

CrowdLabs: A Platform For Human Behaviour And Perception Studies

by

Kunal Parikh

B.E., Gujarat Technological University, 2020

A Project Submitted in Partial Fulfillment of the
Requirements for the Degree of

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ABSTRACT

Advancements in technology encourage researchers to decipher several intricate conceptions such as human perception and behavioral studies. Though engineering science supports scientists, it in turn demands enormous efforts from them. Therefore, the necessity for a system that reduces the academicians' time and toil becomes inevitable. The proposed system – CrowdLabs allows the researchers to conduct a wide variety of human experiments and simulations and can scale up to capture fast-flowing data streams without them worrying about most of the underlying engineering concerns. The apparatus consists of two major traits: The experimenter who creates new trials and collects several forms of data for their studies, and the participants who take part in these experiments. This modular framework offers a minimal backend for different perspective controllers, data collection, and control to the scientists for loading and managing their experimental designs, repetition of scenes, randomizing sequences, and integrating training through a simple interface. The system was assessed for an interactive experiment to determine the system's capability to conduct a wide variety of complex human perception and behavior experiments. Subsequently, the system's performance was evaluated for CPU, GPU, memory, and frame rates. This analysis indicated that the apparatus was responsive and robust for all the experiment scenarios. Furthermore, the system was evaluated extensively and several avenues for future work have been identified.

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DEDICATION

I dedicate this project to my parent and peers in the Department of Computer Science who have always supported and encouraged me.

Chapter One

Introduction

Exploring human behavior and perception is an area of study that has brought about significant improvements in various domains such as architectural planning, virtual realities, games, movies, and training environments. In recent years, research in behavioral science has focused on understanding multiple realities based on human perceptions. Simulation modeling is critical in aiding human behavior and perception studies by providing valuable and clear insights into complex problems. However, the control and development of complex, active, and immersive tasks pose distinct challenges, requiring the need for a system that facilitates trials and collects accurate data while reducing researchers' time and effort.

The proposed framework aims to address these challenges by creating a streamlined process for simulations and trials. It consists of two major aspects, namely the experimenter and the participant. Experimenters leverage the modularity of the system by designing, generating, and saving a plethora of trials, while participants take part in the experiments designed by the experimenters. The experiments might range from a single scenario to a series of randomized experimental scenarios along with the participant training scenarios. Once participants complete the sequence of experiments, the captured data is stored in the appropriate file/folder hierarchy as discussed in section 3.4. This data is then used by the experimenter to derive valuable insights. The framework opens the door to incorporate *eXtended Reality*. XR is an emerging umbrella term for all the immersive technologies

experienced by blending the virtual and “real” worlds. Virtual reality (VR) is a subset of XR that simulates situations and scenarios seen in the real world. Users may engage in regulated and repeated interactions with virtual objects and settings, creating a very immersive experience.

In the past, researchers have used various techniques including questionnaires, observation, and interviews to study human behavior and perception. However, drawing genuine responses from the participants and regulating the environment were some of the drawbacks of these methods. The capacity of VR to provide an immersive experience and expand participants’ efficiency to gain knowledge is one of the major advantages in studies of human perception and behavior. In VR simulations, users have the impression that they are physically present [1][2]. This drastically increases the scenario’s realism and generates more genuine and natural human responses. Therefore, researchers may learn more about how people react and behave in various contexts.

Researchers can modify numerous environmental elements in ways that real-world circumstances cannot. Researchers can explore the influence of these elements on human behavior and perception by changing them. VR enables academics to explore sensitive themes without jeopardizing participant safety or well-being. Researchers, for example, can utilize VR to simulate a fire evacuation scenario without subjecting individuals to real-life horrific situations. Aside from these benefits, VR may be utilized to research and comprehend social interactions. Researchers may learn about how people perceive and react to social events by examining these instances [3][4]. VR may be used to instruct people in various skills, such as teaching a kid to cross the street confidently. Furthermore, VR may be utilized to gather data from a large number of participants simultaneously, enhancing the scope of future analysis.

To showcase the capabilities and accuracy of the proposed system, a combination of short and long experiments were conducted. The short experiment’s primary objective was to evaluate the alignment between the digital world and the real world by allowing participants

to move around the virtual environment and assess its accuracy and realism. The longer experiment was conducted to demonstrate the system's potential applications and robustness to conduct a sequence of interactive scenarios and collect accurate data. Participants were asked to walk on a crowded digital sidewalk while attempting to maintain social distance. The experiment aimed to capture data on the effectiveness of social distancing in reducing the spread of the virus. The collected data was then analyzed to determine the effectiveness of social distancing and identify any challenges participants faced while trying to maintain social distance during the surge of COVID-19. The results revealed that it was difficult to maintain social distance on a crowded sidewalk, indicating the importance of developing effective strategies to tackle such complex problems. The proposed apparatus showed promising potential in identifying solutions to such challenges by providing researchers with accurate and immersive simulations that can aid in understanding human behavior and decision-making in real-world scenarios.



Figure 1.1 Design, Generate, Analyse!

The performance of the apparatus was evaluated and detailed to depict its robustness. The apparatus proved to be efficient and effective in providing researchers with valuable data. The suggested technology may be used to create and test numerous situations to better understand human behavior and perception. It could greatly contribute to the development of a wide range of fields, including architecture, games, movies, and training

settings. Researchers may use the system to produce a large range of situations and experiments, making it easier to evaluate diverse theories. The apparatus is also designed to provide accurate data, making it easier for researchers to derive valuable insights. To explore the effects of variables on behavior and perception, researchers might create a sequence of complex trial sequences with various conditions. For example, the system can be used to research the impact of bus seating arrangements or pedestrians strolling on the pavement. The modularity and scalability of the system enable the creation of many types of tests and rapid integration of new features as per requirements over time.

Moreover, the proposed system may be utilized remotely, making it available to researchers all around the globe. Researchers may create experiments and gather data from participants from all over the world, allowing them to explore cultural variances in human behavior. This system aspect is especially essential in studying human behavior, which varies greatly among cultures. There are various ethical aspects to the suggested system that must be examined. For example, researchers must guarantee that the system-designed studies are safe for participants. Furthermore, the system must secure the privacy and confidentiality of participants by applying suitable data protection mechanisms. Before collecting any data, researchers must also get informed consent from individuals.

1.1 Contribution

The contributions are as follows:

- The suggested system offers scientists a platform to carry out a variety of simulations and experiments. Because of the system's modular architecture, researchers may create, generate, and save a large number of trials. The system is made to make trials and simulations more efficient, saving researchers time and effort while they carry out their research. The system is adaptable to varied research needs and can be applied in a variety of fields, such as architectural design, virtual worlds, games, movies, and

training settings.

- The system has a framework that accurately captures and stores the fast-flowing data streams that result from the experiments. The framework lessens the effort of the researcher by offering a basic backend for laborious implementations. The system’s architecture is built to enable the experiments to run continuously while collecting and storing the data they generate. To make it simpler for researchers to retrieve and analyze data, the framework has been built to store data in a structured and hierarchical manner.
- A simple user interface that offers researchers a user-friendly platform to carry out their experiments. High modularity and scalability in the architecture of the user interface make it possible to easily add new functions. Researchers can perform experiments, design and generate trials, and analyze data using a variety of tools and features available on the user interface. The user interface is made to be flexible to meet the needs of the researcher, allowing for platform modification and customization.

1.2 Structure of the Report

The rest of the project report is organized as follows:

Chapter two summarizes the related work, including existing ideas and approaches in this area.

Chapter Three covers the system overview, design, and architecture, as well as optimizations and performance tuning.

Chapter Four presents the experiments that were conducted to evaluate the system’s accuracy, realism, and robustness in conducting various studies.

Chapter Five presents an in-depth system evaluation.

Chapter Six concludes the project, its limitations, and future research.

Chapter Two

Related Work

The swift creation of experiments has always been a challenge for researchers, especially for those who lack programming expertise. Several approaches have been developed to address this problem, including designing a toolkit with a drag-and-drop graphical interface, creating a set of tools and programming syntaxes to enable logical encoding of conventional experimental aspects, and developing flexible frameworks that can control behavioral experiments.

2.1 Existing Approaches for Swift Experiment Creation

Bebko et al. [5] designed the BiomotionLab Toolkit for Unity Experiments (bmlTUX) to make experimental development more approachable for new coders and faster for experienced coders, especially in scenarios where frequent iterative design was necessary. The bmlTUX system offered a drag-and-drop graphical interface that allowed the experimenters to test new configurations iteratively while maintaining the ability to easily revert to previous ones. This approach closely resembles the proposed implementation of using toggle switches for providing choices to the experimenter, thereby maintaining the system's modularity and ease of use. Brookes et al. [6] worked on a Unity Experiment Framework that provided the nuts and bolts that worked behind the scenes of an experiment and allowed researchers to readily implement several forms of data collection. Their work utilized the session-block-trial

model, where many experiments comprised multiple repetitions of trials, with only minor changes between the trials. A substantial change of content in the trial was described as creating a new block, and a single iteration of a task by a participant was called a session. Their idea of using an event-driven system that reduces the interdependencies between the components is leveraged in improving the flexibility of the proposed work. Additionally, their work illustrated a multi-threading architecture to optimize the blocking nature of writing a file, which is utilized in the current system.

Watson et al. [7] developed the Unified Suite for Experiments (USE), a flexible framework that could design and control behavioral experiments, and supported the pliable use of 3D or 2D scenes and multiple input methods. The system offered tight control and nested commands over complex tasks. It was also capable of completing the offline reconstruction of experiments with the temporal alignment of data streams, which is similar to the current system’s way of handling new experiment development. Sangalli et al.[8] worked on a framework for the evaluation of locomotive motion datasets through motion-matching techniques. With advancements in technology, some substantial work has been done to make mixed reality further accessible. Jangraw et al.[9] built the Naturalistic experimental design environment (NEDE), a Unity3D application that allowed experimenters to employ powerful rendering tools while interfacing eye-tracking, randomizing stimuli, and providing custom task prompts. Gruenefeld et al.[10] extended these concepts by bringing rapid prototyping in cross-reality systems (AR/VR). Their proposed VRception Toolkit leveraged the notion of easy remixing of elements from all continuum levels and was able to reduce the implementation time from days to just about eight minutes.

