Development of Customizable Head Mounted Device for Virtual Reality Applications

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CERTIFICATE

It is certified that the work contained in this thesis, titled ***"Development of Customizable Head Mounted Device for Virtual Reality Applications"*** by Pawankumar Gururaj Yendigeri, has been carried out under my supervision and is not submitted elsewhere for a degree.

Date	Advisor: Prof. Syed Azeemuddin	Advisor: Prof. Raghu Reddy

To *My Family and Friends*

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Abstract

Metaverse is predicted to be the next game changer after artificial intelligence. In this work, we operationally define metaverse applications as virtual reality (VR) applications with possibly multi-modal, multi-user, and multi-sensory inputs. The idea of creating a VR space with a hardware-software co-design system can enhance user interaction. Additionally, the VR based systems interacting in the 3-dimensional environment can be beneficial in addressing the socio-economic reforms currently faced in society. The potential extent that VR systems can be used in medical, educational and defence capabilities is substantial. Such scale can be recorded only if components of VR based systems like head-mounted devices are compliant with standards, and are available to common masses. The road to widespread usage of VR systems is a challenge. Cost, technological capabilities, hardware-software co-design, learning curve, mass adaptation and usability analysis of VR systems are significant issues that need to be addressed. In this thesis, we focus on designing and implementing low-cost, customizable head-mounted devices for Virtual Reality applications.

The cost aspect of the head-mounted device is addressed by making it application-specific (using degrees of freedom) and customizable (hardware and software development). As part of this work we studied currently available solutions and compared their sensing capabilities. The outcome resulted in choosing sensors based on the type of locomotion involved in the application and finalizing the hardware schematic. We further designed and fabricated the prototype to address VR applications with 3 degrees of freedom (roll, pitch and yaw). The application used to validate the prototype lies in Optometry domain. We propose a head-mounted device named CHORD (Customizable Head-mounted device for Occular disoRder Detection) to detect visual acuity disorders using VR applications. CHORD uses a standalone system with customizable VR scenes to detect myopic vision, astigmatism, colour vision deficiency and age-related macular degeneration. The product is validated using an empirical study with results showing an average accuracy of 85% in the tests conducted.

Locomotion in VR acts as a motion tracking unit for the user and simulates their movement in the virtual scene. These movements are commonly rotational, axial or translational based on the DoF of the application. To support effective locomotion, one of the primary challenges for VR practitioners is to transform their hardware from 3-DoF to 6-DoF or vice versa. We systematically reviewed different motion tracking methods employed in the HMD to understand such hardware transformation. Our observations led us to formulate a taxonomy of the tracking methods based on system design, which can eventually be used for the hardware transformation of HMDs.

Based on the insights gained from outcomes of the review study, we proposed a 6-degrees of freedom for inside-out and out-in tracking methodology. Furthermore we provided a platform for VR community to bridge the gap between the hardware and software design and discuss the complexity involved in the design process.

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Chapter 1

Introduction

Reality is often categorized as things that can be seen. In other words, the belief in things that are real can be directly correlated to the person having seen it without their own eyes. The word 'virtual' literally means something that is not real or simulated. It is a contronym fact that when two antonym pairs (virtual - real) form altogether, a term called 'Virtual Reality' (VR). The idea of VR is all about simulating artificial environments in a manner such that the user is tricked into perceiving virtual objects as real assets. So, when one tries to simulate a virtual environment, the extent of perception created is the major factor of importance. VR has often been in the limelight in the past 2-3 decades as an emerging technology. Simulating a realistic environment in the virtual environment with the help of a sophisticated design model emulates the experience of being in a scene without actually being in it. A perception of getting realism from an artificially simulated system is what makes a successful virtual reality experience. This phenomenon has many uses in medical, enterprise, gaming applications, etc.

In this thesis, we detail the process for building a cost-effective head mount display that can be used to run VR applications in the healthcare domain, with a specific focus on applications in the area of Optometry. VR technology has often been considered to be expensive and limited to niche domains. Making VR applications widespread requires one to reduce the cost of building and running VR applications. This can be achieved in part by designing application-specific systems and by making the corresponding hardware cost-effective. Making VR systems (Software + Hardware) cost-effective advances the reach in diverse geographic areas and also enhances the ability to execute VR applications in remote localities.

1.1 Background

1.1.1 Embedded System

Embedded in layman's terms is an element that is attached to another element. An embedded system can be an autonomous system, or it can be a part of an extensive system. An embedded system is a microprocessor-based system designed to perform a specific task. It has a Real-Time software system

(RTSS) that supervises the appliance software system and supply mechanism to run a process as per programming by following an inspiration to manage the latency. RTSS defines the means for how the system works. So, an embedded system is primarily a controller-based, software-driven, reliable, reactive system.

1. **Characteristics of an Embedded System**

    - **Application specific** An embedded system usually performs custom handling and does the same constantly. It is an ideal connecting element between the hardware and software parts of the system.
    - **Secure** All computing systems have limitations on method checkpoints, but those on an embedded system can be quite consolidated. Design metrics are a measure of an implementation's features such as its cost, size, power, and performance.
    - **Reactive** Many embedded systems must continuously respond to changes in the system's conditions and must calculate certain results in real-time without any uncertainty.
    - **Processor based** It must be microprocessor or microcontroller based.
    - **Memory** It must have a memory, as its software usually runs in ROM.
    - **Peripherals** It must have interconnected peripherals to connect i/o devices.

2. **Embedded system structure**

    - **Sensor** It measures the physical quantity and converts it to an electrical signal to read by an observer.
    - **Memory**- stores data recorded by the sensor or processed data from a hardwired unit.
    - **ADC** An analog-to-digital converter converts the analog sensor value sent by the sensor into a digital.
    - **DAC** A digital-to-analog converter converts the binary values fed by the processor to analog.
    - **Processor** Processors carry the adaptation of the data to measured output.

3. **Design Characteristics and Challenges** - Any embedded system is built for a particular application; thus, the system should fulfil the application's requirements. These requirements dictate the characteristics of the embedded system. Also, for a system to be perfect, it needs to overcome specific challenges. Some of the prominent challenges that are faced by the majority of the designs are as follows -

    - **Dependability:** A system is said to be dependable if it is reliable, maintainable, secure and safe to operate. The need for dependency occurs when the system is directly in contact with the environment. Also, the dependence of a system should be examined in the design stages itself, it will only work if it is considered in the development stages.

- **Efficiency:** Resources for any technology are always limited. Energy consumption in the case of embedded systems is in terms of hardware and software usage. Hardware efficiency involves dimensions, weight and component specifications, while software efficiency involves code size, complexity, memory space, etc.
- **Bridge:** – Hardware and Software are of equal importance
- **Real-time constraints:** – These challenges are application specific and can be identified by validating the design models practically in a real-time environment.

1.1.2 Head-mounted Device

The head-mounted device majorly finds its roots in the field of wearable devices. The first head-mounted device traced its origin back in 1970. Ivan Sutherland first developed the concept of head-mounted devices for entertainment purposes. The idea was to replace the perception of eyes with an artificially simulated environment. When we replace the real environment with virtual assets, it is deemed as virtual reality. When we use virtual assets in a real environment, it is referred to as augmented reality. A combination of augmented and virtual reality leads to mixed reality. In any of the above three cases, hardware plays a crucial role in seamlessly carrying out the immersive experience. Presently available head-mounted devices have travelled a long journey of silicon limitations. On the verge of disobeying Moore's law of semiconductors, the hardware industry has some constraints to satisfy.

Many hardware and software aspects of a complex system, like a head-mounted device, must be considered when it comes to system design. The head-mounted device needs to replace the sensory action done by stereoscopic human eyes and their perception in the brain. If we consider the hardware, the device will consist of a processor to act as a brain, a display unit to perceive what eyes see and a controller to serve as our sensory organs. We will discuss deeply the hardware architecture of a head-mounted device in Chapter 3. When it comes to the design of a wearable device, many commercial factors need to be considered. For a product to be validated for specific parameters, the best way to test it is through user studies. But it is better to have a fixated design process when it comes to architectural change or behavioural modelling. Search procedures will help us achieve an optimised solution without violating primary design constraints. This thesis focuses on addressing the problems related to the hardware architecture of designing head-mounted devices. The parameters we have chosen are divided into two types: design and application. Design parameters include all the hardware configurations required for product technical superiority. While application parameters talk about the usability aspects, validation methods, product commercialisation, and its scope over locomotion.

1.1.3 Useful Terminologies

- **Degree of Freedom** - Number of logically available data values (in our case locomotion in 3-D space)

- **Stereoscopy** - the cognitive ability to visualize the 3-D space using two visual inputs
- **Pixels per Inch** - unit area occupied by the number of pixels depicting the screen resolution of any display unit
- **Stereo-lithography** - the format in which 3-D models are blended for slicing
- **Motion to Photon latency** - the time duration between the pixel change and corresponding sensor value change. Usually used to calculate motion sensing capabilities.
- **Embedded system** - a group of individual systems functioning in a way to collectively form one whole system
- **Inertial Measurement Unit** (IMU) - device used to measure change in velocity in any particular axis of rotation
- **Compensation Filter** - the system designed to enhance one parameter by adjusting the dependant variables
- **Ophthalmology** - study of optics related to human eye
- **Visual acuity** - the sense of distinguishing two objects at a unit stereoscopic distance
- **Field of View** - the angle subtended at the visual point by the extent of the observable world
- **Velostat** - a polymer that has a unique property of changing its resistance upon external force
- **Normalized vector** - unidirectional quantity that is scaled to the mapped value based on the optimum value in the sample space
- **Potentiometer** - a electronic device with variable resistance
- **Low-pass filter** - system that passes low frequency and blocks high-frequency values

1.2 Research Overview

We aim to provide low-cost, standalone and customizable HMDs with 3-Degrees of Freedom (DoF) and 6-Degrees of Freedom (DoF) tracking. The research journey is divided into the following phases -:

- Design and Implementation of the customizable 3-DoF HMD
- Application of Customized 3-DoF HMD in Ophthalmology
- Review on the presently available Motion tracking methodologies and their transformation in VR
- Develop inside-out and outside-in tracking methodologies for VR locomotion
- Design and Implementation of a customizable 6-DoF HMD

1.3 Summary of Contributions

The contributions from the thesis can be illustrated in the following-

- **Design**
  - Proposed a customizable Head-mounted device hardware architecture for low-cost VR applications.
  - Proposed novel compensation filtering mechanism for motion tracking methodology for head-tracking systems.
  - Presented stereo-lithography models (STL) for 3-D printing the HMD casing based on the campus-wide empirical study.
- **Application**
  - Proposed a novel, standalone and customizable Head-mounted device named CHORD to detect visual acuity disorders.
  - Carried out focused group studies for validation of CHORD for 30 participants with varied demography.
  - Proposed an outside-in tracking methodology with the help of a velostat-based mat to track users in 6 degrees of freedom.
- **Literature**
  - Proposed a Taxonomy for hardware transformation of 3 DoF tracking to 6 DoF tracking methodologies based on the locomotion involved in the application.
  - Proposed a metric-based checklist to classify the locomotion into the hardware requirements to build a standalone tracking methodology.
  - Proposed validation methods corresponding to the locomotion involved in the VR application.

1.4 Thesis Structure

The thesis structure is divided into the following chapters-

- **Chapter 2** talks about the contributions and literature related to head-mounted devices, VR in healthcare, military and education and various locomotion involved in VR tracking systems.
- **Chapter 3** discussed the design and hardware implementation of 3-DoF HMDs and the various challenges involved.
- **Chapter 4** presents the application that we proposed CHORD, used to validate the 3-DoF HMD in Opthalmology.

- **Chapter 5** presents the systematic literature review discussing the hardware transformation of 3-DoF devices to 6-DoF devices.
- **Chapter 6** presents the design and implementation of 6-DoF HMDs based on the outcomes of SLR study.
- **Chapter 7** concludes the thesis by discussing the contributions, limitations and Future aspects of the research.

Chapter 2

Related Work

2.1 Works in Head mounted devices

2.1.1 History

In 1968, the first HMD for 3-D display was demonstrated using an ultrasonic head position sensor [1]. Since then, VR has evolved gradually until the first half of the 21st century [2]. The evolution of VR led to significant research in the issues related to diverse applications as one may experience in the real world despite continued innovation [3]. Some researchers explored the possibilities of HMDs as a tool for interactive education for both teaching and learning. They observed that VR technology far outweighs its technical and cultural challenges. A systematic survey was conducted on understanding the impact of HMD and VR to judge the learning experience compared with typical sessions. VR has wide acceptance in the military, entertainment, and healthcare [4] [5].

2.1.2 In Healthcare

In recent times, under ophthalmology, a symptom calibration method for testing the disorders related to visual acuity using AR was introduced [6]. A study of a method for recognising escape-route signs concluded with an essential contribution for conducting user studies to investigate visual impairments. The research inferred the vital role of lighting compositions and calibration procedures in the experimental setup of a visual test [7]. The review concluded that current AR could tackle problems related to many ophthalmic diseases, but still, efforts need to be put in this direction.

Over the past decade, attempts have been made to develop a low-cost HMD in healthcare. Products such as smartphone-based HMD's and some commercially available solutions provide prescriptions for visual acuity disorders [8] [9]. However, scaling up peripheral systems introduces multiple complications in smartphone-based solutions. [10] developed a DIY interface for HMD, which inspired us to look into a robust tracking mechanism for our HMD. Attempts to use external processing elements for developing customized HMD [11] did not address issues related to geometric distortion and customization of applications. A method based on projection displays was devised to test visual acuity with decent accuracy using portable HMD [12]. The study involved 53 participants that reported the mean difference in visual acuity between HMD and standard Snellen practice to be 0.05 log-MAR. However, the setup cost and some outliers for a particular range of visual acuity led to inaccuracy. Thus, there is a need for low-cost HMDs to run simple VR applications that can address some societal challenges.

2.2 Works in Hardware Transformation reviews

In the past couple of decades, research on locomotion in the virtual environment started gaining its pace. Initially, the navigation in the virtual world was restricted to 3-DOF. Eventually, researchers focused on the user's other locomotive or navigation feedback to enhance involvement and immersive experience in VR. Many motion tracking techniques were implemented based on actions like walking, steering, selection and manipulation. Al Zayer et al. surveyed multiple tracking methods and discussed their strengths, weaknesses and application to provide an overview for the researchers to apply a particular technique [13]. When it comes to movements that can be employed in VR using locomotion, there is a need for proper classification based on the body organs involved, the extent of the action and its repeatability. Mahdi Nabiyouni et al. proposed a taxonomy of walking based locomotion techniques in VR [14]. This work with comparative analysis provides insight to the researchers and system designers into choosing walking techniques and performing experiments to evaluate them. Lisa Prinz et al. carried out a review and analysis of 29 papers providing locomotion techniques taxonomies. The work inspires the researchers to develop taxonomies in coming up with a novel tracking methodology [15].

Heni Cherni et al. conducted a review for 22 motion tracking methods from 2012 to 2019 and provided guidelines to choose the method based on the user's application. The research was based on the HCI aspect of the VR locomotion and proposed a taxonomy based on user body-centred, external peripheral and mixed methods. The role of user body-centred motions and their relation to motion sickness were some of the paper's significant contributions. VR locomotion and sickness induced by it needs to be evaluated and corrected. Thomas Gemert et al. highlighted some key components to quantify VR sickness and metrics to counter them [16]. However, these reviews on VR locomotion do not discuss the device parameters and the hardware requirements for designing a particular motion tracking system. The data relating to the device's operating range, the ability of the sensors, and its relation to the target application are essential viewpoints for a researcher developing a novel tracking method.

Chapter 3

Design and Implementation of 3-DOF HMD

In this chapter we discuss about hardware-software co design of the 3-DOF HMD and discuss about its implementation in subsequent sections.

3.1 System Architecture

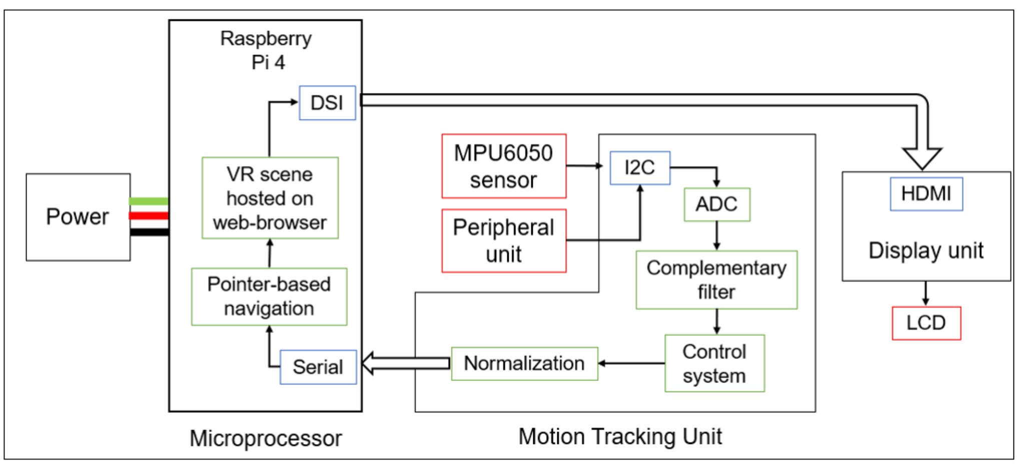

Figure 3.1 Block diagram representation with hardware components

The architecture of an HMD can be realized as an embedded system. An embedded system is a software-driven, reactive, and reliable processing unit that can be part of an extensive system. A typical embedded system varies based on its characteristics and performance, depending on its hardware components and system specification. A typical HMD has three modules: (1) a Display unit comprising of an LCD screen used to project and play the 3-D VR scene, (2) a Microprocessor that processes the incoming requests, and (3) an open-source operating system. Additionally, depending on the purpose of the HMD, a Motion tracking unit that includes an accelerometer and other peripherals associated with the micro-controller may be part of the device. The microprocessor initiates the flow of events by hosting the VR scene loaded from its memory and waiting for data from the micro-controller to be visualized on the display unit. The performance of such system hardware depends on the processor, sensor and actuator's sensitivity towards the information based on its use case. In the following section, we discuss the components of CHORD in detail.

