of acceleration when connected to light loads. From the range of frequency that the motor provides, it can be noticed that this project specifically focused on the foot receptors that simulate the feeling of touch to deliver the haptic feedback. Furthermore, the motors used in this project can have high acceleration which gives a change to produce a higher number of possible feedbacks when combined with vibration.

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The position of the actuators in the footwear should be taken into consideration to target the proper parts of the bottom of the foot. In this project two actuators as shown in Figure 12 were placed under the heel of the wearer and the other two under the ball of the foot. There were bonded in place to ensure good transmission of the vibrations inside the soles. When activated, vibrations propagated far in the light, stiff foam. In the present configuration, the four actuators were driven by the same signal but could be activated separately to emphasize, for instance, the front or back activation, to strike a balance, or to realize other effects such as modulating different, back-front signals during heel-toe movements.

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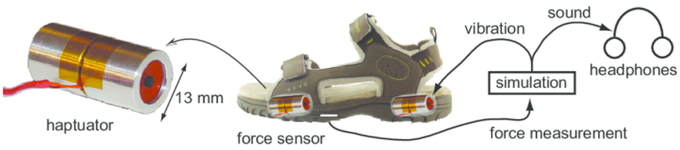

Figure 12: System model [20]

The sole has two force sensitive resistors (FSRs) pressure sensors whose aim is to detect the pressure force of the feet during the locomotion of a subject wearing the shoes. The two sensors are placed in correspondence to the heel and toe respectively in each shoe. In order to control the vibrators and sensors a micro-controller was needed as illustrated in Figure 13.This project used an Arduino Diecimila board. The analogue values of each of these sensors are digitized by means of the Arduino Diecimila board and used to drive the audio and haptic synthesis.

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To criticize the work done in this project, it can be noticed that the project did not take the different parts of the foot into consideration when choosing where to install the actuators. The project installed one actuator in the front part of the shoe and another actuator under the heel. One concern can be noticed is that the whole front part of the bottom foot was considered one part when installing the small-sized actuator. This can raise a question: Can one actuator really transmit vibrations equally to a relatively large part of the foot? Or should this be more studied in the area of human foot perception? We think that more actuators should be used based on a deeper understanding on human perception of different materials [11].

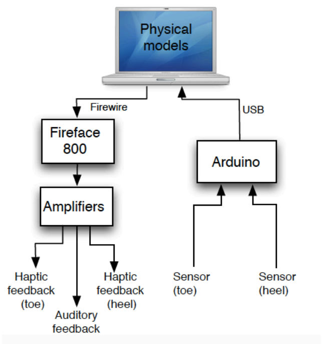

Figure 13: Illustration of the different hardware components of the system [20]

A more comprehensive research in [21] is introduced by the same lead investigator of the last mentioned paper [20]. In this paper, several experiments were conducted to evaluate the role of plantar vibrotactile feedback in enhancing the realism of walking experiences in multimodal virtual environments. To achieve this goal, both an interactive and a noninteractive multimodal feedback system were built as illustrated in Figure 14.

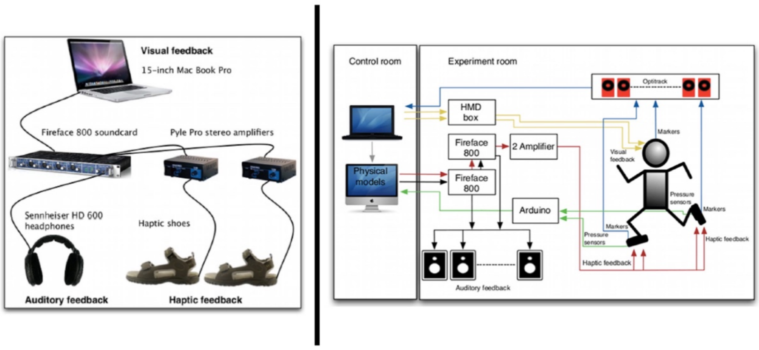

Figure 14: Schematic representation of the overall architecture of the noninteractive (left) & the interactive (right) [21]

In both noninteractive and the interactive experiments the participants were experiencing visual and auditory effects. However, in the interactive configuration, the subjects were actually walking on their feet as long as they were exposed to a VR environment. On the other hand, the subjects were setting a chair and the locomotion were simulated in the noninteractive configuration. In both configurations, the first part was introduced without providing any haptic feedback. On the other hand, the second part of the experiment introduced a corresponding haptic feedback to the feet. All participants were asked to state if they noticed any difference between the two parts and about which part they preferred.

As expected, the results provided a clear preference toward the simulations enhanced with haptic feedback showing that the haptic channel can lead to more realistic experiences in both configurations. Although, the majority of subjects clearly valued the additional haptic feedback, others did not like the added haptic feedback. The researchers suggested that they did not like it because of the difference of individual's desire to be involved in the simulations.

The findings of this study can be applied to the context of physical navigation in multimodal virtual environments as well as to enhance the user experience of watching a movie or playing a video game. On the other hand, the work still does not provide the user with a fully generated illusion of textures based on haptic. The researches considered the haptic feedback as an additional feature that can enhance the user experience. In fact, this study supports our solution since it proves that haptic feedback enhances the virtual experience of the user. However, we aim to in our project to introduce the haptic feedback as an essential mean of simulating the illusion of walking on different grounds.

4. Requirements analysis

4.1. Functional requirements

This project has four main functional requirements:

i. The insole should be able to simulate three different types of material's textures at least.
ii. The insole should be able to communicate the data of the sensors with the simulation software system.
iii. The insole should be able to receive the type of texture that the user is walking on and the status of the feet from the software system.
iv. The feet activity recognition unit should be able to analyze the status of the feet's movement.

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Use case Diagrams

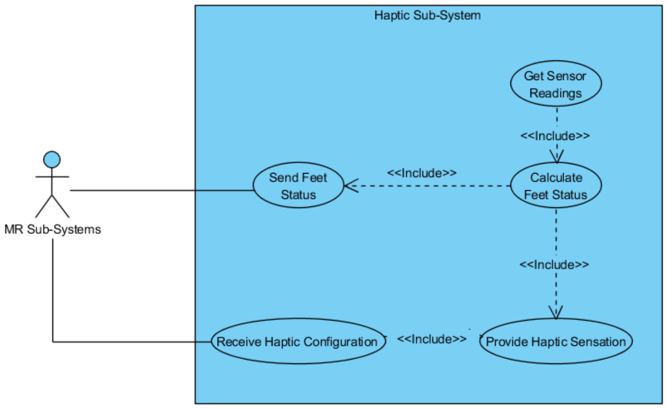

Figure 15: Use Case 01 Diagram for the Proposed Solution

Table 1: Use Case 01 Specification

Functionality	Description
Get Sensors Readings	Receive the readings of the haptic insole sensors.
Calculate Feet Status	Use the sensors received to calculate the status of the feet.
Receive Haptic Configuration	Receive the appropriate configuration for the current environment running on the MR sub-system.
Provide Haptic Sensation	Run the appropriate configuration based on the information received from the MR sub-system.
Send Feet Status	Send the calculated feet status to the mixed reality sub-system.

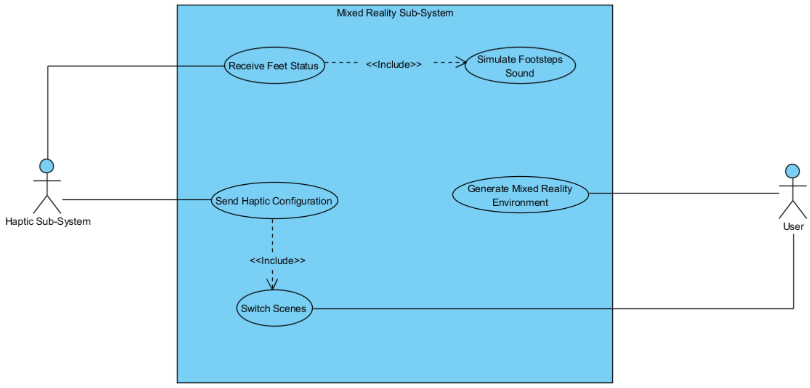

Figure 16: Use Case 02 Diagram for the Proposed Solution

Table 2: Use Case 02 Specification

Functionality	Description
Simulate Footsteps Sound	Receive the feet status and run the appropriate step sound accordingly
Send Haptic Configuration	Send the appropriate configuration id to the haptic sub-system
Generate Mixed Reality Environment	Use the structural sensor to scan the area surrounding the user and augment it to the start the simulation
Switch Scenes	Change the current scene to the appropriate virtual environment
Receive Feet Status	Receive the status of the feet

4.2. Design constraints

Table 3: Technical Design Constraints

Name	Description
Power	Power requirement of motors, microcontroller and sensors: 3V battery.
Vibration Threshold	The vibration frequency should not exceed 800 Hz
Vibration Frequency	Frequency range from 0 Hz to 800 Hz The vibration threshold is 400 Hz
Pulse Duration	Pulse duration should be as twice as the internal vibration period (2/f) sec
Latency	The visual delay threshold should be 60 ms.
Hardware	Limited number of analog input pins in RFduino 6 pins.
Robustness	Battery life should be at least 60 minutes.

Comment [OH9]: Are you sure about this? The threshold is the max frequency!

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Table 4: Practical Design Constraints

Type	Name	Description
Usability	Simplicity	The system should be very simple and user friendly.
	Learnability	The system should not consume time from the user to discover how to operate (only few minutes).
	Comfortability	The system should be comfortable for the user to wear since it is a haptic insole.
Environmental		The system cannot operate in wet environment.
Maintainability	Fixes and updates	The system should be easily updated and easy to fix.
Safety		All the connections (wires) inside the insole should be isolated.
Economic	Cost	The system cost should be affordable for regular user.
Quality	Performance	The system should be efficiently controlling the motors and the sensors should provide very accurate readings.
	Long-life	The system should still operate for the whole testing period (2 months) at least.
Physical	Dimension	The insole should be suitable for the majority of regular users (size 42, 43).

4.3. Design standards

Table 5: Design Standards

Name	Description
BLE - Bluetooth 4.0 (IEEE 802.11)	The system will use a Bluetooth connection between the Mixed Reality subsystem (iPhone 8) and the haptic subsystem (RFduino microcontroller).
GZLL	GZLL is used to communicate between RFduino devices.
USB micro	To connect the iPhone with the Structural Sensor.

4.4. Professional Code of Ethics

Table 6: Code of Ethics

IEEE	ACM	Project Perspective
1. To accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to	- Contribute to society and human well-being. - Avoid harm to others	- The designe in this project guarantees users' safety - The hardware implementation will minimize the power consumption as much as possible

IEEE	ACM	Project Perspective
disclose promptly factors that might endanger the public or the environment		
2. To be honest and realistic in stating claims or estimates based on available data	- Be honest and trustworthy	- All the work and the assumptions are based on respected resources and the latest available data - All results analysis will be performed in the highest possible criteria. Any uncertainty of results will be clearly mentioned in the reports
3. Contribute to society and human well-being.	- Manage personnel and resources to design and build information systems that enhance the quality of working life	- The design will contribute to the obtain a higher level of benefits in rehabilitation and entertainment that is based on integrated haptic & AR/VR technologies
4. To improve the understanding of technology; its appropriate application, and potential consequences	- Strive to achieve the highest quality, effectiveness and dignity in both the process and products of professional work - Improve public understanding of computing and its consequences	- Introducing the integration of both haptic and AR/VR technologies in rehabilitation and entertainment applications will help in familiarizing the public with technology usage in several aspects of life
5. To maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations	- Acquire and maintain professional competence	- Applying the latest available needed technologies in both haptic and AR/VR fields to design this project - Doing deep research about the potential use of technologies for both haptic and AR/VR

IEEE	ACM	Project Perspective
6. To seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others	- Honor property rights including copyrights and patent; - Give proper credit for intellectual property	- All other's work, resources patents are referred to their owners whenever they are used in this project and cited
7. To treat fairly all persons and not to engage in acts of discrimination based on race, religion, gender, disability, age, national origin, sexual orientation, gender identify, or gender expression	- Be fair and take action not to discriminate	- This design can to be used by all people, and benefit them regardless of race, religion, or gender - The team members work together and with others respectfully and collaboratively

4.5. Assumptions

For implementing this project, the following is a list of assumptions:

1. The system will provide enough AR/VR scenarios to test the desired functionality.
2. The data required to simulate different textures is either provided or obtained.
3. The feet activity recognition algorithm provides accurate results.
4. The latency between the software system and the hardware system is negligible.
5. The system takes in consideration both male and female users.

