ABSTRACT

Title of Thesis: EFFECTIVENESS OF AUGMENTED REALITY INTERFACES FOR REMOTE HUMAN SWARM INTERACTION

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Human Swarm Interaction (HSI) is a fast-growing research area in swarm robotics. One challenging aspect of HSI is facilitating how humans can effectively handle the many degrees-of-freedom present in a swarm of robots. One emergent option is the use of Augmented Reality (AR) systems. AR based interfaces are attractive as they can help provide a human operator with visual cues about the swarm's states and control to facilitate decision-making. In research settings, AR systems can address issues such as limited availability of lab spaces, limited access to robotics resources, and the need for the ability to simulate dynamic environments with which robots and humans can interact. Further, to make swarm robotics more accessible and ubiquitous, HSI systems that support remote interaction would allow humans to interact with robot swarms and multi-robot systems regardless of the geographical distance between humans and swarms. Taking these into consideration, this thesis aims to investigate the effectiveness of AR based interfaces as tools for remote interaction in HSI systems. We develop a simple AR based interface and evaluate its effectiveness against an unaugmented interface, by means of remote human user studies. The results of these studies help demonstrate the effectiveness of AR based interfaces for remote HSI.

EFFECTIVENESS OF AUGMENTED REALITY INTERFACES FOR REMOTE HUMAN SWARM INTERACTION

by

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Advisory Committee:

Professor Yancy Diaz-Mercado (Chair)
Professor Jeffrey W. Herrmann
Professor Mumu Xu

Dedication

To Thaathu, my dearest grandfather.

Acknowledgments

My most heartfelt gratitude to my advisor, Dr. Yancy Diaz-Mercado, without whose guidance this thesis would not have been possible. Thank you for agreeing to advise me, even with my ambitious timeframe. Thank you for always being kind and approachable. You bring with you an infectious enthusiasm for robotics, that is truly inspiring. I am very fortunate to have worked under you.

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Chapter 1

INTRODUCTION

1.1 Motivation

Swarm robotics is a fast-growing research area in the world of robotics [1]. Robot swarms and multi-robot systems can serve unique purposes that cannot be accomplished by single robot systems. These systems make it possible to use a team of simple robots to perform tasks that would otherwise require a larger, more complex or more expensive single robot system. They perform seemingly complex tasks with a combination of much simpler rules and interactions between agents. Popular applications of swarm robots include search and rescue operations [2], space exploration [2], warehouse applications [3] among others.

However, multi-robot systems and robot swarms are yet to become a part of daily human life. Making swarm robotics more accessible could lead to potential applications in agriculture, package delivery, cleaning, and grazing, to name a few. Research and development in this area can also be furthered if more researchers and students have access to these systems. Remote control of swarms is one possible approach to making swarm robotics more accessible and ubiquitous. Remote access can aid this cause by making robotics hardware and resources available to all. Remote operation can also promote collaboration between researchers and sharing of resources, irrespective of geographical separation. For example, remote access multi-robot test beds such as the one at the Georgia Tech Robotarium [4], aid research by letting individuals submit experiments to their online portal and returning video recordings of the implementation, using their team of robots.

Swarm robotics can also be made more powerful by allowing for human-swarm collaboration while performing tasks. As in any engineering system that involves human beings, it is necessary to take into account the human factors in swarm robotics systems, to improve accessibility and usability. Human Swarm Interaction (HSI) is a research area that addresses how humans and swarms of robots interact. These are among the reasons why interest in HSI has been increasing in recent years. This thesis aims to contribute to the area of remote HSI. In particular we explore how to make remote interactions between humans and robots more intuitive, more efficient, more effective, and easier to use.