The overall connection between the various systems in embedded hardware can be visualized using block diagram representation. In Figure 3.1, as shown, the Motion tracking system is interfaced with the micro-controller, which in return feeds the analog to digital converted data to the processor.

For any system to be fully efficient in terms of performance and accessibility, the role of a processor is very significant. The processor acts as the computational element of the embedded system. Table no 3.1, depicts the requirements of the microprocessor for heavy graphics applications like virtual reality scene rendering. The processor that needs to be used in the HMD should satisfy the minimum criteria of the above mentioned constraints. Taking into consideration the present microprocessors available in the market, it is very beneficial to have a comparative study on their capability, support and performance. While studying and comparing processors the parameters to be considered are memory, processing ability, interface for communication protocols and peripherals. Table no 3.2 depicts the comparative study of prominent microprocessor and controllers along with their features and relevance with building head mounted display.

From the information in 3.2, we can do a detailed analysis of choosing the right microprocessors. If the study is done chronologically, it is beneficial to take open points on each item in the table.

- Raspberry Pi 4 – offers most of the onboard RAM; hence good video rendering and audio support, O.S. supported by major domains with the stable build is a significant advantage, implements the majority of communication protocols, and is a community favourite as not many processors provide dual HDMI ports.

- Orange Pi 4 – Average video and audio capabilities, O.S. support good, average processing clock cycle, so not recommended for high graphical scene rendering applications.

- BITalino – The processor is more interfaced with sensory applications suitable for medical practices and works on less input power but is not appropriate to handle any graphical applications.

- C.H.I.P. - More of an IoT-based processor, no practical use for graphical applications, but can be used as hardware peripherals for improved applications in V.R.

- Dragon Board 410c – Faster processing ability than any other processor equipped with A.R.M. v8, GPU capabilities same as Rpi and only close points, is RAM that it offers ¡1 G.B. so can render introductory V.R. scenes but cannot handle animation.

- Beagle Bone Black – GPU still in the development stage, not compatible with all OS.

Name	Memory & Processor	OS support & Peripherals	GPU	Price
Raspberry Pi 4 B series	RAM-8GB ROM-MicroSD Processor-Broadcom BCM2711, ARM v8 32/64bit@1.5Ghz	OS support- Raspbian/ Android/Ubuntu/ Debian/ Red hat, etc. Peripherals-STD 40 GPIOs, 2x micro-HDMI ports, 2x USB 2.0 and 3.0 each, 2 lane MSI DSI ports, four pole stereo audio port, IEEE 802.11 ac Wi-Fi, Bluetooth 5.0	Broadcom Video Core VI, OpenGL ES 3.0 graphics	5280
Orange Pi 4	RAM-4GB ROM- 16 GB Flash Processor- Rockchip RK3399, 6 – core, ARM 64bit	OS Support-Android/Ubuntu/ Debian 9 Peripherals-40 GPIO's, 1 x HDMI 2.0, Supports 4K @ 60fps output, 1 x DP 1.2, Supports 4K @ 60 fps output, 3.5mm Jack, IEEE 802.11 a/b/g/n/ac, BT5.0	Mali-T864 GPU Support OpenGL ES 3.1	4780
BITalino	RAM- 16 MB Flash Processor- CC3200 36 bit ARM	OS Support- Kernel required Peripherals- 40 GPIO's, 1 x HDMI 2.0, Sensors for Electro-cardiography, Electro-dermal Activity, Electro-encephalography, Accelerometer	Ext.	7500
C.H.I.P	RAM- 512 MB ROM-4GB Processor- 1 GHz, ARMv7	OS Support-Linux/Debian Peripherals- 40 GPIO's, Wi-Fi (b/g/n) and Bluetooth 4.0 built-in	Ext.	3820
Dragon Board 410c	RAM-1GB ROM-8GB onboard storage and external Processor- Snapdragon 410E, Quad Core ARMv8	OS support-Android/Linux/Windows /Fedora/Ubuntu Peripherals- USB 2.0, 1 x HDMI 1.4, 1 x MIPI-DSI HDMI output, FHD 1080P, WLAN 802.11 2.4 GHz	Qualcomm Adreno 306 GPU	4963
Beagle Bone Black	RAM-2GB ROM-4GB flash & Micro SD Processor - ARM Cortex-A8	OS Support- Angstrom/UbuntuAndroid, Peripherals- 2x 46 headers, USB client &host, Ethernet port, HDMI	Beagle bone GPU offload	4800
Arduino Mega 2560	SRAM- 8KB EPROM- 4KB	OS Support-Kernel required Peripherals-Improved reset circuit, Atmega 16U2 replace the 8U2 for USB connectivity	-	850

Figure 3.2 Parametric comparison of various microprocessors

- Arduino Mega 2560 – Microcontroller but with equipped sensor interfacing configuration, could digitize raw sensory data by using on-chip A.D.C.'s and can render basic animation applications like 3D games.

Having discussed all the aspects of the controlling block of the head mount, the Raspberry Pi 4 B series seems to be ticking most of the check-boxes, so it will be used to build on further models.

So as per remarks obtained in Table no 3.2, Raspberry Pi 4 B series satisfies all the requirements for the VR scene hosting.As per study done by Sachdeva et al. [17], the specification can be illustrated as follows–

- **OS support** - Raspbian, Pidora, RISC OS, Ubuntu, Mozilla Core, Debian, etc.
- **Peripherals**- STD 40 GPIOs, 2x micro-HDMI ports, 2x USB 2.0 and 3.0 each, 2 lane MSI DSI ports, 4 pole stereo audio port, IEEE 802.11 ac Wi-Fi, Bluetooth 5.0

Also, the fact that Raspberry Pi 4 is the only microprocessor to provide dual HDMI ports for third person view, which prove essential in VR technology visualization.

3.2 Processing Unit

HMD hardware architecture can be realized as an embedded system that is by definition application-specific, secure and easily customizable. An embedded system, as defined, is a software-driven, reactive and reliable processing unit that can be an individual or part of a more extensive system. The process flow for designing an embedded system directs requirements that define the system's characteristics and level of performance. Challenges such as dependability, efficiency and constraints validation can be addressed and rectified if the design flow is systematic and structured.

The microprocessor will be acting as the brains of the system. The open-source operating system flashed on the processor's memory will be hosting the VR scene on the web-based browser. The VR scene interaction will be taken as input from the motion tracking unit and a peripheral device. The motion tracking unit will have a controller to convert raw values from the gyroscope sensor into digitized values to map them accordingly to the head movement. The additional buttons provided on the peripheral device will be used as navigation feedback for the VR scene. The whole visualization will be rendered on the browser and displayed via the 7-inch LCD screen.

A hardware system's performance is proportional to the ability of components like processor, sensors, actuators, or transducers to apprehend the values and process them. The analytical comparison between the presently available components considering the parameters essential for the application yields satisfactory results.

For any system to fully procure in terms of performance and accessibility, the role of a processor is very significant. The processor acts as the computational element of the embedded system. Table no 3.1, depicts the requirements of the microprocessor for heavy graphics application like virtual reality scene rendering.

NAME	DESCRIPTION
Memory	RAM = 4GB, Storage = 16GB
Graphical ability	60Hz frame launch, host 1080p frames at 30fps
Processor capability	32/64-bit
Peripherals	20 pins GPIO's pins, 2 x micro-HDMI ports, DSI port 1080P @ 60hz, USB, Wi-Fi and Bluetooth enabled
Adaptability	Local server hosting capability, Compatible version of OS for Communication protocols like, I2C, UART, SSH

Table 3.1 Minimum microprocessor requirements

The processor that needs to be used in the HMD should satisfy the minimum criteria of the above mentioned constraints. Taking into consideration the present microprocessors available in the market, it is very beneficial to have a comparative study on their capability, support and performance. While studying and comparing processors the parameters to be considered are memory, processing ability, interface for communication protocols and peripherals. Table no 3.2 depicts the comparative study of prominent microprocessor and controllers along with their features and relevance with building head mounted display.

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Also, the fact that Raspberry Pi 4 is the only microprocessor to provide dual HDMI ports for third person view, which prove essential in VR technology visualization. Now that we have successfully justified the use of Raspberry Pi 4B as the processing unit, lets check the relevant communication protocols that it offers to interface the peripheral units.

3.3 Motion Tracking Unit

The basic operation of tilting and rotation action of head must be able to be realized by the sensor. This action can be termed as motion processing unit in the head mount. The combination of gyroscope, magnetometer and accelerometer is practically possible with use of electronic sensors. The gyroscope can be used to simulate action of tilting as it can feed the values of rotation for all three x, y and z axis. Magnetometer can be used to take a reference point in 3-D plane as it has ability to depict East-West-North-South direction.

Interface of Motion Tracking Unit can be visualized in the Figure no 3.3.

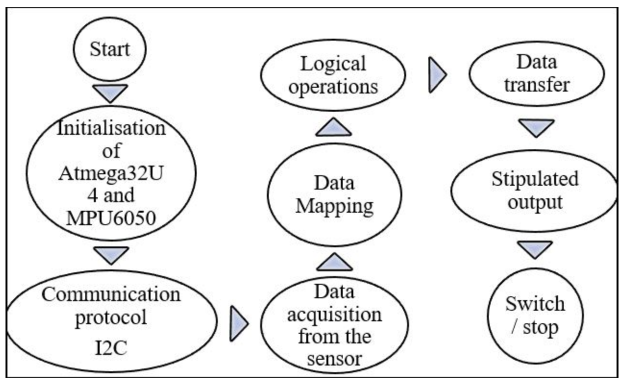


Figure 3.3 Work flow for Motion tracking unit

MPU6050 used for head motion simulation is restricted to 3 degrees of freedom. The raw, pitch and yaw as suggested in 3.6 represents the action of motion tracking. The As per research done by [18] suggested on determination of angular velocities and linear acceleration using MPU6050

- **Initialisation of ATmega32U4 and MPU6050** (Td=150ms) – It involves interfacing the MPU6050 with software IDE for establishing data transfer.
- **Communication protocol I2C** (Td=50ms) – This is the key element in the process. The way I2C protocol works same as serial communication protocol, only the thing is its data contains separate allocations for start bit, address bits, data and stop bit that is exchanged between master and slave. (here Atmega32 being the master and MPU6050 being the slave) The Arduino Micro has I2C pins at GPIO's 2 and 3 being SDA and SCL respectively. The pin outs for the interface can be shown in the Figure no 3.4.
- **Data acquisition** (Td=20ms) – This part of the process involves getting raw inputs from MPU6050 and storing or displaying the simultaneously in serial monitor. For MPU 6050, the gyroscopic values vary between ±2500 degree/sec. According to the working of MPU6050, it gives the relative values of change in angular motion with respect to current position. So, for angular position, the gyroscopic values need to be integrated over time to get position. (in degree)

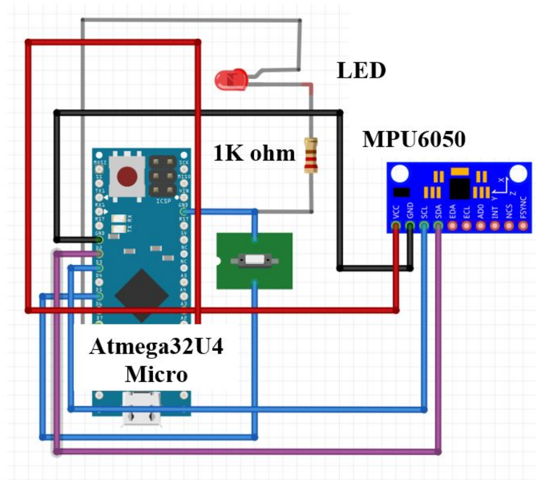


Figure 3.4 MPU6050 interface with Atmega32U4

The data flow is illustrated as part of the process diagram in Fig. 3.5. The system majorly uses velocity-based angular value ($angle_{vel}$) for short term compensation and a small amount of accelerometer-based angular value ($angle_{acc}$) for long term compensation, as seen in Fig. 3.8. Followed by a filter to ensure the system is immune to sudden changes in movement and mapping of normalized data to provide accurate values to the pointer.

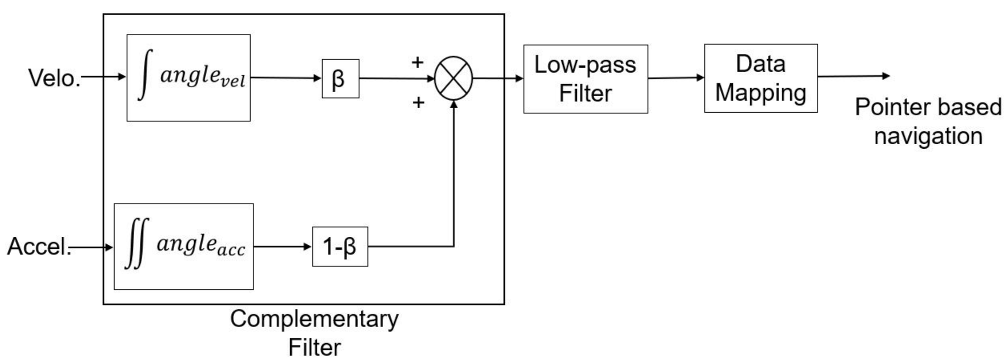


Figure 3.5 Workflow of the Motion Tracking Unit

$$X = \beta * angle_{vel} + (1 - \beta) * angle_{acc} \tag{3.1}$$

- **Data mapping** (Td=20ms) – After getting the data in the raw form, the analog to digital conversion (ADC) of the data is the task to be done. This is essential in the logical operations that will be performed in order to achieve the desired output. The mapping of the data involves using following equation to implement the normalisation for ease of access-

$$X = \frac{(x_{new} - x_{avg})}{max(x_{max}, y_{max})} \tag{3.2}$$

$$Y = \frac{(y_{new} - y_{avg})}{max(x_{max}, y_{max})} \tag{3.3}$$

- **Logical operations and data transfer** (Td=10ms) – The values that are obtained after mapping are subjected to certain logical operations. For example, when user wants values to be mapped to values in particular range of data relevant to the application. In this case, The digitized data is needed to be mapped with head movements such that user experiences same perspective in the VR scene as in the real life field of view. It portrays the mapping done on the 3 DoF head movement into pointer navigation in form of mouse movement in the web browser as suggested in Figure no 3.6.

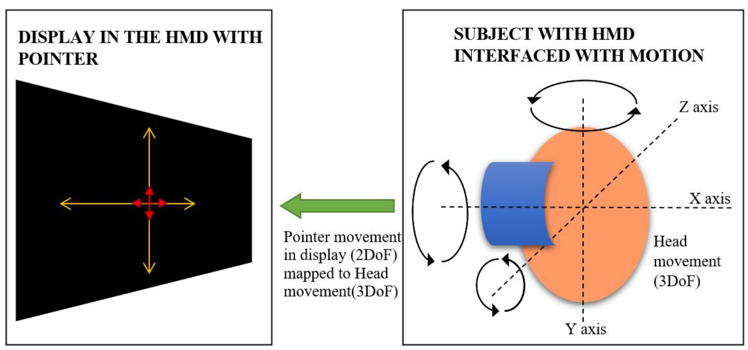


Figure 3.6 Head movement mapped with the motion tracking unit

- **Stipulated output** – The output of the process results in proper conversion of raw values from the sensor into digital programmable data. The subsequent result that is obtained using equation 3.2 and 3.3 can be seen in the Figure no 3.7. This data is then used in mouse manipulation based on scene requirements.

MPU6050 captures acceleration and velocity in the 3-axis and needs an additional control system that provides angular values for our module. However, every Micro-Electro-Mechanical System (MEMS) accounts for unusual errors in the practical reading due to various environmental factors. These unusual errors in the acceleration and velocity values of MPU6050 are minimal. However, when integrated over time to obtain angular values, these errors become significant. We recorded the angular values using gyrocompass at a particular instant for three momentary action iterations and calculated values for MPU6050. We compared angular values of MPU6050 and actual gyroscope (as a reference) for the same momentary action as shown in Fig. 3.8. We noted that a similar error pattern was validated in the previous experiment [19]. In order to compensate the deflection, we proposed a complementary

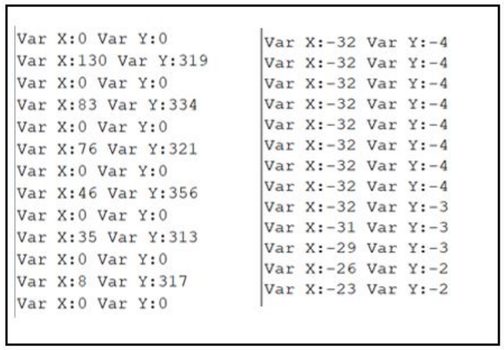


Figure 3.7 Data acquired from MPU6050

filter that uses converted acceleration and velocity values at different rates as shown in (3.2), where β is experimental constant (between 0 and 1) that determines phase delay (here 0.98). However, a simple offset in the accelerometer data is needed to compensate for the final value with this method.