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5. Detailed Solution Design

5.1. Solution overview

The proposed system is an integration of two subsystems: haptic subsystem (haptic insole) and MR subsystem (AR/VR environment). Firstly, the haptic subsystem generates the illusion of walking on a specific surface texture that corresponds to the MR environment such as sand, tree leaves, rocks, etc. The insole utilizes two force sensing resistors in order to provide more realistic experience that takes in consideration the movement and the location of the feet. Besides, the insole deploys an array of three vibrators to simulate the illusion of different surface textures where the vibrators are placed in the insole in a layout that is suitable for the nature of human feet's sensors. The vibrators are controlled using two main parameters: PWM frequency of the motor, and the activation time during a cycle. It appears that through those two parameters, it is possible to provide an assistive feeling to create a more realistic experience of walking on a variety of different textures [22]. The sensors and the vibrators are connected to a microcontroller that acquires the sensors' readings and controls which vibrators to be activated accordingly.

Secondly, the MR subsystem which contains the MR simulator represents the MR environment the user will experience, and it provides the graphics and sounds needed to create the desired environment. The MR simulator also communicates with microcontroller in order to inform the haptic subsystem of which texture is needed to be simulated. On the other hand, the microcontroller performs a certain algorithm to detect the feet status (standing, walking, standing on one foot, etc.) and communicate the status to the MR subsystem. This MR subsystem deploys an algorithm to perform movement analysis using the iPhone's gyro sensor readings. Which provides the system with the user movement statues including the speed and the direction of movement.

A wireless connection between the two subsystems is established using a Bluetooth module. The MR development kit is used to display the AR/VR environment to the user and gives the capability to the user to control the environment options by an associated remote control.

5.2. High level architecture

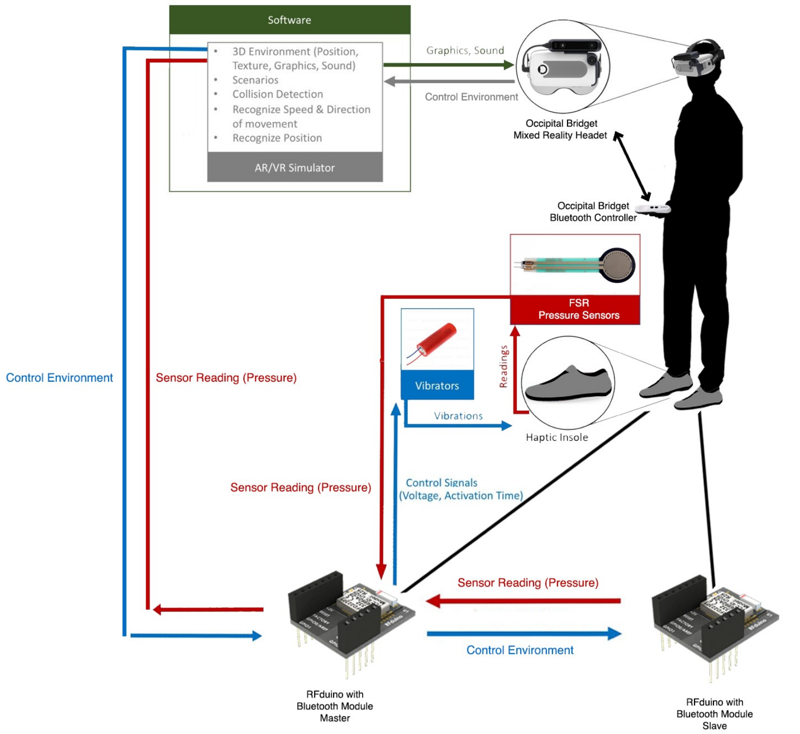


Figure 17: High-level Architecture (Integrated Haptic Insole with MR Environment)

The desired system of this project consists mainly of two co-related subsystems. Each subsystem executes specific tasks and that can be described as follows:

- **Haptic Subsystem (Haptic Insole):**
  In this part, FSR sensors and vibrators are placed inside the insole. The data acquired are send to an RFduino microcontroller which in its turn perform some analysis and recognize the feet status. Then it sends a signal to the MR subsystem if a footstep is taken. It also receives the environment configuration from the MR subsystem and based on that, it controls the vibrators. The hardware connections between the FSR sensors, the vibrators, and the RFduino are shown in figure 18.

Comment [OH10]: We talked about using force sensors as well to measure the weight?

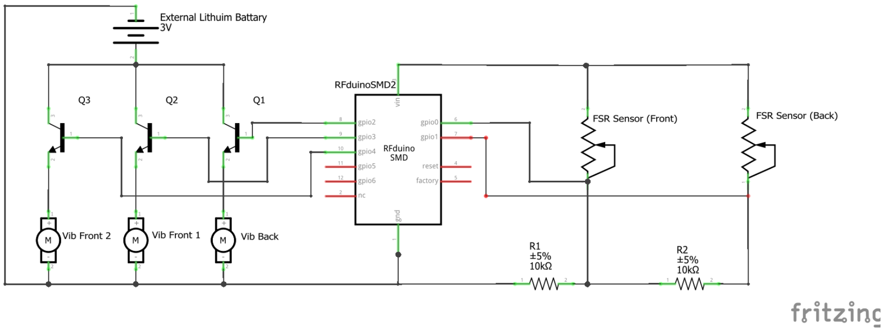


Figure 18: Haptic Subsystem Schematic Diagram

- **Mixed Reality Subsystem:**
  This part of the system generates and renders the AR/VR environment that the user will experience providing him/her the needed graphics and sounds through the AR/VR development kit. It also, as described above, provides the haptic insole with the texture needed to be simulated. All the development is done through Unity software, and then run on an iPhone 8 for the user. The MR subsystem is able to recognize the user's position as well as the speed and the direction of the movement.

- **Foot Statues Recognition Algorithm:**
  The haptic subsystem establishes a connection with the MR subsystem and then runs as described in the algorithm in figure 19. While the flowchart in figure 20 shows how foot statues recognition algorithm works.

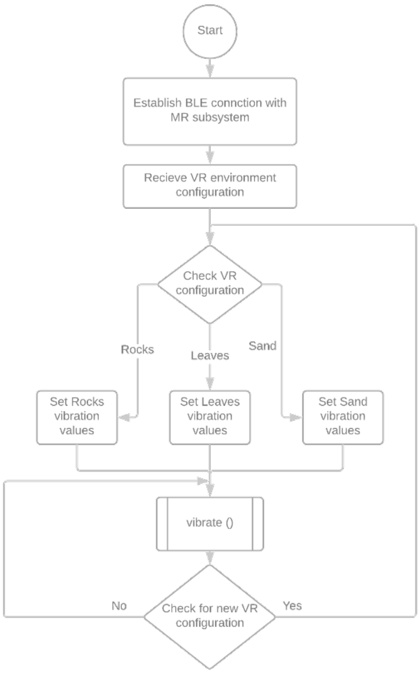


Figure 19: Haptic Insole Logic

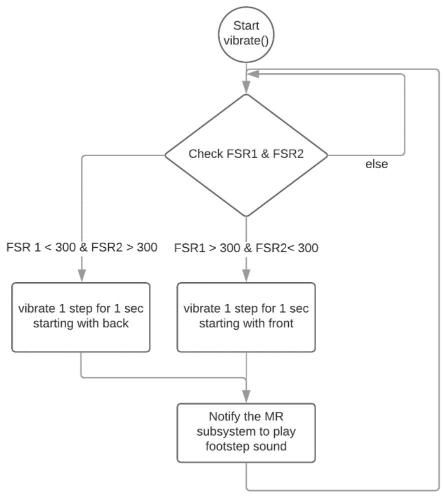


Figure 20: Foot status recognition algorithm

5.3. Behavioral Model

In this section we present the associated sequence, activity, and state diagrams with our desig.