The research works mentioned above strongly stick to the current problem space, which revolves around minimizing the researchers’ efforts by providing them with a modular yet scalable system that has many essential backends already deployed to support the efficient conduction of a series of experiments. Additionally, these works focus on providing flexibility in integrating new implementations with less complexity, collecting accurate data, and stor-

ing it in an orderly manner for future studies. The approaches developed for swift experiment creation have been successful in providing researchers with easy-to-use toolkits, frameworks, and flexible systems to conduct experiments quickly and accurately. These advancements have made it easier for both novice and experienced researchers to conduct experiments and gather accurate data.

2.2 Virtual Reality Studies in Understanding Human Behavior and Perception

Many of these systems including the one proposed in this report open the door to Virtual Reality (VR) studies for understanding human behavior and perception. A wide variety of VR experiments and studies including realism, immersion, accuracy, and social interaction, to name a few, have been conducted over the years. This gives a thought to the extent of studies conceivable on the proposed framework. The concept of "presence" refers to the sensation of "being there" in a virtual environment. It is the abstract insight of feeling like one is present in the simulated world. The earliest studies led by Slater and Horrocks [1] fostered a virtual presence counter that actions the degree of presence experienced by participants in a virtual environment. They observed that the degree of presence is affected by different elements, like the degree of immersion and interactivity. Witmer and Singer [2] observed that the degree of realism is affected by the degree of sensory fidelity in the virtual environment. They led a study in which the participants were immersed in a virtual environment. They observed that the degree of presence was higher when the visual and auditory cues in the virtual environment were more realistic. VR can be utilized to concentrate on how individuals see their general surroundings. For instance, one study by Kim et al. [11] utilized VR to research how individuals see spatial connections between objects. Participants were approached to gauge the distance between objects in a virtual environment, and the outcomes showed that

individuals would in general misjudge distances when items were farther away. VR has been also been used to examine how individuals see movement. Väljamäe et al. [12] found that individuals see movement distinctively in a virtual environment compared to the real world. They found that members would in general misjudge the speed of items moving toward them in a virtual environment.

One of the main benefits of virtual reality is its ability to accurately and realistically recreate real-world environments. For instance, a study by Won et al. [13] utilized VR to examine the impacts of various lighting conditions. In a driving simulator that was very similar to a real car, participants were asked to drive in various lighting conditions. The outcomes showed that participants displayed different driving behavior based on the lighting conditions, demonstrating the realism and accuracy of the simulation. Similarly, Sanchez-Vives and Slater [14] leveraged VR to examine how individuals respond to the deception of possessing a virtual body, and how the illusion that they were in control of a virtual body affected their physiological responses such as changes in heart rate. These results also demonstrated the realism and accuracy of the simulation.

VR can be utilized to investigate how individuals interact with others in social settings [15][16][17]. A study by Bailenson et al. [18] investigated how social cues affect behavior using virtual reality. Members were immersed in a virtual environment that recreated an auditorium and was offered directions to either pay attention to the talk or overlook it. The findings demonstrated that when other people in the virtual environment were also paying attention, participants were more likely to pay attention. Similarly, social anxiety research has utilized virtual reality. In Freeman et al.'s study [19], participants with social anxiety disorder were asked to give a speech in front of a virtual audience while immersed in a virtual environment. According to the findings, VR exposure therapy reduced participants' symptoms of social anxiety.

Another advantage of VR is its capacity to make realistic and accurate simulations of social interactions [20][21][22]. For example, a study by Slater et al. [3] examined social

exclusion. The participants were immersed in a virtual setting and given the impression that they were competing against other players in a game of ball tossing. The outcomes showed that members displayed close-to-home and conduct reactions (e.g., expanded hostility) when they were prohibited from the game, exhibiting the capacity of VR to simulate realistic social interaction. Further, VR has been used to investigate how people respond to social norms and expectations. Bailenson et al. [4] carried out a study in which participants were placed in a virtual setting and required to select one of two virtual characters to hire for a job. The participants were more likely to select the character who complied with social norms and expectations, indicating that virtual reality can simulate these factors. Additionally, VR can be used to investigate decision-making processes. A study conducted by Hsu et al. [23] utilized VR to examine how individuals respond to risk in a gambling task. Another study led by Kahane et al. [24] in which participants were asked to decide whether they would give up one person's life to save the lives of a lot of others in the virtual environment. These VR-based studies helped investigate how individuals respond to moral dilemmas.

2.3 Crowd Simulation and Interaction

Realistic crowds and their interactions play a crucial role in increasing the realism of studies. In crowd simulation, steering and avoiding collisions are essential components that have been addressed through various techniques and strategies, and numerous studies have been conducted on these aspects over time. One such technique is Optimal Reciprocal collision avoidance, or ORCA, which was developed by van den Berg et al. [25]. ORCA aims to compute collision-free velocities for agents in real time by considering the potential future trajectories of nearby agents. ORCA uses linear programming to determine the agent-specific optimal velocity for moving toward its goal and avoiding collisions. Helbing and Molnar [26] proposed the Social Force (SF) model as a prevalent approach to simulating the behavior of crowds. This model proposes that crowd agents experience social forces like repulsion,

attraction, and alignment with nearby agents, which influence their movement direction. The SF model has undergone refinements and extensions by researchers like Moussaïd et al. [27] who introduced the Social Identity Model for Crowd Dynamics (SIM). The SIM model integrates social identity and group behavior into the SF model, making it more realistic for simulating crowds with diverse group dynamics. The predictive Avoidance Model (PAM) is another strategy that employs machine learning techniques to forecast agent motions and avoid collisions. Some studies including Phan et al. [28], Khorramshahi et al. [29], and Huang et al. [30] propose a hybrid model integrating a probabilistic model with Machine Learning.

Fiorini and Shiller [31] proposed velocity obstacles (VO), a collection of velocity obstacles that represent the velocities of other agents that would result in a collision, and impede an agent's movement in VO. After that, the agent chooses a velocity that gets around all obstacles to velocity and moves in that direction. Further, Reciprocal velocity obstacles (RVO), a widely used strategy, was developed by van den Berg et al. [32]. The velocity obstacles that RVO calculates are cones in the velocity space that represent the potential future velocities of other agents in the event of a collision. After that, the agent selects a velocity that will allow it to move in the same direction as all velocity obstacles. RVO's ability to handle large crowds with thousands of agents is one of its main advantages.

Further, path planning is also a crucial component in crowd simulation. A* and Iterative Deepening A* (IDA*) are among the popular algorithms used for path planning in crowd simulation. For instance, in a study by Ju et al. [33], the A* algorithm was used to find the shortest path for pedestrians in a virtual environment. Similarly, in another study by Zhang et al. [34], the IDA* algorithm was applied to improve the efficiency of path planning for pedestrians in a crowded environment. These studies demonstrate the effectiveness of these algorithms in path planning for crowd simulation.

Chapter Three

Design And Architecture

Human behavior and perception studies by providing valuable insights into complex problems pose challenges in terms of development time and complexity. The proposed system is designed to aid in the rapid prototyping and execution of research experiments and collect accurate data while reducing researchers' time and effort. It caters to two primary actors: the experimenter and the participant. The experimenter leverages the system for creating, saving, and generating new trials and collecting data for their research. The participant follows the experiment sequence and participates in it. Consent is obtained from participants to ensure that they are aware of every aspect of their involvement in the study, including what procedures or treatments will be used and the potential outcomes, including any hazards.

3.1 Overview

The system's use case diagram illustrated in (Fig. 3.1), presents an overview of its various interactions and features. The proposed framework is developed using C# and Unity (2021.2.10). Its modularity enables the experimenter to effortlessly design, save, and generate new trials with different configurations, such as perspective, scenarios, and data matrices, among others. The proposed system's design and system architecture (section 3.4) aim to make it user-friendly and efficient for conducting research experiments. By catering to both

the experimenter and the participant, the system enables researchers to collect reliable and precise data while ensuring the participants' safety.

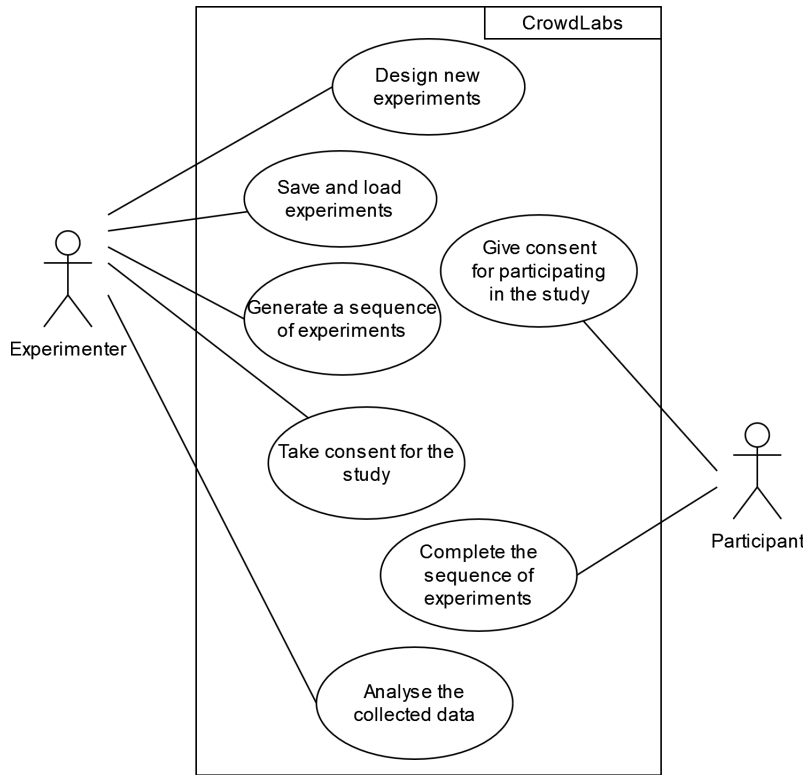


Figure 3.1 Use case diagram

3.2 Configuration User Interface

The framework offers the experimenters an easy-to-use, modular configuration user interface (Fig. 3.2) that aids them to generate the series of experiments for their studies. The system's UI currently supports the following configurations:

- i *Scene Selection*: In order to begin with the experiment, the experimenter has to select the appropriate traits that best describe their notion of the experiment. All the attributes in the built system (except the UI) are scraped and rendered as toggle switches in the 'Scenarios' section. The experimenter could select one or multiple options.