The microcontroller ATmega32U4 and MPU6050 were integrated to function separately from the processor. To counter sudden actions like head-stroke, sneeze or cough where head acceleration can go up to 70g (m/s^2), we applied a simple low-pass filter at the output [20]. Furthermore, the resulting data were mapped to normalized values to achieve pointer-based navigation using (3.3), where X and Y are changes in pointer locations in horizontal and vertical axis respectively.

The data flow is illustrated as part of the process diagram in Fig. 3.3. The system majorly uses velocity-based angular value ($angle_{vel}$) for short term compensation and a small amount of accelerometer-based angular value ($angle_{acc}$) for long term compensation, as seen in Fig. 3.8. Followed by a filter to ensure the system is immune to sudden changes in movement and mapping of normalized data to provide accurate values to the pointer.

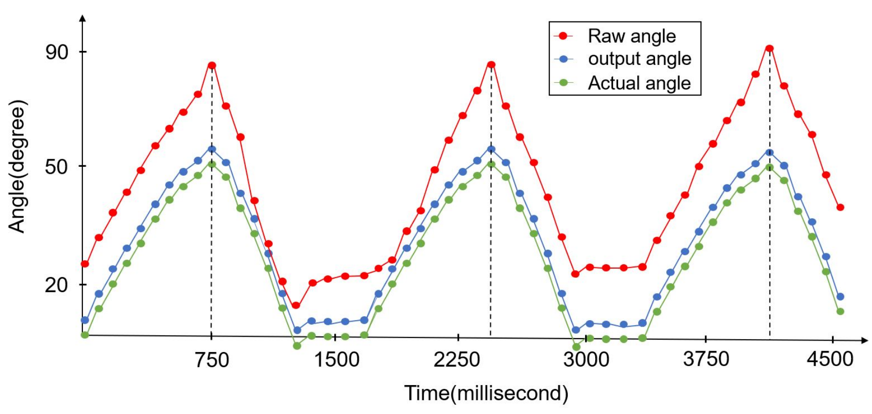


Figure 3.8 Values from MPU6050, output angle of motion tracking unit and actual angle measured

Once the setup of the motion-tracking unit is complete, the validation of the system is performed using measurement studies. Motion sickness in VR is mainly due to motion-to-photon (M2P) latency [21]. In previous studies, a complex measurement system was proposed for the evaluation of M2P latency [22]. Inspired by such a system, we devised a method with a slow-motion camera (960 fps) that records the time when there is a slight change in the frame of the HMD display at the time of any head movement. The M2P latency for the CHORD values varied from 65ms to 150ms. Observation showed that higher values of M2P were due to the overtime heating of the processor. To tackle this problem, we installed a heat sink to improve the run-time of the HMD. The M2P perceived in CHORD (65ms) is suitable for our low-cost healthcare application [23].

Name	Experimental requirements	MPU6050 specifications
Inertial measure	3-axis gyroscope	3-axis gyroscope 3-axis accelerometer
Programmable ability	Any values varying between the 8-bit range.	User programmable data range: ± 250, ± 500.
Filters	Immune to external induced noises	Digital programmable lowpass filter
Communication protocol	SPI / I2C / Wi-Fi	I2C interface for writing and reading device registers
Data conversion	ADC for conversion of raw input into usable quantity	Built-in 16-bit ADC

Table 3.2 MPU Specification details

3.4 Peripherals

As discussed in hardware design, the joystick can be used as a mechanical haptic device to provide an interface to the user with the virtual environment. The joystick used has two axis motions which are coupled to two 10k potentiometers. The joystick fundamentally has five pins in the schematic. As shown in Figure no 3.9, the pin-outs of the joystick include one digital, two analog and +5V source and ground as five inputs.

In the circuit schematic, one analog pin gives values of change in the X direction and the other in the Y direction. At idle case, both potentiometers read 500 ohms each. When moved up in -Y direction, the value of one potentiometer changes to zero while the other remains 500 ohms. Similarly, when the joystick is moved down, one potentiometer changes to 1K ohms while the other remains 500 ohms. It goes with the same logic for the right and left movements of the joystick. The up-down and right-left movements are captured using potentiometers that are read by analog pins of the micro-controller. The joystick is mounted on 3D printed box with slot for interrupt key. The interrupt key is to reset the micro-controller

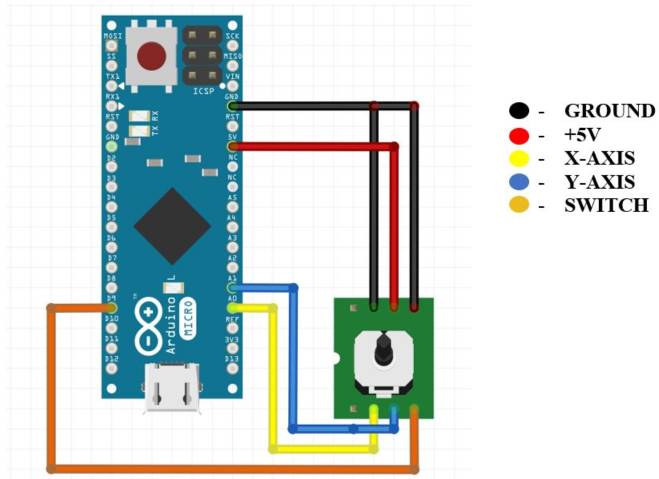


Figure 3.9 Joystick interfacing with micro-controller

and avoid run-time error. The working of each movement of the joystick can be visualized using Figure no 3.9. However as the simulation of each VR scene demands separate action to be performed. As

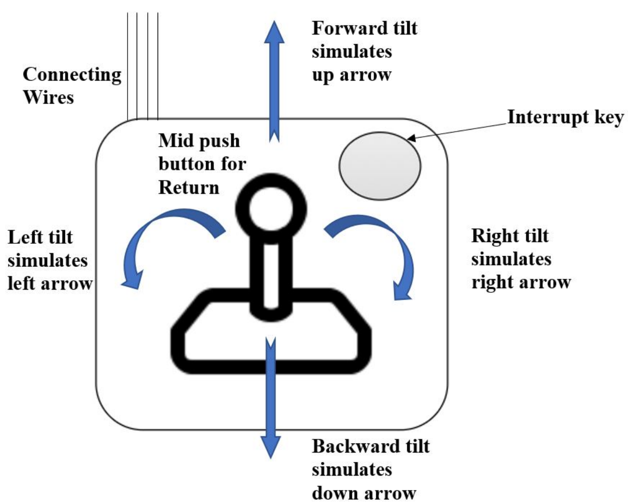


Figure 3.10 Working of joystick with VR scene

joystick functions should inherit multiple functions using fixed set of inputs, it is essential to standardize set of key to be used. As most of feedback offered by the user are navigation based, use of arrow keys is significant approach. Table no 3.3, depicts the joystick action and its corresponding action in VR scenes.

JOYSTICK ACTION	VR ACTION
Forward Tilt(UP ARROW)	Pan up
Backward Tilt(DOWN ARROW)	Pan down
Left Tilt(LEFT ARROW)	Forward movement or Navigate Left
Right Tilt(RIGHT ARROW)	Backward movement or Navigate Right
Center key(RETURN)	Select

Table 3.3 Standard inputs to VR scenes and their action

3.5 Software Design

ll the VR scenes used in the experiment were developed in the Unity3D platform. Jason Jerald et al. developed VR applications using Unity which helped us understand the platform and components to build our own VR scene. [24] For designing a scene, we collected relevant open-source assets from the asset store and set the ground. After that, we set the scene parameters using a Unity editor called GameObject. It helps us assign properties like camera position, lighting conditions and other effects. The performance of the GameObject depends on the sub-components appended to it. Although the components have various features, we created our feature using C# based editor called scripts. The scripts allowed us to trigger or modify a particular event based on the user feedback in the scene.

We hosted the scene on a processor over a web-based server and got the output in monoscopic view. To simulate the visual perception of eyes for HMD, we wanted a stereoscopic output. So to simulate two eyes, we used two cameras and virtually positioned them with an inter camera distance x. We measured the inter-ocular distance of 10 random participants and mapped its value with inter-camera distance through the experiment(here x=0.75). The assets and build files of VR scenes used in the paper are made available. [25] Overall, Unity provides an excellent interface for VR development and needs minimal technical expertise to build a custom scene.

3.6 Customization of Hardware-Software Co-design

A Raspberry Pi-based HMD for VR can be customized in both the hardware and software domains to suit specific applications in entertainment, therapy, healthcare, and military simulation. In the hardware domain, customization can be done by selecting different sensors, display screens, and input devices depending on the requirements of the application. For instance, in the entertainment sector, high-resolution displays, high fidelity audio, and motion tracking sensors can be used to enhance the user's experience.

In the healthcare sector, sensors that monitor vital signs such as heart rate and blood pressure can be incorporated into the HMD to monitor patients during therapy sessions. Similarly, in the military simulation sector, input devices such as gun controllers and haptic feedback gloves can be used to simulate real-world scenarios. In the software domain, customization can be done by using different programming languages and libraries to develop applications that suit specific needs. For instance, in the entertainment sector, game engines such as unity and unreal can be used to create immersive VR experiences. In the healthcare sector, custom software can be developed to provide therapy sessions that are tailored to the patient's needs. Similarly, in the military simulation sector, custom software can be developed to simulate various scenarios such as combat, training exercises, and emergency response.

By customizing the hardware and software domains, developers can create applications that are tailored to specific needs, providing a better experience for the end-user. This can lead to better outcomes in terms of patient care, entertainment experiences, and military training simulations.

After integration of system, next phase is testing its reliability and performance. The parameters need to be categorized in fixed and flexible. The customized HMD that is to be designed has certain hardware specifications as shown in Table no 3.11. Multiple tests will be conducted based on hardware specifications.

PARAMETERS FOR DESIGN	SPECIFICATIONS OF HMD
Focal length of lens	35mm
Diameter of lens	40mm
Inter-ocular distance	64mm
Distance between screen and lens	35mm
Distance between eye and lens	12mm

Figure 3.11 HMD parameters

3.6.1 Optical aspect

For any HMD design, the crucial aspect is the optical parameters like the location of the pupil, inter-ocular distance and optical geometry. The distance between the left and right pupil of the user's eye is necessary for HMD calibration and its ability to focus on display. Jung son et al. work suggests, however, for normal HMD, the inter-ocular distance is fixed to 65mm, the value roughly varies from 51 to 77mm. Efforts have been made previously to make automatic adjustments in the system using linear motors, but they make the system heavy. [26].Still, it is recommended to use customizable inter-ocular distance due to its variability from user to user.

The other viewpoint involving in VR scene testing is its mode of display. Usually, VR scenes are monoscopic or stereoscopic in terms of visualization. Monoscopic is when both eyes perceive an same set of data. It lacks the depth of field and immersive experience that stereoscopic scene can provide. Stereoscopic is when each eye is subjected to graphically different data, such that it simulates the vision of two eyes. This method can be simulated electronically using two identical camera's separated at a certain inter-ocular distance. When two outputs are rendered, they provide a sense of depth and realism. The Figure no 3.12a and 3.12b compares the actual perception of same image when looked in different configuration. Both the configuration have their individual importance when it comes to applications. Stereoscopic VR is mainly used in VR headsets for being more realistic and immersive while monoscopic has its applications in 360 photography and graphical advertisement content.

(a) Monoscopic image output

(b) Stereoscopic image output

Figure 3.12 Comparison of monoscopic and stereoscopic based on imagery

3.6.2 Field of View

The Field of View(FOV) of an optical device is its ability to cover the observable area in the environment at a given moment. Horizontal FOV of normal human being is around 220 degrees. [27] Mathematically, it is a length created by an angle subtended in the exterior of an eye by the display unit. FOV is dependent on many parameters like lens diameter, focal length, the measure between the eye and lens, etc. As per Kevin Arthur [28], shortening the distance between eye and lens or increasing lens size is undesirable as it messes with the symmetricity and makes HMD bulkier. Slater et al. [29] suggest using distorted edges with compressed scenes to accommodate more field areas of the VR module. It is perceived that the central area of display covers over 90% of the FOV of the system.

Zhang et al. [27] suggests, wider the FOV for an HMD, more immersive is the user experience. The mathematical expression to calculate FOV can be represented as -

$$FOV_{degrees} = \arctan(\frac{H}{f}) \tag{3.4}$$

where, H is the size of the display and f is the focal length of the lens or also can be distance between screen and lens. There is also a indirect relationship between the resolution and FOV that will be addresses separately. However, in the case of customizable HMD, the application mandates a single eye at an instance. According to the standard optical procedure, it is advised to test each eye separately. Operations such as visual acuity and astigmatism are traditionally tested on individual eyes, as each eye may end up having different ailments. For testing visual acuity using Snellen, as suggested by Sue Stevens [30], the participant is expected to cover the left eye while keeping it open and then undergo a test with the right eye to yield accurate results.

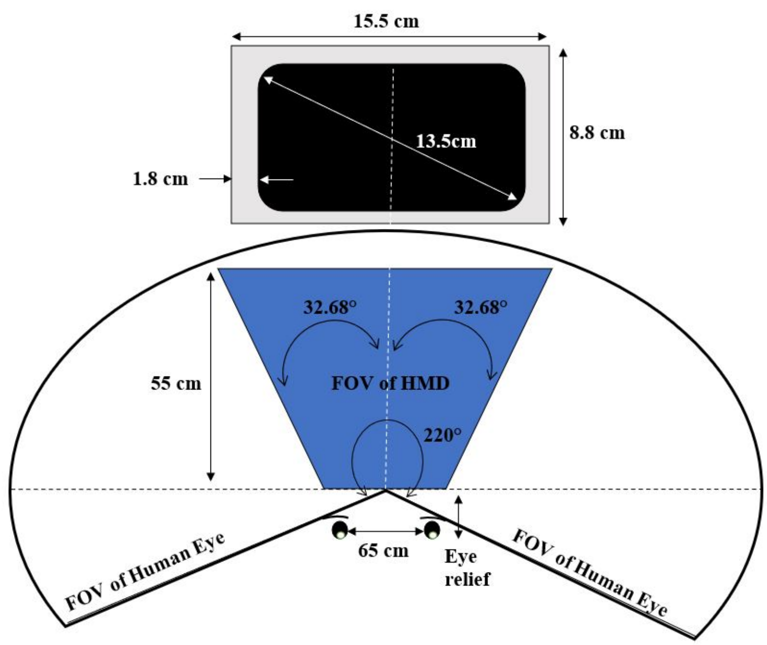


Figure 3.13 FOV of the customized HMD

So according to system design, focal length of lens used is 5cm and dimension of LCD is 12.2 cm. So after using equation no 4.1, the value of FOV obtained is 65.36 degrees. Figure no 3.13, is the pictorial representation of the FOV for customizable HMD.

3.6.3 Screen resolution

After FOV, the following essential aspect is screen resolution. The number of pixels allocated to a particular object in a perceived scene through the eye defines the quality of the scene. For any HMD presently available, the parameter that decides the resolution is called pixel density.

$$Resolution = \frac{N}{FOV} \tag{3.5}$$

As mentioned in equation no 3.5, it mathematically, a number of pixels present in the given axis(N) of FOV(in degrees). [27] It is usually measured in pixels per degree(PPD) or pixels per inch(PPI). Presently HMD like Oculus Rift offers 640x800 resolution per individual eye with 251PPI. [31] The display monitor used for customized HMD is 7 inch in size and provides a resolution of 800x480. The operating system on Raspberry Pi provides a set of configuration to be tested on HMD for maximum quality. Optimum configuration can be set by using a custom made VR scene. These configurations can be tested on any display unit to get accurate image quality.

Experiment - In the past, VR scenes have been designed in order to test HMD capabilities. L.E.Buck et al. used VR scenes for distance estimation and mapping virtual values to real life values. The experiments involved VR equipment subjected to participants with varying parameters. [32] The VR scene involves using a custom made environment with two opaque objects. The two objects are placed at an adjustable distance with respect to each other. The user can virtually navigate in forward and backward direction in the scene. The idea is to set the inter-object distance to a particular value and navigate the objects in backward motion until the two objects are distinguishable. The point at which two separated objects seem to be intersecting can be recorded corresponding to a particular screen configuration, and similarly, the test can be conducted for another iteration. Figure no 3.14, is the user perception of the VR scene that is used to test screen resolution. The number displayed in the VR scene is the virtual distance of

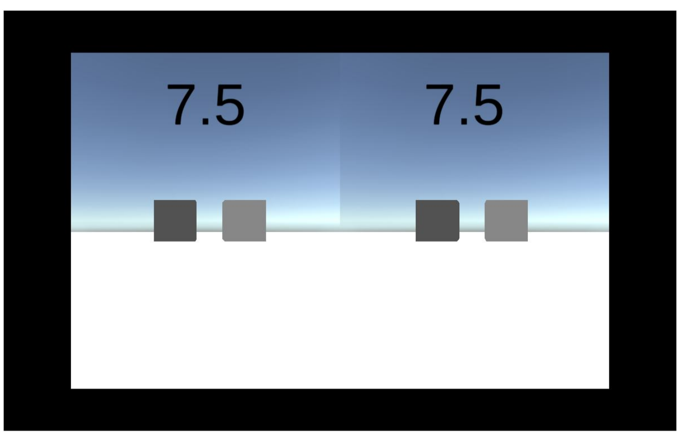


Figure 3.14 VR scene used to test resolution

objects with respect to observer. Readings recorded for multiple configuration can be analyzed and best resolution can be predicted based on the results.