- **Sequence Diagrams:**

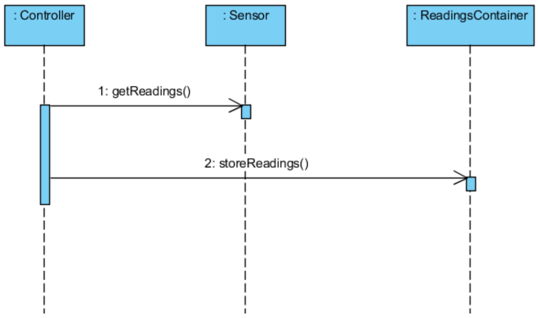


Figure 21: Get sensors readings sequence diagram

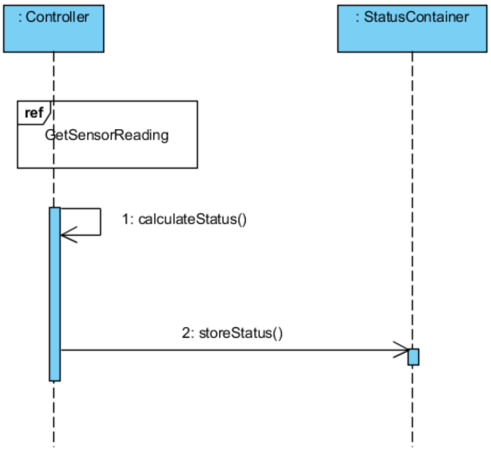


Figure 22: Calculate feet status sequence digram

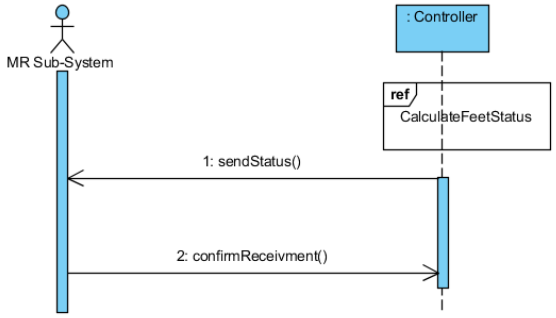


Figure 23: Send feet status sequence diagram

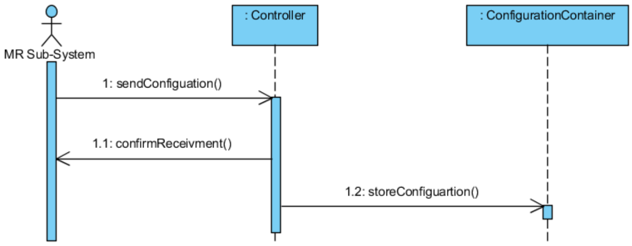


Figure 24: Receive haptic configuration sequence diagram

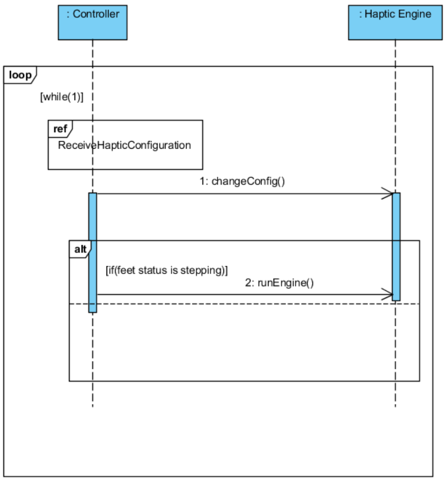


Figure 25: Provide haptic sensation sequence diagram

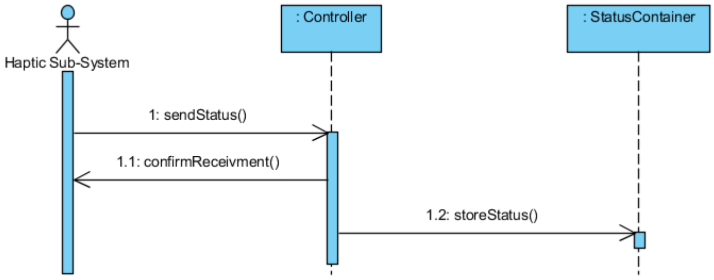


Figure 26: Receive feet status sequence diagrams

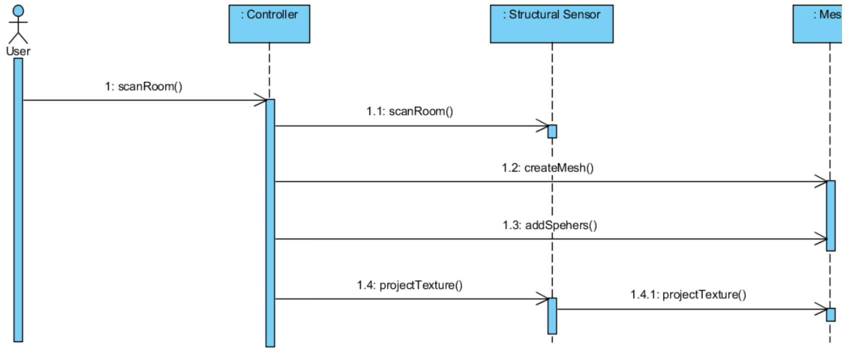


Figure 27: Generate mixed reality environment sequence diagram

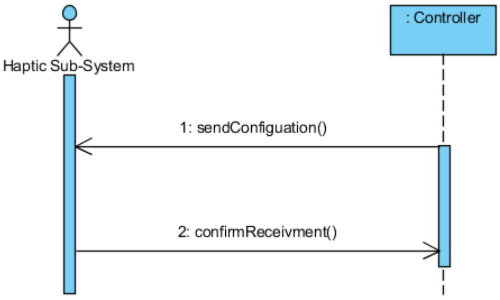


Figure 28: Send haptic configuration sequence diagram

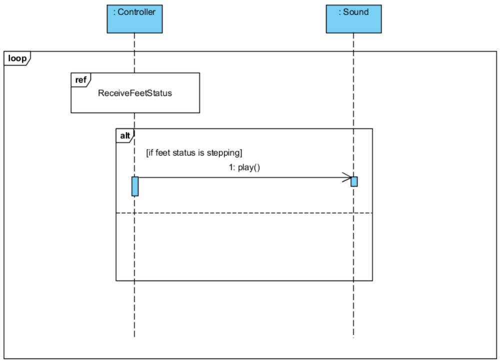


Figure 29: Simulate footsteps sound sequence diagram

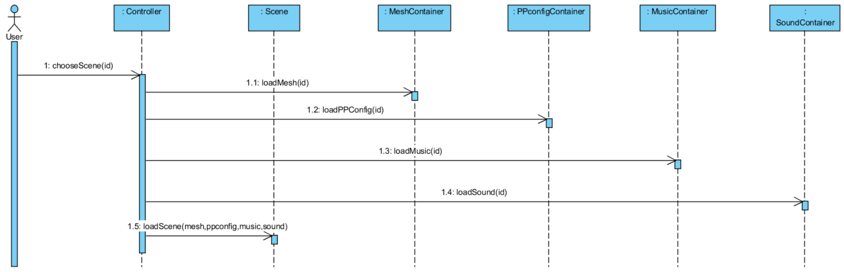


Figure 30: Switch scenes sequence diagram

- **Activities Diagrams:**

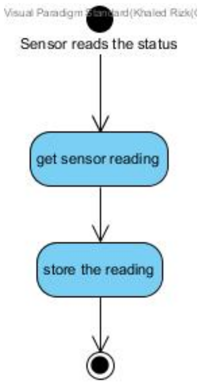


Figure 31: Get Sensor Reading Activity Diagram

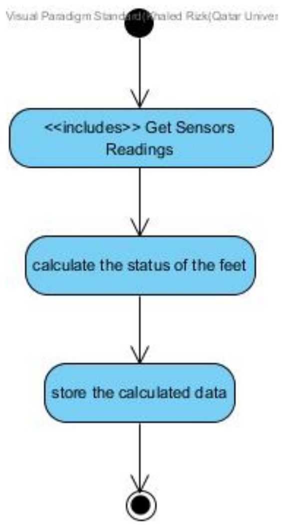


Figure 32: Calculate Feet Status Activity Diagram

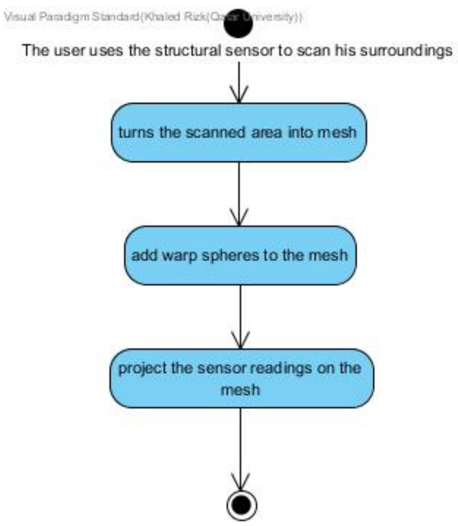


Figure 33: Generate Mixed Reality Environment Actvity Diagram

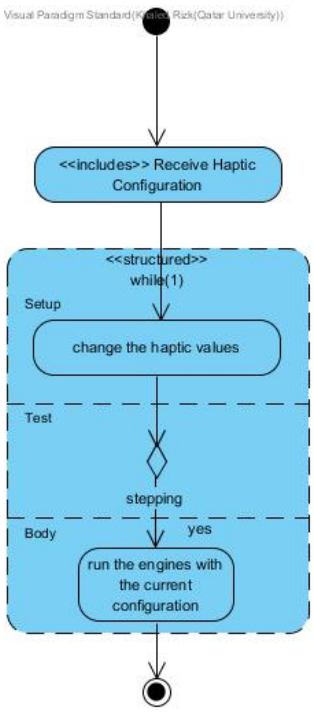


Figure 34: Provide Haptic Sensation Activity Diagram

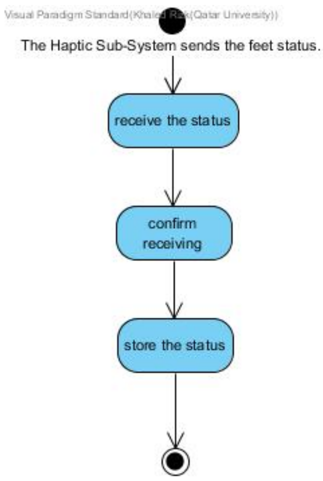


Figure 35: Receive Feet Status Activity Diagram

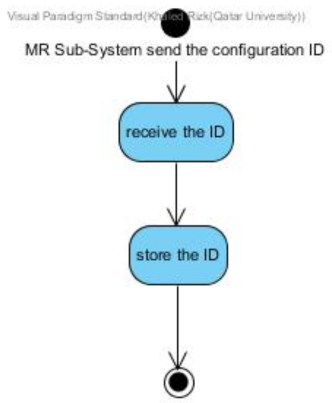


Figure 36:Receive Haptic Configuration Activity Diagram

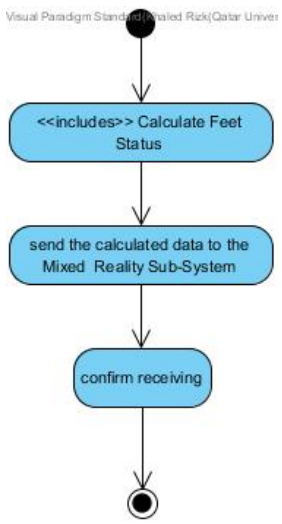


Figure 37: Send Feet Status Activity Diagram

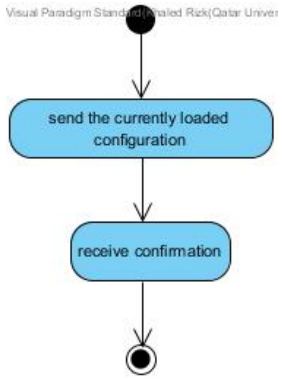


Figure 38: Send Haptic Configuration Activity Diagram

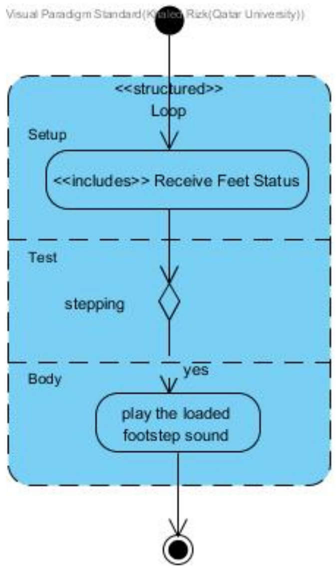


Figure 39: Simulate Footsteps Sound Activity Diagram

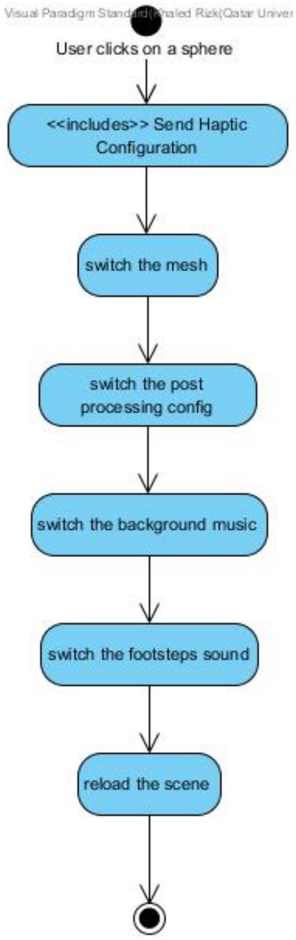


Figure 40: Switch Scenes Activity Diagram

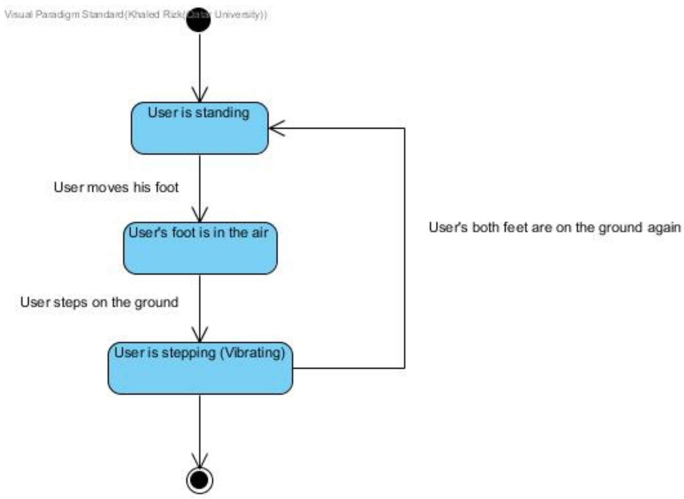


Figure 41: Haptic State Diagram Activity Diagram

- **State Diagram:**

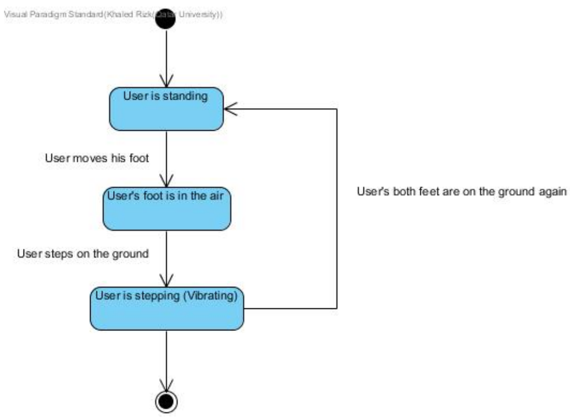


Figure 42: Haptic subsystem state diagram

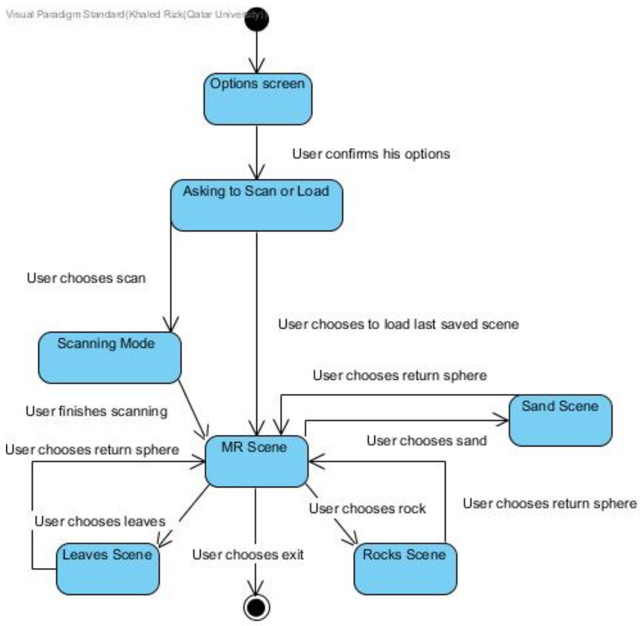


Figure 43: MR subsystem state diagram

5.4. Database Design

Although that our system requires a very simple database, we present in this section the entity relationship design as shown below in figure 33.

