ECE 445

SENIOR DESIGN LABORATORY

DESIGN DOCUMENT

Augmenting Virtual Reality (VR) with Smell

Team #15

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1 Introduction

1.1 Problem and Solution Overview

Virtual reality (VR) technologies are rapidly growing and becoming more prevalent in our daily lives. However, these technologies have not yet fully addressed the sense of smell, which is a critical aspect of human experience. The absence of scent in virtual reality (VR) experiences limits the immersive potential of these technologies, preventing users from experiencing a full sensory experience.

Augmenting virtual reality (VR) systems with smell refers to the incorporation of olfactory stimulation into virtual and augmented reality experiences. This technology aims to provide a more immersive and realistic experience for users by integrating scent cues into the virtual environment. This field of research is also referred to as ”Olfactory VR” or ”OVR”.

The sense of smell is an important part of human perception, and it plays a crucial role in our daily experiences. The sense of smell is incredibly powerful, with research showing that it is 10,000 times more sensitive than any other sense, and humans can discriminate more than 1 trillion olfactory stimuli [1], [2]. The olfactory system is responsible for detecting thousands of different chemical molecules that are vaporized and floating in the air, and the olfactory bulbs and limbic system are strongly connected, leading to the imposition of emotions and memories, and modification of conscious thought and learning [1]. Despite the potential benefits of smell augmentation in virtual reality (VR) systems, there is a research gap in tracking and analyzing chemical data [1]. To address this gap, this project proposes a case study to design and implement a practical plan for smell augmentation in maintenance diagnosis, with the aim of evaluating feasibility, identifying challenges, and summarizing initial results of overlaying information through smell augmentations. By incorporating scent cues into virtual reality (VR) environments, users can be transported to a different world and can experience a heightened sense of realism. For example, users in a virtual forest could smell the scent of pine trees, while users in a virtual bakery could smell the scent of fresh bread.

There are several challenges associated with integrating smell into virtual reality (VR) systems. One of the main challenges is replicating scents accurately and consistently. Unlike visual and auditory cues, scents are complex and difficult to reproduce. Additionally, the delivery of scent cues must be carefully controlled to ensure that users are not overwhelmed or nauseated.

Despite these challenges, the potential applications for augmented virtual reality (VR) systems with smell are vast. This technology has the potential to be used in a variety of fields, including entertainment, education, healthcare, and marketing. For example, olfactory virtual reality (OVR) could be used to simulate a medical environment to help train medical professionals or to treat patients with phobias or anxiety disorders. It could also be used to create immersive marketing experiences for products such as perfumes or food.

According to the problem we mentioned above, and based on research in Olfactory virtual reality (OVR), we propose a device that augment virtual reality (VR) experiences with smell, enabling users to experience a full sensory experience.

To achieve this objective, we will need to incorporate hardware and software components that can simulate various scents in real-time, in response to events in the virtual reality (VR) environment. As we will explain the detailed connection and layout in the following sections, here we just provide a general overview for our proposed solution.

Our whole device consists of five subsystems, including two software subsystems: a virtual reality (VR) software to generate virtual scenes and a scent simulator to generate correct scents information corresponds to the given virtual scenes. To be more specific, the scents information will include scent species, scent intensity and scent duration. The remaining three subsystems incorporate hardware components: the virtual reality (VR) hardware for users' motion capture and model rendering, a scent emitter to emit scents based on information got from scent simulator, and an external perception module to collect environment information such as room size and wind speed.

Two softwares run on the computer, where data transmission will be handled by process communication protocols. The scent emitter and external perception module will be integrated together into a neck scent emitter, which users can hang it on their necks. The VR headset and the computer is connected via DisplayPort1.2, where the virtual scenes will be loaded via the wired connection. The scent-emitter and external perception module use wireless communication protocol–bluetooth to talk with softwares on computer. The nolvelty of our proposed solution is that we not only emit scents based on corresponding scenes, but also integrates environment information in our virtual scenes. For example, when users use our device outside, they may feel a guest of wind. We will also generate wind in virtual scenes, enabling users to experience a full sensory experience.

1.2 Visual Aid

Figure 1: Visual Aid

Our proposed solution is composed of two parts physically: one virtual reality (VR) headset and one neck scent-emitter which is responsible for emitting scents and collect environment information such as wind speed and wind direction. As shown on the graph, the headset needs to be connected via DisplayPort 1.2 and USB 3.0 to a computer to load virtual scenes we built. The sensors on the neck scent-emitter will be connected to the computer via bluetooth, a wireless communication protocol.

1.3 High-level requirements list

- The scent-emitting device will need to be able to emit various scents for normal operation, that is, walk or adjust view with normal speed in our constructed virtual world for a period of at least 1 hour without adding new materials.
- The scent-emitting device should emit proper scents in 300 milliseconds after the sensor capturing the user's location and orientation. This also includes time a scent simulation software needs to calculate the intensity and duration of scent emissions. To be more specific, as the major delay may happen in data transmission stage, the time for scent simulation software to calculate scent species, intensity and duration should be under 100 milliseconds.
- As a wearable electronic device, we want our device to be portable and lightweight. We expect the weight of the headset not exceed 0.5 kilograms, and the weight of the neck scent-emitter will not exceed 0.3 kilograms, making it easy for users to carry around during virtual reality (VR) experiences, and have less stress on users' neck.

2 Design

2.1 Block Diagram

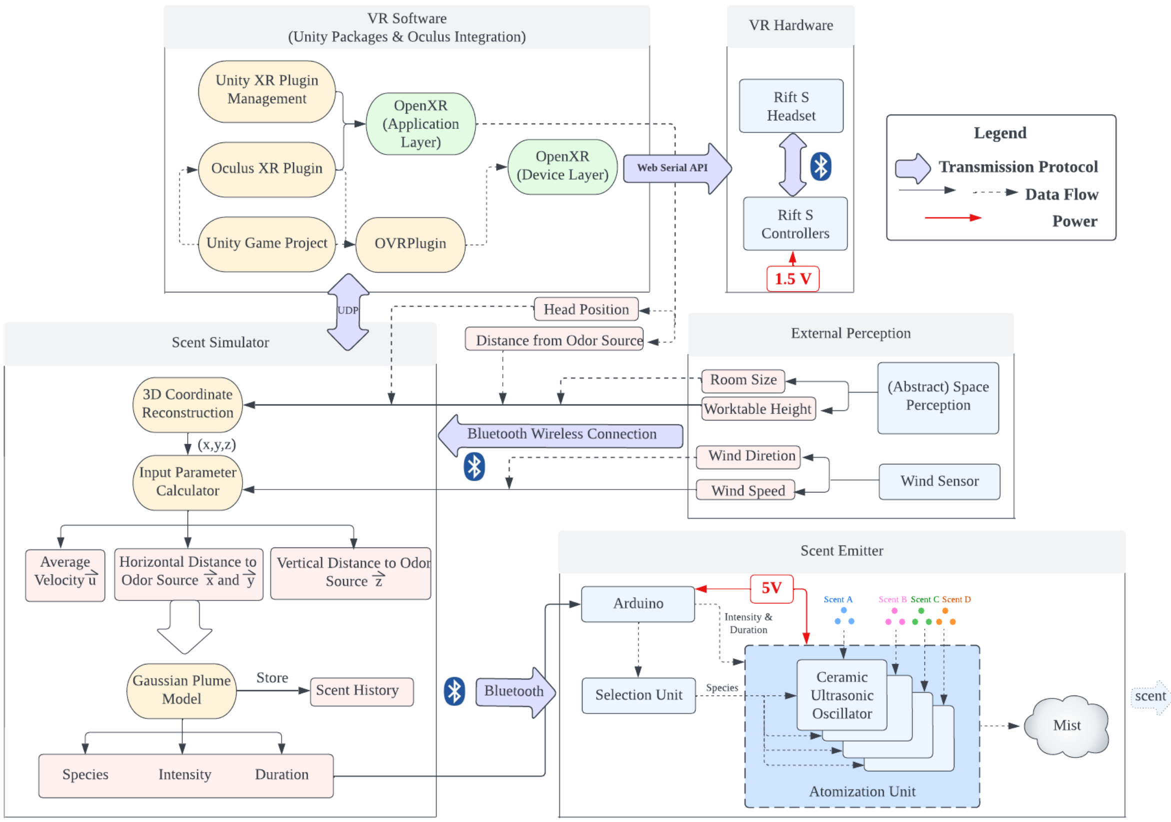

Figure 2: Block Diagram

The system consists of five subsystems, including two software subsystems: a VR software to generate virtual scenes and a scent simulator to generate correct scents information corresponding to the given virtual scenes. In the VR software part, we will build a demo project using Unity and connect its plugin with Oculus. The scent simulator can simulate and control the process of real-time scent emitting according to the user's position information and virtual scenes. The remaining three subsystems incorporate hardware components: the VR hardware for users' motion capture and model rendering, a scent emitter to emit scents based on information obtained from the scent simulator, and an external perception module to collect environment information, including wind direction, wind speed, room size, and worktable height. Two programs run on the computer, where data transmission will be handled by process communication protocols. The VR headset and the computer are connected via DisplayPort1.2, where the virtual scenes will be loaded via the wired connection. The scent-emitter and external perception module use a wireless communication protocol–Bluetooth, to talk with programs on the computer. The wind information collected by the external perception module and the scent simulator's simulation result (including scent species, scent intensity, and scent duration) will send to VR software and scent-emitter, respectively.