Figure 3.2 Configuration User Interface

- ii *Data collection:* Any data produced at the end of the trials had to be collected and stored for future findings. The existing system provides the options to capture the agent’s position, time taken, and exposure (elucidated in the later parts of this section). The agent’s position is recorded at every instance in a Vector3 format (x,y,z coordinates) and the raw position data can easily be fed to any plotting library to trace the path. The time taken is the total time spanned to complete each experiment in the chronology.
- iii *Load/manage experiment Design:* Once the experiment’s configurations are chosen and its name is entered, the researcher could save their experiment design i.e. the sequence of experiments. The design is saved in an XML format that could be effortlessly loaded for later usage. This saves time for experimenters by removing the need to select the same sequence repeatedly in future trials.
- iv *Scene repetition:* If the experimenter is interested in building a sequence with scenarios that occur more than once, this feature supports the requirement to create repetition in the scenarios which can be randomized, if required.
- v *Visualization mode:* These modes enable the participants to perceive the digital world and make retrospective decisions. The system’s ‘perspective’ section currently supports Third Person View (TPV), First-Person View (FPV), and Virtual Reality (VR). In TPV,

the participants could witness the character they play on-screen. In FPV, the player perceives the game through the eyes of the character thereby observing the world around them while in VR they get immersed in the digital environment.



Figure 3.3 Visualization mode, (L) First Person View, (R) Third Person View

- vi *Scene randomization*: Sometimes, the order of the scenario sequence might introduce a bias leading to false observations. This configuration offers an opportunity for the experimenters to randomly change the order of the experiments in the sequence to minimize cognitive biases.
- vii *Training first*: If the experimenters necessitate the participants to get familiar with the scenarios prior to the experiment commencement, this option could be enabled to push all the training setups to the top of the arrangement.

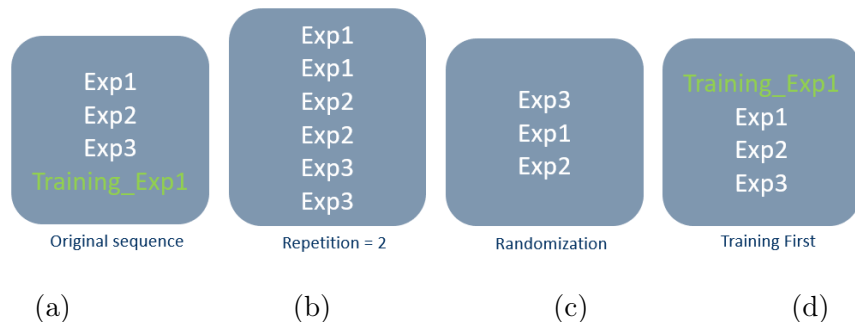


Figure 3.4 Exploring Experiment Customizations: (a) Initial List of Experiments with Training scenario, (b) Repetition of Experiments (2x), (c) Randomized Experiments, (d) Training First: Experiments start with Training Scenarios

3.3 System Workflow

The proposed system offers an approach for rapid prototyping and conducting a sequence of experiments. Once the research study has been designed, the system can be leveraged to conduct experiments with ease and efficiency. Upon launching the application, the experimenter is presented with the Configuration User Interface, which allows them to configure and design experiment scenarios on the system. If the experimenter has not yet configured the experiment scenarios, they can design them and generate a chronology of experiments with the required configurations, such as perspective, scenarios, and data matrices, and save them with a unique experiment name for future use. The experiment design file is stored on the disk in an XML format, which can later be loaded. The researcher can then load the same file to conduct experiments for multiple participants with the same configuration.

To initiate an experiment for a specific participant, a unique participant ID is entered, and the start button is pressed. The experiment sequences are then completed by the participant in a varied configuration, and the data are simultaneously saved on the disk in a defined file folder hierarchy. A description of the subsequent experiment or training is displayed between each experiment. Once the last scenario of the sequence is concluded, and all the data is stored on the disk, the system is ready to take in the next participant. The exit button is used to exit or stop the application at any instance.

During the trials, the system design ensures seamless communication between the experimenter and participants by considering numerous criteria such as user experience and convenience of use. The experiment data can be used for further analysis and inference, providing significant insights into the experiment's studies.

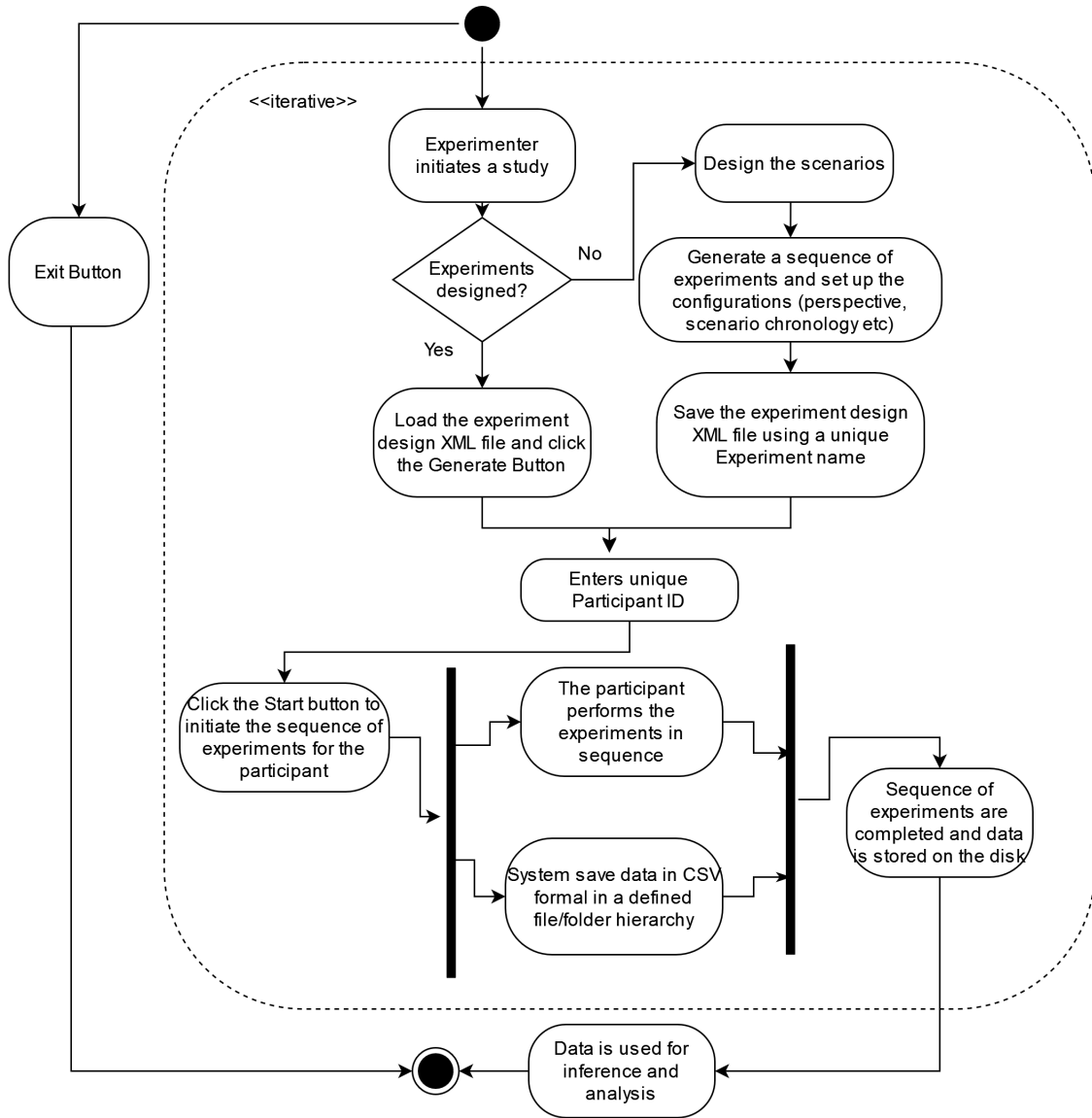


Figure 3.5 Activity UML diagram

3.4 System Architecture

In this section, the architecture of the back-end process of the framework (Fig. 3.6) is elaborated. The process starts with the generation of data from the Configuration User Interface, which is then stored centrally as static variables to ensure its system-wide access. The stored data is then utilized by the experiment manager (EM), a persistent script responsible

for maintaining states and orchestrating the trials. The data for a particular experiment sequence is passed on to the scene by the EM, which consumes the data, activates the necessary scripts, and generates the desired experimentation. This approach significantly reduces the interdependency amongst modules and the tight coupling of data, thus making the system more robust and less prone to errors. To facilitate the seamless flow of the experiment sequence, the EM makes use of the observer pattern. This approach enables the system to remain event-driven, where a completed experiment from the sequence would notify the EM to move on with the flow. This pattern ensures that the different modules can communicate effectively with each other and that the whole system can function efficiently.