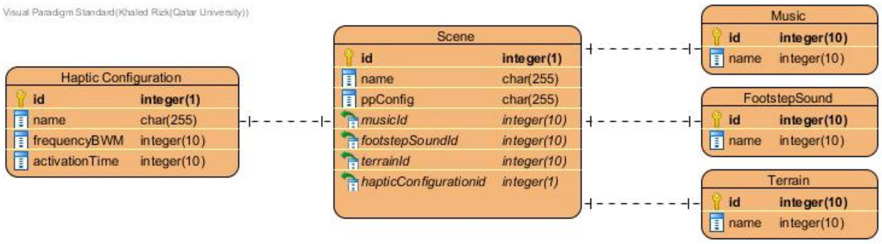


Figure 44: Entity relationship diagram

5.5. Hardware/software used

The implementation of our system requires different hardware and software components. Following are the specification of each device or software used in the system. All related datasheets are available in the appendix as well.

5.5.1. Hardware

Table 7: RFduino Microcontroller Specifications

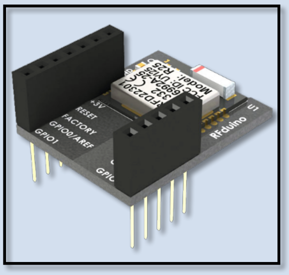
Arduino Mega	Specification	
Microcontroller	RFD22102 RFduino DIP	
Min Operating Voltage	2.1V	
Input Voltage (recommended)	3.0V	
Max Input Voltage	3.6V	
General I/O Pins	6 (all provide digital, analog, and PWM output)	
General I/O Pins Limitation	Max 3 pin to derive current	
Flash Memory	128kb	
SRAM	8 KB	
CPU	16MHz ARM Cortex-M0	
Bluetooth Transceiver	Bluetooth 4.0	
Length	22.86 mm	
Width	28.95 mm	
Depth	18.4 mm	

Table 8: iPhone 8 Specifications

Meta 2 Augmented Reality Development Kit		Specification	
Display	**Resolution**	1334 x 750	
	Refresh rate	60 prs	
Interfaces	**USB Device**	Yes	
	USB Host	1x USB 2.0 ports	
Weight		148 g	

Table 9: Force Sensing Resistor Specifications

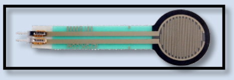
Flexiforce Sensor	Specification	
Thickness	0.008 in	
Length	2.375 in	
Width	0.75 in	
Sensing Area	0.375 in	
Connector	2-pin Male Square Pin	
Substrate	Polyester	
Pin Spacing	0.1 in	
Response Time	< 5µsec	
Operating Temperature Range	-40°C - 60°C	

Table 10: Vibrator Specifications

Enclosed Vibrator	Specification	
Body Diameter	8.7 mm	
Body Length	25.1 mm	
Rated Vibration Speed	13,800 rpm	
Typical Rated Operating Current	100 mA	
Rated Operating Voltage	3 V	
Typical Normalized Amplitude	7 G	

Table 11: Occipital's Bridge Headset Specifications

Occipital's Bridge Headset		Specification	
Display	Resolution	326 PPI	
	Refresh rate	60 Hz	
Viewing Optics		90° Field of View (nominal)	
Operating System		iOS 9+	
Camera Input to Fully Tracked Pose		10 ms	
Lens		PMMA Optical-Grade Acrylic	

Table 12: Occipital's Structure Sensor Specifications

Occipital's Structure Sensor	Specification	
Resolution	VGA (640 x 480), QVGA (320 x 240)	
Refresh rate	30 / 60 frames per second	
Maximum Recommended Range	3.5m+	
Precision	0.5mm at 40cm (0.15%), 30mm at 3m (1%)	
Field of View	Horizontal: 58 degrees, Vertical: 45 degrees	
Battery Life	3-4 hours of active sensing.	

5.5.2. Software

Table 13: Software Components Specifications

Name	Description	
Arduino IDE	Arduino software supports C/C++ based programming language. It is used to write program to control the Arduino microprocessor to generate feedback.	
Unity	Unity is used to design an augmented reality environment to create a 3d model of a virtual road in addition to enabling the interaction with the insole.	
MATLAB	MATLAB is a high-level language that enables you to perform computationally intensive tasks MATLAB was used to extract the required amplitude from the step sound recordings.	
Adobe Audition	Digital audio editing software by Adobe for creating sound effects and cleaning noise.	
XCode	Platform for building iPhone applications.	
Visual Studio	Writing and compiling C# scripts.	

6. Implementation

The proposed solution involves hardware and software development for both subsystems, as well as it requires a high level of integration between the subsystems. Haptic subsystem development and MR subsystem development were running in parallel tracks until the last stage of integration. In this section, a detailed explanation of the implementation process is described into three subsections as shown below.

6.1. Haptic subsystem implementation

6.1.1. Software Implementation

The software development of the haptic subsystem involves two main platforms: MATLAB, and Arduino IDE. Firstly, we recorded the sound of walking footsteps on three different real surfaces: sand, small rocks, and tree leaves. The sound recording was performed using a Samsung S7 Edge mobile phone in a quite QU laboratory. Then, the sound recordings were filtered from noise and divided to three small tracks each of 1 second length and of type (.wav) files using Adobe Audition software. Each sound track contains the sound of one footstep only. These tracks will be used for two proposes: to be played to the user when a real footstep is taken forward or backward during the testing, as well as to extract the sound wave amplitudes for the vibrators usage. Secondly, the three (.wav) file were processed using MATLAB code that extracts the required amplitudes and converts each of them into an array of 10 values in order to be generated as vibrations for each footstep. Which means that for one footstep, the vibration internal frequency will change every 100 milliseconds for 10 times. The values are scaled in a scale from 255 down to 0 as it is the range of understood values by the microcontroller logic. Where 0 means that 3.3 volt is applied to the vibrators and they are working on maximum speed, and 255 means that there is no voltage applied on the vibrators and there is no vibration. This scaling of values is required due to the circuit design and arrangements.

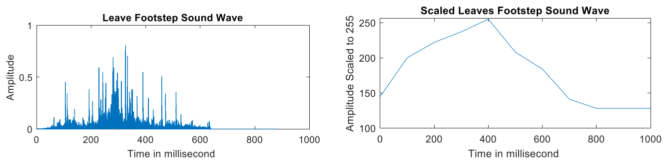


Figure 45: Extracting amplitude from the footstep sound wave example

Thirdly, the vibration control logic was developed according to the algorithm described above. Since we are placing two FSR sensors in each insole as illustrated in figure 45, we utilized a function named *void vibrate(void)* operated in the haptic subsystem to control the vibration that uses those sensor's readings to determine the foot status. This function knows if the user is standing on his/her foot, walking, pushing on the back or the front of his/her foot, or even if the foot is not touching the ground. This is achieved through classifying the foot statues based in the FSR readings. For instance, if both FSR are reading a value that is above 300, then the foot is standing steady on the floor. While if only one FSR is above 300 while the other is less and the readings are flipped directly, then it means that the user is walking.

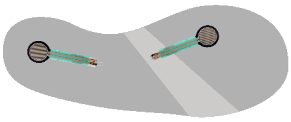


Figure 46: FSR sensors positions

Once the user is recognized in a walking status, the array of vibrators is activated by the *vibrate()* function for 1 second for each footstep. The vibration for one footstep is demonstrated over 10 intervals each of 100 milliseconds. During each interval, the two front vibrators are activated for 50 milliseconds while the back vibrator is off and vise-versa. This transaction between vibrators contributes to enhance the illusion of walking on virtual textures. Moreover, when the *vibrate()* function is called, a notifying signal is sent to the MR subsystem to play a footstep sound simultaneously. The communication with the MR subsystem is done using several functions from RFduinoBLE library.

6.1.2. Hardware Implementation

In addition to acquiring the needed frequencies for the vibrators, designing the logic of understanding, and controlling the vibrations, the haptic insole setup of vibratos and FSR sensors were prepared. Figure 45 below shows the vibrators placement inside the insole. For further details, we used a p-channel transistor to control each vibrator by the microcontroller, and an external 3 volts lithium battery to power the vibrators. While on the other hand, the two FSR sensors were connected to the microcontroller using a 10 K Ohm's resistor each as illustrated in figure 46.

Figure 47: Vibrators positions inside the insole

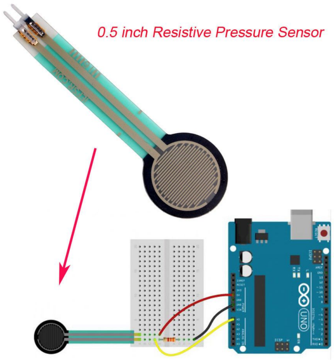


Figure 48: FSR connection illustration

6.2. MR subsystem implementation

The MR subsystem we built utilize Unity 2018.2b, Bridge Engine, Post Processing Stack, Virtual Reality, and Mixed Reality to provide the most immersive experience possible for the user, enhancing the haptic experience with visual and auditory means.

The subsystem first asks the user to scan his surroundings, providing the terrain for the mixed reality scene and using it as a way for the system to track their position and movement. After that, the subsystem starts the simulation by putting the user in a mixed reality scene resembling the physical surroundings they scanned, except for the existence of three spheres which he can click on using the bridge controller to switch to different environments. We preferred using those spheres as augmented objects showing into what's otherwise a realistic environment over a traditional menu to maintain immersion and to avoid the game-y feel as much as possible.

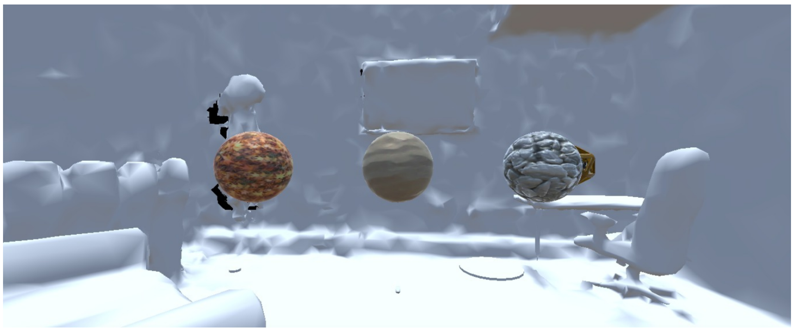


Figure 49: MR scene resembles the room scanned. Sphere-shaped Augmented objects are used to switch to virtual environments

When the user clicks on the sphere he chooses, the scene switches to the associated virtual environment and sends a signal to the haptic subsystem to switch the configuration as requested. It also switches the step sounds to corresponds to the current floor material. Each virtual scene uses different lighting and post-processing to provide a more immersive experience as shown figure 22 and figure 23. The post processing effects include fog, motion blur, chromatic aberration, and many other.

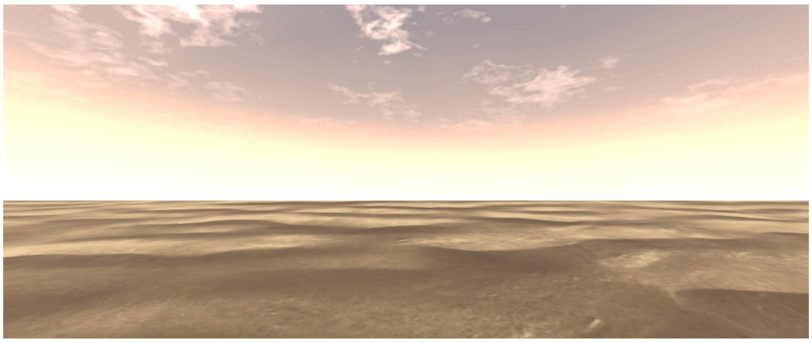


Figure 50: Virtual Environment without lighting and post processing

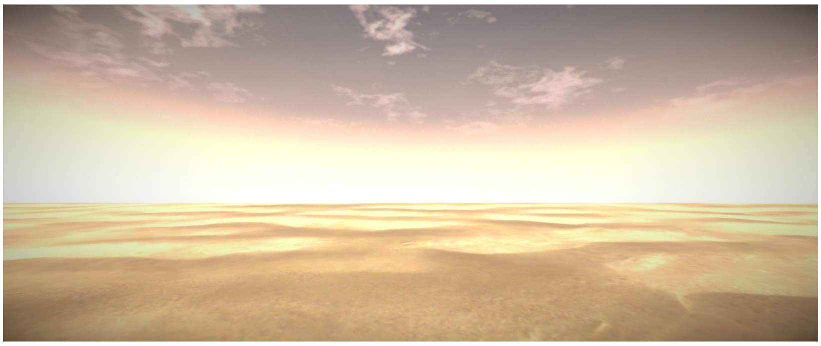


Figure 51: Virtual Environment with lighting and post processing

The system tracks the position and speed of the user and everytime a footstep is taken, the haptic subsystem sends a signal to the MR subsystem to play the appropriate sound, providing the auditory feedback necessary for the simulation. The user can get back to the mixed reality scene resembling his current surroundings by clicking on a sphere that is always behind him if he rotated backward, and from there, he can switch to different scenes. We chose to keep the mixed reality as the link between all the virtual environments to ground the experience to reality.