2.2 Physical Design

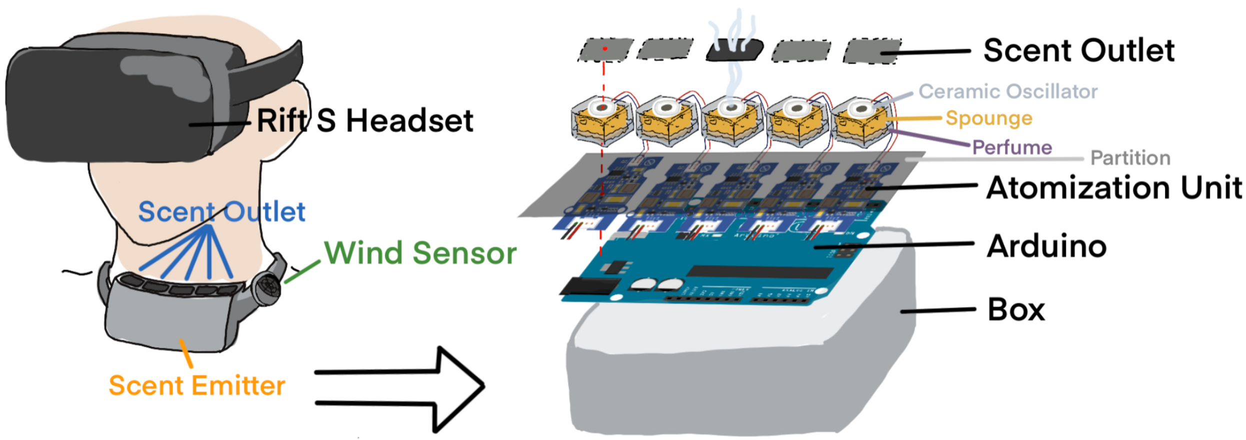

Figure 3: Physical Design of Our Proposed Solution

The above graph shows the physical design of our proposed solution. Our device is composed of two parts visually, a Rift S headset and a scent emitter. As we will have five different scents, we will design five horizontally arranged air outlets. The oscillators used for forming the mist and the control unit used for triggering the oscillators are both put in a box, and the box is also designed to be worn around the neck. The wind sensor will be based near the box. Inside the box, we plan to put the Arduino and the printed circuit board (PCB) of the atomization unit on the button and will be separated from the above scent cartridges via a waterproof and corrosion-resistant groove. On top of this control unit, we have five separate scent cartridges. In each scent cartridge, we have a sponge immersed in the perfume and a ceramic ultrasonic oscillator that touches the surface of the sponge. On the top of the box, there are air outlets, and the formed mist will be scattered to the atmosphere from this interface.

2.3 Virtual Reality (VR) Software

2.3.1 Block Description

Based on Unity, this subsystem is responsible for creating virtual scenes for users. The virtual reality (VR) software enables us to build engaging scenarios, tell users interactive stories, and transport people to new worlds by building virtual reality experiences, which allows our device to fulfill the most important high-level requirement–immersive experience. This subsystem also needs to pre-process users' movement information and head orientation collected by virtual reality (VR) hardware and transmit the information to scent simulation software for further calculation. Our software is designed to be effective and accurate, which also meets the second high-level requirement listed in the previous section. To be more specific, this module takes sensory information from virtual reality (VR) hardware (includes users' location, head position information, and physical actions) and external perception module (includes wind direction and wind speed) as input, and output is constructed virtual scenes based on the data. If there is an odor source in the scene, virtual reality (VR) software will also output the head position and users' position towards the odor source to the scent simulator. This data transmission will be reached by Inter-Process communication protocols using sockets. Besides, we have built some demo scenes using virtual reality (VR) software, as shown in the below sketch map.