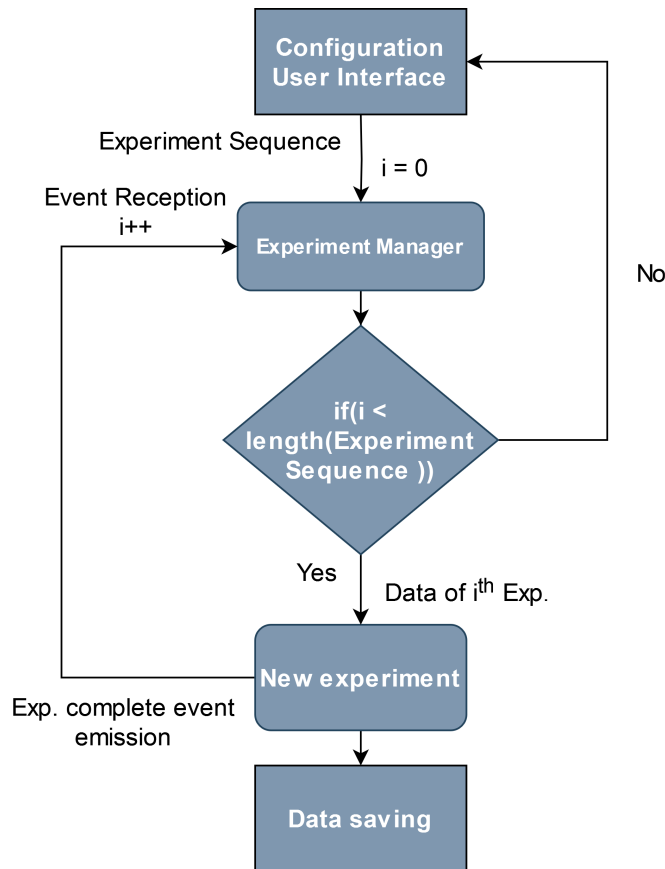


Figure 3.6 System flow diagram

At the end of each experiment in the sequence, the captured data is stored in a .CSV

format in the hierarchy as shown in Fig. 3.7. A loading screen is also displayed, detailing the subsequent experiment’s information. This approach provides a buffer between the experiments, lowering the participants’ fatigue and enabling them to remain more engaged throughout the process. The captured data is stored in a hierarchical format that enables easy access and retrieval during analysis. The entire process continues until the completion of all the experiments in the sequence. As soon as the sequence finishes, the flow is transferred back to the Configuration UI.

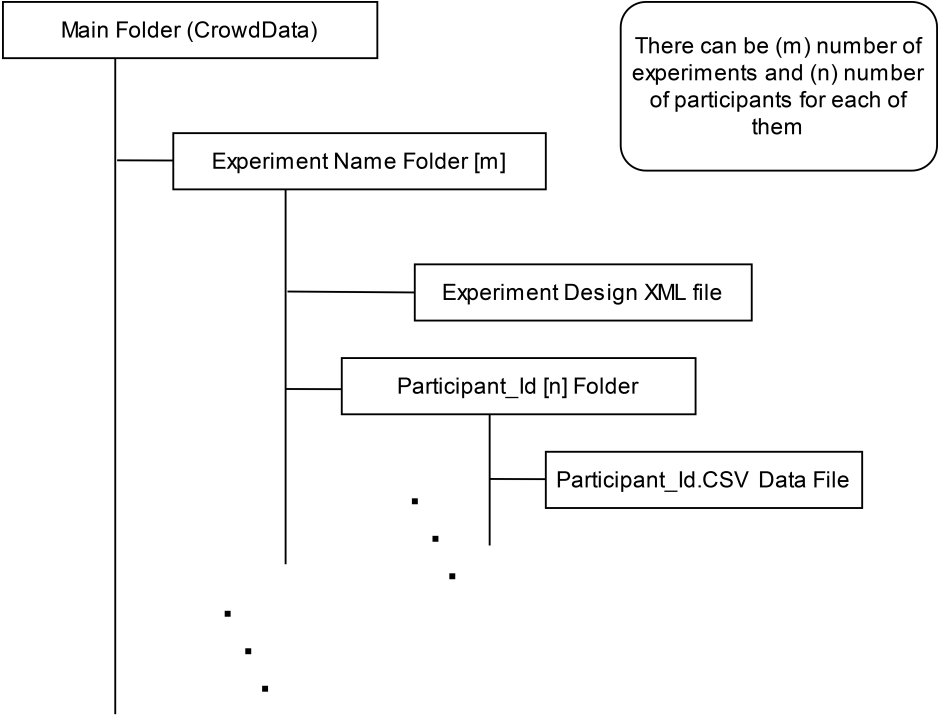


Figure 3.7 Folder Hierarchy

The event-driven approach employed by the EM and the observer pattern reduces the interdependency amongst modules, making the system less prone to errors. The use of static variables ensures that the data is accessible system-wide, enabling seamless communication between different modules. The hierarchical storage of data in a .CSV format (Fig. 3.8) provides an easy way of retrieving the captured data, enabling efficient analysis and interpretation of the results.

Participant ID	Scenario	Viz Mode	Start Time	End Time	Total Time Taken(mins)	Player Postion
P_ID	Training_Exp1	FPV	2022-04-03 16:48	2022-04-03 16:50	2.4	Position Data
P_ID	Exp1	FPV	2022-04-03 16:50	2022-04-03 16:51	1.8	Position Data
P_ID	Exp2	FPV	2022-04-03 16:51	2022-04-03 16:53	1.6	Position Data
.			
.						

Figure 3.8 File structure

In addition to its core features, the proposed apparatus prioritizes modularity and scalability. The framework includes a "Default" scene (Fig. 3.9) that contains all the necessary components for conducting a basic experiment. Researchers can easily customize and build upon this scene by incorporating various prefabs, textures, and materials within the existing framework. Moreover, they have the flexibility to add their own unique features by creating a new option and assigning it a corresponding tag.

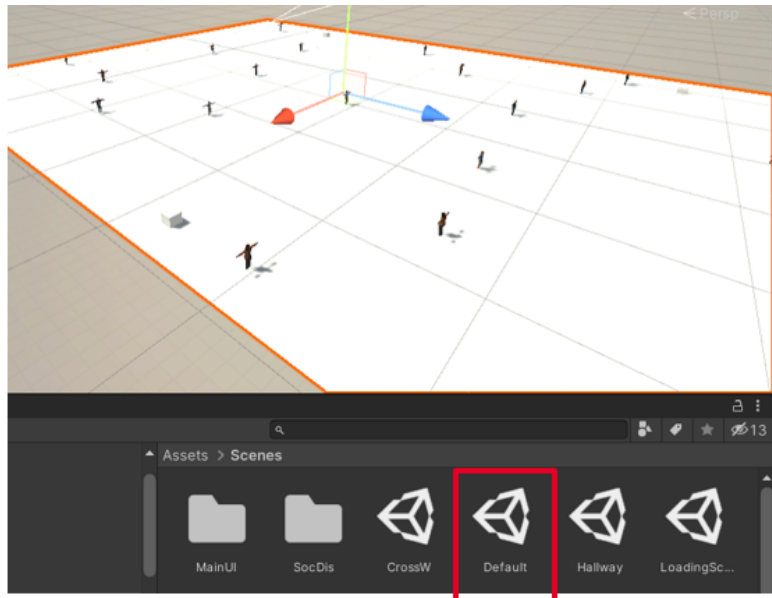


Figure 3.9 Default experiment template

Fig 3.10 depicts the integration of an additional component i.e. orthogonal perspective into the existing perspective controllers. To enable this feature, the user introduces a checkbox in the configuration user interface and incorporates a designated tag, "vizmode,"

(in this case) which is the tag for managing perspectives. This newly introduced perspective gets added to the experiment design, allowing the user to activate the corresponding functionality implemented within the scene associated with the perspective when checked. This streamlined approach allows for efficient experimentation and easy integration of new customization, making the framework a versatile tool for researchers.

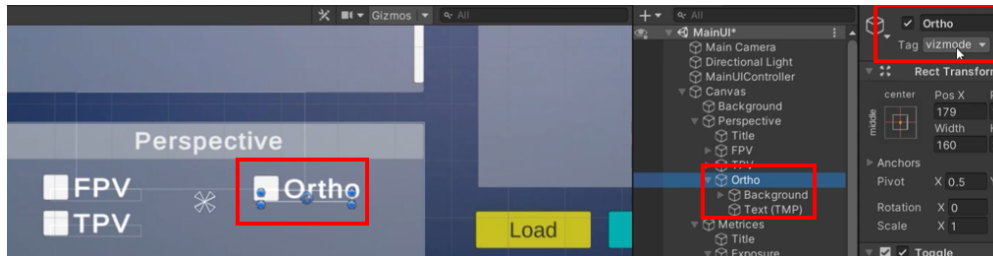


Figure 3.10 Integration of orthographic perspective to the existing perspective controllers

3.4.1 Storage and retrieval of experiment design

In the proposed application, experimenters were able to save their experiment design, making it essential to have a well-structured design file that could be easily retrieved. One of the challenges in this process was ensuring that the saved file could be loaded correctly. The structure of the stored data is in the form of an array of single experiment data ($[["Exp1", "FPV", \dots], \dots]$). This structure is necessary since there could be a series of experiments, and each experiment would have its own unique configurations. As explained in section 3.3, the generate function retrieved the experimenter's inputs from the system's configurations, including scenario, perspective, repetition, and more, to establish the sequence. The initial straightforward idea was to store all of the options selected by the experimenter as a list. Astoundingly, this implementation worked for all the configurations except for the *randomize* option. As the sequence order generated for every instance of the 'randomize' was unique, just storing the selected options resulted in the loss of the original sequence. Hence storing the

exact sequence of experiments becomes mandatory and was attained by storing the required information as an array of strings in the XML format. The Experiment design XML format consists of the experiment name (string), sequence of experiments with specification (list of array of strings), data to be collected (list of strings), and the customization options such as randomization (boolean), repetition (integer) and training first (boolean) (Fig. 3.11).