Unity has been the main tool we used to build the required software for this project, combined with additional plugins, add-ons, and engines. Bridge Engine by Occipital, Bluetooth LE for iOS, tvOS and Android by Shatamlic, and Post Processing Stack by Unity Technology have been the main components for building the software, along with Microsoft's Visual Studio which was used for both writing and modifying the scripts.

Unity offers an enormous array of options for building virtual scenes, allowing the user to design their own terrains with different geometry, texture, and materials. It also provides handy tools for spreading objects like trees and buildings in random but convincing ways, which cuts a considerable amount on the required time to build a virtual scene. Moreover, Unity offers a lighting system that allows the user to adjust the values, direction, colors and intensity along with other attributes of the lighting sources to their linking, offering the option to pre-bake the lighting designed for a consistent user experience as illustrated in figure 50. This lighting technology proved handy in giving each virtual environment its own unique atmosphere and sense of place, combined with the auditory elements.

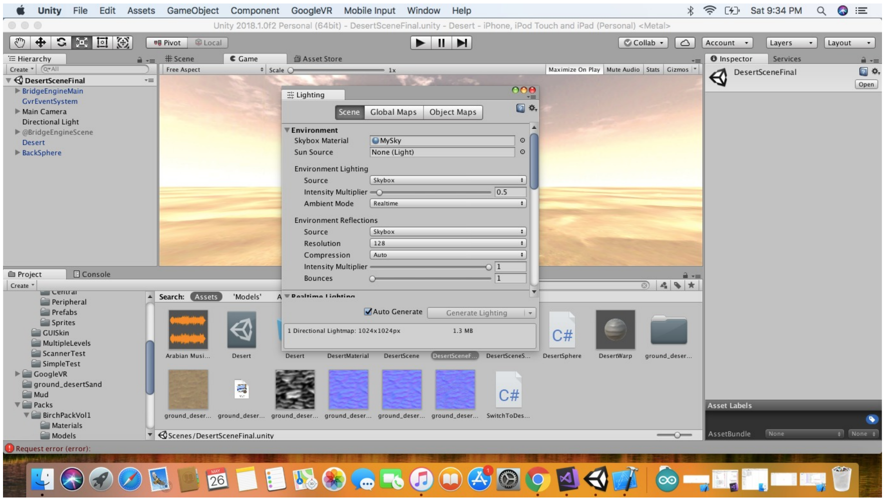


Figure 52: Lighting option in Unity

Bluetooth LE for iOS, tvOS and Android by Shatamlic is a plugin that works as an implementation of Bluetooth Low Energy technology in unity, allowing it to communicate with other devices while running on iOS or Android. We used this device as the main integration tool for our system, allowing two-way communication between the haptic subsystem and the MR subsystem.

Bridge Engine comes with useful tools to enhance both the virtual and mixed reality experience for the user. Offering integration with the structure sensor, interrogation with the bridge controller and open control over its scripting, implementation of the scanning process, providing the information necessary to build a mixed reality scene, and modified version of the Google VR camera that uses gyro technology to track the user's head movement, among other things. Our software was built mainly around this engine, which proved a competent implementation of VR technology to start building on.

Post Processing Stack by Unity Technology is a plug-in that helps tremendously in giving depth and atmosphere to the virtual environment. The plugin gives the user a wide array of options that they can adjust and mix together to build the final image they aspire. Those options include antialiasing, which is essential in giving the environment a realistic feel, fog, depth of field, motion blur, bloom, and other. Those options allow to make the scenes behave more like they should in real life, giving the desert the wide depth of field and bloom effects emphasizing its wideness and hot nature, for example. PPS was one of the essential tools in providing an immersive and different experience from a scene to another.

6.3. Implementation Challenges

The system is fully integrated through establishing a Bluetooth channel of communication between the two subsystems. Each subsystem is prepared to send and receive the data with the other subsystem as explained above. However, establishing the Bluetooth communication was difficult and needed to try more than one option of Bluetooth module. Resulting of changing many of the hardware components such as the lilypad Arduino that was considered at the beginning of the project. Even though RFduino is more suitable when it comes to communicate with iPhone using BLE, achieving the synchronization needed consumed a lot of time. In addition, finding the most appropriate way to place the vibrators required testing many proposed layouts as shown in figure 51.

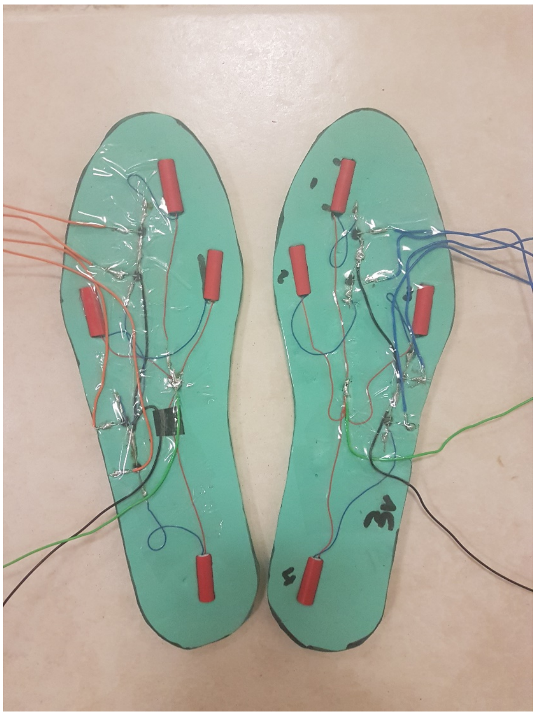


Figure 53: Testing 4 vibrators layout

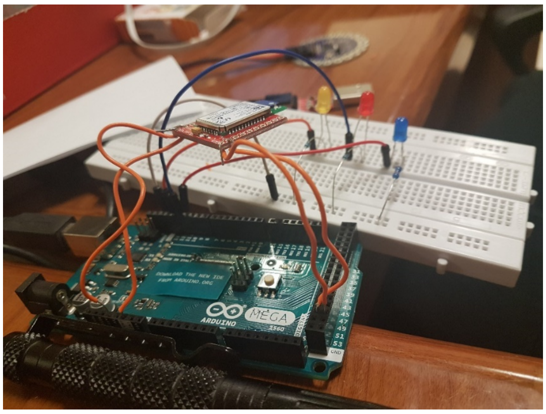


Figure 54: Testing the response several types of Bluetooth modules

Figure 55: A sample form the testing process

Figure 56: Testing the real textures

Figure 57: Full system initial testing

Figure 58: Haptic insole functionality testing

7. Testing

7.1. Testing methodology

The first goal behind the testing of this project is to study the effect of media (audio, video and MR) with haptic vibrations to deliver a more-realistic feeling. The second goal of the testing is to find out the ability of the project to deliver three distinguishable feelings of materials. Therefore, two experiments will be conducted to achieve these goals: Haptic Efficiency Experiment, and Haptic Texture Recognition Experiment. Before testing the system, we considered two ways to divide the subjects:

- Between-group Testing Design:

  A between-group design is an experiment that has two or more groups of subjects each being tested by a different testing factor simultaneously. This means each group will be a subject of an experiment.

- Within-subject Testing Design:

  This design applies the same variations of conditions to each subject to observe the reactions. This means that subjects within one group will conduct the same type of experiment with identical circumstances and conditions.

By applying the above into our system's testing, two groups of subjects (24 subjects each) are tested separately. The first group participated in an experiment called Haptic Efficiency and the second group took part in Haptic Texture Recognition. Therefore, the best type of testing design is between-group testing design. The reason for choosing this design is that it separates the two groups such that a subject who has tried the haptic vibrations in the first experiment will not try it in the second. Such separation is important so that the experience of the subjects from one experiment does not affect the results of the other one.

For each of the two experiments, the within-subject testing design is applied as the results of each subject is observed and recorded. Each of the subject (within one experiment) is put under the same condition and is asked the same questions other are asked. Their feedback was recorded in a table where data is collected for later analysis.

To analyze the collected data and test the hypotheses, the T-test is chosen. In fact there are three reasons for this choice:

- The two experiments were conducting independently from one another.
- The number of subjects in each experiment is less than 30.
- The goal is compare two means.

7.1.1. Haptic Efficiency Experiment

To achieve the first goal, 7 models are created. The comparison among them will provide a chance for analysis. In each model, the subjects will provide their feedback of experience as a number on a scale from 0 to 10. On this scale, 0 represents the feeling of walking of a flat ground with no texture where 10 represents the feeling of walking on a real material. Each of the subject will be asked to provide a number that expresses the quality of feeling.

- Model 1 (The Trivial Model): In this model, the user is asked to walk on flat ground and asked to focus on the feeling on their feet. Despite the triviality and simplicity of this model, it is important because it allows the user to consciously experience the feeling of walking of a flat floor, so they can feel the difference between flat floor, simulated texture and real texture. After that, the subject is asked to walk on real material to experience the feeling before trying the haptic insole.

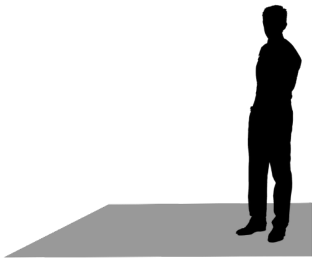


Figure 59: The trivial model setup illustration

- Model 2 (The Basic Model): In this model, studied frequencies and amplitudes of vibration are used and delivered to the user through the foot-wearable haptic insole.

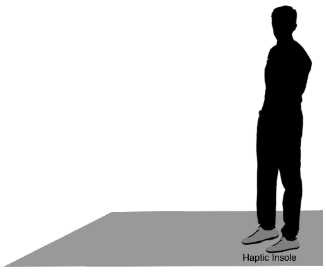


Figure 60: The basic model setup illustration

- Model 3 (The Audio Model): An audio material related to the type of material is viewed the user in addition to the foot-wearable haptic. For example: "A sound track of footsteps on sand is played to the user when the feeling of sand is delivered to them using the haptic insole."

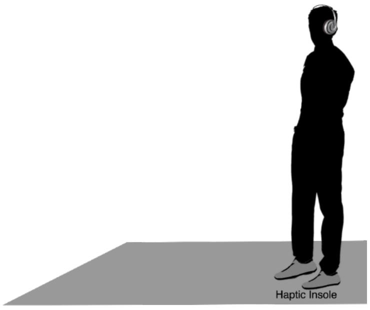


Figure 61: The Audio model setup illustration

- Model 4 (The 2D Model): A two-dimensional visual material related to the type of material is viewed the user in addition to the foot-wearable haptic. For example: "A video of a beach is viewed to the user when the feeling of sand is delivered to them using the haptic insole."

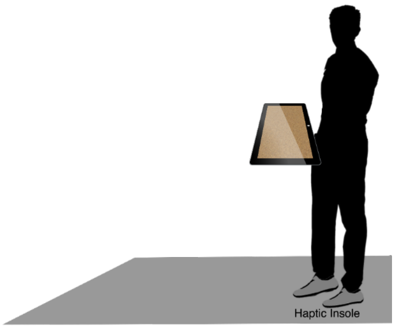


Figure 62: The 2D model setup illustration

- Model 5 (The Audio-2D Model): Both audio and two-dimensional visual material are viewed to the user in addition to the foot-wearable haptic. For example: "A video of a beach and a sound track of footsteps is viewed to the user when the feeling of sand is delivered to them using the haptic insole."