We exploit augmented reality (AR) as a an approach to make the interaction feel more 'real' and reduce the perceived difficulty introduced by physical separation between humans and robots. Augmented Reality, according to [5], can be defined as any scenario in which visualization of a real world environment has been enhanced or augmented with virtual objects by means of computer generated graphics. Increasing availability of AR technology, through integration within smartphones and tablets, makes AR an attractive option for improving remote HSI. Thus, the motivation for this thesis stems from the following components:

i Accessibility: Making swarm robotics available to all and promoting research that works towards the same.

ii Human Factors and Human Robot Collaboration: Taking into account human factors while developing these systems and taking advantage of human swarm collaboration

iii Augmented Reality: Exploiting the power of AR to extend reality and make remote interactions easier and more natural.

1.2 Thesis Statement

In this thesis, we demonstrate that 'incorporating information directly into the robot workspace, by means of augmented reality, in remote human swarm interaction interfaces can help make them more effective'. This is achieved through comparison of augmented and unaugmented interfaces by means of remote human user studies in which participants direct a team of robots to given goal locations using each interface. The effectiveness is assessed with respect to robot trajectory and control data collected from the trials, as well as from surveys administered to subjects.

1.3 Thesis Scope

In this thesis, we consider robot swarms that operate as a collective team. In this regard, the swarm may appear to behave as a single system or unit. This abstraction of the individual robots helps to improve the operator control ratio as described in the next section. However, this approach limits the study's ability to assess the effectiveness of other control algorithms that focus on independent control of smaller (potentially heterogeneous) multi-robot teams, where individual robots play a bigger role. This is left as the subject of future studies.

1.4 Thesis Organization

The following chapters in this thesis are organized as below: Chapter 2 provides a summary of related works in the fields relevant to this thesis such as swarm robotics, Human Robot Interaction (HRI), Human Swarm Interaction (HSI), and Virtual and Augmented Reality (VR/AR). Chapter 3 details the hardware and software subsystems that comprise the system of interest, and the components of each. Chapter 4 summarizes the participant recruitment and selection processes, details experiment design, protocol and procedures, discusses the results of the experiment and provides an analysis of the experimental data. Finally, Chapter 5 summarizes the thesis and states the conclusions of the study.

Chapter 2

LITERATURE REVIEW

In this chapter we take a look at the basic concepts of swarm robotics and Human Swarm Interaction (HSI). We then discuss some of the recent work related to swarm robotics, HSI, Human Robot Interaction (HRI), as well as applications of Augmented/ Virtual Reality (AR/VR) in these areas. We also look at methodologies used for human user experiments, conducted to study and evaluate HRI and HSI systems.

2.1 Swarm Robotics

Swarm robotics is a fast-growing research area [1] that has a wide range of applications and numerous advantages over single robot systems. Robot swarms consist of mostly homogenous groups of agents [6] that interact to optimize a function or goal by collectively adapting to the local and/or global environment [7]. Swarm robotics makes it possible to use a set of basic robots performing simple tasks in coordination to accomplish goals that would otherwise require larger, more complex, more expensive single robot systems. Possible application areas of swarm robotics include exploration, search and rescue, and defense. However, swarm robotics also has potential in everyday household and commercial settings for cleaning, package delivery, and other similar tasks that require repetitive or large scale performance of simple tasks.

2.2 Human Swarm Interaction

Robot swarms are often used with some degree of autonomy to perform tasks such as exploration, foraging, or moving large objects. However, human robot collaboration can expand the horizons of what is possible for a swarm robotics system. For tackling complex tasks, robot autonomy can be aided by human operators who adapt better to increasing mission complexity. Human operators also appear to be crucial in scenarios where robot swarms need to react to abrupt changes [1]. The need to improve “control ratio”- increasing the number of robots that a single human operator controls is discussed [8]. However, as the number of agents to be controlled by a single human operator increases, the task of human swarm interaction becomes a challenge [1],[9]. This makes it important to design better HSI interfaces that account for human factors in the system, promote better awareness of the space and the robots, and facilitate ease of use.