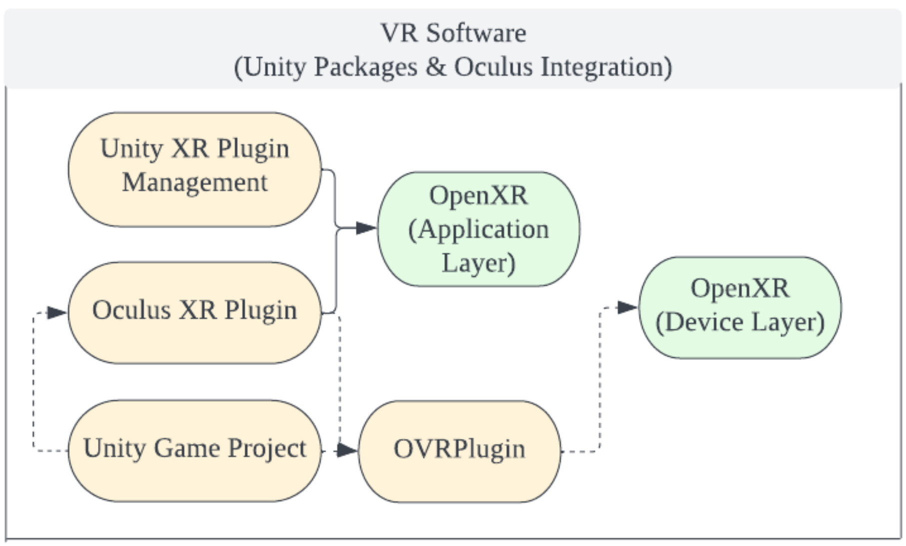

Figure 4: Block Diagram of Virtual Reality (VR) Software

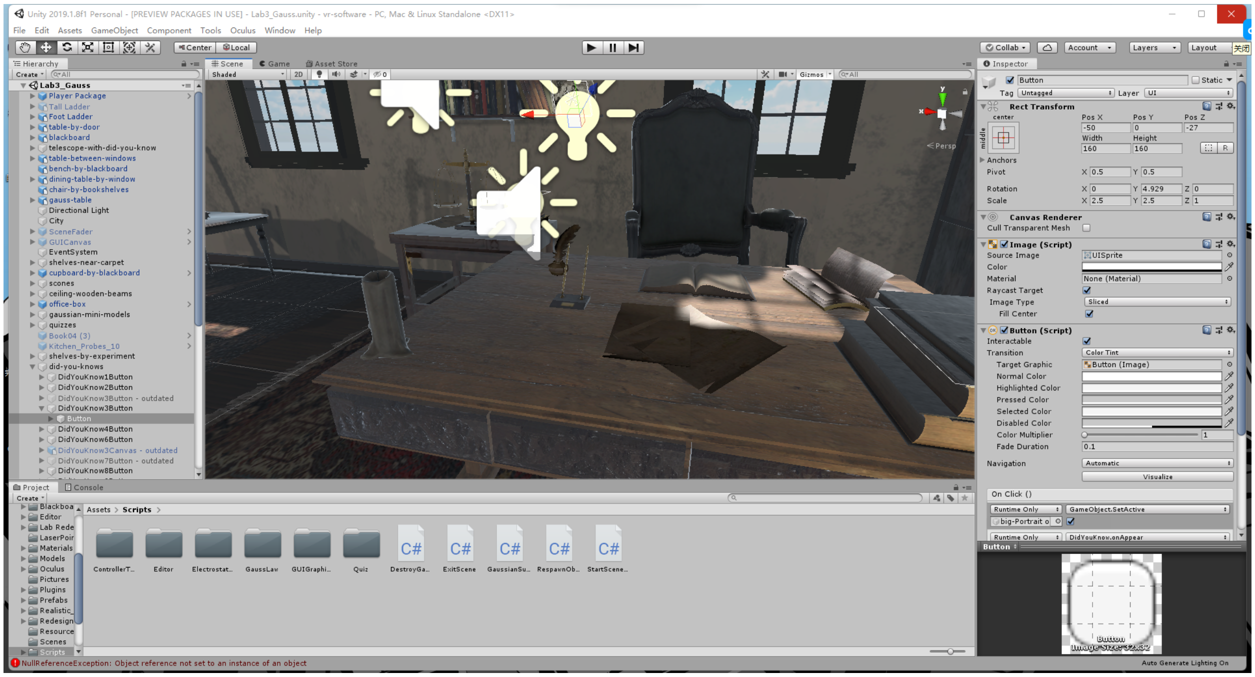

Figure 5: Demo Scenes of Virtual Reality (VR) Software

2.3.2 Data Transmission Protocol

Data transmission is a necessary part of software design. As we mentioned above and as shown in the block diagram, virtual reality (VR) software needs to transmit the user's position information, including distance to the odor source in virtual scenes and the user's head orientation to the scent simulator. To be abstract, scent simulator and virtual reality (VR) software are two processes run on the computer. We plan to use socket, an inter-process communication method that encapsulates the details of the network communication and allows us to connect and transfer data to any communication endpoint on the network. Actually, we don't require two processes to run on the same host, as the socket is able to maintain communication between processes on different hosts. We plan to adopt a lightweight data transport protocol that works on top of IP–user datagram protocol (UDP) to ensure transmission efficiency, as packet loss is acceptable in our case. The flow chart for data transmission is shown in the following diagram. Basically, both the virtual reality (VR) software and the scent simulator create a socket. They will then call socket API–bind, to bind their own IP addresses and ports. After that, virtual reality (VR) software sends data packets to the scent simulator using socket API–$sendto()$, and the scent simulator receives the message using another socket API–$recvfrom()$.

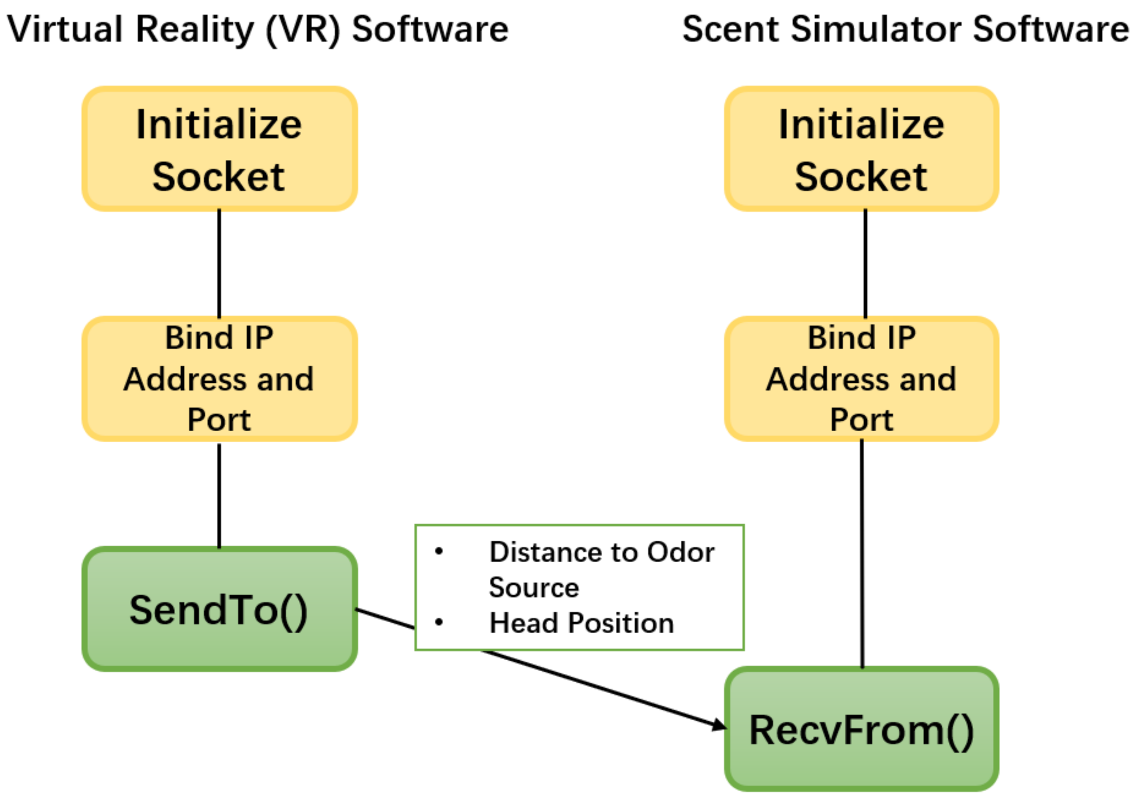

Figure 6: Data Transmission Protocol Flow Chart for Softwares

2.3.3 Requirements and Verifications

Requirements	Verifications
1. The demo should run smoothly and consistently with at least 90 Hz frames per second(FPS) to provide visually comfortable and immersive experiences to users.	1. Use bench-marking tools, such as *Oculus Tray Tool* or *SteamVR Performance Test*, to measure the frame rate of the VR demo while it is running. 2. Conduct user testing: Invite potential users to test the VR demo and provide feedback based on their experience.
2. The software must be designed to work seamlessly with the latest lineups of Oculus virtual reality (VR) devices.	1. Ensure that the design is compatible with Oculus' software development kits(SDKs) and tools to guarantee that the software is optimized for Oculus devices and takes advantage of their features and capabilities. 2. Create and validate our demo software using an Oculus Rift S, and if feasible, test it on other Oculus device models.
3. The demo needs to include adequate examples to be considered a comprehensive and general implementation of incorporating scent into virtual reality (VR) systems.	The demo should offer at least 3 different scenes/objects, such as a bakery or a bouquet of roses, to incorporate different scents for the users to interact with and experience.

Table 1: Requirements and Verifications of the Virtual Reality Software

2.4 Scent Simulation Software

2.4.1 Block Description

This subsystem is responsible for calculating which species of scents our device needs to emit based on our users' action information in the virtual world. This scent simulation software gets the pre-processed data from virtual reality (VR) software and uses our efficient and effective algorithm to decide which scent to emit, how long the scent last, and how strong the smell is. This information will then be transmitted to the scent emitter subsystem for the release of real scent. To be more specific, this module takes the external perception module's output, including wind direction, wind speed, room size, and worktable height, and pre-processed data, including the user's head position and odor source's position, from virtual reality (VR) software as inputs. This subsystem will first reconstruct 3D coordinates based on the user's head position and the odor source's position. We plan to model the odor source as the original point. This step will generate the coordinate (x, y, z). Next, together with room size and worktable height information, these data will be put into the input parameter calculator. This includes average wind velocity $\vec{v}$, horizontal distance to odor source $\vec{x}$ and $\vec{y}$, and vertical distance to odor source $\vec{z}$. Note that the parameters above are all vectors instead of scalars. Finally, these parameters will be put into the Gaussian Plume Model, which outputs the scent species, intensity, and duration. The output will be transmitted to the scent emitter via Bluetooth. The details of the Gaussian Plume Model will be discussed in the next section. Our software is designed to be effective and accurate, which also meets the second high-level requirement listed in the previous section.