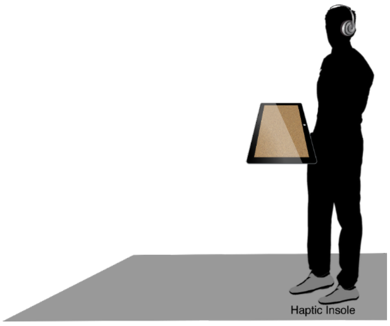


Figure 63: The audio-2D model illustration

- Model 6: (The MR Model): Using Occipital Bridget headset and an environment that we designed on the software, the user is put in an environment related to the type of material that is being delivered to them via the foot-wearable haptic insole. For example: "The user is put in a virtual/augmented environment of the real room they are physically at plus beach-related elements such as a ground of sand and a sound track of footsteps on sand."

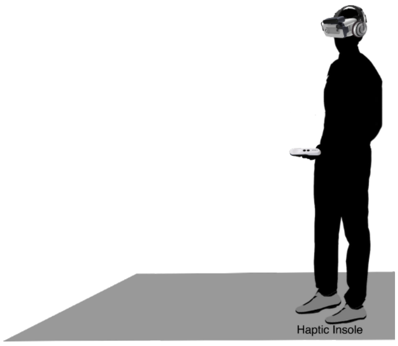


Figure 64: The MR model setup illustration

- Model 7: (The Real Model): In this model, the user is asked to walk on a real material. For example: "the user is asked to walk on sand". Each of the subject is asked to provide their feedback.

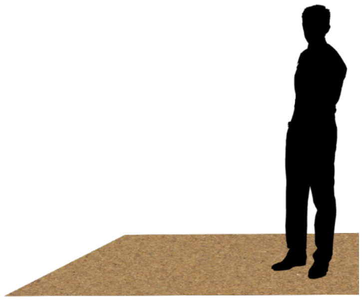


Figure 65: The real model illustration

The importance of this model is to refresh the human memory of how real material feels like. The comparison of one subject of this model with other models helps the subject to provide an accurate feedback of their experience. For this model, samples of real materials are collected in boxed that are large enough for a full average human step.

Figure 66: Prepared real surfaces samples used in the testing

7.1.2. Haptic Recognition Experiment

This test is made to tell whether subjects can tell the type of texture (sand, rocks, leaves) they are experiencing as they are wearing the haptic insole and listening to the associated recorded footstep sound. To achieve this, the subjects are asked to wear the haptic insole, listen to the associated sound without having any visual aid and then they are asked to choose the type of the texture they are feeling out of the three textures (sand, rocks and leaves). After each subject tries the experiment, the feedback is recorded in the form of true or false (true if the subject can tell the type of texture and false if not.

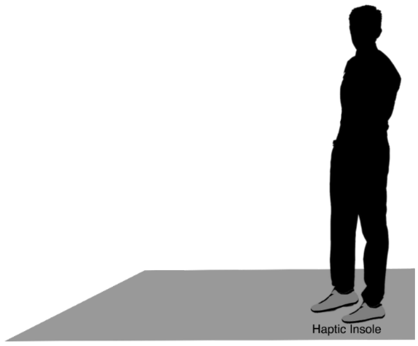


Figure 67: Recognition test setup illustration

7.2. Testing results

7.2.1. Haptic Efficiency Testing Results

The bar chart below shows how the subjects responded differently to different models. As a result of our testing procedure we were able to reach the following conclusions:

1. The haptic insole vibration is able to deliver 58.5% of the real feeling to the user. This rate is far from the real experience. However, it is much enhanced by using different types of multimedia as shown in the next two results.
2. Looking at second and third bars from the left, it is possible to see that audio enhances the experiences of the subjects 32% more while viewing a two-dimensional material (video) to the subjects enhances the experience by only 14%. Furthermore, the forth bar which is a mix of both audio and video shows that the performance is enhanced to 33%. This can be explained by studying the human behavior while walking. Humans often do not look at each step they are taking as muscle takes care of walking without counting of the sense of vision. However, the ear is always listening to the interaction sound of steps. So, the feeling of walking on texture is strongly related to the sense of hearing.
3. Looking at the first two bars on the right, it is possible to notice the most important conclusion with is that the experience of the user using both haptic insole combined with virtual/augmented reality comes very close to the true experience with real material with percentage of 93%. The reason that the MR model performs better than the audio/video model is due to the fact that it takes the user to a full environment that immerses him/her for an almost real experience.

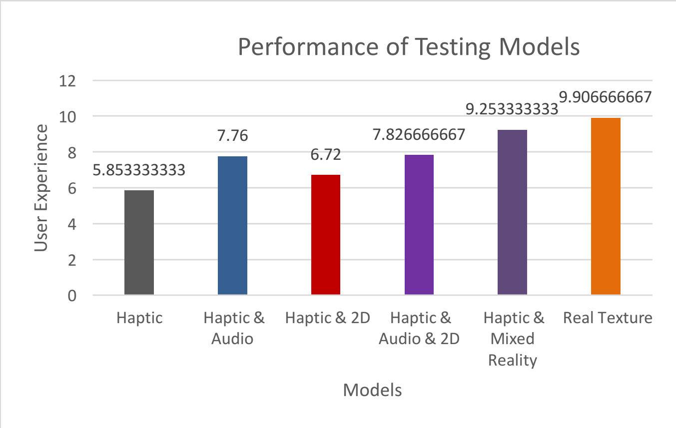


Figure 68: The performance of different Testing models based on subjects' experience

7.2.2. Haptic Recognition Testing Results

The bar chart below shows how the subjects responded recognition test. Which resulted to the following conclusions:

1. The recognition of the three different materials (sand, rocks and leaves) are above 80%.
2. Subjects scored 92%, 81%, and 85% on the recognition of sand, rocks and leaves respectively.
3. Sand scored best because of the many continuous high amplitudes compared to rocks and leaves.
4. The recognition of leaves scored second best because of the sharp amplitudes of its signal in addition to the uniqueness of the feeling of walking on leaves compared to other materials.

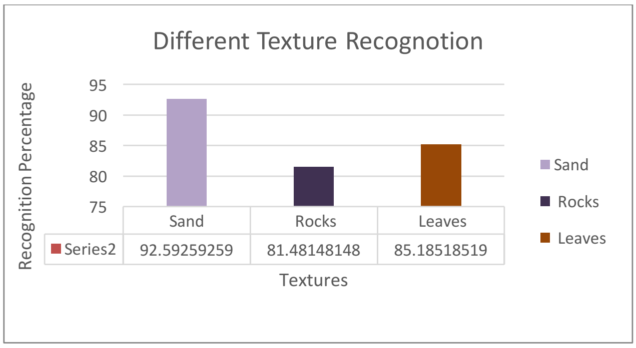


Figure 69: Recognition of different materials through haptic insole

7.3. Hypotheses testing and interpretation

Through the testing we were able to verify that a set of hypotheses are proven to be true. We know that a hypothesis is accepted when the p-value of the testing sample is less the significance value of 0.05. All the following hypotheses were accepted:

1. Playing audio of the material being tested significantly enhances the user experience when using it haptic vibration with it.
2. Playing 2D visual material (video) of the material being tested with enhances the user experience when using it haptic vibration with it.
3. Playing both 2D visual material and audio of the material being tested with enhances the user experience by more than playing only audio or video when using it haptic vibration with them.
4. Applying haptic vibration with Virtual/Augmented Reality Environment significantly enhances the user experience by more than both audio and video combined when using it haptic vibration with it.
5. By applying only haptic vibration, the recognition between the three different materials (sand, rocks, leaves) has a success rate of more than 78%.

Table 14: Data analysis of testing results

	Model 2 Haptic	**Model 3 Haptic & audio**	**Model 4 Haptic &video**	**Model 5 Haptic audio & video**	**Model 6 Haptic and VR/AR environment**	**Recognition Test**
t (Observed value)	2.304	2.248	2.285	1.854	2.029	2.304
t (Critical value)	1.714	1.714	1.714	1.714	1.714	1.714
DF	23	23	23	23	23	23
p-value (one-tailed)	0.015	0.017	0.016	0.038	0.027	0.015
alpha	0.05	0.05	0.05	0.05	0.05	0.05

- Difference: is the difference between the measured mean and theoretical mean.
- T (Observed Value): is the value collected from the observed test.
- T (Critical Value): it entails comparing the observed test statistic to the cutoff value.
- DF: The degree of freedom and it is equal to number of subjects -1.
- P-value: the probability of finding the observed, or more extreme, results when the null hypothesis (H0) of a study question is true.
- Alpha: The significance value and it is the probability that a result occurred by chance. The significance value is compared to a predetermined cutoff (the significance level) to determine whether a test is statistically significant. If the significance value is less than the significance level (by default, 0.05), the test is judged to be statistically significant.

- **Hypothesis 1:**

"Playing audio of the material being tested significantly enhances the user experience when using it haptic vibration with it."

Model 3: Audio with Haptic Insole

Test interpretation:
H0: Audio enhances the experience by 29%
Ha: Audio with enhances the user experience by more than 29%

As the computed p-value is lower than the significance level alpha=0.05,
one should reject the null hypothesis H0, and accept the alternative hypothesis Ha.

The risk to reject the null hypothesis H0 while it is true is lower than 1.72%

Therefore, the hypothesis is accepted, and audio enhances the experience by 29%.

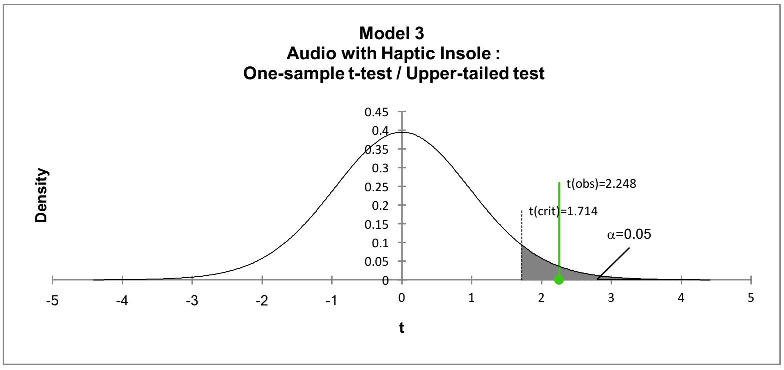


Figure 70: Hypothesis 1 testing

- **Hypothesis 2:**

"Playing 2D visual material (video) of the material being tested with enhances the user experience when using it haptic vibration with it"

Model 4: 2D Visual Material with Haptic Insole

Test interpretation:
H0: 2D visual material enhances the experience by 10%
Ha: 2D visual material with enhances the user experience by more than 10%

As the computed p-value is lower than the significance level alpha=0.05,
one should reject the null hypothesis H0, and accept the alternative hypothesis Ha.

The risk to reject the null hypothesis H0 while it is true is lower than 1.59%

Therefore, the hypothesis is accepted, and video enhances the experience by 10%.

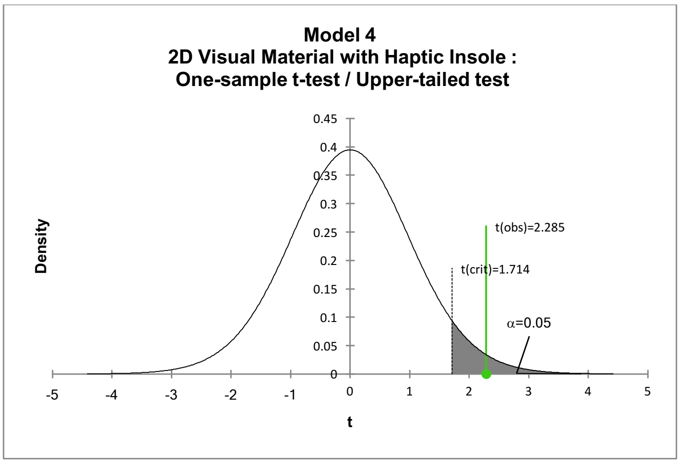


Figure 71: Hypothesis 2 testing

- **Hypothesis 3:**

"Playing both 2D visual material and audio of the material being tested with enhances the user experience by more than playing only audio or video when using it haptic vibration with them."

Model 4: Both 2D Visual Material Audio with Haptic Insole

Test interpretation:
H0: 2D visual material enhances the experience by 10%
Ha: 2D visual material with enhances the user experience by more than 10%

As the computed p-value is lower than the significance level alpha=0.05,
one should reject the null hypothesis H0, and accept the alternative hypothesis Ha.

The risk to reject the null hypothesis H0 while it is true is lower than 3.83%

Therefore, the hypothesis is accepted and playing both audio and video enhances the experience by 30%.