2.3 AR/VR for Human Robot Interaction (HRI)

HRI is a closely related research area to HSI. In [10], the HRI problem is defined as understanding and shaping the interactions between one or more humans and one or more robots. This means that many principles and results from HRI are applicable or translatable to HSI. Although there are problems that are unique to HSI and cannot be addressed by general HRI principles, HRI can be viewed as the foundation from which HSI expands. This makes HRI interesting for our purposes. In particular, it is interesting to see how AR/VR has been used to support HRI. In [11] augmented virtuality was used while teleoperating a robot. Participants in this study stated more intuitive control and motivation for the augmented interface. In [12], the researchers studied using AR for remote electrical engineering labs, including robotics, and found it to be useful and intuitive for both students and teachers. Researchers in [13] also show that it is possible for VR based HRI to feel similar to the real life system. These studies indicate that it may be possible for AR/VR to be useful for the case of HSI, also. However, this cannot be assumed to be true since HSI presents its own set of challenges. For these reasons, investigating whether AR aids HSI may be useful.

2.4 AR/VR for Human Swarm Interaction (HSI)

AR/VR is also finding use in HSI applications. In [14], researchers provide an implementation of a VR headset based HSI interface for a coverage problem. Here they demonstrate added functionality such as allowing aerial view of workspace, teleportation between different locations in the space, and adding or removing obstacles in the virtual environment by means of VR. However, since this systems requires a VR headset, it may aid teleoperation in certain cases, possibly for specialized applications such as searching hazardous spaces.

2.5 Summary

In summary, swarm robotics have found important applications and show potential in more commonplace settings. Remote access to swarm robotics resources can further swarm research and enable certain applications such as package delivery, cleaning of large spaces etc. Swarms can be made more powerful and useful through human swarm collaboration. Some recent human user studies in HRI show that AR/VR can be used to aid HRI. There have also been implementations of HSI that use VR. However, for everyday applications and improving accessibility to swarms, AR may be a less expensive and more convenient option. For the aforementioned reasons, in this thesis, we study and demonstrate the effectiveness of AR for remote HSI.

Chapter 3

SYSTEM DESCRIPTION

The primary aim of this thesis is to evaluate whether augmented reality aids remote HSI. The first step to this is to develop an interface through which a swarm of robots may be remotely controlled. We may then use this interface to run remote experiments to compare an augmented reality version of this interface, against an unaugmented version. In this chapter we describe the the hardware and software components used to develop the interface and to run experiments. The various components in the system were chosen in order to satisfy the following objectives:

- Ability to run robot swarm navigation experiments in an indoor environment.
- Ability to track the position and orientation of each robot in the swarm in real time.
- Ability to augment information to the real world system.
- Ability to remotely perceive and control the robots.

3.1 Hardware Subsystem Description

This section describes the components of the hardware subsystem, detailing in particular the choice of components and the features they offer. The hardware components in this system include a team of five Khepera IV robots, Vicon motion capture cameras for localization, a webcam for remote perception of robots, and an overhead projector to augment the space in real time.

3.1.1 Khepera IV Robots

In order to run robot swarm navigation experiments it is essential to have a team of robots that are capable of communicating with one another, as well as with the human operator. The team must preferably be homogenous and made up of simple robots that are able to coordinate with each other. The robot swarm system used for the purpose of this study was a team of five Khepera IV robots. The Khepera IV robots are off-the-shelf differential-drive wheeled mobile robots, that are suitable for swarm navigation applications. These are small, cylindrical robots that have a diameter of 14.08cm and a height of 5.77cm [15]. The compact nature of these robots makes them a great choice for running experiments in indoor laboratory environments. They also have in-built communication modules such as WiFi and Bluetooth, making it possible to relay commands in real time. The robots are programmed to receive velocity commands from a host computer via WiFi using universal datagram protocol (UDP).

The robots being differential-drive and also equipped with caster wheels, are able to spin on their own axis. This gives them a turn radius of 0 cm, i.e., the ability to change directions by turning at one spot without having to make an arc. This is particularly attractive for two reasons: (i) With limited space and while navigating in a swarm a shorter turn radius allows the robots to move freely without the need for additional clearance to turn. (ii) Since the robots do not take arcs to turn, and rather just turn at the same spot where they are at the moment, it is easier for the remote operator to control the swarm. This is especially useful in the case of a human participant study, as some participants may not have any previous experience controlling robots. Finally, the robots also come with an approximately 7 hour long battery life making them desirable for the purpose of this study.