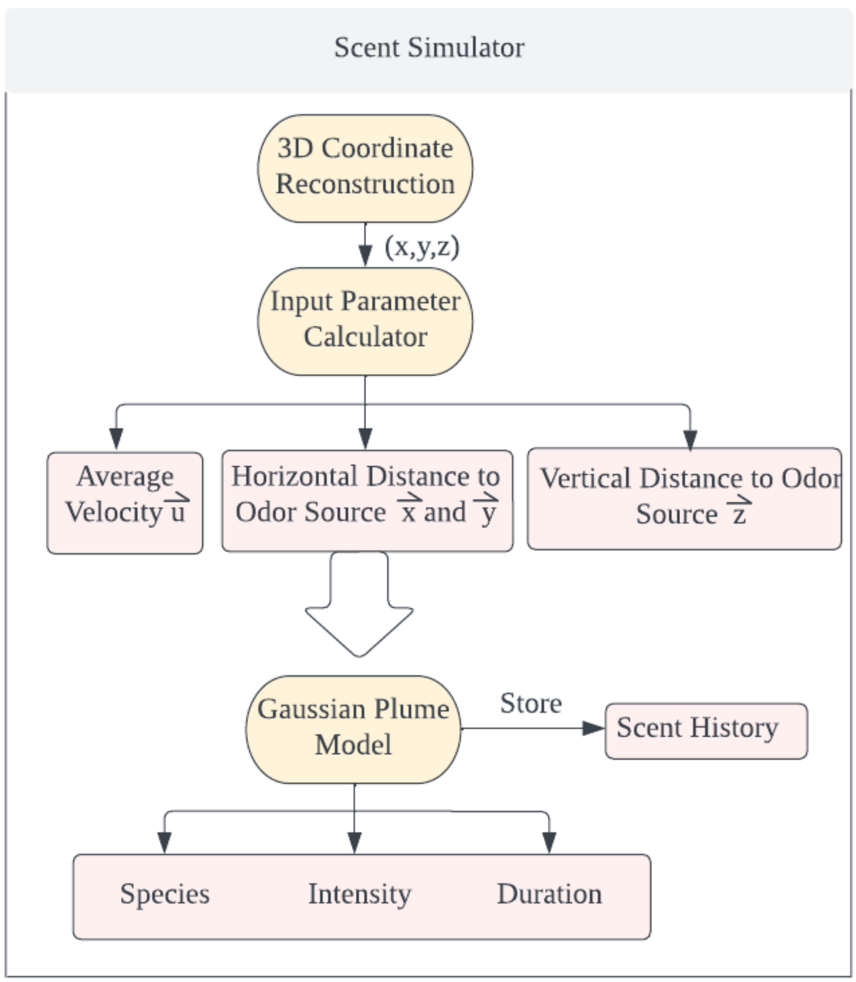

Figure 7: Block Diagram of Scent Simulator Software

2.4.2 Gaussian Plume Model

The Gaussian Plume Model[3] is a widely used mathematical model in the field of air quality and environmental engineering for estimating the dispersion and concentration of airborne pollutants released from a point source, such as industrial stacks or chimneys. Developed in the early 20th century, it is based on the Gaussian distribution (also known as the normal distribution) and simplifies the complex dispersion processes in the atmosphere by making certain assumptions. In our case, we think the scent particles should follow similar physical models.

The Gaussian Plume Model assumes that the scent disperses in a symmetrical, bell-shaped distribution, both horizontally and vertically, around the center line of the plume. The resulting concentration at any given receptor point is calculated using a series of equations that take into account the source emission rate, wind speed, atmospheric stability, plume rise, and the distances between the source and receptor. The specific relationships of these quantities are shown in the following equation:

$$C(x, y, z) = \frac{Q}{2\pi u \sigma_y \sigma_z} e^{-\frac{y^2}{2\sigma_y^2}} \left\{ e^{-\frac{(z+H)^2}{2\sigma_z^2}} + e^{-\frac{(z-H)^2}{2\sigma_z^2}} \right\}$$

Where C denotes scent concentration, Q denotes scent emission rate, H is the effective stack height, u is the wind speed, and σ_y, σ_z denotes plume standard deviations in the y and z directions.

However, it is important to note that the Gaussian Plume Model has some limitations. For instance, it assumes steady-state conditions and a constant wind speed, which may not always be the case in our scenario as the user explores the room. Despite these limitations, the Gaussian Plume Model remains a viable tool for our application because more complex models are not feasible or data is limited.

2.4.3 Requirements and Verifications

Requirements	Verifications
1. The simulator should be able to calculate the appropriate intensity and duration of the scents emitting based on the diffusion equation.	1. Through careful experiment and referring to the Odor Detection Threshold (ODT) which is the minimum concentration of an odorant that can be detected by humans, and Oder Intensity Standard Curves (OISC)[4], we can make sure that the scents can be emitted within an acceptable and comfortable range. 2. Use specialized equipment: Use specialized equipment, such as gas chromatography-mass spectrometry (GC-MS), to verify that the simulator accurately calculates scent intensity and duration.
2. The real-time result should be delivered correctly to the emitter.	Use Arduino's Universal Serial Asynchronous Receiver Transmitter(USART) protocol to transmit real-time signals to the PC for debugging.

Table 2: Requirements and Verifications of the Scent Simulation Software

2.5 Virtual Reality (VR) Hardware

2.5.1 Block Description

This subsystem provides the hardware basis for virtual reality (VR) software and is responsible for motion capture and model rendering, which uses Rift S as the key hardware component. It consists of a virtual reality (VR) headset and two controllers. Through the headset, the user (as the camera inside the project) can see virtual scenes. The headset can track the direction of users' sight. The Rift S uses an LCD with a resolution of $1,280 \times 1,440$ per eye, and refresh rates are slightly lower at $80Hz$ to $90Hz$. The controllers are used to track the position of the hands and control the experience inside the virtual reality (VR) environment. They feature a protruding black handle and a ring extending from the top for six degrees of freedom (6DOF) position tracking via a camera mounted on the headset. The rings extend to the physical controls of each device and wrap around the user's thumb while giving them plenty of room to move. This allows our device to fulfill one important high-level requirement–immersive experience. The data collected by the sensors will be transmitted to the virtual reality (VR) software subsystem for virtual scene generation and movement information pre-processing. More specifically, as we use Oculus Rift S, the virtual reality (VR) headset must be connected to a personal computer (PC) via DisplayPort 1.2 and USB 3.0. As Rift S's camera faces outward, it then doesn't require any external sensors, so one USB 3.0 is enough.

2.5.2 Requirements and Verifications

Requirements	Verifications
1. The virtual reality (VR) hardware should be equipped with wireless or wired connection with a personal computer (PC) to enable model rendering.	Check whether the personal computer (PC) is equipped with a DisplayPort adaptor. Note that if the connection only supports HDMI personal computers (PCS), Oculus does not guarantee compatibility. So make sure they have a DisplayPort or Mini DisplayPort and a USB 3.0 port.
2. Use at least an Nvidia GTX 1060 or AMD Radeon RX 480 graphics card, an Intel i5-4590 or AMD Ryzen 5 1500X or later CPU, and at least 8GB of RAM for the personal computer (PC).	First, right-click on Computer – Properties and go to the Computer Properties Tab. We can see the basic CPU and memory configurations in the Properties TAB. For more details, we can click Device Manager on the left of the selection. Check these configurations to ensure they satisfy the requirements.

Table 3: Requirements and Verifications of the Virtual Reality Hardware

2.6 Scent Emitter

2.6.1 Block Description

This subsystem is responsible for emitting the scent based on data from scent simulation software. It consists of a scent cartridge, an Arduino module, a selection unit, and an atomization unit with several ceramic ultrasonic oscillators. The overall hardware is portable and light, which fulfills the high-level requirement listed in the introduction section. To be more specific, different scents are protected in individual units in scent cartridges. In those units, we plan to use a sponge to fully absorb the liquid. The reason we don't directly use the essential oil is that sponge, as a solid body, has less risk when we put it with a circuit (although we will definitely make separate layers). The Arduino module takes scent species, scent intensity, and scent duration from the scent simulator as input and generates control signals to the selection unit and atomization unit, respectively. To be more specific, the selection unit works as a mux and is connected to five different ceramic ultrasonic oscillators. The selection unit triggers the correct signal based on species, and the corresponding ceramic ultrasonic oscillator will be connected to the rest part of the atomization unit. The circuit details of the atomization unit will be provided in later sections. For data transmission between the scent simulator and the scent emitter, we plan to use Bluetooth wireless connection protocol. The details of the protocol will also be discussed in later sections. Overall, this subsystem allows the users to have an immersive virtual reality (VR) experience that incorporates smell as a key sensory input.