Results - Linux based OS on Raspberry Pi offers seven sets of screen configuration to test on 7 inch

LCD. However, the resolution LCD offer is 800x600 pixels; the experiment is conducted from 640 x 480 to 1024 x 600 pixels. The virtual distance obtained corresponding to the resolution will be compared, and the highest distance will be recommended for VR scenes. The graphical comparison of screen resolution with virtual distance can be seen in Figure no 3.15. As per experiment, the configuration 832 x 624, 800 x

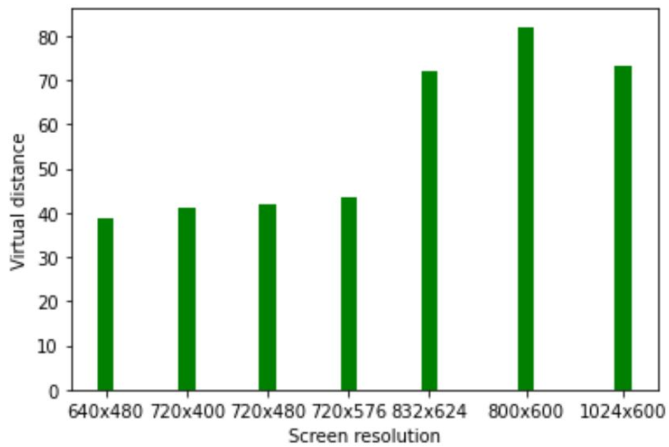


Figure 3.15 Graph for comparison between different screen configurations

600 and 1024 x 600 pixels record higher virtual distance where the two objects were distinguishable. The VR scene henceforth will be tested on 800 x 600 resolution or moreover 400 x 300 resolution per eye.

3.6.4 Immersive experience

The basic VR scene designed using default parameters in the rendering software when tested on HMD hardware, exhibited some problems to be addressed in the following-

Binocular Disparity - The difference in the perception experienced by the user when he observes object individually from the left and right eye, thus producing a parallax effect, can be referred to as Binocular disparity. Virtually simulating the binocular display that the human eye perceives is the challenging part of virtual reality headsets. Methods like tracking eye movements with the camera and finding coordinate in cyclopic camera space using algorithm have been studied continuously. [33] In the case of customized HMD, as the application involves individual eye testing, the disparity observed was not that significant. Still, to provide accessibility for future advancements, the aspect ratio of the VR was adjusted with respect to the design model. As the FOV is less for HMD, the parameter that can be manipulated is the lens's focal length. So for the known value of focal length, offset were added to the original VR scene and, therefore, overcame binocular disparity as shown in Figure no 3.16.

Motion Parallax - This phenomenon mainly occurs when one system is tracking a object with certain orientation with reference to a mirrored system tracking the same object with different orientation. For

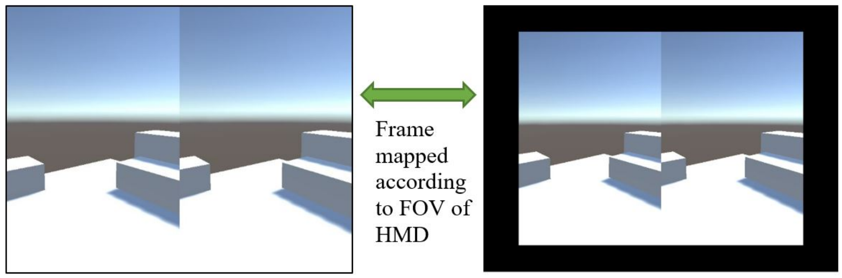


Figure 3.16 Corrected stereoscopic frame to match HMD requirements

example, let us consider the scene is displaying a car moving. If the both camera are not in sync, then in either one of display the car will appear to be slightly slow or fast based on the latency in communication. However in real time, human brain does this calculations effortless which result in information of depth by compositing the two images. In case of web based stereoscopic view, both the cameras are in synchronization, and act as per the users feedback. However, to reduce effect of parallax, objects can be placed at distant areas, because, closer objects exhibit more parallax. [34]

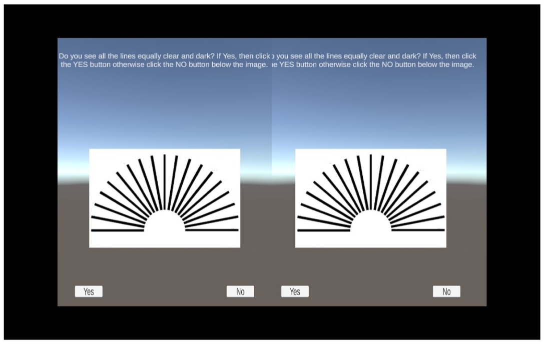
Screen Warping - When a planar image is observed through the lens, it causes certain warpage in the picture. This effect is analyzed thoroughly by Christoph Anthes et al. [35] This distortion is produced by the convex lens, where images bend slightly inward is referred to as pincushion distortion. It can be compensated by applying the reverse action of pincushion that is called barrel distortion. However, in the case of customized HMD, due to lesser FOV, the screen warpage is negligible.

3.6.5 Scene chromatic analysis

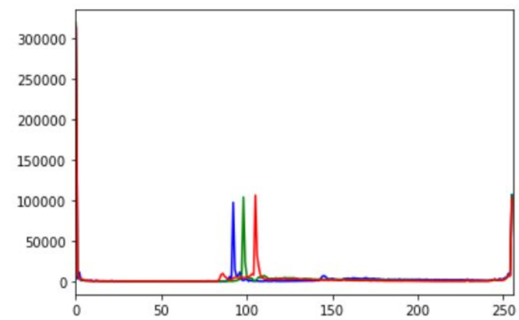
The realism of the VR scene depends on the chromatic distribution of the elements in it. According to the research of Jeanine Amman et al., an experiment was conducted where real-life life and VR aspect was compared by mimicking a regular activity. Although many people found to have particular difficulties with VR objects colouring with resemblance to real-life objects, the results were very encouraging. [36]

In the case of optical analysis, as specified for customized HMD, the colour density of the VR scene is kept very simple. The colouring in the room is made such that the object to be focused gets maximum illumination. The background is made pitch black in order to achieve accurate results for optical tests. As the audience targeted for this particular application is supposed to be diagnosed with the visual ailment, so, the testing element and the navigation panel must be designed such that even a person with a particular visual ailment is comfortable with it. For example, if a person has color blindness, care should be taken that he/she does not find any problems while reading instructions because of the font color. The VR scenes are designed to focus more on black and white colours to minimise these usability issues for people suffering from some visual ailment.

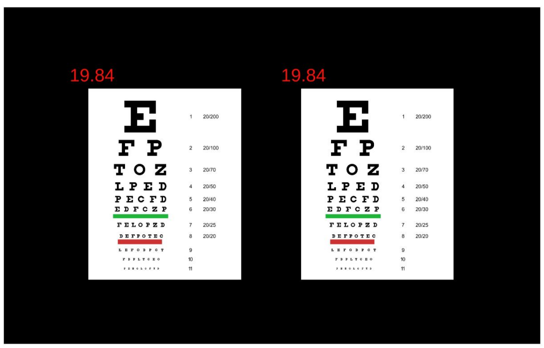
Multiple colours are used in the scenes where they hold significance. Figure no 3.17a is an image of



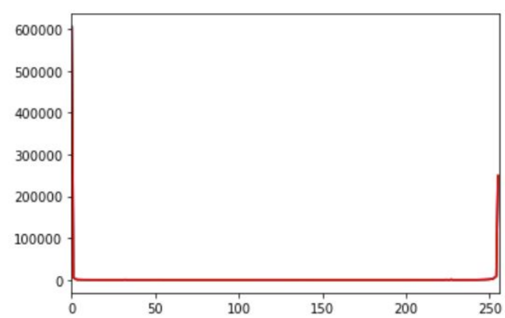
(a) Test VR scene output



(b) Histogram of the scene



(c) Modified VR scene output



(d) Histogram of the scene

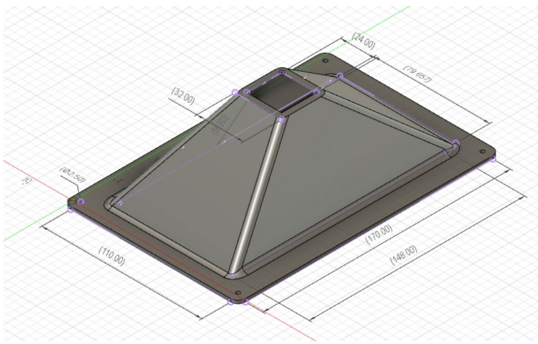
Figure 3.17 Comparison of histogram of two different VR scenes

the test VR scene, Figure no 3.17b depicts its histogram representation. Similarly, Figure no 3.17c is a modified VR scene emphasising two colours and Figure no 3.17d shows a corresponding histogram. It is evident that, changing the colouring of the background can add a significant impact on scene chromatics and subsequently help user to be comfortable to read instructions.

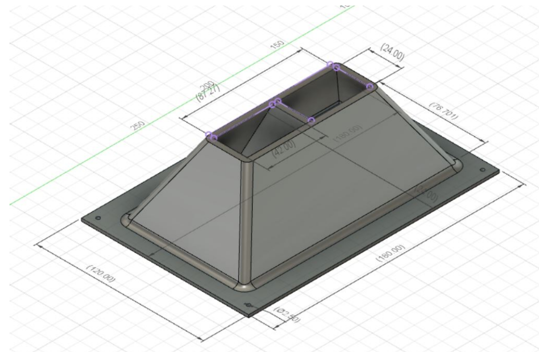
3.7 Prototype Design

The prototype of any product is often regarded as a sample module that has not been exposed to usability analysis. To design the HMD that is fully operational for the optical applications, the user study is significant. So initially, the idea was to come up with the design based on the works of Olson et al. [8] and J.Y.Son et al. [26] The review done by Rajesh Desai et al. on Oculus Rift helped in devising the basic framework of the 3D model. [31]

The orientation of each system in the HMD architecture is essential for its calibration and compact structure. The layout is arrangement of the individual units on the actual hardware. The construction of the layout helps in size estimation and setting the range for the design architecture. The outer range of the HMD layout cannot be smaller than the display itself(7 inches). So the processor element can



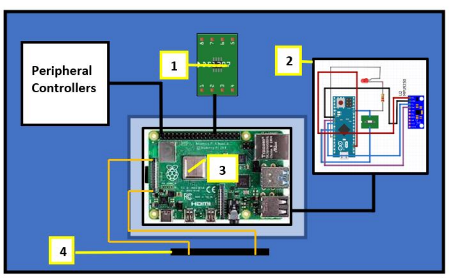
(a) 3D model prototype of Monoscopic HMD



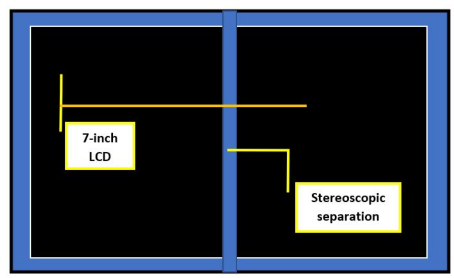
(b) 3D model prototype of Stereoscopic HMD

Figure 3.18 HMD basic design architecture

be stationed in the center and individual units can be positioned in its vicinity. The layout of all the components can be represented in Figure no 3.19a and 3.19b.



(a) Back layout of HMD



(b) Front layout of the HMD

Figure 3.19 Layout of the HMD design

Based on the study done on presently available HMD's, two models were designed. One model designed was monocular, as shown in Figure no 3.18a, and another model was binocular, as shown in Figure no 3.18b. The design of models was initially basic and customizable in order to incorporate further changes. The models were then subjected to usability analysis to detect the cause and effects of HMD's performance. Based on the survey conducted in the analysis, the Pareto distribution of the issues faced by the users was tabulated as shown in Figure no 3.20. Each design defects and errors were then eradicated by revising and validating the HMD design systematically. Issues presented in the analysis can be minimized by inculcating following corrections in the HMD design-

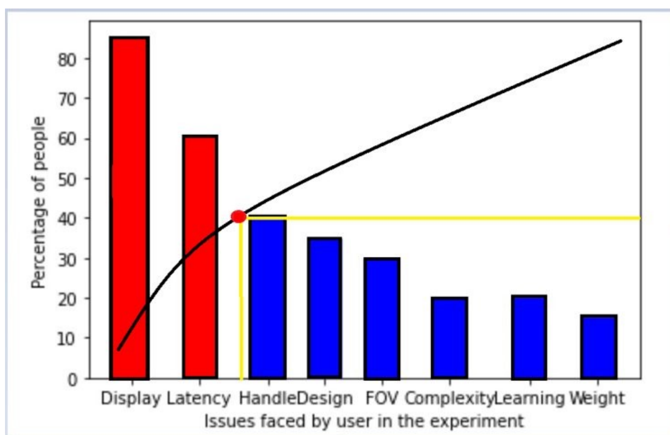


Figure 3.20 Issues faced by the user in the survey

Chapter 4

CHORD-Customizable Head-mounted device for Ocular disoRder Detection

In this chapter we discuss about the application of the previously developed 3-DOF HMD in the field of Healthcare.

4.1 Motivation

World Health Organization's (WHO) global data on visual impairment 2010 report estimated 285 million people to be visually impaired, 39 million of whom were blind. Countries like India, China and the African sub-continent suffer a lot due to a lack of enough tool support to detect and cure these visual disorders at early stages [37]. In the past decade, the number of people with disorders like Myopia, Hypermetropia, Color blindness and AMD and the type of eye disorders and ailments has increased. Early detection of the impairments can aid in taking preventive measures that avoid further degradation of the impairment. However, in countries with large populations, the ratio of healthcare professionals to the number of people is still an issue. Regular tests for detecting various health issues like visual impairments requiring complex optometric devices are still an area of concern. A relatively inexpensive device that does not require domain expertise or minimal intervention from healthcare professionals and is used to detect visual impairments can be helpful in early detection and seeking a subsequent course of action for treatment.

We present an approach to develop a customized low-cost HMD named CHORD (Customizable Head mount device for OculaR disorder Detection) to run VR scenes developed to detect human eye defects. As part of this paper, we discuss our efforts toward developing CHORD and a few test cases using VR-based scenes to conduct tests on visual acuity, astigmatism, color vision deficiency and age-related macular degeneration.

4.2 Background

Visual acuity is the ability of the eye to measure the clearness in vision, which depends on parameters like accommodation, retinal focus, and the nature of ciliary muscles. Over a while, a person's visual acuity was measured using his/her ability to distinguish the slightest detail in a character chart. The Snellen chart is a leading test used as a standard procedure for determining visual acuity. It includes eleven lines of block letters, each representing a Snellen ratio. [38] The Snellen ratio is the distance at which the user can see the line to the distance at which the normal person sees the same line in the Snellen chart. So, for the normal person, the vision is 20/20, which means he/she can see the line at 20 feet, the same as what a normal person will be able to see in the Snellen chart.

Shivang Shekhar et al. developed a visual acuity test based on VR using the Unity platform. [39] The results obtained from the test for myopic vision were encouraging and helpful to construct web-based scenes for customized HMD. The Snellen chart as shown in Figure no 4.2 is displayed to the participant for visual acuity test. The objective is to check for myopic disorder in the participant by performing standard visual acuity test.

Astigmatism is a common vision disorder caused due to irregularities in the shape of the cornea. The error in the shape of the cornea leads to partial refraction across the curve of the eye lens, causing blurring or distorted vision. It is categorized as a genetic disorder but directly relates to people suffering from near or short-sightedness. [40] In Ophthalmology, astigmatism is diagnosed using keratometry, refraction test and retinoscopy. [41] As the astigmatism test involves using Fan chart for estimation, VR can prove vital in the experiment. As scene requirements are minimal, an interactive VR scene can be constructed where the user will experience the same surrounding as a regular optometrist and then get tested virtually. Figure no 4.2 depicts the VR scene designed for Astigmatism test.

Colour vision in any biological organism is when light is reflected through the object and focused on a retinal screen consisting of photo-receptors made up of rods and cones. The photo-receptors behave as transducers converting light energy into electrical energy to be sensed by the nervous system. [42] However, due to defect in the structure of rods and cones, which has mainly genetic cause, the person experiences inability to perceive colours. This defect is termed colour vision deficiency.(CVD)

Shinobu Ishihara et al. developed a colour vision test based on different colour patterns. [43] He designed the charts so that the normal person will perceive different numeral compared to a colour blind person. The chart provided merit of distinction for CVD as the results obtained were accurate. Hatem M. Marey et al. focused on implementing the Ishihara test as a computer-based test and yielded productive results when tested on around 200 participants. [44] Since the customized HMD will be hosting web-based VR scenes, the module can display Ishihara charts and test users CVD. The VR scene for colour blindness is shown in Figure no 4.2

The human eye's retina is classified into two parts, the peripheral retina, which covers most part and the other is macula, which helps focus on the things present in the central part of FOV. The defects in the macular area result in blurry vision, distortion or dark spots in the central vision. According to the Eye disease prevalence research group(EDRP), AMD mainly occurs in people aged above 65. Hence the defect is termed age-related macular degeneration.(AMD) [45]

The cause of AMD is still not known, however wearing of retinal muscles over time can be the contributing factor. Anat Loewenstein et al. stated patients at risk of AMD were subjected to the Amsler grid test to diagnose visual field scotoma or blurry vision. But as said, Amsler grid results were not reliable due to low compliance, crowding effect, and non-interactive nature. [46] Wolfgang Fink et al. implemented a 3D Amsler grid on the computer for the macular test, and the results obtained were encouraging. [47] The VR scene displaying the Amsler grid can be interactive and avoid the crowding effect caused by multiple lines. Figure no 4.2 represents the VR scene showing the Amsler grid for the AMD test.