Figure 3.1: A team of five Khepera differential-drive wheeled mobile IV robots.

While swarms are typically constituted of a larger number of robots, we used a team of only five robots for the purpose of this study. The reasoning behind this is stated as follows:

- Ease of use: Using a larger number of robots may have been overwhelming for participants not familiar with robotic and multirobot systems, especially considering the remote manner in which the experiments were conducted.
- Building redundancy: With a set of 10 robots available 5 were used for running experiments with the remaining 5 serving as backup in the event of hardware failure.
- Limited space: Within the limited indoor space available and the nature of the task - remote controlling robots to navigate through a cluttered environment - using a smaller number of robots was safer

Even though only a small number of robots were used, the control law implemented is agnostic to the size of the robot team, letting the robots operate like a swarm. They collectively adapt to cover a changing domain, as will be described in section 3.2.1.1. The algorithm is also scalable with the number of robots.

3.1.2 Vicon Motion Capture Cameras

Vicon motion capture cameras were used to track the position and orientation of the robots in real time. To do this the cameras are equipped with infrared strobes. These strobes emit infrared rays that are reflected by the retroreflective markers placed on the robots. The reflected light is then filtered and captured by the camera lens. The filter allows only the reflected infrared light to pass through. The markers on each robot are set to form unique patterns to make it possible to distinguish between and identify individual robots. In total a set of 7 motion capture cameras were used. These cameras were each positioned to cover the space from a different angle. This configuration allows to fully perceive the space from various angles, as well as to build redundancy into the system in case of occlusions or device failures.

Figure 3.2: One of the Vicon Motion Capture cameras used to track the position and orientation of the robots.

3.1.3 Projector and Webcam

The fundamental components of this study, apart from the robots, are augmented reality and remote control. In order to make the augmented reality component possible, a simple combination of a projector and a mirror was used. The mirror allows to increase the throw of the projector (increasing the size of the image) due to the limited space, as well as adjusting the angle of the projection. The projective distortion due to the angle of the image is corrected for in software. This setup would allow direct projection of images onto the robot workspace, thereby enabling the augmented reality aspect of the study. For the remote control aspect, it is essential that the remote operator be able to perceive the robots and their environment. For this purpose, a webcam was mounted at about the same height as the projector, capturing a live video feed of the robots and the floor space.

The projector was also used to create the cluttered environment, by adding virtual obstacles and goals. This was done from a safety perspective, so as to avoid having the robots run into physical obstacles. For the purpose of the study, however, the goals and the obstacles are not considered part of the augmented reality environment, as they are present in both of the test scenarios.

Figure 3.3: The projector and mirror (top-left and center) and webcam(bottom) that were used to enable augmenting information and remote viewing, respectively.

3.2 Software Subsystem Description

This section describes the software subsytem used to control, track, and interact with the robot swarm. The software components include a MATLAB application that runs the control algorithm as well as serves as the User Interface (UI), Vicon Tracker software that supports the Vicon Motion Capture cameras and allows us to visualize the robot localization, and Zoom video conferencing software to enable remote operation.

3.2.1 MATLAB

MATLAB is a popular and powerful programming language and numeric computation platform that has a wide range of uses. The platform allows for simulation as well as implementation of robot control applications. The control algorithms for the robots as well as the robot driver software were therefore written using MATLAB. MATLAB also has MATLAB App Designer built in. This is an application building environment that makes it easy to design Graphic User Interfaces (GUIs) and program their behavior. This environment allows for building interactive UI options with a variety of input modes as well as the ability to display figures, videos, and messages. The aforementioned features made MATLAB App Designer the platform of choice for building the user interface through which the remote study participants interacted with the robot swarm. The following subsections describe the robot swarm control algorithm and the user interface.