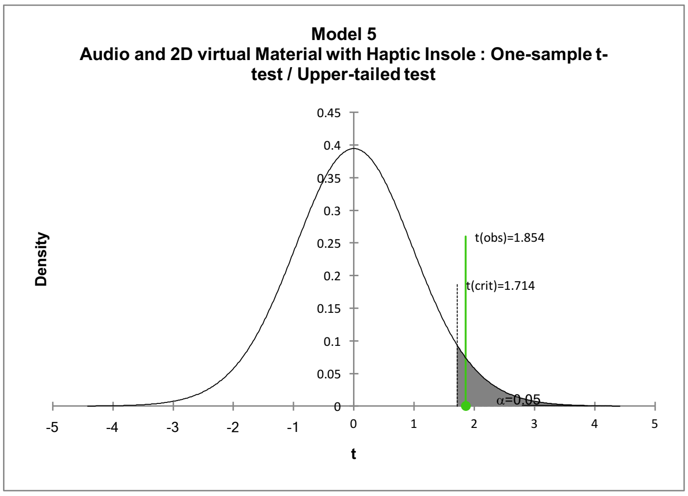


Figure 72: Hypothesis 3 testing

- **Hypothesis 4:**

"Applying haptic vibration with Virtual/Augmented Reality Environment significantly enhances the user experience by more than both audio and video combined when using it haptic vibration with it"

Model 6: Virtual & Augmented Reality with Haptic Insole

Test interpretation:
H0: Virtual/Augmented Reality Environment enhances the experience by 55%
Ha: Virtual/Augmented Reality Environment with enhances the user experience by more than 55%

As the computed p-value is lower than the significance level alpha=0.05,
one should reject the null hypothesis H0, and accept the alternative hypothesis Ha.

The risk to reject the null hypothesis H0 while it is true is lower than 2.71%.

Therefore, the hypothesis is accepted and having a Virtual/Augmented reality enhances the experience by 55%.

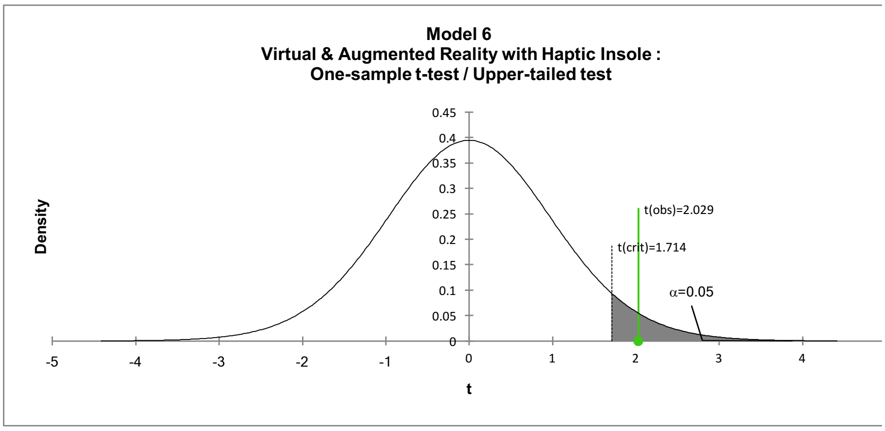


Figure 73: Hypothesis 4 testing

- **Hypothesis 5:**

"By applying only haptic vibration, the recognition between the three different materials (sand, rocks, leaves) has a success rate of more than 78%"

Recognition Test: Material Recognition Success Rate

Test interpretation:
H0: Haptic insole vibrations allow user to recognize the type of material with success rate of 78%
Ha: Haptic insole vibrations allow user to recognize the type of material with success rate of more than 78%

As the computed p-value is lower than the significance level alpha=0.05,
one should reject the null hypothesis H0, and accept the alternative hypothesis Ha.

The risk to reject the null hypothesis H0 while it is true is lower than 4.90%.

Therefore, the hypothesis is accepted, and the success rate of material recognition is 78%.

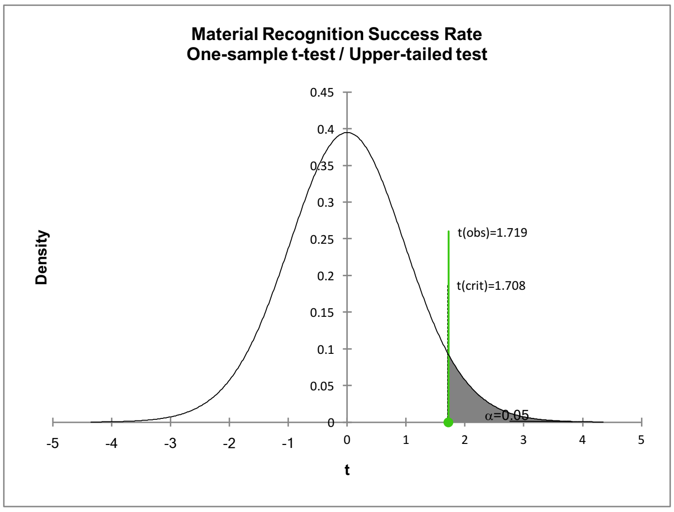


Figure 74: Hypothesis 5 testing

8. Evaluation of the impact of the engineered solution

The proposed solution contributes, if implemented, to the solving of some economic, environmental, and societal problems on different levels. For the last decade, VR technology applications were involved in many training areas such as medicine, police forces, army forces, fire fighters, and rehabilitation. In addition to that, it is used for cultural and entertaining purposes. The design in this project introduces an essential enhancement by providing foot haptic feedback. This enhancement increases the realism of the wide range of possible applications. Which in turns increase the efficiency of MR-Haptic systems when they are applied in different training and entertainment field.

- Economic: Indeed, it is much cheaper for training academies to use MR-Haptic training environment than real environments. To illustrate, some very specialized police and army training require sensitive and expensive tools, which costs those academies very high budget. If the integrated system developed in our project were applied to create a fully immersive training environment, it will contribute to increasing the efficiency of these virtual training systems and make more reliable, leading to saving police and army forces budgets.
- Environmental: Providing more immersive MR-Haptic experiences decreases the need to run real training environment. As it is known, some training environment causes high damages to the environment, especially in army areas.
- Societal: This is an essential aspect of the expected impact of MR-Haptic systems. In fact, the implementation of the proposed design in rehabilitation and cultural applications assists in solving several issues. For example, too many old people who are in a rehabilitation period are not able to take a walk in real natural environment due to their health conditions. By introducing this solution, we can bring any desired environment on a high level of realism to the rehabilitation centers, which we assume will reflect on the users' psychological wellness. Moreover, using a fully immersive MR-Haptic designs can significantly assist in developing more realistic experiences for cultural purposes. For example, one of the potential applications is to create and develop a full simulation for the Qatari people live before 300 years using MR-Haptic system.

Table 15: Impact evaluation

	Evaluation Context	Level of Impact (High, Medium, Low)
1	Global	Low
2	Economic	High
3	Environmental	Medium
4	Societal	High

9. Conclusion

In this project, we proposed a design for an integrated immersive MR-Haptic system that enhances the user's experience of walking on virtual textures. Our system deployed the newest available technology for creating the MR environment, as we were able to develop our own haptic insole. The results of the experiments that we conducted show that applying haptic feedback to the user enhances the user's experience by 29%. In fact, this project adds a valuable contribution to the foot haptic research area since only few works were presented to the engineering society before. We believe that by developing more immersive MR-Haptic systems, like the one developed in this project, we can improve the quality of many training, entertainment, and rehabilitation applications.

10.Future work

The human's perception of texture depends on 5 dimensions as discussed earlier in the background section. In our system we were only able to generate the vibration dimension, while for achieving a more realistic and immersive experience future work should extend the design, so it can provide a way to control the friction and the viscosity of the desired texture. Off course this is not an easy mission to be accomplished due to the limitation of the related work in this field. In addition, keeping the mobility feature in the system makes it hard for new designs to provide the other dimensions such as friction and viscosity.

The vibration that was provided in our system depends on the associated sound wave of a footstep on the desired texture. However, in theory it is possible to generate vibrations that depends on the physical properties of the texture, ad these vibrations are able to create the required illusion. In order to accomplish this in future designs, we need firstly to acquire the frequencies of each texture and create our own database due to the shortage in these data online. Since it is not published by other researchers. We believe that acquiring this database will enhance the quality of the generated vibrations leading to more realistic experience.

11.Student reflections

11.1. Faher's reflection

Senior Project 2018 was an end of long journey and beginning of a very promising one. I have been blessed to work with my two partners Mohamed and Khaled and my kind supervisor Dr. Osama Halabi who was an older brother that took held our hands not only through our project but through important parts of my journey in computer science.

Our project combined both principles of computer science and computer engineering in a beautifully complex ways. I had to learn things I have not learn in any course in Qatar University not only to work on the project but for the passion of building skills in our wide field that I would not have learnt anywhere else. Working the Haptic Insole was a window that had a beautiful view to the sea of human-computer interaction. Going from the bare basics of understanding human perception using our senses and deploying technology to take interaction to another new level was an astonishing trip filled with bumps and surprises that we had to deal with to reach the deadline.

As for the project, it has forced me to build a new set of academic and non-academic skills that I did not know existed. One of the skills I am happy to learn is soldering wires and components to build a hardware product. Two, writing a professional research after long days of collecting information and extracting what is required. Three, data analysis, which was one of my future plans to specialize in, is a skill I learned in less that a week to analyze the data we collected in the project during the testing phase. Four, project management and time control are something that was hard to maintain but I learned to take a look at the bigger picture of projects first then break it down into pieces and work on them separately. This also known as divide and conquer which is something I realize that I am far away from mastering the more I learn about it.

As for my partners, Mohammad and Khaled are two of the kindest people I have met in university. The three of us have very different interests and goals in life. However, we were able to combine our skills in one project that asked for them. Mohammad, a great manager and a very diplomatic person, took upon organizing big parts of our project and taking our project goals to more ambitious levels. He has also deployed his skill in hardware design and implementation in a great effort. I learned many things from Mohammad. A lot of these things are non-academic such as communicating with people which was a weakness for me and overcoming one's emotions when it comes to team work. Khaled, my computer science colleague, taught me how to love virtual and augmented reality and how to be patient with them especially that the machine we were using had humble capabilities. Khaled and I had different views about a lot of things, but we put effort to respect each other's ideas and opinions not matter how much we disagree. I had a great time working with my partners for a whole year and I would love to work with them on something in the future. Yes, we did have tough time times where we yelled at one another and reacted emotionally to come difficult situations, but I would not change anything about this experience.

As for my supervisor Dr. Osama Halabi, the Master of Human-computer interaction and the prince of brainstorming and innovative ideas, has left a lot in my personality not only as a student but also a person. Dr. Halabi flow of ideas impresses me. He bounces from one creative idea to a more innovative one. He is not only a great leader but an amazing listener who listened to our opinions and problems and handled our laziness, at some points, with patience and love instead of judgment and disappointment. I envy Dr. Halabi's kids for the great father they have and his fun passion that he shares with everyone around him.

I would like to thank everyone who took part in this journey, helped us practically or emotionally. I would like to thank the computer science and engineering department and the great support it has provided us.

11.2. Khaled's reflection

Throughout the year, this senior project proved a tremendous learning experience for me, not just on an academic level, but also on a managerial and even human level. It helped me learning the importance of teamwork, and how to divide the work between me and my colleagues, and to focus on my strongest suites, accepting and weaknesses, and trusting in other people abilities. It also taught me how to work around deadlines and under pressure, and what it means to tackle a project of this size for the first time in my life. Virtual Reality has always been a passion of mine, and this project has been a blessing giving me the opportunity to work and develop for both VR and AR hardware. It's an experience that I'm glad I went through.

11.3. Mohammad's reflection

In this project I had the opportunity to go through very rich, challenging, and unique experience. I had the chance to apply several concepts that I studied in the previous years. As well as I learned too many new concepts and techniques in VR, AR and Haptic fields. The hands-on experience we have gone through in this project was very useful in several aspects. For instance, I had to do a lot of hardware debugging, and to work hard on accomplishing the full system integration. This project thought me how to be patient and how to learn from failure. I also had the pleasure to work days and nights with my incredible colleagues Faher, and Khaled. We shared many beautiful moments together and were able to go through challenges together. Moreover, I was glad to be working under the supervision of Dr. Osama who thought us about Haptic research methodologies. He was always supportive to us through his notes and direction all along the past year. The regular meeting that were attending with him helped us to keep our project on the right track. To conclude, I can only say that I learned in this project about myself more than I have expected.