4.3 Evaluation Study

We conducted an experiment to test human eye disorders, namely visual acuity test to check myopic vision, astigmatism to judge imperfections in the cornea and lens, CVD to check color blindness and AMD to study vision loss in the fovea (centre) of an eye. The final version of CHORD used for the experiment is demonstrated in Fig. 4.1.

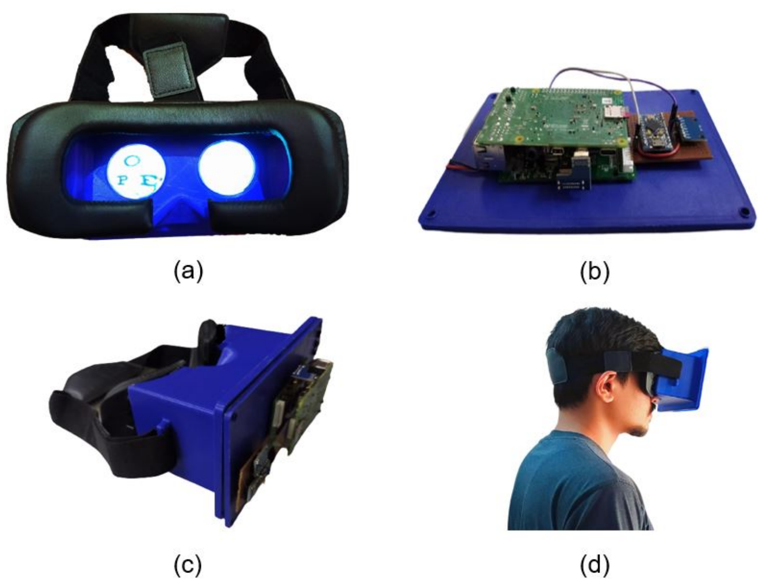


Figure 4.1 (a) CHORD running visual acuity test, (b) Hardware setup of CHORD with all components, (c) side-view and (d) a participant wearing CHORD

4.4 Experimental setup

For visual acuity, we followed BS 4274–1:2003 as a testing standard [48]. According to the standard optical procedure, it is recommended to test each eye separately. Visual acuity and astigmatism are traditionally tested on individual eyes, as each eye may have a different level of disorders [30]. The Snellen chart is displayed as shown in Fig. 4.2a, and the participant is asked to follow the standard testing procedure to detect the myopic disorder. To detect AMD, we designed Amsler's grid to detect a defect in the central region, mainly macula, as illustrated in Fig. 4.2b [49]. For CVD, we implemented a widely approved Ishihara test as shown in Fig. 4.2c [50]. For astigmatism, standard diagnose techniques are keratometry, refraction test and retinoscopy [51]. We made use of Fan chart as a testing tool for astigmatism in the VR scene, as illustrated in Fig. 4.2d. The testing procedure and the experimental setups in the paper are approved by the domain experts in Opthalmology.

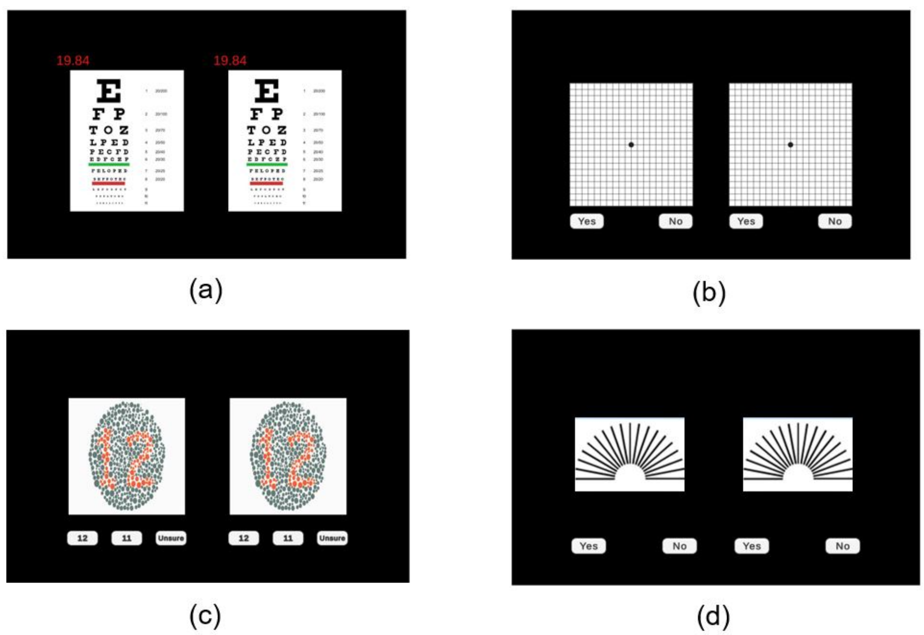


Figure 4.2 VR scenes for the experiment

4.5 Procedure

At the beginning of the experiment, HMD is set up based on the disorder to examine. This is a relatively simple process, and novice users can also learn the configuration process.

- The technician configures the VR HMD for the visual acuity test.
- The participant is made comfortable with the VR headset as he/she is made to wear the HMD and interact with the peripherals.

- While testing the right eye, the left eye is practically covered using a flap on the headset. Similarly, while trying the left eye, the flap is moved to the left eyelid on the HMD.
- The VR scene displays a scene for testing visual acuity, astigmatism, colour blindness, and age-related macular degeneration.
- The questions will be asked to the participant based on the VR scene related to a particular eye disorder.
- The participant can navigate the scene using joystick by using right-left tilt as forward-backwards movement and front-back tilt as pan up-pan down movement or answer Yes/No questions as advised by the technician.
- After done with the test, the responses of the participant are recorded and analysed.

4.6 Participants

30 participants (20 male and 10 female) within the age of 22-40 years ($\mu_{age} = 23.5$) were selected for the eye-testing experiment. They were primarily students, professionals and institutional staff. All the participants confirmed not having any prior experience related to using of VR HMD's. We had diversified data with a combination of participants with normal or myopic vision. The average time spent on each participant to carry out all the tests was around 15-20 minutes. Fig. 4.1d shows the participant wearing CHORD. We took a break after every hour to avoid excessive heating of the device.

4.7 Results

We further classified the results based on the target disorder that is been diagnosed. For each iteration of test we performed corresponding testing procedures.

4.7.1 Visual Acuity Disorder

Iteration-1 - The test was conducted on around 30 participants, specifically 10 females and 20 males aged 22-28 years with some visual acuity disorders. Initially, the Snellen chart is displayed to the user. After that, the user is asked to read out the corresponding lines in the Snellen chart starting from 1 to 11. If the user finds it difficult to read a particular line in the chart, he/she can virtually navigate forward or backwards using the joystick to make the line readable. Steps in the virtual scene for which line in the Snellen chart is visible are simultaneously recorded as test observations. The virtual steps in the scene were mapped to a range of values from 5 to 18 units. For reference, practical visual acuity was done to cross-check and map the virtual values with actual values. Based on the observations carried out for the participants, people suffering from the myopic disorder can be diagnosed and assigned a Snellen ratio.

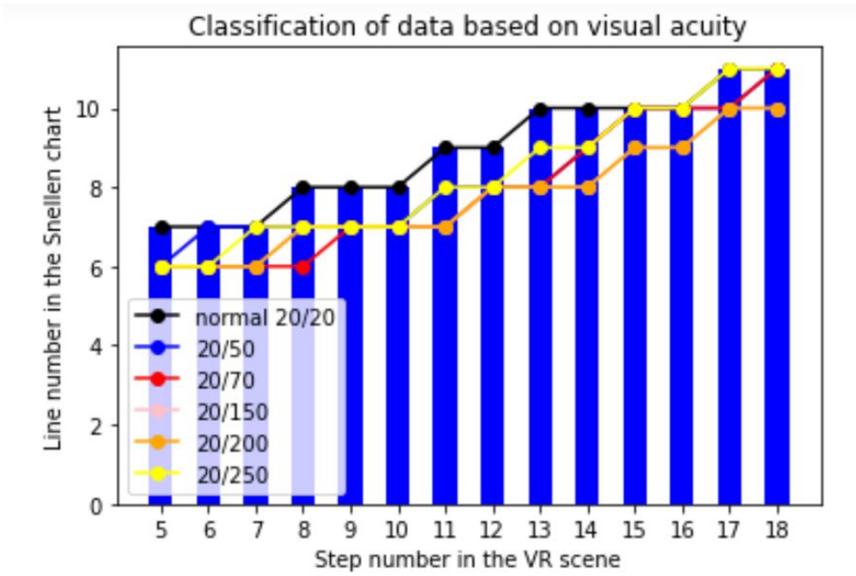


Figure 4.3 Classification of data based on visual acuity

People with normal visual acuity have a 20/20 ratio which means they can see the object at 20 feet what an average person can see 20 feet. The readings obtained from participants tested for visual acuity were analyzed and classified based on the ratio. As per the graph in Figure no 4.3, the 20/20 vision represented by the bar graph observed in the average non-myopic person was taken as a reference. The people with visual acuity will be compared with the 20/20 reference obtained from the participants with no visual acuity disorder. Table no 4.1 shows the evaluation based on the Snellen experiment, corresponding values in the VR scene and experimental values diagnosed for the participant.

Iteration-2 - We did a short study to establish a relationship between virtual distance and the user's eyesight (eye power). We selected participants with diverse vision levels (0 to -3D). The visual acuity of the participants was calculated using the standard Snellen procedure in a well-lit environment. Then the participants were asked to perform the same process using CHORD. We recorded the virtual distance for the corresponding value of eyesight.

It was evident from the observation that both variables had a linear relationship, as illustrated in Fig. 4.4. ($\rho = 0.9367$) So, we performed a regression analysis to develop a model to predict eye power (dependent variable) using virtual distance (independent variable) as input. For the first iteration, we achieved R^2 of 71.42%. We observed higher deviation in eyesight above -2.75D, so we termed them as outliers. In the final iteration, we eliminated three outliers and achieved R^2 of 87.74%. As P-value is much less than $\alpha = 0.05$ as shown in the table in Fig. 4.4, the model will hold its accuracy and reliability even for a large population. For verification, the model was tested with 30 new participants and the accuracy recorded was 93% with a tolerance of ($\pm 0.15D$). The equation of predicting eye power is illustrated in (4.1), where, X = normalized distance = max distance - virtual distance.

REAL SCALE	VIRTUAL SCALE	SNELLEN RATIO
5	12 to 10	-
6	12 to 10	25/20
7	9 to 10	25/20
8	8 to 9	20/20
9	8 to 9	20/20
10	7 to 8	20/50
11	7 to 8	20/100
12	6 to 7	20/150
13	5 to 6	20/200
14	4 to 5	20/250
15	2 to 4	20/250
16	1 to 2	20/300

Table 4.1 Test results for visual acuity test

$$|Power| = 0.4497 * X - 0.173 \tag{4.1}$$

4.7.2 Astigmatism

In the test conducted for Astigmatism, the participant is asked three different questions for corresponding fan chart orientation.

1. The first scene displayed is a square grid. The question showed to the participant is - Do you see horizontal and vertical lines clearly with the same thickness? Yes/No

2. In the second scene displayed is a circular grid. The question showed to the participant is - Are the radiating heavy black lines of the same intensity and thickness? Yes/No

3. In the final scene displayed is a fan grid. The question showed to the participant is - Do you see lines clearly with the same thickness? Yes/No

Based on the answers recorded score is awarded out of 3. The outcome of each possibility is discussed in Table no 4.2.

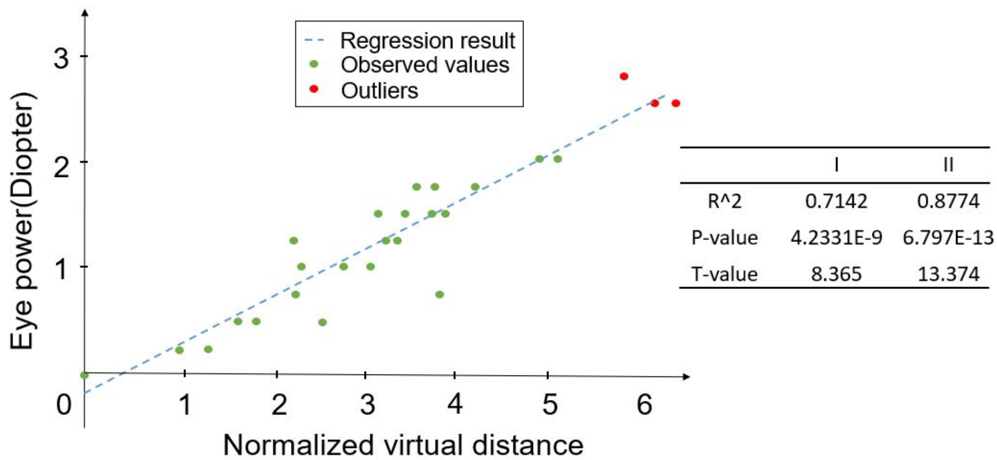


Figure 4.4 Graph for linear relationship between virtual distance and eyesight

EVALUATION	**RIGHT EYE**	**LEFT EYE**
Non-Astigmatic	3/3	3/3
Mild-Astigmatic	1/3 or 2/3	1/3 or 2/3
Astigmatic	0/3	0/3

Table 4.2 Test result for Astigmatism

4.7.3 Color Vision Deficiency

In the test conducted for Colour vision deficiency, participant is asked to identify the numeral that is displayed in the Ishihara chart. The user will find three blocks with three different choice for answers displayed at the bottom of display. All the responses are recorded and analyzed to award score out of 5. The outcome of each possibility is represented in Table no 4.3.

EVALUATION	**BOTH EYES**
Normal	5/5
Deuteranomaly	Error in 2 and 3
Protonomally	Error in 4 and 5

Table 4.3 Test results for CVD

4.7.4 Age-related Macular Degeneration

When the participant is showed the Amsler chart with square grid, he/she is required to concentrate on the central part of the scene. Similarly two more Amsler grid with different schematic are displayed and subjected to same action. If participant experiences strong distortions or blurry vision at the center, he/she is suffering from macular degeneration.

EVALUATION	BOTH EYES
Normal	3/3
Mild	2/3
High AMD	1/3 or 0/3

Table 4.4 Test results for AMD

4.8 Discussion

The results obtained for the eye test led us to think about some interesting hypotheses and research advances that are discussed in the following sections-

4.8.1 Experimental Findings

After concluding the experiment for each disorder, we discussed the extent and the open points of the testing. In the visual acuity test for myopia, the linearity relation between virtual distance and eyesight holds up to -2.75D. On further study, we found that the linearity was again seen in the eyesight above -4D to -5D. Enhanced screen resolution can correct this anomalous behaviour of the model. In the test for astigmatism, we recorded an intriguing observation. The participants who faced difficulty in the Fan chart had relatively high eyesight ($> -2D$), which led us to hypothesize a direct relation between myopia and astigmatism. For CVD, Ishihara test was reliable in terms of clear distinction between the participants. However, some participants found it difficult for a few instances and needed extra effort to identify the number in the test. Further research in hardware design can be done to validate the observation.

4.8.2 HMD parameters

The location of the pupil, inter-ocular distance and optical geometry are crucial optical characteristics for any HMD. CHORD has a fixed inter-ocular distance of 65 mm; however, in future advancements, efforts can be made to make an automatic rack and pinion mechanism to adjust inter-ocular distance using motors [26]. In the VR scene, changing the background color can significantly impact scene chromatics and subsequently help participants read instructions comfortably. Fig. 4.5 illustrates the change in the histogram with of the same test with the removal of background. Added aspect is related to an immersive experience. Straight-line, when observed through a lens, gets distorted at the peripheral region. This effect can be eliminated by pre-processing the image using barrel distortion. We hypothesize that integration of this mechanism can improve the accuracy of the experiment.