3.2.1.1 Control Algorithm Description

The task for the experiments was designed such that the human operator and the swarm must work in collaboration. The swarm would optimally cover a rectangular domain (box). The operator would be able to drive this box to the goal locations in sequence to complete the mission. To coordinate the swarm, an implementation of a coverage control scheme was used [16]. The control law allows a team of robots to optimally cover the domain in a distributed fashion. The domain is then imbued with first order dynamics, tracking a reference provided by the human operator. The coordination by the robots is achieved as follows: The agents partition the domain using a Voronoi tessellation, such that they are only in charge of covering the points nearest to them and no other robot. Then, they compute the center of mass for their individual cells, and regulate to this position while accounting for the motion of the domain induced by the operator, as well as the motion for neighboring robots. It has been shown in [16] that as the number of robots in the swarm increases, robots will only need to coordinate with a constant number of neighboring robots (about 7) on average, regardless of the size of the swarm. This is due to the special properties of Voronoi tessellations and Euclidean geometry. The domain also helps simulate collisions with the virtual obstacles. Since physical obstacles are not used, and the obstacles are essentially just projected graphics, collision detection is included in the control of the robots. When the swarm runs into an obstacle i.e., the domain boundary and obstacle boundary overlap each other, a collision flag is set. This makes the domain velocity in the direction normal to the obstacle zero. The swarm may, however, continue sliding along the domain boundary depending on the direction of the current control velocity.

3.2.1.2 User Interface Description

To allow the operator to interact with and control the robot swarm a UI was designed using the MATLAB App Designer envioronment. Some of the considerations that went into the design of the UI are as follows :

- The UI should allow for visualization of the robot swarm and its environment, and control of the robot swarm.
- The visualization element should include a live video feed of the robot swarm.
- Apart from the video feed, there should be at least one other mode of visualization that does not depend on the webcam to accommodate for any possible webcam failures.
- The control mode for user input should be flexible to be able to accommodate individual user preferences.

Taking these into considerations the UI was built to include the following set of features. The visualization of the robots was facilitated through two figures. One, was a real-time top view plot of the robots, and the environment. The plot would also show the location of the current goal, which gets updated once the goal location is reached. The other, was a live video feed of the robots. This would capture the actual robots in action, as well as all the information overlaid on the floor space by means of the overhead projector.The interface also included a 'status message'. This message was set to show the status of the system to the operator, as well as to provide instructions. Based on the current status of the system the message would change as follows. Initially, when the robots are calibrating and moving to their initial start positions, the message shows 'Loading...' in red. This serves an indication that the system is not yet ready for use and that the operator must wait. Once the robots have arrived at their initial positions, the message changes to 'Go to Blue Box', and is shown in blue. The first goal location can be on the plot and the floor space in blue. Thus, the operator is instructed on the location of the first goal, and to pursue it. Upon arriving at the first goal, the message changes to 'Go to Green Box', as the first goal disappears and the second appears in green on the plot and the floor space. Finally, when both goals have been achieved, the status message changes to 'Mission Accomplished' in green. This lets the user know that they have successfully completed the task.

To control the robots, the user was provide with a few options. The first was a set of push buttons that were built into the UI. In total, there was a set of five buttons available to the user, with the following labels : 'Up', 'Down', 'Right', 'Left', and 'pause'. When any of the first four buttons where clicked, the control algorithm would set the reference point at a fixed distance from the centroid of the domain, in the direction indicated by the label. This would ensure that the velocity of the domain was set so as to pursue this point. As the robots are set to perform coverage within the domain, they start moving with the domain. As the reference is set with respect to the domain centroid, it updates as the domain centroid moves, thereby keeping the domain - and in turn, the robots - in motion. This means that the user only has to provide each command once, and does not have to continuously hold buttons down or push them many times consecutively. This was done with the aim to reduce user fatigue. The robots may be redirected as needed using any of the other push buttons or stopped using the 'pause' button. This button sets the reference point at the centroid of the domain, thereby bringing the domain velocity to zero, and bringing the robots to a halt.