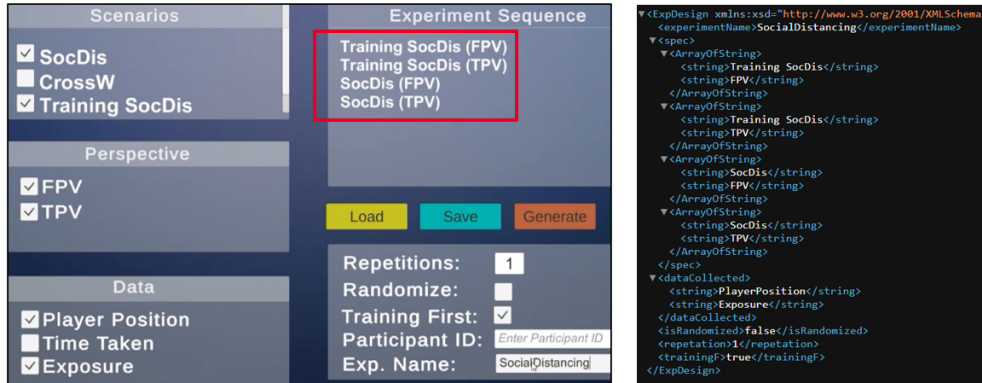


Figure 3.11 Experiment design internal XML structure

3.4.2 VR Setup and Integration

VR was integrated into the framework by utilizing the SteamVR plugin which offers a comprehensive and user-friendly platform to create and optimize immersive virtual reality experiences. The first step involved configuring the base stations in the corners of the room at a height above eye level and facing downwards, with the sync cable connected to the computer. Subsequently, the VR play area boundaries were defined by tracing the perimeter using the headset and controllers through the SteamVR room calibration. The SteamVR package was then incorporated into the project, providing an array of essential tools and assets required for VR development. A camera rig was created in Unity and assigned to the SteamVR camera prefab, followed by positioning and orienting it in the play area to align with the user's physical position. This configuration allowed the user to navigate and interact with the virtual environment within the defined space.

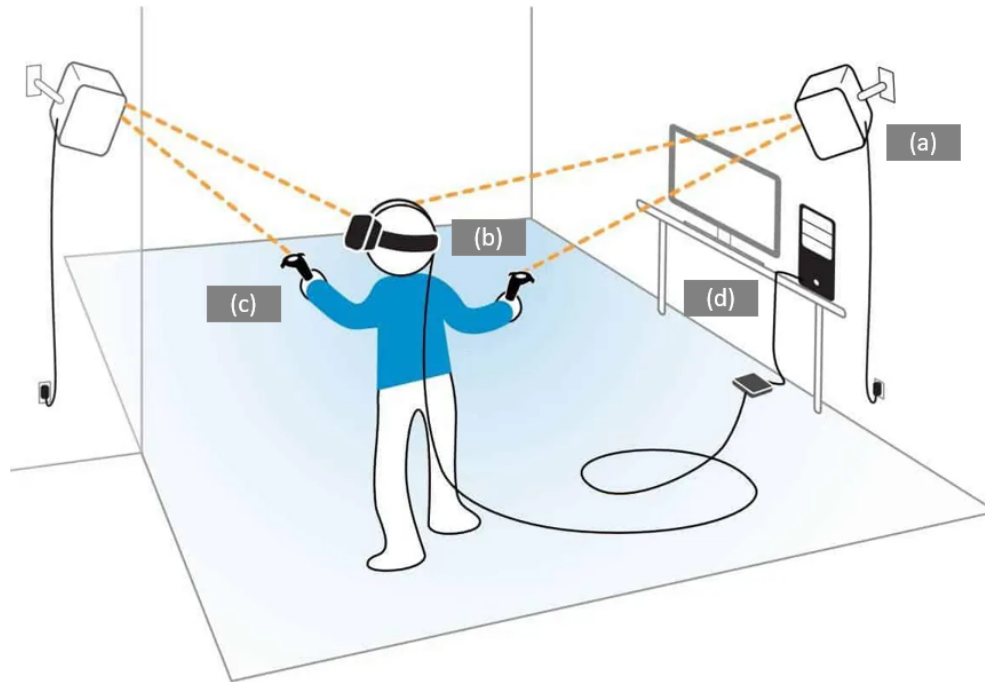


Figure 3.12 Immersive Virtual Reality Setup: A Wall-Mounted Base Stations (a), HTC Vive Pro Headset (b) with Controllers (c), and PC-VR Integration using SteamVR (d)

3.5 Optimization and Performance Tuning

As discussed in section 3.4, once an experiment in a sequence ends, a loading screen appears bearing the details of the next experiment. Frame stuttering was observed initially between the end of the experiment and the emergence of the loading screen. This issue occurred due to the main thread's blockage by an I/O bound operation. The experiments run on the main thread. When the participant reached the desired goal, the current experiment in the sequence ended. The next stage of the application's pipeline was to display the loading screen for the following experiment. But before proceeding to this stage, the captured data had to be written to the disk which blocked the main thread for a split of time resulting in a minor lag. This lag fostered uncertainty in the user experience until the exposition of the loading screen. This occurred as writing a file to the disk is an I/O bound operation and is not bottlenecked by the CPU as shown in Fig. 3.13.



Figure 3.13 Bottleneck causing frame stuttering

Henceforth, the implemented optimization deployed a worker thread as indicated in Fig. 3.14 that made use of asynchronous programming for writing the file. This autonomous thread made the sequence unlogging thereby crafting a smooth transition between the application's states. After this optimization, the lag in boarding the loading screen was not observed.

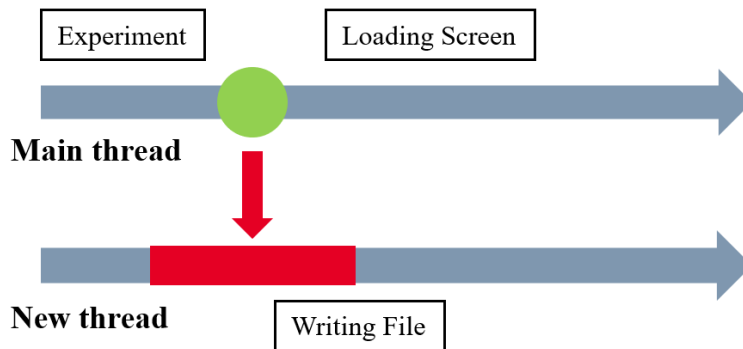


Figure 3.14 Multithreading implementation

Overall, this section discusses the configuration User Interface along with its components, detailed design, architecture, and workflow of the system along with strategies to optimize and fine-tune the performance.

Chapter Four

Experiments

To demonstrate the capabilities of the proposed system to conduct complex perception and behavior studies, a combination of short and long experiments was conducted. The objective of the short experiment was to evaluate the correspondence between the digital world and the real world. Participants were given access to the virtual environment to navigate and evaluate its accuracy and realism. Their inputs were pivotal in evaluating the system's capabilities to conduct studies. The longer experiment aimed to exhibit the potential applications of the system, as well as its robustness in executing a sequence of interactive scenarios while collecting accurate data. 5 students (3 Males and 2 Females) aged between 21-30 participated in these initial experiments. The empirical evidence from the research team served as a testament to the system's effectiveness in conducting intricate operations, showcasing its versatility in various use cases but larger-scale studies would need approval.

4.1 Perceived Accuracy Experiment

Virtual Reality (VR) has emerged as an essential technology with diverse applications in various fields to understand complex concepts, subjects, or theories. However, the accuracy of the virtual environment has been concerning to the researchers. This short study created on the proposed system aimed to assess the accuracy of the VR environment by comparing

the real world and the virtual one.

4.1.1 Methodology

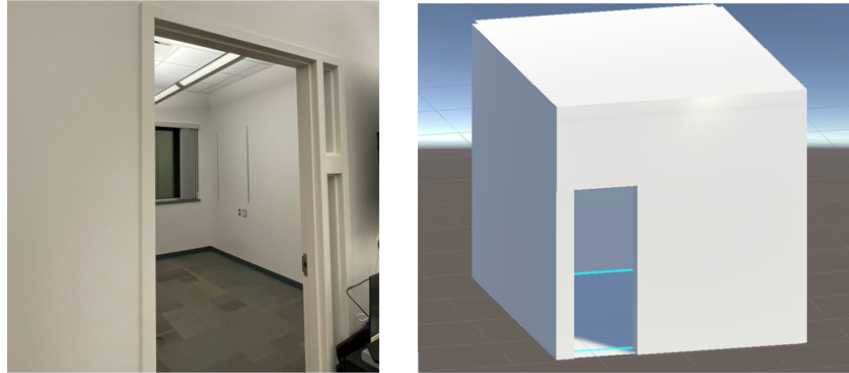


Figure 4.1 (L) GAIDG Lab room, (R) A 1:1 model of the room in Unity 3D

A 1:1 model of the GAIDG lab room was created in Unity 3D, with the dimension of the real room used to create the virtual environment. The playable area matched the real room dimensions as shown in Fig. 4.1. The room was set up for room-scale VR, with cameras, a base station in the corner of the room, and an HTC Vive Pro 2 headset hung from the ceiling to allow movement across the room.

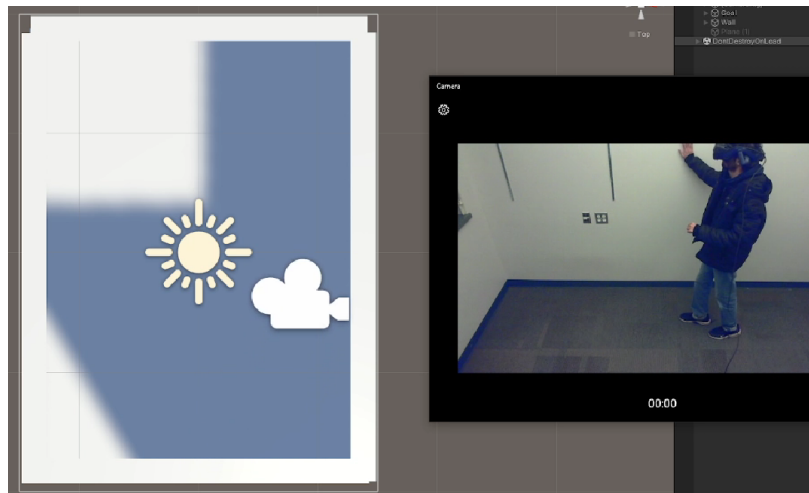


Figure 4.2 The participant's physical contact with the wall in the video feed (R) synchronously corresponds to the camera's interaction depicted in the orthographic view of the 1:1 model of the room (L)

The participants were asked to move around and touch the walls in the virtual environment and then compare them to the real-world ones (Fig. 4.2). The accuracy of the virtual environment was rated by the participants on a questionnaire on a scale of 1 to 10.