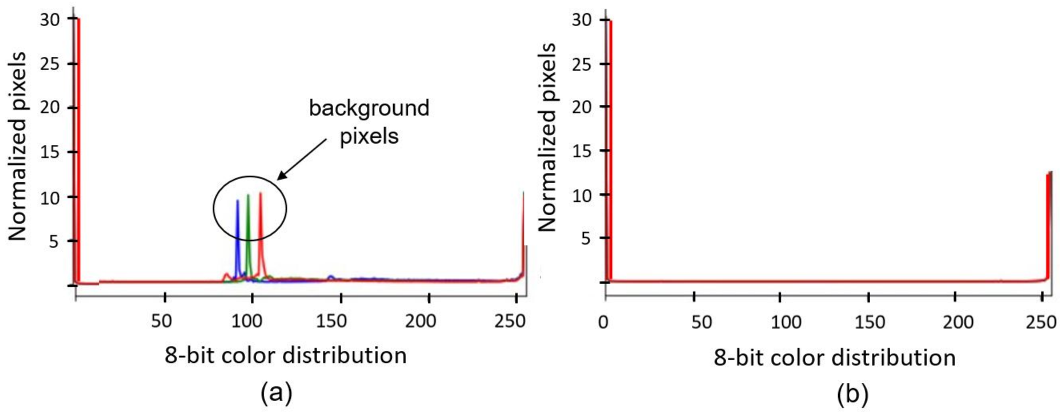


Figure 4.5 Histogram comparison before and after background removal

4.8.3 Comparative analysis

Nowadays, HMD's are available commercially, which are widely used in applications like military, healthcare and entertainment. We did a comparative analysis of CHORD and the available standalone 3-DoF HMD named Oculus Go to get a fair picture of performance and production as illustrated in Table 4.5 [52] [25]. We related the two HMD's based on memory, display used, FOV and pricing. Here, even though the display resolution and FOV of commercially available HMDs is better than CHORD, the application specificity helps in significantly bringing down the cost. The current market price of the Oculus Go is reported around \$ 200, while the cost of the prototype build of the CHORD is \$ 110.

	CHORD	Oculus Go
Memory	32 GB	32 GB
Display	1920 x 1080	2560 x 1440
FOV	∼82 degree	∼110 degree
Weight	450 gm	468 gm

Table 4.5 Comparison of CHORD with Oculus Go

The low-cost characterization of the CHORD is achieved by making it more reliable and application specific. The table no 4.6 depicts the overall expense distribution of the CHORD prototype build. The cost of the prototype can be divided into two parts- Electronic and case design components. Around 80% of the total cost is spent on the microprocessor unit and the LCD display. This can be further brought down with use of FPGAs and other development boards. By scaling up the production, the market value of the CHORD can be reduced significantly. We expect future versions of CHORD to cost less than \$ 50.

	Name	Role	Unit	Price
1	**Electronic components**			
	Raspberry Pi 4 B series	Microprocessor	1	$ 44
	7-inch LCD Screen	Display	1	$ 42
	MPU6050 sensor	Accelerometer	1	$ 2
	ATmega32U4	Microcontroller	1	$ 6
	Joystick	Peripheral	1	$ 1
	Others (connecting wires, PCB, .etc)	Connections	-	$ 4
2	**Design Components-**			
	3D Printer PLA Spool 300 gram	HMD design	1	$ 4
	VR lens (pair) with dia 55mm	HMD design	1	$ 2
	Head strap for HMD		1	$ 3
	GRAND TOTAL			**TOTAL $ 108**

Figure 4.6 Expense table for design of CHORD

Chapter 5

Locomotion in Virtual Reality and its Transformation

In this chapter, we briefly describe the need of HMD hardware transformation when it comes to locomotion in the virtual space.

5.1 Motivation

VR products are on the rise. With facebook^{TM} announcing its vision for metaverse[1], there may be going to be a storm of VR applications into the market like never before. For every VR product, locomotion plays a crucial role in engaging the participant with the VR content. Effective locomotion is achieved if suitable motion tracking methods are best utilized. Unlike external haptic devices, HMDs also offer various avenues to conduct motion tracking to achieve various types of locomotion. However, locomotion capabilities vary between HMDs with a 3-DOF and a 6-DOF. Usually, VR applications that require 3-DOF support can be executed on a 6-DOF supported HMD. However, a VR application that requires 6-DOF support may not be executed on a 3-DOF supported HMD. In contrast, by facilitating some additional hardware on a 3-DOF supported HMD, a closer 6-DOF application can be executed. Such practice is prevalent in the VR practitioner community as most of them upscale or downscale the HMD capacity on supporting motion tracking to manage effective locomotion. Considering these facts, we conducted a literature review on available literature to examine the practices adopted by VR practitioners on how the HMD hardware was transformed from 3-DOF to 6-DOF motion tracking for effective locomotion.

Most VR practitioners who build 3-DOF supported HMD struggle to excel in running rich VR content. However, the slightest hardware transformation will have a significant impact on HMD adoption. This study is scope to understand the hardware transformation of HMDs from 3-DOF to 6-DOF without additional external haptic support. Learning from our study will assist future targetted HMD developers to develop customizable and configurable HMDs for focused applications. This study paves the way for hassle-free substantial hardware transformation of 3-DOF HMDs on supporting 6-DOF in the future. We also illustrate our observations through a taxonomy of tracking methods through hardware-based HMDs.

[1]https://tech.fb.com/connect-2021-our-vision-for-the-metaverse/

This taxonomy will also help VR practitioners to plan and transform their HMDs to support additional motion tracking for effective locomotion.

5.2 Systematic Literature Review

We conducted our systematic review study by considering the guidelines proposed by Kitchenham et al. [53]. As part of our review, we utilized the PICOC (Population, Intervention, Comparison, Outcome, and Context) method to establish our study's context and relevance [54]. This also helped us design our research questions, search string, and search protocol. Table 5.1 illustrates the PICOC details of our study.

Criteria	Description
Population	For VR HMD users willing to switch locomotion from 3-DOF to 6-DOF
Intervention	Motion tracking methods for VR locomotion
Comparison	Comparison between tracking methods based on hardware requirement, working, performance and target application
Outcome	Studies that employed motion tracking methods for locomotion in VR
Context	Academia, VR community and other empirical studies

Table 5.1 PICOC details our Review Study

5.2.1 Research Questions

The primary objective of our review study is to summarize the motion tracking methods served by HMDs for conducting effective locomotion in VR applications. Below research questions are expressed to capture the insights of our objective.

- **RQ1**-What types of motion tracking methods are operated for head tracking by an HMD for VR applications?
- **RQ2**: What are the hardware components required for transforming a VR HMD from 3-DOF to 6-DOF motion tracking?

- **RQ3**: What are the metrics practiced to evaluate the effectiveness of motion tracking methods after transforming the VR HMD from 3-DOF to 6-DOF?

5.2.2 Search strategy

We used our research questions to deduce our search strategy. We first created a list of keywords that are relevant to the research questions. We later generalized the keywords by streamlining the scope of the review. We finalized the search string by considering all possible synonyms and have divided them into three parts, i.e., S_1, S_2, and S_3. Below is our final Search string:

S_1**:** "Virtual Reality" **OR** "VR"

S_2**:** "Head mounted device" **OR** "Head mounted display" **OR** "HMD" **OR** "Head-mounted display" **OR** "Head-mounted device" **OR** "headset" **OR** "display" **OR** "projection"

S_3**:** "Degree of Freedom" **OR** "Degrees of Freedom" **OR** "DOF" **OR** "3 DOF" **OR** "3-DOF" **OR** "3DOF" **OR** "6 DOF" **OR** "6-DOF" **OR** "6DOF" **OR** "motion tracking" **OR** "motion-tracking" **OR** "head tracking" **OR** "head-tracking"

Overall our search string is defined S_1 **AND** S_2 **AND** S_3.

The search string is divided into three parts to carry an organized filtration. The scope of search statement S_1 is limited to the abstract of the research paper only. Both S_2 and S_3 are used to search across the full text of the research paper. We worked with our peer-researchers at our research center over group discussions to address the necessity of each keyword described as part of S_1, S_2, and S_3. We conducted multiple iterations to arrive at a finalized search string. These iterations include a severe review on synonyms, a keyword's relevance, and additional reasoning on search interval to make the search more reasonable. As part of our initial search, we divided our search interval into two periods, i.e., between 2000 - 2010 and between 2011 - 2021. Our cumulative search outputs show that the period between 2000 and 2010 does not provide any significant research contribution. After a three-fold search review by individual peer-researchers, we concluded that the research contribution between the period 2000 and 2010 is either obsolete or not relevant to the current maturity of the VR domain. Thus, we limited our search period between 2011 and 2021 for the essence of a better review. Our review study includes papers published until August 2021.

5.2.3 Search Quality Assessment

We designed a set of ten interrogative questionnaires to aid our review to filter the research papers based on their relevance, reliability, and nature of the study. This questionnaire awards a Yes or No, i.e., 1 or 0 as a score, where yes represents review consideration and No for ignore for review consideration. For a given paper, it requires a score of 6 for review consideration. Our quality questionnaires are explained as follows:

- Is the tracking methodology novel or follow-up research?
- Is there clarity in explaining the objective of the research?
- Is it possible to realize the study as a real-life application?
- Was the application/necessity of the method addressed in the paper?
- Is the data provided in the study addressing objectives of the research?
- Is the motion tracking method validated using a study?
- Was the validation technique for motion tracking explained appropriately with description and reference?
- Is the information provided enough to replicate the design?
- Is the study of value for further research?
- Is there mention of findings, limitations, future scope, or discussions in the paper?

Apart from the search quality assessment, we employed below inclusion and exclusion criteria to further filter our search output.

- **Inclusion Criteria** - Only research papers written in English are considered for our study. Only papers published between 2010 and 2021 are considered. The study that provides transparent information about the design, implementation, and evaluation of motion tracking techniques in VR is considered. Papers that discuss and authenticate the motion tracking accuracy based on some user-study are considered.

- **Exclusion Criteria** - Studies that are not available in Full Text are not considered for review. Research contributions published as articles, magazines, review Notes, datasets, archives, books, book chapters, reference works are excluded from the study as they are informal and incomplete in regards to the goal of our search. Studies involving motion tracking using external haptics, external controllers, or objects are excluded from our study. Paper without proper study to validate the hardware is excluded.

5.3 Results

We conducted our literature search in digital libraries like ACM, Springer, IEEEXplore, ScienceDirect, Wiley. We managed to extract relevant research papers from ACM, Springer, and IEEEXplore. We had to exclude ScienceDirect and Wiley from duplicates, and the results are relatively low compared to other digital libraries. These two libraries have minor literature on both hardware and user interaction in context to VR Domain. We have considered only research articles only for our review study. By following our search strategy, we conducted an extensive search on the respective databases. As illustrated in Fig: 5.1, we extracted our search results in multiple levels by applying inclusion and exclusion criteria. As part of the initial search, we extracted 998 papers from ACM digital library, 726 papers from IEEEXplore, and 1285 papers from Springer Journal. We conducted a peer review and have reportedly removed seven duplicates across the search results. We extracted 3009 papers in total as part of the initial search. As part

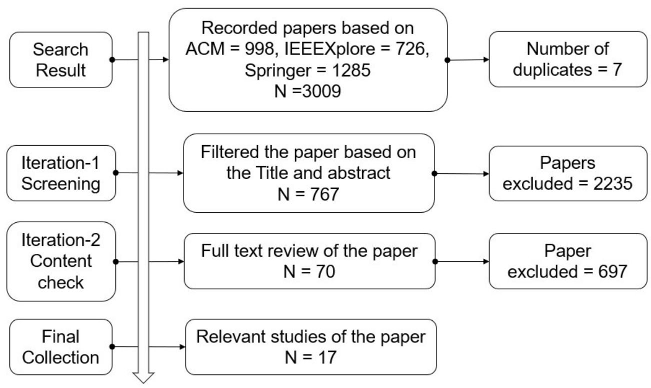


Figure 5.1 Illustration of filtering our Search Output

of our first iteration of screening, we filtered papers based on title and abstract. We excluded around 2235 papers and considered 767 papers as part of this step. In the second iteration of screening, we conducted a full-text review of the paper based on the context of our search and have further filtered the search results to 70 papers by excluding 697 papers. We conducted a detailed study on the filtered papers regarding relevance, technique, and metrics as part of the final consideration. We managed to filter the results to 14 papers, and after further snowballing on related work [54], 17 papers are finalized for our review study. All the authors have individually reproduced the search and applied the filters in respective iterations. All the authors have arrived at a similar conclusion towards the search results. All the supplementary material of our search iterations and review are made available for replicating our study [55].

5.4 Contributions

By considering the finalized research papers, we conducted an elaborated study to record our findings. In this section, we discuss our insights in regards to respective research questions as follows:

RQ1-*What types of motion tracking methods are operated for head tracking by an HMD for VR applications?*

Table 5.2 illustrates the HMDs transformed to 6-DOF support with respective details on their hardware setup, working principle of the underlying motion tracking method to facilitate locomotion in VR

S. No	Application	Tracking method	Hardware setup	Working principle	Locomotion involved	Year	Ref.
1	Sports commodity	Color tracking	camera setup & HMD	Image segmentation followed by a classifier & filtering algorithms	rotation & translation	2011	[56]
		VR-STEP	IMU, pedometer & HMD	Real-time pedometry to simulate virtual locomotion	rotation & translation	2016	[57]
		Walking by Cycle	VR strider, HMD & pressure sensors	Strider action mapped to virtual locomotion with pressure sensors	rotational & axial	2020	[58]
2	Exploratory study	Omnidirectional treadmill	treadmill, camera setup & HMD	Treadmill coupled with motor with the camera setup	rotation & translation	2013	[59]
		Object tracking	camera setup & HMD	3D human model rasterized view using CUDA-OpenGL	rotation & translation	2014	[60]
3	Cognitive study	Suspended walking	IMU & HMD	3-axis IMU attached to the leg as a step counter	rotational & axial	2013	[61]
		Walking in Place	OptiTrack system & HMD	The height of the foot is mapped to data in a virtual environment	rotational & axial	2013	[62]
4	Multi-user application	Infrared tracking method	IR camera setup & HMD	Use of IR cameras to track markers on user to calculate the position	rotation & translation	2017	[63]
		Multi-user tracking	camera setup & HMD	Depth images captured from Kinect sensors and processed using a model	rotation & translation	2019	[64]
5	Redirected motion	NaviChair	motion cued chair & HMD	Leaning motion on the chair simulates an action in the virtual environment	rotational & axial	2015	[65]
		Virtusphere	suspended sphere setup & HMD	Freely suspended spherical frame simulates action in a virtual space	rotation & translation	2015	[66]
		Tapping in Place	walking pad, IMU & control system	The walking pad acts as a navigation key to simulate on IMU-based device	rotational & axial	2018	[67]
6	Training	Electromagnetic tracking system	EM tracking, Step sensor & HMD	The user is localized based on the EM track system using step sensor	rotation & translation	2016	[68]
		Elastic-Move	Suspended system, Elastic belt & HMD	Uses elastic rope as force-based feedback to simulate walking action	rotational & axial	2020	[69]
		Electromagnetic tracking system	Tx-HMD, cube-coil, Rx-analyzer	Calculates the location of central magnetic coil using EM systems	rotation & translation	2020	[70]
7	Simulation	Acoustic position tracking method	acoustic Tx-Rx setup & HMD	Uses acoustic sensing using pair of speakers to track users location	rotational & axial	2018	[71]
		Infrared tracking method	IR LED's setup & HMD	The customized camera captures the position of IR LEDs using a filter	rotation & translation	2020	[72]

Figure 5.2 Finalized studies for the review

applications. It also categorizes these HMDs based on the target VR application. Table 5.2 also provides the year of publication along with its reference. We observe that the motion tracking methods are enhanced by hardware transformation largely for targeted applications like training, simulation, and multi-user application. All these hardware transformations are scaled and scoped to HMDs without any external haptic support. In almost all cases, the HMDs primarily supported locomotion techniques like rotational, translation, and axial. We further discuss the effectiveness of the underlying hardware of these transformed HMDs as part of RQ3.

> **RQ2**: *What are the hardware components required for transforming a VR HMD from 3-DOF to 6-DOF motion tracking?*

Considering the insights from the reviewed papers, we address this research question by proposing a taxonomy of locomotion techniques based on hardware support. The underlying hardware is used to conduct locomotion through motion tracking methods in a given HMD. The motive behind illustrating the taxonomy is to help VR practitioners establish a relationship between the hardware needs of an HMD and choose a suitable locomotion method. Lisa Prinz et al. conducted an initial review of primary studies that involved different taxonomies related to locomotion in VR [15]. Previously proposed taxonomies are based on parameters like walking, redirection, teleportation, haptics, hand gestures, and materialistic feedback [73] [74] [75]. These proposed taxonomies of locomotion are either human-centered or software-centered. They do not factor in the customization of HMDs. Data captured in our review study helped classify the locomotion techniques based on motion tracking by considering the customized HMD hardware.

The characteristics of the hardware system can be defined by the performance of sensors [76], actuators [77], control system, and the processing unit [14]. Considering these hardware characteristics, we propose a taxonomy for locomotion techniques as illustrated in Fig 5.3. Based on captured review information, we classify the hardware-based locomotion techniques for HMDs into three main categories as shown in figure. They are *inside-out, outside-in,* and *mixed tracking*. As part of our initial classification, we considered parameters like DOF, peripherals, and transfer function for taxonomy. However, we limited our taxonomy to tracking device's position only, as it will extensively help VR practitioners choose the best locomotion technique for their respective HMD. As shown in Fig 5.3, the boxes in blue are types of respective locomotion techniques categorized as Inside-out, Outside-In, and Mixed. The boxes in green are the instances or examples of these respective types listed in blue boxes. For example, *'Navichair'* and *'Tapping in Place'* are instances of Inertial based locomotion methods supported by the underlying hardware categorized as Inside-Out tracking.