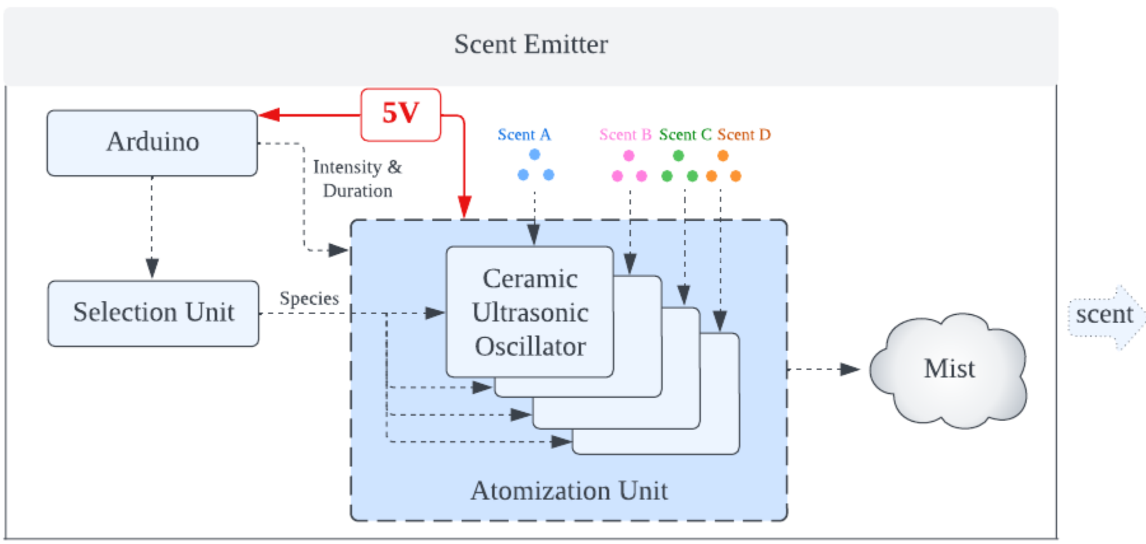

Figure 8: Block Diagram of Scent Emitter

2.6.2 Physical Design Details

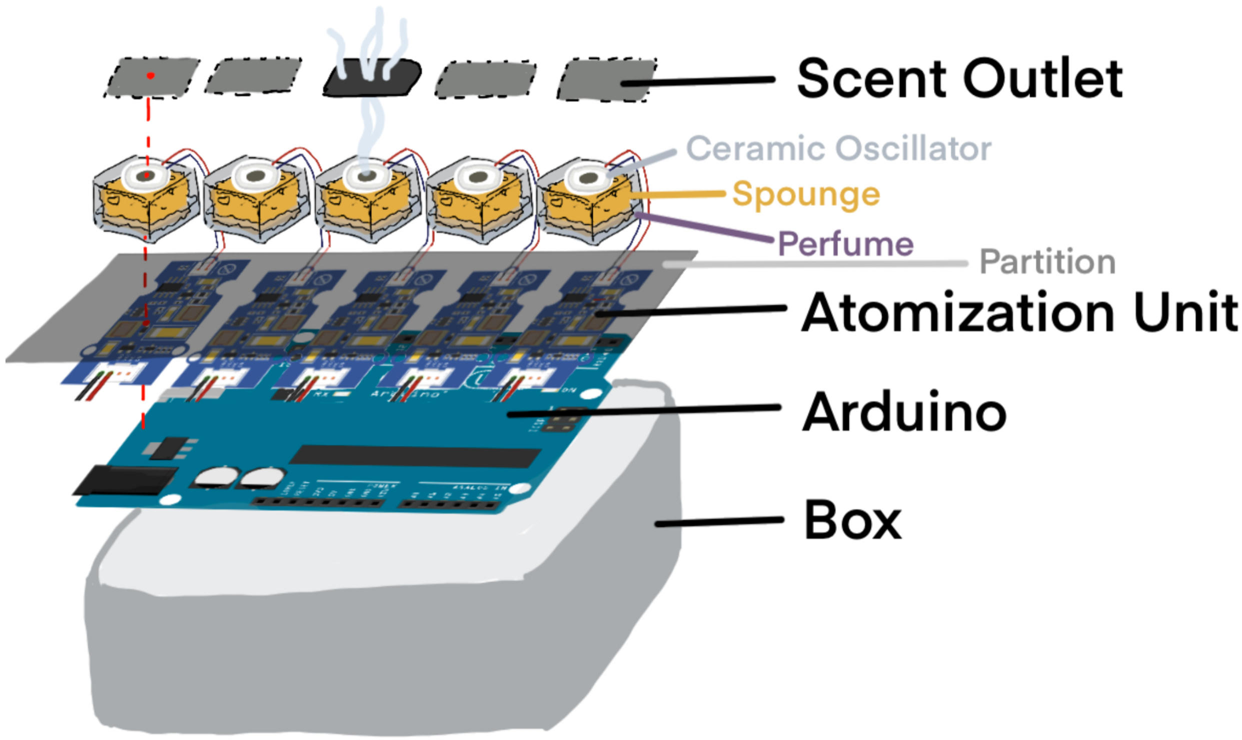

Figure 9: Physical Design of Scent Emitter

The above diagram shows the physical design of our scent emitter. The placement of each hardware component is shown on the left side of the diagram. As we will have five different scents, we will design five horizontally arranged air outlets. The oscillators used for forming the mist and the control unit used for triggering the oscillators are both put in a box, and the box is also designed to be worn around the neck. Inside the box, we plan to put the Arduino and the printed circuit board (PCB) of the atomization unit on the button, which will be separated from the above scent cartridges via a waterproof and corrosion-resistant groove. On top of this control unit, we have five separate scent cartridges. In each scent cartridge, we have a sponge immersed in the perfume and a ceramic ultrasonic oscillator that touches the surface of the sponge. On the top of the box, there are air outlets, and the formed mist will be scattered to the atmosphere from this interface. The diagram below shows our design draft for the scent outlet. We put the multi-view design for this interface. The bottom cubic column will be connected to the ceramic ultrasonic oscillator, which presses against the sponge.