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Appendix A

Project plan

Project milestones

	Description	Deliverable
Milestone 1:		
Project requirements and specifications	• Understand the requirements of the project. • Choose a set of problems and suggested solutions	A list of problems with corresponding proposed solutions.
Problem statement	• Agree upon a problem, and propose a solution. • Finalize the problem statement	Project abstract
Introduction and motivation	• A detailed description of the problem and solution, including technical and non-technical challenges. • Focus on project significance and objectives.	• Introduction and motivation • Project objectives
Milestone 2:		
Background and literature review analysis	• Develop a background to base the project on • Refer to previous work in research papers	• Complete background and literature review analysis
System design	• Develop system use case diagram • Agree upon hardware and software to be used for implementation • Agree upon hardware/software partitioning	• System use case diagram • Hardware/software to be used
Milestone 3:		
Requirement analysis	• Specify functional requirements, design constraints, design standards, professional code of ethics, and project assumptions.	• Detailed requirements analysis
Milestone 4:		
Proposed solution	• Design a high-level architecture of the project • Detailed description of system implementation, including main components, interfaces, and interaction between them.	• System implementation statement • Updating hardware/software to be used • Updating use-case diagram

Milestone 5:		
Complete final report	• Complete and review the final report	• Update the final report with any change or correction
Milestone 6:		
Prepare final presentation and demonstration	• Prepare the final presentation • Rehearse for the demonstration • Demonstrate the project to the examiners	• Final presentation

Project milestones

	Description	Deliverable
Milestone 1: Preparing Phase		
Receiving Hardware Components	• Collecting components and handling financial details	Hardware components
Getting familiar with hardware components and software platforms	• Opening the components • Testing the components • Minor integration between components for testing purposes	Ready functional hardware components for building the project
Setting up coding environment	• Installing MacOS and installing needed tools • Finding needed libraries • Installing needed SDK's	• Implementation environment ready to build software
Milestone 2: Project Architecture Design		
Designing Virtual/Augmented Reality Scenes	• Creating the skeleton for the virtual reality • Creating the skeleton for the augmented reality • Compiling • Creating the first sample app	• Skeleton to implement the software • Sample Application
Designing Haptic Insole Architecture	• Putting together hardware components • Creating the first prototype • Setting the components layout	• Hardware prototype • Vibrators optimized layout • Sensors proper layout
Creating voice signal amplitude models	• Recording audio • Removing audio noise • Creating envelops for vibrations	• Amplitude Signals
Designing Integration Model	• Planning the integration of software and hardware	• New high-level architecture
Milestone 3: Hardware and software Implementation		
Building first hardware prototype	• Putting together hardware components and with specific vibrations	• Hardware Prototype

Testing First Prototype	• Evaluating the first prototype and collecting results for upgrade	• Prototype evaluation results • Weaknesses and notes
Modifying Prototype	• Upgrading the first prototype and fixing weaknesses	• Updated prototype
Integrating Sensors with Vibrators	• Connecting sensors and allowing vibrators to work according to step pressure	• Prototype with vibrators and sensors
Building The Haptic Insole	• Installing integrated hardware like vibrators and sensors in a wearable insole	• Fully working wearable insole prototype
Building VR/AR application prototype	• Creating a VR/AR application on unity as a prototype	• First VR/AR software
Testing software prototype on Occipital Headset	• Compiling the Unity application on XCode to create the iphone application	• VR/AR application on iphone
Building three different VR environments and an AR environment	• Creating different scenes according to the desired material: sand, rocks and leaves	• 1 AR environments and 3 VR environments
Milestone 4: Building Test environments		
Collecting Material Samples	• Getting real sand, rocks and leaves for testing	• Samples of three materials
Creating Multimedia (audio and video)	• Recording the sound of steps on the sample of real material	• Audio tracks of steps on sand, rocks and leaves
Building Testing Models	• Creating different testing scenarios to evaluate the performance of the haptic insole	• 7 Testing Models
Verifying Testing Model	• Revising and modifying the test models to ensure the scenarios are set before conducting experiments	• 4 Finalized Testing Hypothesis
Milestone 5: Integrating Hardware and Software		
Establishing Two-way Connection between Headset and RFduino	• Connecting RFduino microcontrollers to the headset using Bluetooth modules	• Connected System via Bluetooth
Data Transfer and Triggering Actions	• Transferring data between the headset and the haptic insole to trigger the activation of vibrations	• Fully integrated system
Milestone 6: Testing		
Contacting Subjects	• Looking for students who are willing to be subjects in the experiments	• List of subjects
Conducting Experiments &	• Applying experiments on subjects • Collecting feedback	• Testing Data

Collecting Data		
Data Analysis	• Analyzing data and finding correlations • Testing hypothesis • Plotting graphs of the results	• Proven sets of hypotheses
Collecting Results	• Describing the analyzed data • Representing test results • Evaluating results compared to project goals	• Finalized results
Milestone 7: Writing Final Report and Presentation Preparation		
Writing report	• Dividing writing tasks among team members • Working on tasks • Combining the tasks into the report	• Senior Project Report
Designing Presentation	• Collecting content to be presented • Designing presentation slides.	• Senior Project Presentation
Designing Poster	• Collecting content to be put in the poster • Designing the poster	• Senior Project Poster
Presentation Practice	• Dividing the turns of team members • Presenting 3 times before the real presentation	• Senior Project team Ready to present

Project timeline

Faher	
Khaled	
Mohamed	
Teamwork	

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Sep			Oct				Nov					Dec		
	13	20	27	4	11	18	25	1	8	15	22	29	6	13	20
Introduction and motivation															
problem statement															
project significance															
project objective															
Background															
Virtual and Augmented Reality															
Sensors and foot activity															
Vibration and texture sensing															
Hardware-Software Co-design															
Related work															
Requirements analysis															
Functional requirements															
Design constraints															
Professional Code of Ethics															
Design standards															
Assumptions															
Proposed solution															
Solution overview															
High level architecture															
Basic Testing															

Week	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Feb			March				April				May				
	14	21	28	6	13	20	27	3	10	17	24	1	8	15	22	29
Preparing Phase																
Receiving Hardware Components																
Getting familiar with hardware components and software platforms																
Setting up coding environment																
Project Architecture Design																
Designing Virtual/Augmented Reality Scenes																
Designing Haptic Insole Architecture																
Creating voice signal amplitude models																
Designing Integration Model																
Hardware Implementation																
Building first hardware prototype																
Testing First Prototype																
Modifying Prototype																
Integrating Sensors with Vibrators																
Managing Portability																
Manage Power and Voltage Consumption																
Building The Haptic Insole																
Software Implementation																
Building VR/AR application prototype																
Testing software prototype on Occipital Headset																
Building three different VR environments and an AR environment																
Building Test environments																
Collecting Material Samples																
Creating Multimedia (audio and video)																
Building Testing Models																
Verifying Testing Model																
Integrating Hardware and Software																
Establishing Two-way Connection between Headset and RFduino																
Data Transfer and Triggering Actions																
Testing																
Contacting Subjects																
Conducting Experiments & Collecting																

Data																
Data Analysis																
Collecting Results																
Documentation																
Writing Final Report																
Prepare Documents for publishing in conference																
Presentation (design and practice)																
Send the Papers to Conference/Journal																
Demonstration																

Note: a group meeting with the mentor will be conducted on a weekly basis.

Anticipated risks

The risks management is not totally clear as the implementation phase has not started yet. However, a number of expected risks will be taken into consideration the entire project to ensure the delivery of the project objectives. The main risks expected in this project and their initial solution are listed in the below table:

Risks	**Proposed Solutions**
Damaging the Arduino processor while walking.	Placing hardware parts in a safe place around the footwear.
Having a disconnection between the haptic insole and the AR/VR headset.	Using a secure connection method without disturbing the user experience.
Capturing inaccurate footsteps and walking patterns can negatively affect the experience.	Designing an algorithm to identify proper walking patterns and calculate foot pressure accurately.

Appendix B

Use Case Specifications:

Use case Id: UC**01**	Get Sensors Readings
Brief Description	Receive the readings of the haptic insole sensors.
Primary actors	
Preconditions:	
Post-conditions: The current sensors readings are received and stored in the unit	
Main Success Scenario:	
Actor Action	**System Response**
	1. Get the sensors readings
	2. Store the sensors readings
Alternative flows:	

Use case Id: UC**02**	Calculate Feet Status
Brief Description	Use the sensors received to calculate the status of the feet
Primary actors	
Preconditions:	
Post-conditions: The current status of the feet is calculated and stored	
Main Success Scenario:	
Actor Action	**System Response**
	1. <<includes>> Get Sensors Readings
	2. Calculate the status of the feet at the time.
	3. Store the calculated results
Alternative flows:	

Use case Id: UC**03**	Send Feet Status	
Brief Description	Send the calculated feet status to the mixed reality sub-system	
Primary actors	MR Sub-System	
Preconditions:		
Post-conditions: The current status of the feet are sent to the mixed reality sub-system		
Main Success Scenario:		
Actor Action		**System Response**
		1. <<includes>> Calculate Feet Status
		2. Send the calculated data to the Mixed Reality Sub-System.
3. The MR Sub-System receives the status.		
Alternative flows:		

Use case Id: UC**04**	Receive Haptic Configuration	
Brief Description	Receive the appropriate configuration for the current environment running on the MR sub-system.	
Primary actors	Mixed Reality Sub-System	
Preconditions:		
Post-conditions: The appropriate configuration is received and stored		
Main Success Scenario:		
Actor Action		**System Response**
1. MR Sub-System send the configuration ID.		2. Receive the ID.
		3. Store the ID.
Alternative flows:		

Use case Id: UC**05**	Provide Haptic Sensation
Brief Description	Run the appropriate configuration based on the information received from the MR sub-system.
Primary actors	
Preconditions:	
Post-conditions: The appropriate configuration is running.	
Main Success Scenario:	
Actor Action	**System Response**
	1. <<includes>> Receive Haptic Configuration
	2. Change the haptic values to the appropriate ones.
	3. Run the engine with the current configuration. (See 3a for alternative scenario)
Alternative flows: **3a. If the feet status isn't "stepping", don't run the engine.**	

Use case Id: UC**06**	Receive Feet Status
Brief Description	Receive the status of the feet
Primary actors	Haptic Sub-System
Preconditions:	
Post-conditions: The feet status is received.	
Main Success Scenario:	
Actor Action	**System Response**
1. The Haptic Sub-System sends the feet status.	2. Receive the Status.
	3. Store the Status.
Alternative flows:	

Use case Id: UC**07**	Generate Mixed Reality Environment	
Brief Description	Use the structural sensor to scan the area surrounding the user and augment it to the start the simulation.	
Primary actors	The User	
Preconditions: The environment is 5m x 5m or smaller.		
Post-conditions: The mixed reality environment scene is generated.		
Main Success Scenario:		
Actor Action		**System Response**
1. The user uses the structural sensor to scan his surroundings.		2. Turns the scanned area into mesh.
		3. Adds three warp sphere to the mesh, one for each virtual environment.
		4. Project the structural sensor readings to give the mesh its texture.
Alternative flows:		

Use case Id: UC**08**	Send Haptic Configuration	
Brief Description	Send the appropriate configuration id to the haptic sub-system	
Primary actors	Haptic Sub-System	
Preconditions:		
Post-conditions: The haptic configuration id is sent.		
Main Success Scenario:		
Actor Action		**System Response**
		1. Send the current loaded configuration id to the Haptic Sub-System.
2. The MR Sub-System receives the status.		
Alternative flows:		

Use case Id: UC09	Simulate Footsteps Sound
Brief Description	Receive the feet status and run the appropriate step sound accordingly
Primary actors	Haptic Sub-System
Preconditions:	
Post-conditions: The correct footstep sound is played or not played.	
Main Success Scenario:	
Actor Action	**System Response**
	1. <<includes>> Receive Feet Status
	2. Play the footstep sound. (See 2a for alternative scenario)
Alternative flows: **2a. If the feet status is not “stepping”, don’t play any sound.**	

Use case Id: UC10	Switch Scenes
Brief Description	Change the current scene to the appropriate virtual environment.
Primary actors	The User
Preconditions:	
Post-conditions: The current scene running is the one the user intended.	
Main Success Scenario:	
Actor Action	**System Response**
1. The User clicks on the sphere representing the scene they want to load.	2. <<includes>> Send Haptic Configuration
	3. Switch the current mesh.
	4. Switch the post-processing configuration.
	5. Switch the background music.
	6. Switch the footsteps sound.

	7. Load the scene.
Alternative flows:	