Inside-Out tracking - The sensors are located on the hardware (HMD) or the user peripherals as part of the Inside-Out tracking. Based on our review, three out of seventeen (17.6%) locomotion techniques belong to inside-out tracking. The inside-out tracking can be further divided into two groups based on the hardware description: inertial and laser-based tracking. Inertial tracking involves analysis based on Inertial-Measurement-Unit (IMU) to track the rotational and translational locomotion in VR HMDs [67].

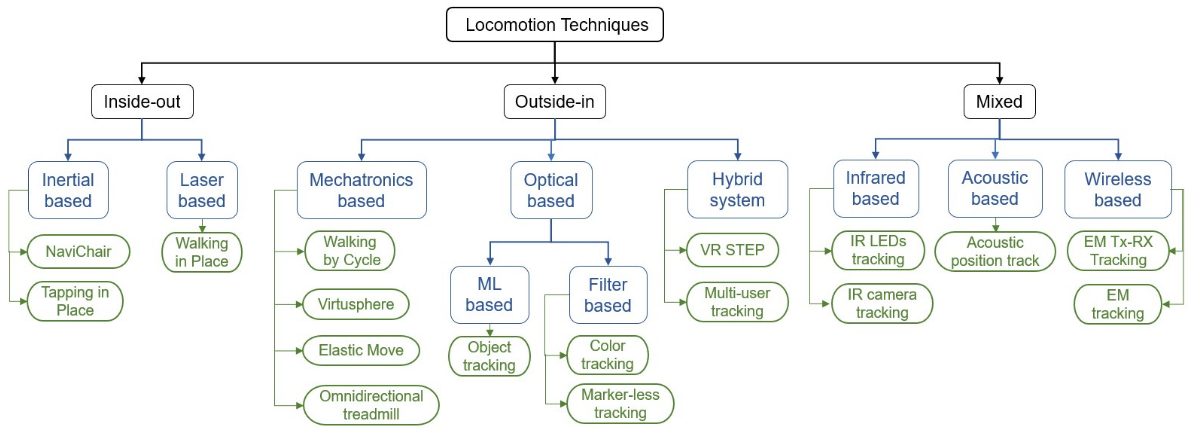


Figure 5.3 Taxonomy of the locomotion techniques based on motion tracking hardware

They are primarily mounted to track the head movements of the user. However, they are not immune to external noise and need a compensation mechanism to counter motion sickness-related problems [65]. On the other hand, laser-based systems like lighthouse tracking use rectangular base stations as reference points to accurately track the user's position, and orientation [62]. These are user-centric, and the data points are gathered based on user stimuli.

Outside-In tracking - The sensors are placed externally, preferably in a stationary position, and are not administered directly on the user's device as part of Outside-In tracking. This locomotion technique is observed to be dominant in practice with nine out of seventeen (52.9%). As per our review, the outside-in tracking can be further classified into three groups. They are mechatronics, optical and hybrid systems. The studies involving redirected actions using mechanical instruments like treadmill, cycle, hamster ball, or suspended walking using elastic can be categorized as mechatronics systems [59] [58] [66]. Locomotion that involves camera-based tracking are categorized into optical systems. Considering the working principle of the camera setup, the optical systems can be further subdivided into two groups: filter and machine-learning (ML) based techniques. The filter-based techniques used color tracking or projection-based detection methods [56], while object tracking and data prediction are achieved using neural networks [62]. Further studies on simulation of motion using mechanical instruments followed by prediction model using ML tools are classified as hybrid systems [60] [64].

Mixed tracking - Further studies have found to be following mixed-methods i.e., they employ both Inside-Out and Outside-In tracking. We categorized them as Mixed Tracking methods. Five out of seventeen (29.4%) locomotion techniques use the user as a receiver and an external point as a transmitter to track position and orientation. Considering the working principle of these systems, we further divided them into three groups: infrared, acoustic, and wireless-tracking systems. Infrared tracking involves locomotion using remote communication utilizing IR cameras [63]. In some cases, position tracking was conducted using the IR LED's on the user body using an external camera [72]. The tracking involving Electro-Magnetic(EM) transmission using base station [68] [70]. These are classified as wireless tracking methods. A novel tracking method for localization using audio inputs(stereo speakers) is categorized as acoustic tracking [71].

> **RQ3**: *What are the metrics practiced to evaluate the effectiveness of motion tracking methods after transforming the VR HMD from 3-DOF to 6-DOF?*

Table 5.4 illustrates the evaluation details of the effectiveness of motion tracking methods after transforming the VR HMD from 3-DOF to 6-DOF. Table 5.4 is a matrix table with the measures listed in the first row and first column grouped by the citation of the respective paper that employs these measures. The measure listed in the first row is the empirical method used to conduct the evaluation. The measure listed in the first column describes the metrics gathered to understand the effectiveness of the respective motion tracking method after transforming the HMD from 3-DOF to 6-DOF. We address this research question we categorized the research contributions based on type of the empirical study. We also present the underlying participant experiences and metrics used by VR practitioners.

Exploratory Studies - The following evaluations are conducted using Sports VR applications like basketball, Jogging In-place, and Walking-by-Cycling.

Robert Wang et al. used a two-camera system in real-world indoor and outdoor environments for various activities and lighting conditions. They conducted a focused group evaluation, including basketball players with 3-DOF HMD wearing colored t-shirts set to be detected by these two camera systems. This camera input is sent as locomotion feedback to the HMD. They captured footage in a dimly lit indoor basketball court through a glass panel of a squash court. Their study was easy to set up with less use of additional lights or equipment [56]. They managed to capture Position accuracy, Drift measure, Precision, and System stability to understand the effectiveness of this setup.

Sam Tregillus et al. have conducted a comparative study of all Walk-In-Place (WIP) methods as part of their study. Several such studies exist that compared WIP with joystick-based virtual locomotion. However, Sam Tregillus et al. presumed that comparisons of WIP methods involving extensive instrumentation are not helpful as the users of mobile VR do not access such instrumentation. They created VR-STEP that is hands-free and requires no instrumentation. It is more meaningful to compare its performance with another hands-free navigation method like *"look down to move"* (LDTM), widely used in several VR apps. Here, the users toggle a button at their feet by briefly looking down at it, then back it up. When activated, the user will move with a fixed horizontal velocity in the direction of their gaze. Similar to other WIP evaluations, they compared VR-STEP to LDTM by having users perform several navigation tasks [57]. They used a Jogging-Inplace VR sport application to conduct the study. They captured track resolution, Motion-to-Photon (M2P) latency and conducted a Statistical analysis to evaluate their 3-DOF HMD.

Jann Freiwald et al. conducted a focused group study using their 3-DOF HMD with a non-swiveling chair setup. 20 participants (Mean = 30.6, SD = 6.82, 7 female) took part in the experiment. The mean time per participant was about 60 minutes. They build a Walking-by-Cycling sports application using Unity3D. The rendered scene is run on HTC Vive Pro and a non-swiveling chair to seat the participants within the tracking space for the bike and joystick conditions. The participants are asked to stand for the teleportation condition. Standing was required to let the participants use their full head and body pro-reception for angular estimation as a baseline to test against. Depending on the condition, they used an Xbox One Controller or the HTC Vive Wand for input [58]. Response Time, Force Feedback, Track resolution, and Drift measure to evaluate the effectiveness of the locomotion.

Computational Studies - The following evaluations are Computational and Parametric studies using omni-directional treadmill and object tracking.

Razvan Boboc et al. conducted an exploratory study to examine locomotion using the neural-network-based algorithm. Six participants took part in this study in a virtual environment over an Omni-directional treadmill simulating the sense of steep in the hill or slove in a cave using a 3-DOF HMD. The position and orientation of the user's feet are captured using the motion tracking system. These are input features of the algorithm. Later, the data is processed to extract the angle between the foot and tibia; the foot's orientation regards the reference position for the right and left rotation of the Omni-directional treadmill. Using Matlab Simulink, the authors have modeled positions of the motors related to a reference factor and a parameter for the scenario, i.e., the model is used to tilt the platform depending on the inclination angle of hills scenarios. For choosing the number of neurons, the neural network is trained in Matlab. The number of neurons in the hidden layer is reduced until the error can be accepted. [59]. They captured metrics like position and rotation accuracy, precision. They also conducted statistical analysis to understand the significance of their data points.

Boguslaw Rymut et al. conducted an exploratory computational study on object tracking in VR Sence based on a real-time multiuser interface using a 3-DOF HMD. Their algorithm's performance has been evaluated on sequences with walking persons. They demonstrated that the average speed-up of GPU over CPU is about 7.5. The overall time taken by PSO searching for the best matching image is far shorter than the time needed for evaluation of the fitness function, which is about 0.9 ms. [60]. They captured track resolution, portability, precision, motion-to-photon (M2P) latency, and response time metrics. They conducted statistical analysis to understand the significance of their data points.

Cognitive Studies - The following evaluations are Cognitive studies using Suspended walking and Walking-in-Place.

Benjamin Franks et al. conducted a focused group assessment with 18 test persons aged 22 to 30 years (average 26.3). Seven of the participants were male, eleven of them were female. The participants are instructed to play a customized level in the game 'Portal 2' using a 3-DOF HMD. The level consisted of an obstacle course specifically designed for the experiment using a level editor [61]. After the game completion, they captured the feedback to evaluate the hardware based on drift measure, track resolution, force feedback, and system stability. The response revealed that none of the participants found the suspension setup most comfortable. Some participants criticized that contrary to WIP, the setup restricted the backward locomotion.

Luis Bruno et al. conducted a cognitive study using the OptiTrack motion system. The experiment involved was divided into three segments. Prior to the test, the participants are asked to take a pre-test questionnaire to gather each participant's demographic and navigation skills data. The participant was made comfortable with the environment by performing travel and stopping tasks. The actual test involved traveling all nine paths and making stops before each target as early as possible [62]. The path was repeated in case of system error or difficulty. After the task, the participants were subjected to the post-test questionnaire to get feedback about their experience. The metrics evaluated using the experiment are drift measure, switching rate, interface network, and response time.

Multi-User Applications - The following evaluations are Multi-user applications using infrared markers and markerless multi-view tracking.

Wenhui Xu et al. performed a focused group assessment using two individual experiments based on the parameters [63]. The first experiment uses three infrared cameras with a resolution of 1280 x 720 pixels. The participant with the LED module is made to stand three meters away from the cameras. The test was conducted for varying positions and orientations of the participant. The observations suggested that fluctuations do not alter the behavior of the VR display. The second experiment tests the data refresh rate of the system. They experimented with varying resolutions of display for three cameras and a four-camera setup. The results show that resolutions have a slight effect on the accuracy in the indoor environment. The metrics captured in both experiments are positional accuracy, rotational accuracy, precision, response time, and system stability.

Dylan Bicho et al. conducted a user-centered study and proposed a method using four Microsoft Kinect sensors [64]. The intent was to capture the locomotion of the participant in the different orientations using a 3-DOF HMD. The participant was asked to perform individual tasks like walking straight, following a square-shaped path in a closed-loop, moving in a random path with sudden body or head motions or standing stationary on a single leg with arms wide open. The metrics captured in the experiment are drift measure, track resolution, portability or customization, learning curve, and switching rate.

Redirected Motion - The following evaluations are conducted using redirected motion applications like NaviChair, Vitrusphere and Tapping-in-Place.

Alexandra Kitson et al. conducted a user-centred study to evaluate the factors responsible for motion sickness in NaviChair [65]. The participants tested for two locomotion techniques in the experiment. The first experiment involved motion using a user-powered swivel chair called NaviChair. The participants can move forward by tilting the chair forward and rotating the chair to rotate in the virtual environment. The second experiment involved a similar set of locomotions, but the joystick was used as the input device. The observations concluded that NaviChair did not help the participants localize and adjust to the virtual environment. The metrics evaluated using both experiments are drift measure, learning curve, interface network, M2P latency and statistical analysis.

Mahdi Nabiyouni et al. conducted a simulation-based study using a suspended sphere called Virtusphere [66]. The user's walking is mapped to a viewpoint translation in the virtual scene. They performed a comparative analysis of semi-natural techniques like Virtusphere with an entirely natural technique like walking and artificial technique using a game controller. The analysis suggested that the Virtusphere method was significantly slower and less accurate than the other two techniques. The parameters involved for the comparative analysis were drift measure, rotation accuracy, force feedback and system stability.

Marian Hudak et al. did the comparative analysis using a customized CAVE setup [67]. They used the 250-degree panoramic view to simulate the surface of the cave as a virtual environment. The participant was asked to perform standard walking and rotation movements. The forward movement was represented on the central tile, and step-aside rotation tiles represented pan rotation movements. The metrics captured in the analysis were position accuracy, precision, noise immunity, interface network and response time.

Training - The following evaluations are conducted using training applications like Electromagnetic tracking and Elastic-move.

Markus Zank et al. did a comparative study for walking in a straight line with the old autonomous tracking system [68]. The comparison was made primarily on parameters such as signal for foot movements, base's movement along the walking direction and movements in upward and sideward direction. The metrics evaluated in the study were drift measure, rotational accuracy, noise and power analysis, system stability and statistical analysis.

Da-Chung Yi et al. conducted a focused group study to evaluate the elastic-move system [69]. The experiment was performed using Simulation Sickness Questions (SSQs) to validate the use of Elastic-Rope and Elastic-Box in VR. The participant was asked to move from a base point to the route ends in a customized virtual environment. The duration of the entire experiment is about 15 minutes. The metrics evaluated for successful motion tracking were rotation accuracy, learning curve, force feedback and noise immunity.

Shantanu Barai et al. did an experimental analysis to localize the participant using an EM-based Tx-Rx system [70]. The EM transmitter was set up at a stationary point, and the secondary coil was mounted on the custom 3-DOF HMD. The experiment is carried out with the varied location of the secondary coil in the X-Y plane. The Z-value is kept constant and is compensated by transformation. The metrics captured using the experiment are position accuracy, drift measure, noise immunity, power and statistical analysis.

Metrics \ Study	Focused Group studies	Cognitive Studies	Comparative Studies	Compute Studies	User-centered Studies	Simulation Studies	Experimental Studies
Position Accuracy	[56] [63] [71]	[62]	[67] [72]	[59] [70]	[63]	[67]	[62] [63] [68]
Drift measure	[56] [58] [61] [62]	[61] [62]	[68] [72]	[70]	[63] [64] [65]	[66]	[63] [65] [68]
Rotation Accuracy	[63] [69] [71] [72]		[68] [72]	[59] [69]	[63] [65] [66]	[65] [66]	[63] [65] [68]
Track Resolution	[58] [61] [71]	[61] [64]	[57] [67] [70]	[60]	[64]		[64]
Portability		[64]	[60] [72]	[60]	[64]		[64]
Learning curve	[69]	[64]		[69]	[64] [65]	[65]	[64] [65] [69]
Precision	[56] [63]		[60] [67]	[59] [60]	[63]	[67]	[59] [63]
Switching Rate	[62] [63] [72]	[62] [64]	[72]		[63] [64]		[62] [63] [64]
Force feedback	[58] [61] [69]	[61]		[69]	[66]	[66]	[69]
Noise Immunity	[68] [69] [71]		[67] [68]	[69] [70]		[67]	[68] [69] [70]
Interface network	[62] [67] [71] [72]	[62]	[60] [67] [72]	[60] [69]	[65]	[65] [67]	[62] [65] [69]
Power Analysis	[71]		[68] [70]	[70]			[68] [70]
Response Time	[58] [62] [63]	[62]	[60] [67]	[60]	[63]	[67]	[62] [63]
System Stability	[56] [63] [72]		[68] [72]		[63] [66]	[66]	[63] [68]
Statistical Analysis	[71]		[57] [60] [68]	[59] [60] [70]	[65]	[65]	[65] [68] [70]
M2P latency			[57] [60]	[60]	[65]	[65]	[65]

Figure 5.4 Evaluation and metrics for the locomotion techniques

Simulation Studies - The following evaluations are conducted using Simulation-based VR applications like tracking using acoustic and infrared LED setup.

Majed Al Zayer et al. used two acoustic speakers as the communication model to track the user's location who wears a 3-DOF HMD. They conducted a focused group evaluation for StereoTrack with a smartphone-based microphone to record ultrasonic tones. Multiple tones with varied frequencies were played on three different speaker interfaces to analyze the values [71]. They succeeded in verifying the hardware by measuring positional accuracy, rotational accuracy for 180 degrees, noise immunity, power, and statistical analysis.

Rasmus Eklund et al. conducted a comparative study for infrared tracking systems based on tests inspired by the Brimijoin experiment. The experiment confirmed that the participants with 3-DOF HMDs slightly moved their heads back and forth at about 15 degrees compared to no head movement. They repeated the experiment to see if participants could notice the degree of externalization once they stopped moving their heads [72]. They captured rotational accuracy, switching rate, interface network, and system stability to evaluate the performance of the hardware.

Strategizing Hardware Transformation: We presume that the observations captured from the above research questions will provide VR practitioners a reasonable choice for hardware transformation of their 3-DOF HMD. We systematically structured our observations so that the VR practitioners can understand the prevailing practices and channelize their HMD needs by picking up the desired evaluation method and metric to judge their transformed HMD. We have ensured that our complied taxonomy is compact and easy to comprehend the locomotion techniques for better hardware transformation.