4.1.2 Results and Discussion

The outcomes of short VR perceived accuracy experiment were evaluated through a survey, measuring accuracy. The results (Fig. 4.3) indicated an average score of 8.5/10. The accuracy score signifies the extent to which the VR simulation replicates real-life situations.

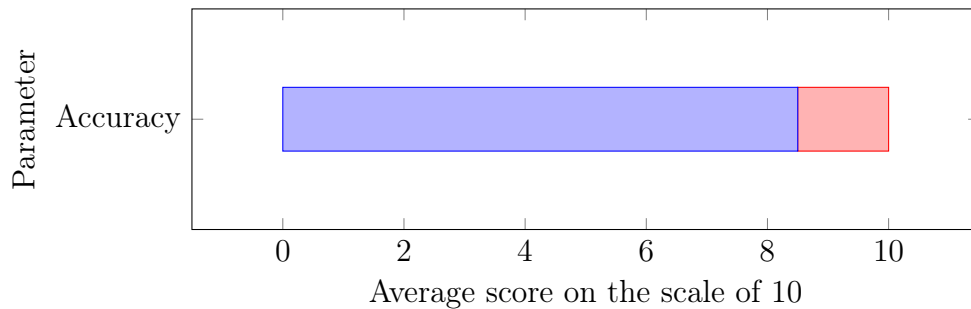


Figure 4.3 Average Accuracy score for Perceived Accuracy Experiment

The high accuracy score of 8.5/10 suggests that the VR experiment successfully replicated real-life scenarios, making it a dependable tool for simulating complex situations such as emergency response or hazardous work environments. The participants found the simulation realistic, indicating the potential usefulness of VR in real-life training.

4.2 Perceived Realism Experiment

The traction that VR studies have gained in research questions their effectiveness which largely depends on the ability to replicate realistic real-world environments. This study aimed to determine the realism of a VR environment by constructing a model of an entire cityscape complete with sidewalks and pedestrian crossings.

4.2.1 Methodology

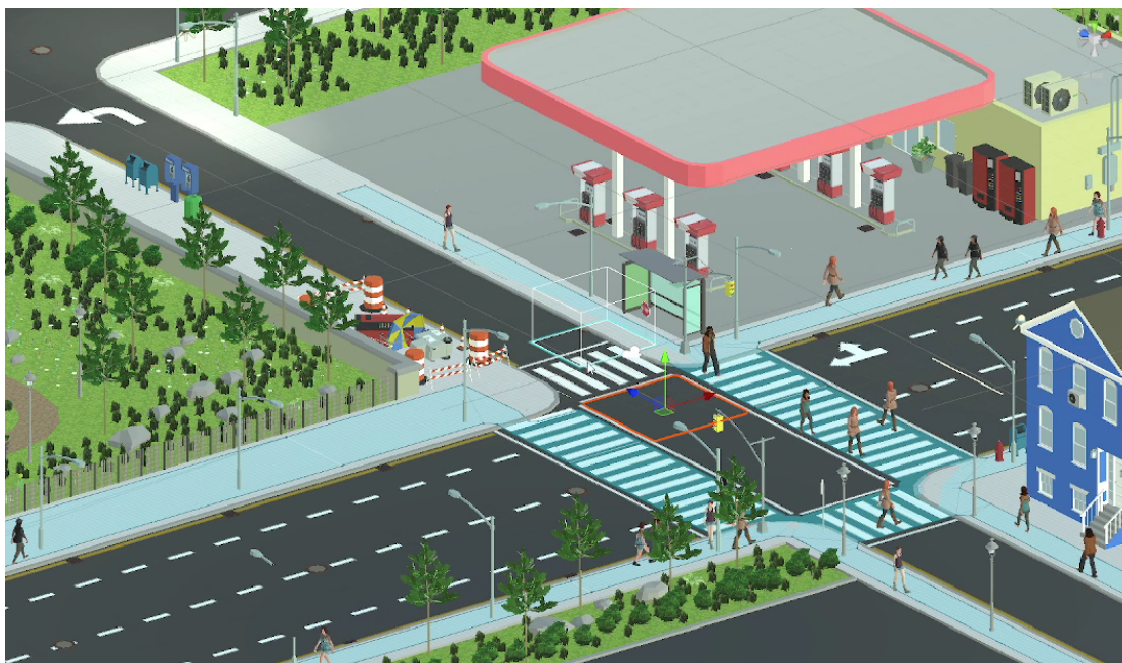


Figure 4.4 Model of a cityscape with crosswalks and highlighted Navmesh

To create a navigable environment, a walkable Navigation Mesh was developed on the sidewalks and crossing. The NavMesh was created by collecting Render Meshes and terrains of all game objects marked as Navigation Static and processing them to approximate the walkable surfaces of the level. The resulting NavMesh (overlaid in blue) is shown in Fig. 4.4. The crowd for agents or non-player characters(NPC) was designed using the Mixamo platform, allowing for a wide variety of animations to be incorporated and enhancing the overall realism of the environment (Fig. 4.5, 4.6). The environment was set up with dynamic goals, represented by white cubes, which were used by the pedestrian crowd to maintain continuity of movement. The agents within the environment were programmed to choose a random goal, achieve it, and then select a new goal to mimic real-world behavior. Different locomotory behaviors and speed offsets were integrated into the agents to achieve further realism. The NavMesh agents internally used A* algorithm for path planning and Reciprocal Velocity Obstacles (RVO) for steering and obstacle avoidance [35].



Figure 4.5 Diversity of Crowd in their standard T pose

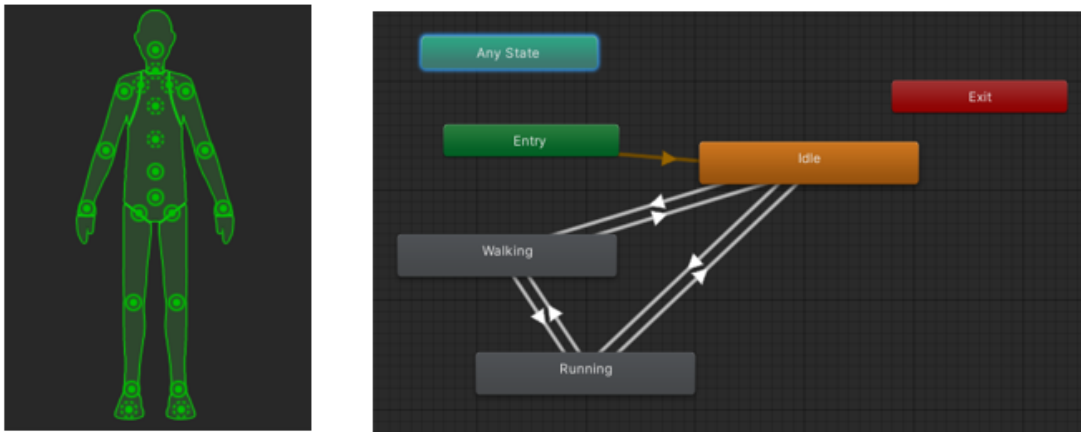


Figure 4.6 (L) Rigged Model of the Character, (R) Character behavior transition graph

Participants were then placed in a room with an HTC Vive pro 2 VR headset and a similar setup as in a previous experiment. The length of the room was equal to the length of the crosswalk in the digital world, allowing for accurate replication of the virtual environment. Participants could move around and avoid the simulated pedestrians or walk and let the pedestrians avoid them. To simulate a crosswalk scenario, one end of the room was positioned at the digital environments’s end of the road and participants were instructed to move to the other end of the room.

Further, post-completion of the experiment, participants were asked to fill out a survey rating the realism of the environment on a scale of 1 to 10, with 10 representing high realism between the real and virtual world crosswalk scenarios, and 1 representing the lowest.

Overall, this study aimed to understand the realism of VR environments and their ability to accurately replicate real-world scenarios.

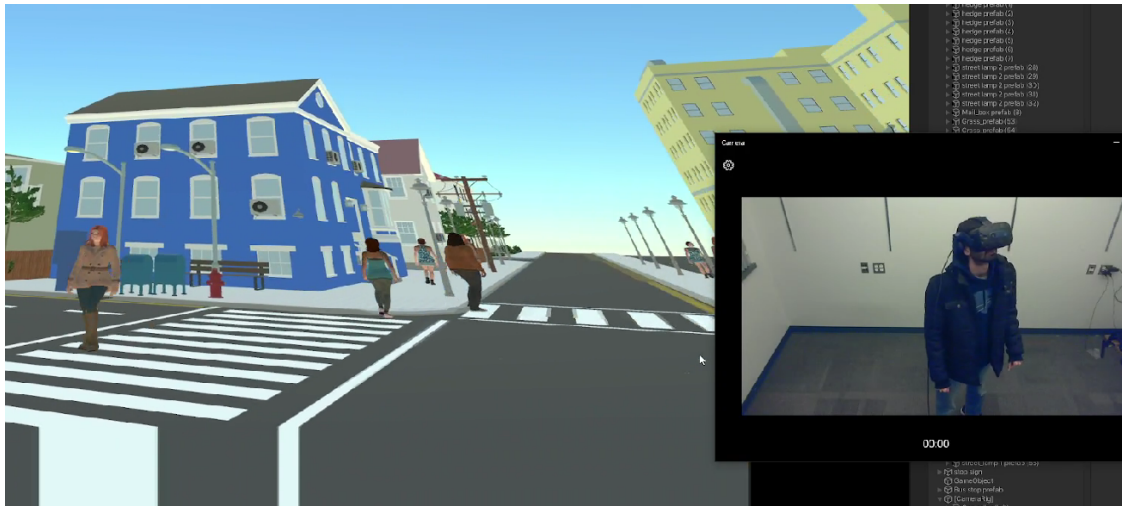


Figure 4.7 Virtual environment perceived by the participant

4.2.2 Results and Discussion

The outcomes of short VR perceived realism experiment were evaluated through a survey, measuring Realism. The results (Fig. 4.8) indicated an average score of 7.8/10.