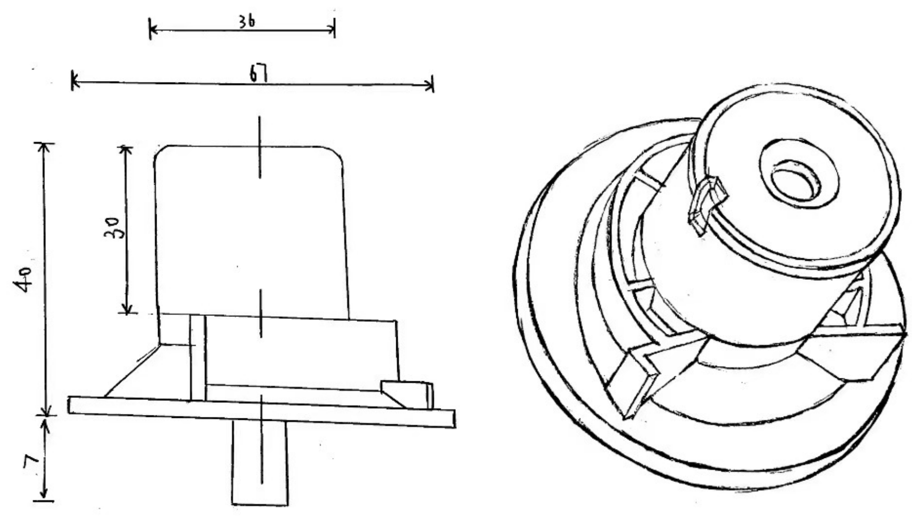

Figure 10: Physical Design of the Scent Outlet

2.6.3 Electronic Design Details

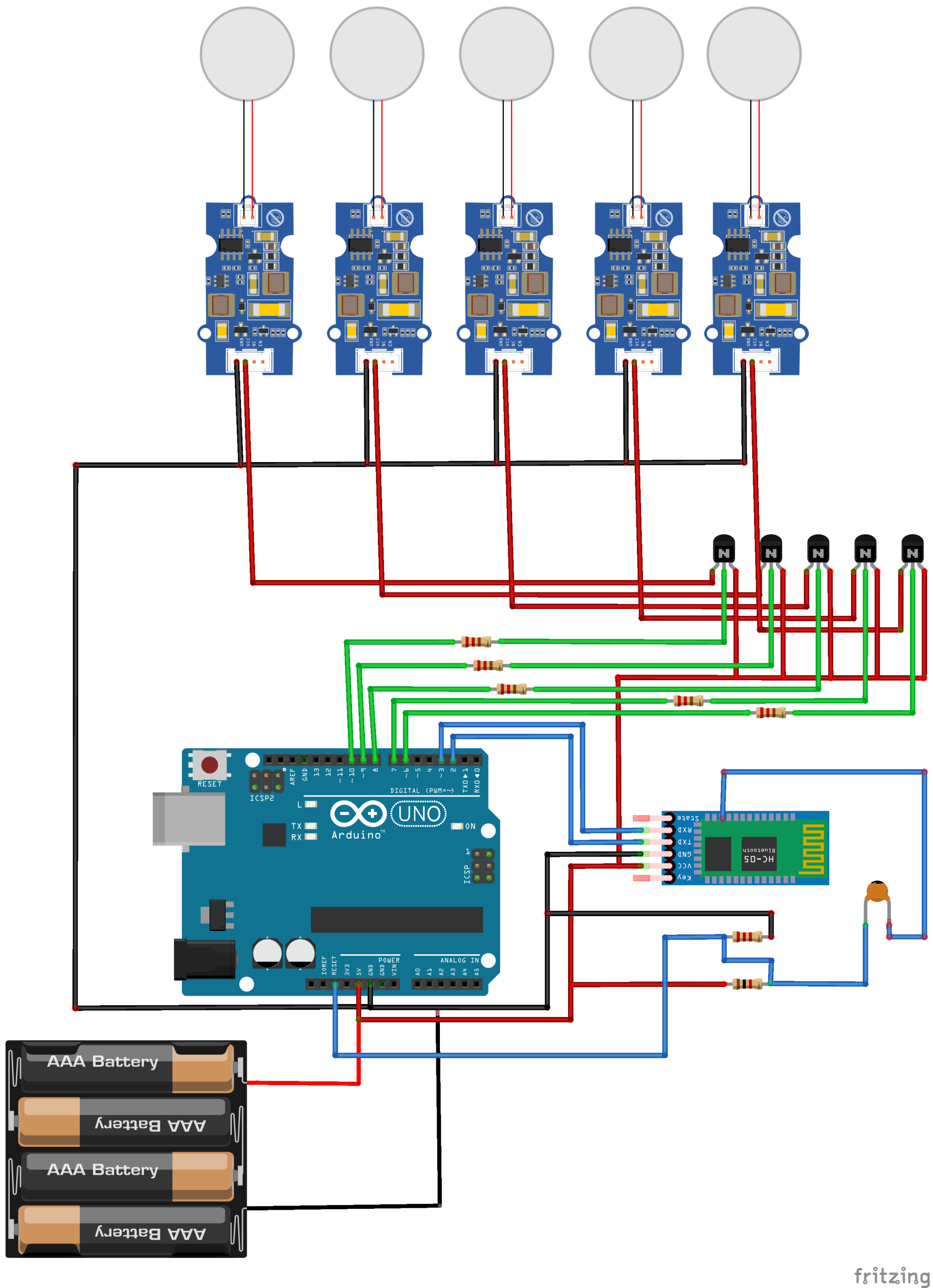

Figure 11: Schematic Diagram of Scent emitter

We use fritzing to draw the schematic diagram of our scent emitter. We connect the HC-05 module with the Arduino module to enable wireless control. To be more specific, the HC-05 module is a Bluetooth serial protocol module designed for wireless communication between microcontrollers. HC-05 Bluetooth module provides a switching mode between master and slave mode configurations and communicates through serial communication at a 9600 baud rate for easy interface with the controller. HC-05 module operates on 3.3 V, but we can connect it to a 4.8 V battery because the module comes with onboard 5 v to 3.3 V voltage regulators. We plan to use five NPN transistors that connect to Arduino and the ceramic ultrasonic oscillators, enabling the Arduino to control oscillators. The circuit details of each atomization unit will be shown in the next paragraph.

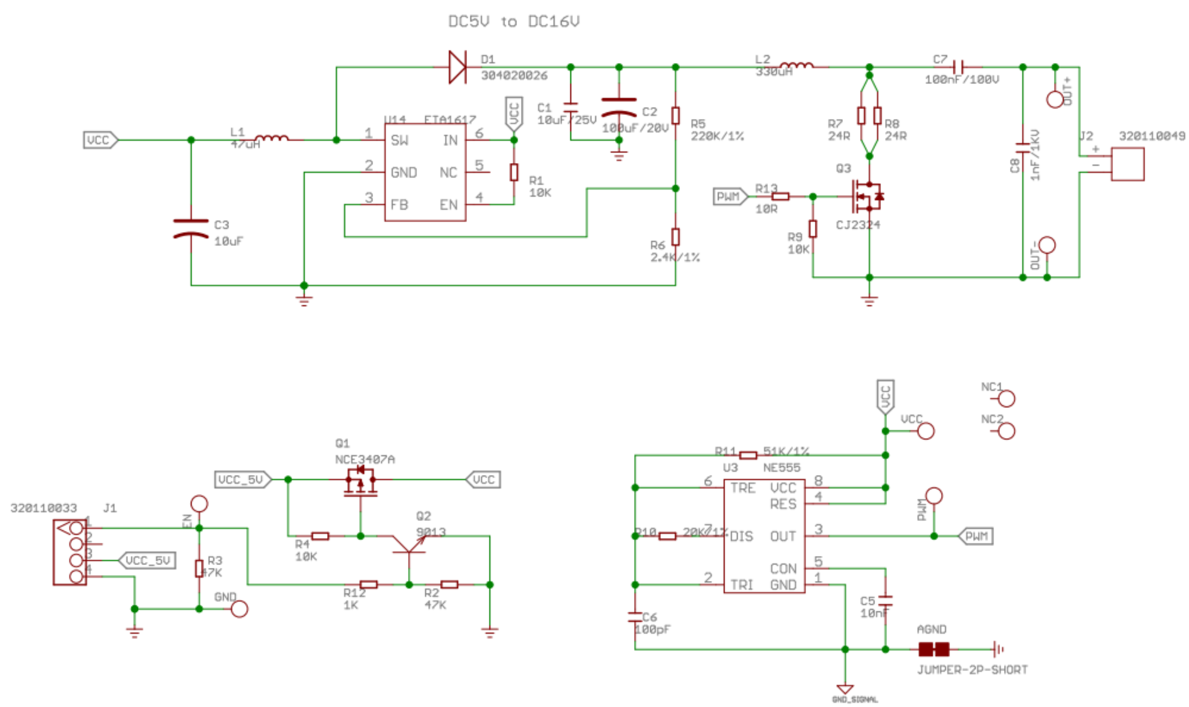

Figure 12: Circuit schematics of Atomization Unit

The micro atomizing plate is composed of a piezoelectric ceramic ring and a metal steel sheet. By driving the circuit board output PMW pulse width modulation, the piezoelectric ceramic produces hundreds of thousands of times per second high-frequency co-vibration, driving the metal sheet vibration. The liquid ejects from the metal steel sheet of thousands of micro-holes, forms 4-6 micron small molecules, and the liquid molecular structure then scatter to form the water mist. We plan to connect a 5 V voltage micro atomizing plate. Compared with the traditional voltage requirements of 12 V or 24 V, this micro atomizing plate has the advantage of low energy consumption, which then reduces the requirements for electricity and further expands the use of the product scenario. We design a to connect the ceramic ultrasonic oscillator's one pin to Arduino's one IO, which allows the oscillator to work during a period of time when a digital signal is in a logic high state, and stop to oscillate otherwise.

2.6.4 Requirements and Verifications

Requirements	Verifications
1. The emitter should be driven by an inexpensive, efficient, and user-friendly microcontroller (MCU), enabling easy setup and operation.	The emitter will be streamed by an Arduino Uno R3 as the microcontroller board based on the ATmega328P.
2. Five ceramic ultrasonic oscillators should all function well when given an appropriate trigger signal.	The range switch of the multimeter should first shift to $2.5V$ DC voltage, and let the red pen connect to the metal sheet, let the black pen be placed horizontally on the ceramic surface, and slightly pressure the left hand, and then loosen so that two voltage signals of opposite polarity are generated on the piezoelectric ceramic sheet. Make the multimeter pointer first swing to the right, then back to zero, and then swing to the left. The swing amplitude is about 0.1-0.15V. The larger the swing, the higher the sensitivity. If the pointer of the multimeter is stationary, it indicates that this ceramic ultrasonic oscillator has some problems.
3. The emitter consists of 5 small scent cartridges with scent cartridges installed. Besides the special scents, the emitter should also be able to clear the scents (deliver pure air or water mist) between the transition of different scents to avoid accidental mixture.	1. Design and conduct extensive unit test cases for every possible scenario. 2. To ensure accurate delivery of scents/water mist, we plan to utilize specialized equipment, such as gas chromatography-mass spectrometry (GC-MS), to verify the precise chemicals being emitted at each time step.
4. Real-time cues from the API through the OpenXR should be delivered to the Arduino using Web Serial to trigger scents.	Utilize Arduino's USART protocol to send real-time signals to the PC, allowing for comparison with signals received through the API.

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Requirements	Verifications
5. The power supply must provide a voltage in the range of 4.5-5.5V.	Measure the output voltage using an oscilloscope, ensuring that the output voltage stays within the range of 4.5-5.5v.

Table 4: Requirements and Verifications of the Scent Emitter

2.7 External Perception Subsystem

2.7.1 Block Description

This subsystem is composed of two parts: one wind sensor and one space perception module. Wind sensors collect wind speed and wind direction information and then transmit them to virtual reality (VR) software using a wireless connection protocol–Bluetooth. The reason we want to collect wind information is that when our users use our devices outside, their sensory experience may be influenced by the external environment. For example, they may feel a gust of wind, and if we don't change our virtual scenes, users will feel strange in the immersed virtual world, and the diffusion direction of scents will also be abrupt. In this case, we want our users to have complete and smooth sensory experiences. For the space perception module, it is actually an abstract module, which means that this functionally belongs to the external perception subsystem, but the actual hardware components are placed in virtual reality (VR) hardware. The measurement of the external environment for the space perception module includes room size and worktable height. The reason we desire to collect this information is that the diffusion of scents highly related to the room's condition. This idea is straightforward as for the same aromatherapy diffuser, the scents will be stronger when it is placed in a narrow room but will be much weaker when it is placed in a big and empty house. Therefore, we will send the room information to the scent simulator to reduce this impact as far as possible.