5.5 Inference

Locomotion in a VR Scene plays a critical role in user engagement. Motion tracking methods play a crucial role in locomotion. The primary goal of this paper is to identify the motion tracking methods operated in HMDs for conducting effective locomotion. This led us to conduct a systematic literature review to analyze the trend adopted by VR practitioners on transforming their 3-DOF based HMDs into 6-DOF for improved motion tracking scoped to HMDs only. Our review study revealed that different motion tracking methods like color tracking, object tracking, walking in-place, tapping in-place, elastic-move, etc., are achieved directly using an HMD without any influence of external haptic controllers. Overall, we expect that our review study will help HMD developers to consider all available observations to build novel HMDs using distinct motion tracking methods for focused VR applications.

Chapter 6

Design and Implementation of 6-DOF HMD

6.1 Introduction

This chapter discusses integrating the previously developed 3-DOF HMD into 6-DOF HMD using outside-in motion tracking methodology.

6.2 Hardware Design

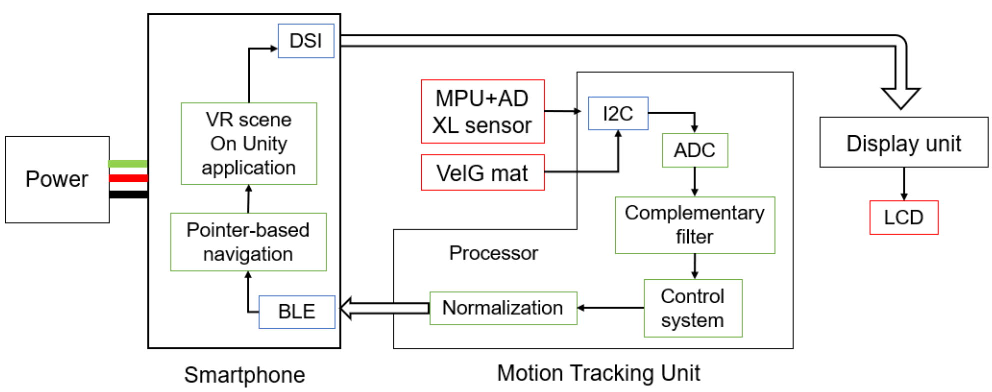


Figure 6.1 6-DoF HMD Hardware Architecture

The hardware realization of 6-DoF HMD can be classified as an integrated system of two standalone systems.

6.2.1 Hardware Architecture

The hardware architecture of the 6-DoF HMD can be realised in the form of 2 separate systems. The first system is the Processing Unit, and the second can be termed the motion tracking unit. The Processing Unit will display the functionality and host a VR scene on the server. The motion tracking unit will comprise a 6-DoF tracking methodology, which will involve 3-D head tracking and 3-DoF translational tracking.

The working of 6-DoF motion tracking methodologies can be realised as an embedded system. It begins with the Processing Unit hosting the VR scene. The VR scene can be an application-specific unity-based software. The 3-D head tracking used is pointer-based navigation with a microprocessor. The motion-tracking unit talks to the microprocessor using Bluetooth enables. The display unit is attached to the processor using DSI ports. The Motion tracking unit involves MPU-based 3D head tracking and a Peripheral device for outside in tracking. The translational movement of the participant is detected using a velostat-based sensing mat. The velostat has the property of changing its resistance upon applying pressure. Integrating both sensing devices forms a 6-DoF tracking methodology. Both systems are standalone in nature yet are combined to form a complex embedded system.

6.2.2 3 DoF HMD

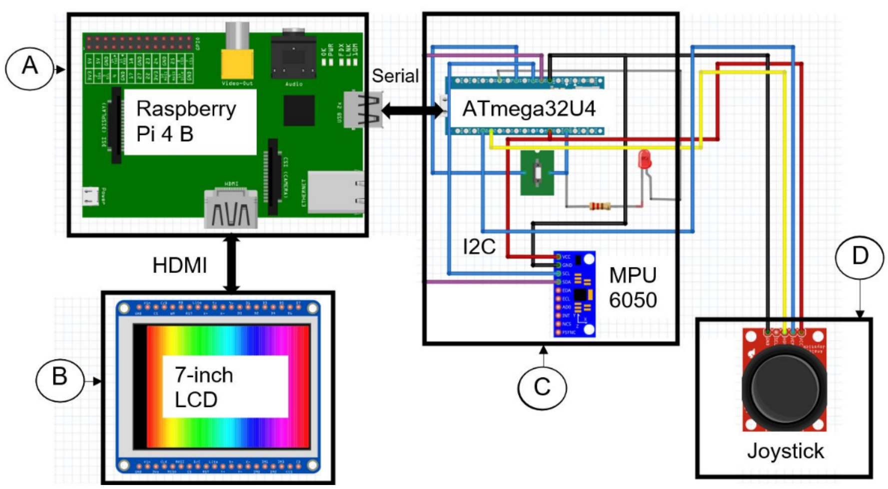


Figure 6.2 Hardware Schematic of 3-DoF HMD

As discussed in Chapter 3, a typical HMD has three modules: (1) a Display unit comprising an LCD screen used to project and play the 3-D VR scene, (2) a Microprocessor that processes the incoming requests, and (3) an operating system (for example, an open-source operating system like Raspberry Pi OS). Additionally, depending on the purpose of the HMD, a Motion tracking unit that includes an accelerometer and other peripherals associated with the microcontroller may be part of the device. The microprocessor initiates the flow of events by hosting the VR scene loaded from its memory and waiting for data from the microcontroller to be visualized on the display unit. The performance of such system hardware depends on the processor, sensor and actuator's sensitivity towards the information based on its use case.

The HMD will act as the processing element of the overall hardware system. It will receive the packets of data from the velostat-based mat using blue-tooth protocol. Based on the values, it will interpret the locomotion in the VR scene using pointer based navigation. The system is designed such that, if there is loss in data transaction between the HMD and mat, the HMD will shift to 3-DoF functionality. For now the system is tested on the serial communication interface (wired) but can be optimised to wireless using BLE. In future the CHORD based HMD can be replaced with camera enabled smartphone to further address the cost issues of the system.

6.2.3 VelGmat for outside-in tracking methodology [1]

The sensing unit is realized as a mat of a specific size with orthogonal copper tapes up and down as a matrix and a velostat in between, creating n x n individual sensors where n is the several copper tapes up and down. The copper tapes are connected with wires directly to the microcontroller or using 16:1 multiplexers. The whole setup, as in Fig. 6.3, acts as an an embedded system containing a microcontroller (ATMega 2560) as a computational element, mat as an input device for data capture, and a biasing circuit for calibrating sensitivity and range. This sensing unit is used to capture the foot pressure during gait analysis.

Overall the working of the system is as follows - The velostat that is sand-witched between the two orthogonally placed copper tapes acts a potentiometer. It localizes the participant based on the position he/she is pressing on the mat. The mat is divided into 4 sections that simulate the working of 4 arrow keys (UP-DOWN-LEFT-RIGHT). The biasing circuit carries out the sensitivity mapping of the overall control system. The hardware realization of the VelGmat as shown in Fig. 6.4 is credited to the research performed by Mohammad Waqas Wani et al.

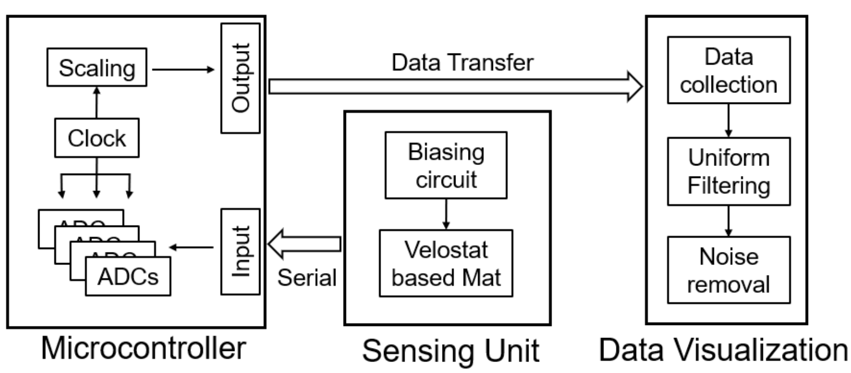


Figure 6.3 Hardware architecture of VelGmat

[1] Credit to this section belongs to Mohammad Waqas Wani

Figure 6.4 Velostat based mat for translational tracking

6.2.4 System Integration

System integration of 6DoF HMD is similar to the architecture of a subsystem. As we know, the subsystem combines individually working control systems that form a closed-loop feedback network. Similarly, 3DoF HMD (CHORD) acts as an individual system, and Velostat-based mat serves as an outside-in tracking methodology. The synchrony of two systems in a closed-loop feedback network gives us a 6DoF HMD. In this section, we will discuss the design of the two systems and their integration with the help of a communication interface individually.

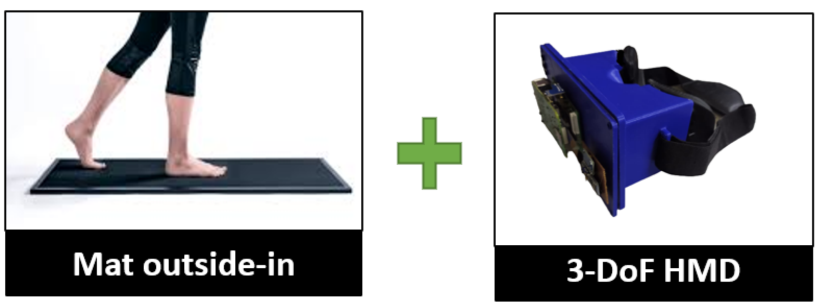


Figure 6.5 System integration for 6-DoF HMD

The communication established between the two subsystems here is serial; Bluetooth for wireless and USB for wired networks. The velostat based mat senses the user position on the copper array. The microcontroller interprets the values and then maps them to corresponding digital output. The output is then carried on to the HMD for data interpretation. The receiver decodes the encoded data into string depicting the virtual inputs. The data helps calculate gait parameters such as stride length, linear acceleration and flight time. Flight time in our case is the time interval for which the foot is not touching the mat. The decoded data is then feeded as an input the web based VR scene hosted on the HMD. In future advances the mat will directly latch the data with the smartphone Bluetooth module and VR scene is hosted via apk file.

6.2.5 Experimental analysis - Walking In Place

At the beginning of the experiment, HMD is set up based on the locomotion involved in the application. The VR scene used in the scene is similar to the one used in check the screen resolution. Refer section 3 for more details related to the scene assets.

- The participant configures the VR HMD for the scene navigation.
- The participant is made comfortable with the VR headset as he/she is made to wear the HMD and interact with the peripherals.
- The participant can navigate the scene using velostat based mat as shown in Fig. 6.6 using feedback from his foot. By placing the foot in the appropriate quadrant across the mat the user feed in the data that simulates arrow keys.
- The experiment helps calculate head rotation parameters like raw, pitch and yaw and gait parameters like stride length, linear acceleration or cadence and flight time.
- After done with the navigation, the responses of the participant are recorded and analysed.

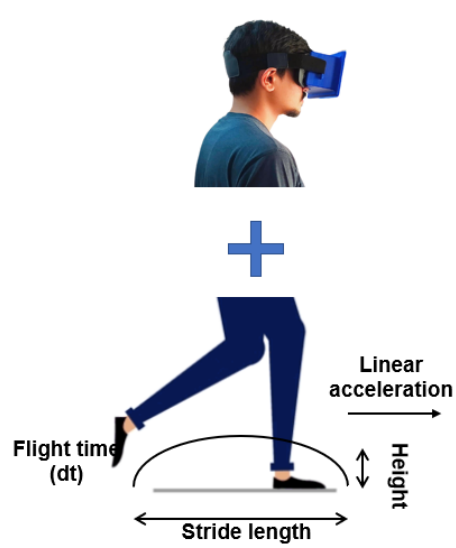


Figure 6.6 Outside-in tracking methodology

6.2.6 Inference

We performed an experimental analysis for the Walking In Place locomotion in our subsystem. The points concluded from the experiment were as follows-

- The latency between the foot press to the virtual transition in the VR scene is recorded to less than 450ms using BLE.
- The wired serial communication between the velgmat and HMD offers better latency of over 250ms but makes the overall system bulky.
- The walking in place can be classified as simple and low-cost form of translational motion technique available in user locomotion after teleportation motion technique.
- The hardware complexity of the system is less as compared to inside-out tracking methodologies.
- The immersiveness and the overall field of view $(95\,\mathrm{deg})$ offered by the subsystem is less as compared to other locomotion methods in VR.
- However, the system is practically not feasible to be scaled after certain threshold value as the immersiveness offered in the walking in place form of locomotion is lesser as compared to other locomotion techniques.
- In future advancements, the mat can be scaled to the room-size version and further immersiveness of the system can be improved drastically.

Chapter 7

Conclusion and Future Work

This section summarises the results from the research task and milestones in the field of hardware in Virtual Reality for Healthcare applications. With the day-by-day increase in data consumption in the market, data presentation has a vital role to play. Fields like virtual reality are not only the source of innovation in technology but also the beginning of a revolution in changing the behaviour of users to consume data. The VR devices are expected to inject as deep as television sets in a couple of decades. For this transition to flourish smoothly, this research thesis identified the factors challenging the hypothesis and proposed appropriate solutions based on empirical studies.

7.1 Contributions

The contributions from the thesis can be illustrated in the following-

- **Design**
  - Human eye disorders are increasing, and early detection of disorders can help mitigate further degradation. Detection requires health care expertise and costly supporting technology. As part of our work, we developed a low-cost HMD named CHORD to detect human eye disorders. We can use such a device to conduct the tests in rural areas or tribal areas where healthcare professionals' availability is limited to negligible.
  - Given that CHORD doesn't require a significant learning curve, a non-healthcare professional can use the device to do the initial diagnosis, which can then be validated by a health care professional. This results in a significant reduction in unwarranted testing and visits to the health care professional.
  - We proposed standalone outside-in tracking methodology using CHORD (3-DoF) and Vel-Gmat for translational tracking as a 6-DoF HMD.
- **Application**

  - We validated low-cost device, called CHORD against various hardware parameters and have used it to conduct preliminary studies on human eye disorders and problems like visual acuity test, astigmatism, colour blindness and age-related macular degeneration.
  - Our CHORD, can be used in rural and tribal areas where a healthcare professional is unavailable. We validated our HMD against various hardware parameters like FOV (81.1), M2P latency (65 ms), chromatic distribution and binocular disparity.
- **Literature**
  - We conducted a systematic review on different motion tracking methods employed in the HMD to understand such hardware transformation.
  - We also constructed a taxonomy for VR practitioners to understand the hardware ecosystem of HMD based on locomotion techniques. This will help VR practitioners expand their current HMDs and upscale them to support new motion tracking methods for effective locomotion.
  - We also recorded potential evaluation methods and their related metrics practiced while assessing the hardware transformation of HMDs in context to their performance and scale.

7.2 Limitations

As per the recommendations from the advisors and the various researchers, exclusive user studies moreover focussed group studies can expose the thesis contributions for further validation. Design-wise: optimizations can be made in deciding the material for fabrication. The model must address the customizable inter-ocular distance, which can be a separate problem statement.

7.3 Future Work

As part of the future work, we would like to expand the scope of our research with following points - The concept of bridging the gap between the technological abilities and usability is bound to have major optimizations in coming future. Product wise as a low-cost VR device CHORD, can be optimized based on the various design parameters like sensing ability, material layouts, processing abilities. We would expect the research communities in VR to tweak particular parameters and propose CHORD version 2.0 as a start.

This review study helped us channelize the strengths of prevailing hardware transformation setups, evaluation practices, and potential metrics practiced by VR practitioners. Plan can be proposed to use this review study to develop a customized motion tracking method for a novel 3-DOF HMD to develop a focused healthcare application. These healthcare VR applications are planned to be low-cost and have better ease of use.

Related Publications

7.4 Relevent Publications

1. **Pawankumar Gururaj Yendigeri**; Sai Anirudh Karre, Raghav Mittal, Y. Raghu Reddy, Syed Azeemuddin ***"Customizable Head-mounted Device for Detection of Eye Disorders using Virtual Reality"***, *The 35th International Conference on VLSID and Embedded Systems*, Feb 2022 **[Published]**

2. **Pawankumar Gururaj Yendigeri**; Sai Anirudh Karre, Raghav Mittal, Y. Raghu Reddy, Syed Azeemuddin ***"Towards Conducting Effective Locomotion Through Hardware Transformation in Head-Mounted-Device-A Review Study"***, *The 29th International Conference on Virtual Reality and 3D User Interfaces*, Mar 2022 **[Published]**

3. **Pawankumar Gururaj**; Sai Anirudh Karre, Raghav Mittal, Y. Raghu Reddy, Syed Azeemuddin ***"Effective Locomotion Through Hardware Transformation in Head-Mounted-Devices"***, *The 29th International Journal on Virtual Reality(IJVR)* , July 2022 **[In Drafting]**

7.5 Other Publications

1. Mohammad Waqas Wani, **Pawankumar Gururaj Yendigeri**; Vivek Pareek, Sai Anirudh Karre Y. Raghu Reddy, Syed Azeemuddin ***"VelGmat : Low Cost Gait Mat for Stance Phase Calculation"***, *The 20th International Conference on IEEE Sensors* , July 2022 **[Published]**

2. Raghav Mittal, Sai Anirudh Karre, **Pawankumar Gururaj**, Y. Raghu Reddy ***"Enhancing Configurable Limitless Paths in Virtual Reality Environments"***, *15th International Conference on Innovations in Software Engineering Conference(ISEC)*, Dec 2021 **[Published]**

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