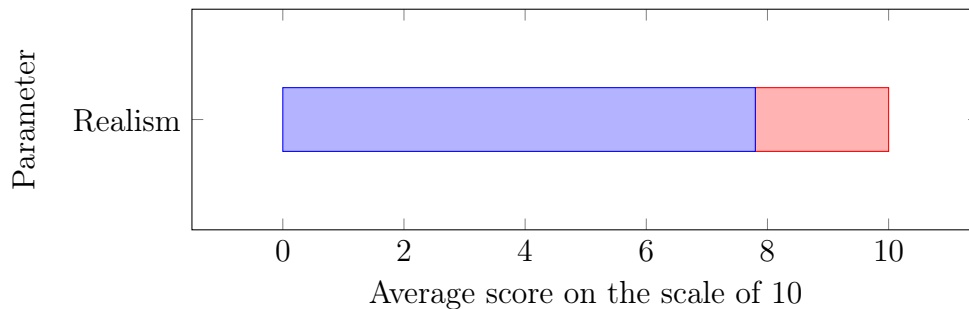


Figure 4.8 Average Realism score for Perceived Realism Experiment

The realism score reflects the participants' level of immersion during the experiment. The score suggests that the VR simulation was immersive, but there is still room for improvement. VR technology has progressed significantly in generating immersive simulations, but there are

still areas to enhance. Haptic feedback and graphic quality, for example, could be improved to make the simulation more realistic.

4.3 Crowded Task Simulation Experiment

The construction of roads and buildings often prioritizes immediate needs, without considering future changes that may be necessary. The concept of social distancing, for example, was not a widespread concern when many sidewalks were designed, resulting in limited space for individuals to maintain the recommended distance of six feet between one another. Consequently, this issue has been utilized as a testing ground to examine the effectiveness of the proposed system designed to collect data. A comprehensive experiment was conducted to demonstrate the reliability and precision of the proposed system, yielding valuable insights into social distancing practices on narrow sidewalks.

4.3.1 Methodology



Figure 4.9 Victoria Sidewalks (Barely 6 feet)

A scaled-down model, that depicts the sidewalk arrangement, was created as shown in Fig. 4.10. The blue area on the pavement shows the baked NavMesh i.e the walkable area for the pedestrians. The crowd consisted of NavMesh agents that utilized the A* algorithm for

path planning and Reciprocal Velocity Obstacles (RVO) for steering and obstacle avoidance. These agents had different locomotory behaviors similar to those in the previous experiment. The environment setup consists of dynamic goals (white cubes as seen in Fig. 4.10), which were used by the agents to maintain the continuity of their movement.

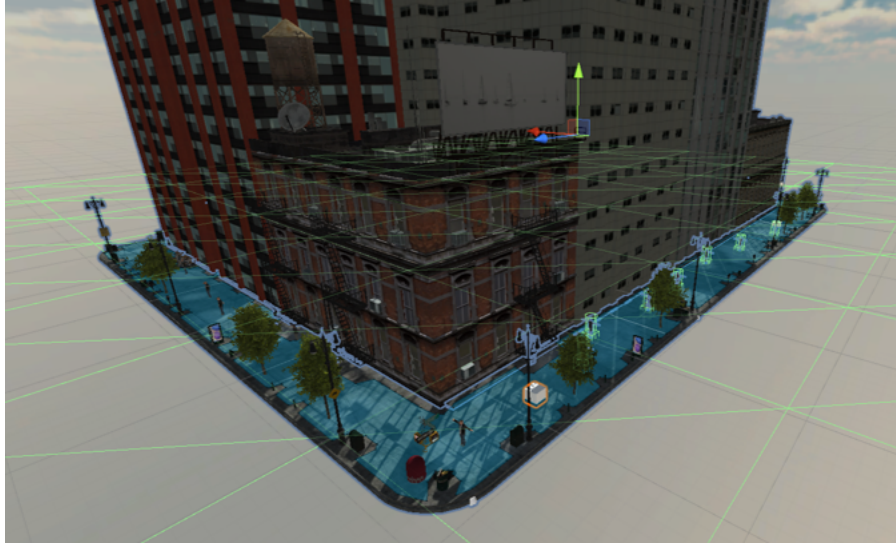


Figure 4.10 Environment setup for the sidewalk experiment

The experiment was interactive i.e. the participant drove the experiment. The aim of the participant was to reach the defined goal while social distancing from the crowd that may be of low, medium, or high density. The participants were provided with the control of a character in the experiment in FPV, TPV and then immerse themselves in the digital environment using VR. The participants utilized the HTC Vive controller to navigate the virtual space while wearing a headset, as in the previous experiments. As the character navigated through the crowd, a perimeter check was made at every instance as shown in Fig. 4.11. During this check, if the object in the radius had a tag of "NPC" then the exposure was incremented for every second. Exposure, the feature integrated into the system, refers to the time the player was unable to social distance from the crowd. The crucial challenge was to complete the quest with the least time and exposure.

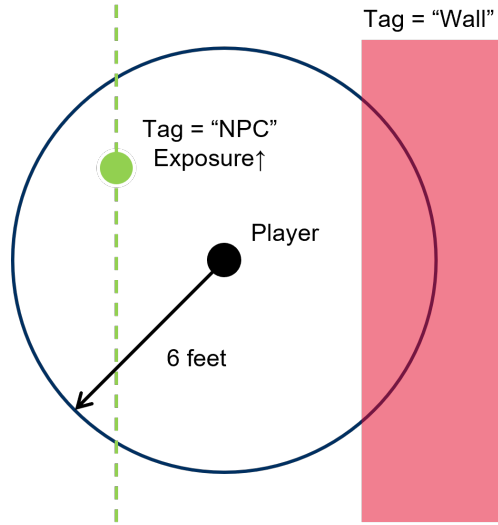


Figure 4.11 Exposure estimation

Overall, this study aimed to test the robustness of the system and its capabilities to collect accurate data for a complex sequence of experiments.



Figure 4.12 Participant trying to social distance in different perspectives

4.3.2 Results and Discussion

The Crowded Task Simulation Experiment consisted of three different crowd densities namely low, medium, and high. The variation in the crowd density is caused by the change in the count of agents present in the experiment. The crowd densities of low (L), medium (M), and high (H) had 10, 25, and 60 agents respectively. Ten rounds of experiments for each type of crowd density were conducted and the obtained average was considered to yield insights. For each class of crowd, the generated values were compared for the three perspectives i.e. TPV, FPV, and VR.

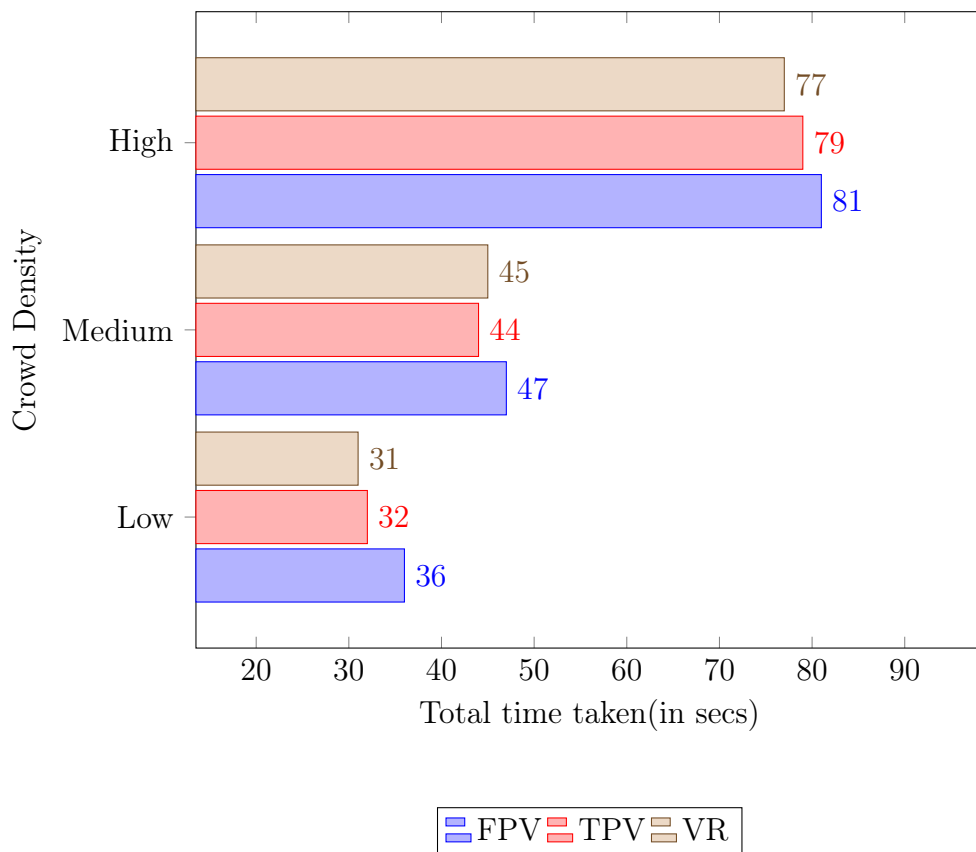


Figure 4.13 Total time taken to complete the quest for different crowd densities and perspectives

The graph in Fig. 4.13 charts the average total time taken to complete the experiment against the crowd density category. There was a gradual increase in the average time taken

by the participant from low-density to medium-density crowds. On the other hand, there occurred a rapid increase in the average time from medium-density to high-density crowds. These results revealed the expected insights that an increase in crowd density, increased the time taken to complete the experiment. This is due to the fact that social distancing was difficult in a high-density crowd, which consequently instigated the participant to move slowly thereby impacting the total time consumed to reach the goal. Alongside, there was no substantial difference in the time taken between TPV, FPV, and VR. This provides us with a new finding that the participant’s perception in this particular experiment did not have an impact on the time taken to attain the quest.