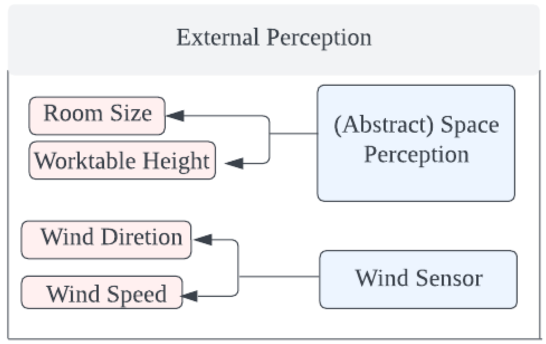

Figure 13: Block Diagram of External perception

2.7.2 Requirements and Verifications

Requirements	**Verifications**
1. The wind sensor should transmit wind direction and speed to the computer smoothly with a speed of at least 100Kbps.	1. Send write instructions to the Bluetooth device that has completed pairing, and record the current timestamp. Note that it contains a verification packet for the Bluetooth device to write. 2. After receiving feedback from the Bluetooth device, calculate the writing time based on the current system time and the first timestamp. 3. Send a read instruction to the Bluetooth device and record the current second timestamp. The Bluetooth device then reads the written verification packet and generates a reply signal. 4. After receiving the response signal fed back by the Bluetooth device, the sending time is calculated based on the current system time and the second timestamp. 5. Calculate the transmission speed based on two time stamps.

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2. The wind sensor must be able to detect wind speed in the range of $1m/s$ to $60m/s$ for the resolution ratio to be lower than $0.2m/s$ to fit our requirements.	1. Design and conduct extensive tests of different wind speeds to make sure the sensor works in these wind conditions. 2. Conduct experiments especially on low wind speed and high wind speed to ensure the property.
3. The power supply must provide a voltage in the range of 4.5-5.5V for a current load up to 20mA.	Measure the output voltage using an oscilloscope, ensuring that the output voltage stays within the range of 4.5-5.5v.

Table 5: Requirements and Verifications of the External Perception Subsystem

2.8 Tolerance (Risk) Analysis

We believe that the scent simulation software poses the greatest risk to the successful completion of the project because, as people are sensitive to scents, slight deviations in the intensity and duration of scents may highly influence people's immersive VR/AR experience. For example, when our user uses our device and enters our constructed scene, he may see a huge orchard. When he is fifty meters far away from the orchard, he is supposed to smell a light fruity scent. And the intensity of this scent should be slowly increased as he moves closer. In the real world, the smell has no clear boundary. That is, people should not feel separated when they are exposed to multiple kinds of scents. For example, if the user stands between tuberose and Hyacinthus orientalis, he may smell a mixture of two scents. If he walks closer to tuberose, then he may smell stronger scents from tuberose, but the scents from Hyacinthus orientalis should not disappear. Both characteristics of scents mentioned above require high accuracy of our scent simulation software, and low accuracy may make users feel strange and unreal, and thus negatively influence the immersive experience. So our research on scent would involve disciplines of thermodynamics, transport phenomena, and psychophysics to predict the odor of mixtures of scents, evaporation/release of scents, diffusion, and performance of scents, which will be applied in our scent simulator.

Besides, in our design, the scent-emitting device is integrated into a neck device, which means the distances between the nose and emission point also need to be considered. As such, it could additionally pose a challenge to meeting our expectations for performance. To ensure success, our team evaluates the feasibility through mathematical analysis and simulation. As we plan to model a garden, we will use the scent of flowers.

By carefully researching, we found that most of these scents have diffusion coefficients between $1.8m^2/h$ and $4.0m^2/h$, Therefore, in simulation, we set diffusion coefficients to be $2.5m^2/h$, and focus on two dimensions. The steady-state diffusion equation is:

$$\nabla \cdot (\Gamma \nabla \phi) + S_\phi = 0$$

where Γ is the diffusion constant. According to the above equation, we can get the diffusion equation for two dimensions:

$$\frac{\partial}{\partial x}(\Gamma \frac{\partial \phi}{\partial x}) + \frac{\partial}{\partial y}(\Gamma \frac{\partial \phi}{\partial y}) + S_\phi = 0$$

Our simulation is based on this formula. Here is the simulation result:

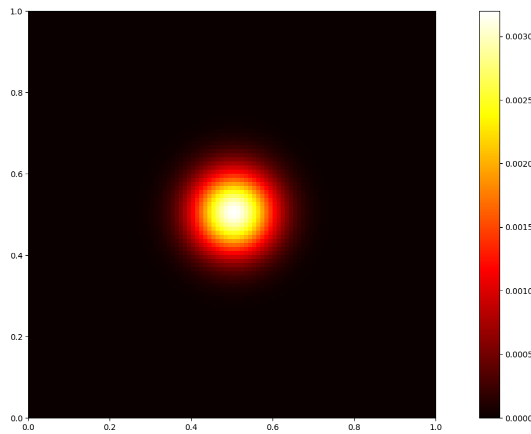

Figure 14: Python Simulation Result

Besides, Teixeira et al.[5] built a relatively complex perfume diffusion model in their research work, which also shows that those scents can be transmitted in a short time. As our scent-emitting device will be about forty centimeters below the nose, this distance should be enough for diffusion.

Considering that the user will not have much movement in our demo, we studied how the concentration of scents changes over time in the 1D case. Considering constant mass evaporation rate of scent:

$$\mu_i^{mass} = k_i M_i C_i^g$$

where k_i represents the mass transfer coefficient concerning the film contributions from both gas and liquid. The gas concentration changes as:

$$C_i(z,t) = \mu_i^{mass} \int_{t_i}^{t} \frac{1}{2\left[\pi \Gamma_i (t-\tau)\right]^{1/2}} \left[exp(-\frac{(z - z_0(\tau))^2}{4\Gamma_i(t-\tau)}) + exp(-\frac{(z + z_0(\tau))^2}{4\Gamma_i t - \tau}) \right] d\tau$$

Another important factor we need to prevent is that when there is not enough liquid or essential oil exist, we should not still let the circuit work. This is essential because as a wearable device, the neck scent emitter should be safe and never be harmful to humans. If the situation mentioned above happens, the device will suffer from short-circuit and become really hot, which may even scald the user. Therefore, we design water-level sensors in the scent cartridge. When the liquid level is lower than the sensor, our device stops working. We will adopt the principle of capacitive water level detection, where the formula for the capacitor is:

$$C = \epsilon A/d$$

where ϵ is the dielectric constant, A describes the area of the capacitor and d means the distance between two plates. The dielectric constant is different in air and water. Therefore, when ϵ changes, C will change with it. In other words, the value of C will depend on whether the probes touch the water or not. The water level sensor determines if there is water in the container by detecting the value of C.

3 Cost and Schedule

3.1 Cost Analysis

3.1.1 Labor

According to the latest available data from UIUC's Engineering Career Services office,the median starting salary for ECE graduates in 2020 was $77,000 per year. Assuming a standard 40-hour workweek, the salary is $37 per hour. For this project, each of us works 12weeks and 12 hours/week. The total Labor cost is:

$$4 \times 12wk \times 12hr/wk \times \$37/hr \times 2.5 = \$53280$$

3.1.2 Parts

Description	Manufacturer	Part #	Quantity	Cost
Rift S	OCULUS	oculus rift s	1	$597
Ultrasonic atomizer : used to build scent emitter. It can turn aromatic liquids into vapor.	MIJIA	MJXFJ01XW	6	$6 \times \$2 = \$12$
Resistor : used to build PCBA in scent emitter.	zave	0805	12	$0.5
Capacitor : used to build PCBA in scent emitter.	Risym	0805	18	$0.7
Triangular inductor : used to build PCBA in scent emitter.	Eckert	6X8(12uH + 440uH)	6	$1
Terminal receptacle used to build PCBA in scent emitter.	WXRKDZ	PH2.0	6	$0.25
MOS : used to build PCBA in scent emitter.	Eckert	SOT 23-3	6	$0.5
SOT 23-6 MCU : used to build PCBA in scent emitter.	Yingguang	PMS160	6	$0.1

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Description	Manufacturer	Part #	Quantity	Cost
EPGC : used to build PCBA in scent emitter. It is original PCB and we should weld parts on it.	Eckert	FR-4	6	$1
Micro mini 5P : used to build PCBA in scent emitter. It is the part to connect power.	yeulnelg	/	6	$6 \times \$0.7 = \$4.2$
Dirt scent perfume : it's used in virtual experience with dirt, to simulate the smell of it.	DORIS FRAGRANCE	2019001299	1	$14
Sweet osmanthus scent perfume : it's used in virtual experience with osmanthus, to simulate the smell of it.	KEYO NKNK	2021004223	1	$3.5
Tea scent perfume : it's used in virtual experience with tea, to simulate the smell of it.	KEYO NKNK	/	1	$3.5
Ink scent perfume : it's used in virtual experience with a Chinese calligraphy work, to simulate the smell of it.	OTHER	J20112481	1	$3
Apple scent perfume : it's used in virtual experience with an apple tree, to simulate the smell of it.	POACHERMAN	/	1	$4.5
Total				$645.75

Table 6: Parts List

Total cost: $53280 + $645.75 = $53925.75

3.2 Schedule

Week	Kaiyuan Tan	Yingying Liu	Xiao Wang	Baoyi He
3/13/23	Discuss with professors and technical staff; Research on physical model of scent simulator.	Discuss with professors and technical staff; Design hardware structure of scent emitter.	Discuss with professors and technical staff; Learn how to model virtual structure using Rift S.	Discuss with professors and technical staff; Design hardware structure of scent emitter.
3/20/23	Define physical model of scent simulator; Use math to theoretically verify the feasibility of the model.	Design circuit of the scent emitter; Decide specific hardware components used in scent emitter; Buy these components.	Continue to learn how to model virtual world using Rift S; Make a demo virtual scene using Rift S.	Design structures of exterior structures; Compare different materials and decide which materials to use. Buy these materials.
3/27/23	Discuss our virtual scenes; Start writing codes of scent simulator.	Discuss our virtual scenes; Start building scent-emitter including hardware and electronic control parts.	Discuss our virtual scenes; Start model virtual world using Rift S.	Discuss our virtual scenes; Decide specific hardware components used in external perception module. Buy these components.

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Week	Kaiyuan Tan	Yingying Liu	Xiao Wang	Baoyi He
4/3/23	Organize calls with our sponsor; Continue to work on modeling the scent simulator.	Build scent-emitter including hardware and electronic control parts; Test reliability of these parts.	Continue to work on modeling virtual world using Rift S; Consider data transmission between Rift S and scent simulator software.	Start building external perception module; Consider data transmission between this module and scent simulator software.
4/10/23	Finish coding part of the scent simulator; Test and debug the software.	Finish prototypes of the scent-emitter; Test and debug the scent-emitter.	Finish modeling virtual world using Rift S; Test and debug the VR software.	Continue to build the external perception module; Test the reliability of finished parts.
4/17/23	Connect scent simulator with external perception model and Rift S; Refine the code to reach best performance.	Connect the scent-emitter with the scent simulator; Test the device and refine based on performance.	Connect Rift S with the scent simulator software; Test and refine the code to reach best performance.	Finish build the external perception module; Test the connection between this module and scent simulator.
4/24/23	Assembly subsystems; Test and debug the whole system; Refine code of scent simulator to reach best performance.	Assembly subsystems; Test and debug the whole system; Fix the broken part of scent-emitter.	Assembly subsystems; Test and debug the whole system; Refine virtual scenes to reach best performance.	Assembly subsystems; Test and debug the whole system; Fix the broken part in external perception module.
5/1/23	Prepare mock demo; Write final report draft.	Prepare mock demo; Write final report draft.	Prepare mock demo; Write final report draft.	Prepare mock demo; Write final report draft.

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Week	Kaiyuan Tan	Yingying Liu	Xiao Wang	Baoyi He
5/15/23	Fix the broken part; Refine our device based on TA and professors' feedback on mock demo.	Fix the broken part; Refine our device based on TA and professors' feedback on mock demo.	Fix the broken part; Refine our device based on TA and professors' feedback on mock demo.	Fix the broken part; Refine our device based on TA and professors' feedback on mock demo.
5/22/23	Prepare final presentation; Work on final report.	Prepare final presentation; Work on final report.	Prepare final presentation; Work on final report.	Prepare final presentation; Work on final report.

Table 7: Weekly Schedule

4 Ethics and Safety

4.1 Ethics

Our device has a few potential ethics concerns that must be considered during the design and implementation process. As an extension of VR/AR system, our device will emit gases, which involves cultural sensitivity. Different cultures have different attitudes towards scent, and certain scents may be considered offensive or inappropriate in some cultures. Concerning the IEEE Code of Ethics, term 3, ”to avoid real or perceived conflicts of interest whenever possible, and to disclose them to affected parties when they do exist”[6], we will be mindful of these cultural differences and ensure that scent cues are not offensive or inappropriate.

Besides, as with any emerging technology, there is always the risk of the technology being misused for nefarious purposes. For example, scent cues could potentially be used to manipulate users or deceive them in some way. Therefore, we will follow the IEEE Code of Ethics, term 6, ”to maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations”[6], and we will only authorize our technology to organizations or companies with valid and legal certificates.

Furthermore, we agree to build a peace, beautiful and loving VR world avoiding any bloody scenes. This will follow ACM Code of Ethics and Professional Conduct, which says ”Examples of harm include unjustified physical or mental injury, unjustified destruction or disclosure of information, and unjustified damage to property, reputation, and the environment”[7]. Our team agrees that violent and bloody scenes is harmful to people especially to children, so we will not put any of these elements in our device.

In addition to the above, our team pledges to follow the IEEE Ethics guidelines[6] and the ACM Ethics guidelines[7] as closely as possible.

4.2 Safety

There are several potential safety hazards with our project. When emitting gases, it is possible to trigger allergic reactions or other health issues for some users. It may also potentially have a psychological impact on them. For example, certain scents could trigger memories or emotions that users may find distressing. To avoid the physical or mental health issues, we will only use harmless and safe gases. We will follow the standard value of poisonous and harmful gases[8] to check the scents. To ensure that scent delivery is carefully controlled, we plan to list the gases we use, and ensure our users know them well before using our device.

Besides, as VR/AR masks need to be worn on the head, our device may cause visual fatigue, wrist or neck strain. For some users, the long time experience on VR/AR devices may even lead to headache, pure photosensitive epilepsy or hearing damage. Unfortunately, this is the potential risk that exist for all VR/AR devices. To minimize the damage, our team plans to display warm tips for every users before they entering our constructed virtual environment.

In addition to the above, our team pledges to follow ECE445 safety guidelines on course website. First, we promise that no one will work in the lab alone. Second, we will complete a mandatory online safety training in order to be allowed to work in the lab. Third, we promise that before working with high voltages, we will first complete additional safety training. Forth, when charging or utilizing certain battery chemistries, we promise to read, understand, and follow guidelines for safe battery usage. Finally, when involving electric current running through a human subject, our team promise to read through and understand these guidelines for Safe Current Limits.

References

[1] J. Wang, J. Erkoyuncu, and R. Roy, "S," *Procedia CIRP*, vol. 78, pp. 109–114, 2018, 6th CIRP Global Web Conference – Envisaging the future manufacturing, design, technologies and systems in innovation era (CIRPe 2018), ISSN: 2212-8271. DOI: https://doi.org/10.1016/j.procir.2018.09.067. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212827118312472.

[2] C. Bushdid, M. O. Magnasco, L. B. Vosshall, and A. Keller, "Humans can discriminate more than 1 trillion olfactory stimuli," *Science*, vol. 343, no. 6177, pp. 1370–1372, 2014. DOI: 10.1126/science.1249168. eprint: https://www.science.org/doi/pdf/10.1126/science.1249168. [Online]. Available: https://www.science.org/doi/abs/10.1126/science.1249168.

[3] F. Pasquill, "The estimation of the dispersion of windborne material," *Meteoro. Mag.*, vol. 90, pp. 20–49, 1961.

[4] H. Wakayama, M. Sakasai, K. Yoshikawa, and M. Inoue, "Method for predicting odor intensity of perfumery raw materials using dose–response curve database," *Industrial & Engineering Chemistry Research*, vol. 58, no. 32, pp. 15 036–15 044, 2019.

[5] M. A. Teixeira, O. Rodriguez, V. G. Mata, and A. E. Rodrigues, "The diffusion of perfume mixtures and the odor performance," *Chemical Engineering Science*, vol. 64, no. 11, pp. 2570–2589, 2009.

[6] IEEE. ""IEEE Code of Ethics"." (2016), [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html (visited on 03/07/2023).

[7] ACM. ""ACM Code of Ethics and Professional Conduct"." (2018), [Online]. Available: https://www.acm.org/code-of-ethics (visited on 03/07/2023).

[8] S. Hazardous and H. T. Gases. ""ACM Code of Ethics and Professional Conduct"." (2022), [Online]. Available: https://ehrs.upenn.edu/health-safety/lab-safety/chemical-hygiene-plan/standard-operating-procedures/sop-hazardous-and (visited on 03/07/2023).