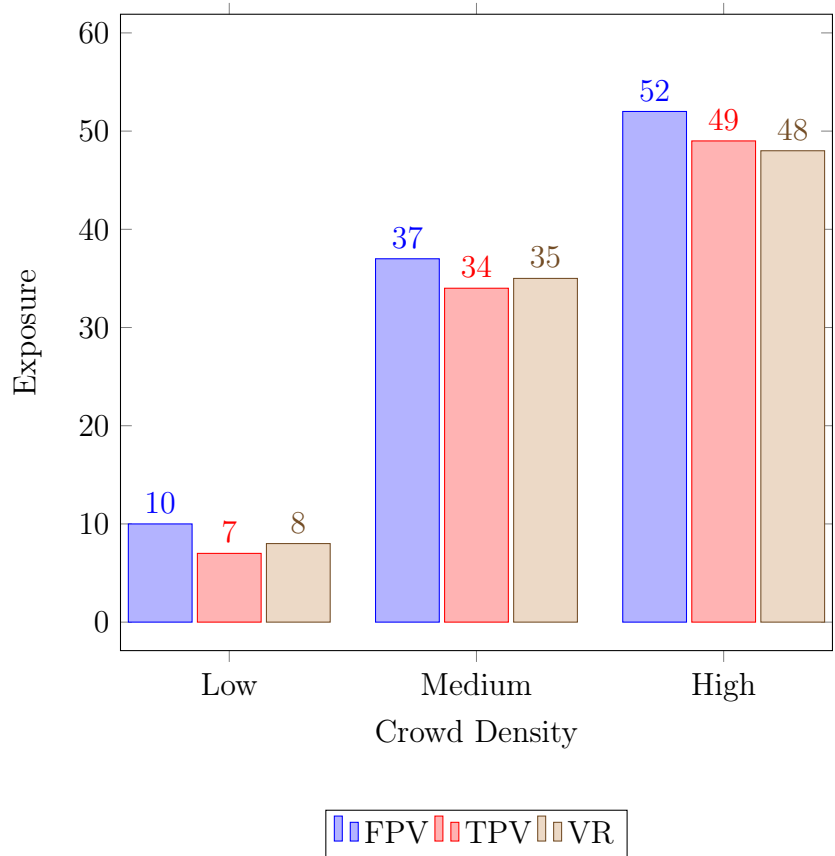


Figure 4.14 Exposure % for different crowd densities and perspectives

Fig. 4.14 portrays the exposure percentage versus the crowd density type for different visualization modes. The exposure percentage is calculated as a fraction of the exposure

time to the total time taken in achieving the goal and is depicted in Eq. 4.1:

$$Exposure \% = \left(\frac{Exposure\ in\ the\ experiment}{Total\ time\ for\ the\ experiment} \right) \times 100 \quad (4.1)$$

The exposure percentage abruptly increased for the crowd from low to medium density whereas it was not the same with medium to high density crowd. The derived results were also startling in means that the high-density crowds had an exposure percentage of around 50. The increase in the number of agents increased the area occupied by the crowd accordingly, reducing the space available for social distancing on the sidewalk. Consequently, the participant was unable to maintain the minimum recommended distance amongst the peers thus intensifying the exposure time. Likewise, to the total time taken comparison graph, the exposure percentage remained nearly the same for both perceptions suggesting that the perspective did not affect the experiment. From both the plotted graphs, it could be deduced that sidewalks pose great difficulty to social distance in high-density crowds.

Chapter Five

System Evaluation

In the motive of evaluating the performance of the system, the application was profiled for the social distancing experiment (section. 4.3) using the Unity profiler as a standalone process so that the other applications running in the background do not introduce some artifacts leading to fallacious observations. The employed rig’s specifications were AMD Ryzen 7 5800HS (8 core, 16 thread), 16GB memory, and 4GB NVIDIA RTX 3050 dedicated GPU running Windows 10.

Idle State(Configuration UI)		
CPU	GPU	RAM
+12%	+56%	+4%

Table 5.1 % increase when system was loaded and idle

As the system was loaded for the first time in the memory (Table. 5.1), the CPU and RAM increased by 12% and 4% respectively. The GPU usage increased drastically over 50% confirming the application’s immaculate operation. Once the experiment commenced, CPU usage gradually increased with respect to growing crowd densities as the increase in agents induced more computation. In contrast, RAM consumption remained nearly the same for all the scenarios. Since the actively used information across different crowd classes was similar,

there was no significant change in the memory. As expected, a major increase in GPU utilization was noticed as rendering the experiments and simulating crowds is a graphic-intensive process (Table. 5.2, 5.3).

Evaluating crowd density performance for VR Perspective			
% Increase	CPU	GPU	RAM
Low	+2%	+12%	+1%
Medium	+3%	+15%	+1%
High	+5%	+21%	+2%

Table 5.2 % increase for different crowd density in VR perspective

Evaluating perspective performance for High Density Crowd			
% Increase	CPU	GPU	RAM
FPV	+4%	+14%	+1%
TPV	+4%	+15%	+1%
VR	+5%	+21%	+2%

Table 5.3 % increase for different perspective controllers with high density crowds

Since the intended system involves the simulation of crowds, Frames Per Second (FPS) was used as a measure to evaluate the performance of the application. Frame rate is the frequency at which consecutive images (frames) are captured or displayed. FPS for different crowd densities is projected as the line graph in Fig. 5.1. For low-density experiments, the system was able to thrust an average of 278 fps. Despite the complexity of the environment and the expense of crowd simulation operations, the developed application shoved copious

frames. The FPS started to decline gradually with an escalation in the number of pedestrians, correspondingly increasing the computation tasks for the simulation due to larger workloads. These results assured that the framework’s overall responsiveness reduces with respect to the increase in the agents further initiating input lag.

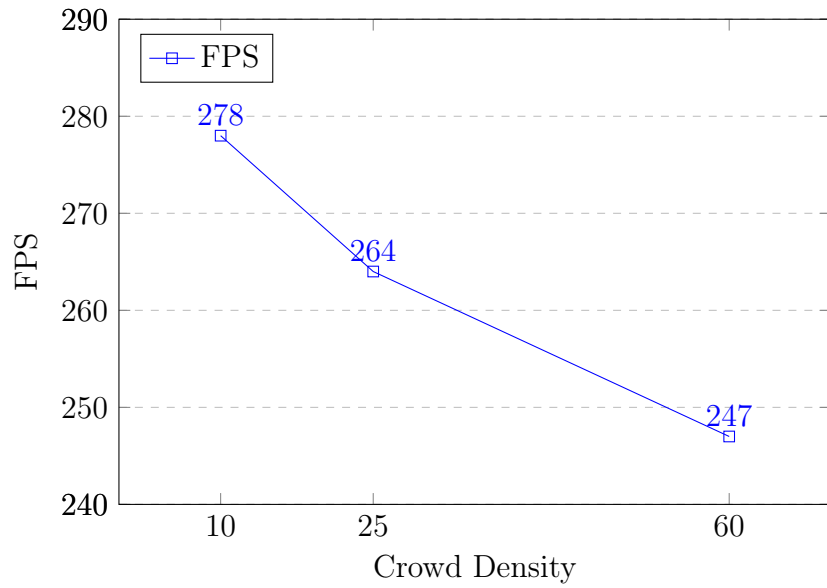


Figure 5.1 FPS drop with increase in agent count

Experiments to find the count of pedestrians that constrained the system were also carried out. At first, a slight decline in frames per second (fps) was observed as the agent count increased. However, this decline escalated rapidly as the number of agents continued to rise, primarily attributed to the increased complexity of interactions among them. For 340+ agents, the FPS dropped to the range of 60s, below which the experiments appear choppy and hamper the participant’s experience. This set-up was executed to test the application’s limitations and is not feasible for the proposed experiment as the sidewalks are narrow and could not fit 340+ agents in them.

Chapter Six

Limitations and Future Work

6.1 Conclusion

The main purpose of the proposed system is to reduce the researchers' time and efforts in human behavior and perception studies. The application aids the researchers to conduct a diverse range of experiments effortlessly. The developed apparatus provides various configurations to the experimenter in designing the trials and capturing the data required for the research. The fabricated system is robust, scalable, and modular for the new feature additions. The framework was tested for scenarios in terms of accuracy, realism, and robustness. The short experiment concluded that the system was capable of conducting accurate and adequately realistic human perception and behavior studies in VR. Further, the longer experiment confirmed the robustness of the system to conduct a wide variety of sequenced experiments and the capability to collect accurate data. The results demonstrated that the surge in crowd density increased both the time taken to complete the experiment and the exposure, irrespective of the perspective chosen. Considering the system's performance, the upswing of the NPCs count resulted in a marginal increase in the CPU and memory. Despite this fact, the system was still able to push adequate frames in all experiment scenarios. As expected, a substantial increase in GPU usage was observed indicating the graphic-intensive nature of the experiments and simulations. The incurred obstacles were tackled using an ap-

propriate structure and employing the concept of multithreading to overcome the stuttering issue. Thus, these impediments paved the way for the optimization of the proposed system.

6.2 Limitations

Being in its early versions, the system has some shortcomings. The existing features are limited in terms of data collection, perspectives, and other aspects. Also, the system has to be manually reset every iteration requiring the experimenter to load the experiment design after every participant. In addition, the empirical evidence is based on data collected from a small set of individuals within the research lab. Further investigation requires experimental design and Human Research approvals. These are earmarked for future work. Furthermore, the current implementation does not provide the experimenter with the flexibility to change the frequency of emerging data collection.

6.3 Future Work

The upcoming plan is to extend the system by integrating full-body MoCap, and haptics, along with no code/low code approaches like Node Editor or graph-based visual programming. The primary focus of the existing framework was to design and implement a robust architecture and backend. The future version will include additional features improving overall modularity, customization, and experiment control. After obtaining the necessary approvals, the plan is to extend data collection beyond the confines of the research lab to include more individuals. This would enhance the robustness and generalizability of the study's findings. Currently, the system's success is primarily assessed through system evaluations but later would be extended to user satisfaction surveys, task completion efficiency, data error rates, and learnability assessments. Further, the integration of different data stream types and processing sensor data like EEG would be addressed.

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