As an alternative to the push buttons, the users could also use the keyboard to control the robots. The keyboard keys that could be used were the arrow keys and the space bar. Each arrow key was set to perform the same function as the corresponding push button, and would operate in the exact same manner. As with the push buttons, in this case too a single keypress would set the domain velocity in the corresponding direction, and the users need not hold down or consecutively press keys to keep the robots in motion. When using the keyboard, the space bar would serve as the 'pause' button, bring the domain and the robots to a halt.

A final control option was a joystick type controller available within the UI. The joystick would appear as a circle in the bottom left of the UI, and is labelled. This controller was used to enable speed control and to drive the domain diagonally. The controller would work as follows. As the user clicks and drags the mouse pointer to any part of the joystick the difference between this point and the center of the joystick (both displacement and angle) is recorded. The reference point for the domain velocity control is then set to an equivalent point on the robot workspace. Since the displacement from the center is also recorded, the speed of the domain can be increased or decreased with the joystick. The farther from the center the user drags the cursor to, the faster the domain moves. In this control mode the user can stop the robots by clicking in the center of the joystick, which is indicated by a small, red, circular marker.

Below is a screenshot of the MATLAB App UI.

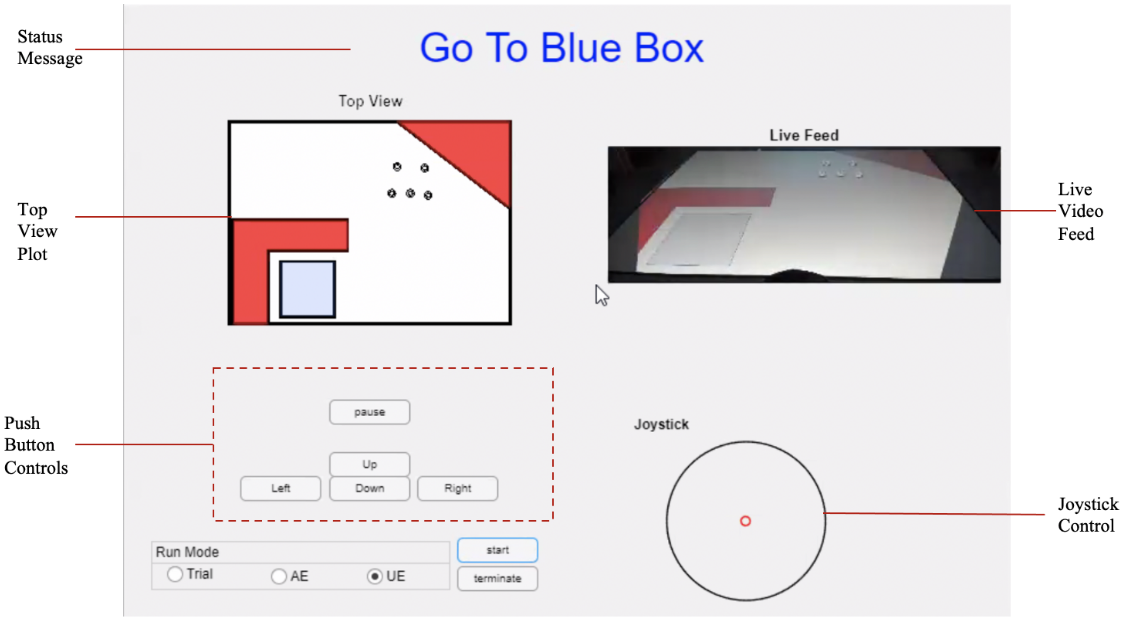


Figure 3.4: The MATLAB App user interface, developed using MATLAB App Designer, showing the various features described in section 3.2.1.2.

3.2.2 Vicon Motion Capture Software

The Vicon Motion Capture software supports the Vicon motion capture cameras. It provides us with an interface by means of which we can visualize the information captured by the motion capture cameras. It also allows us to assign object IDs to agents thereby making it possible to tell them apart from each other and to track their individual positions and orientations. Below is a screenshot of the Vicon software interface.

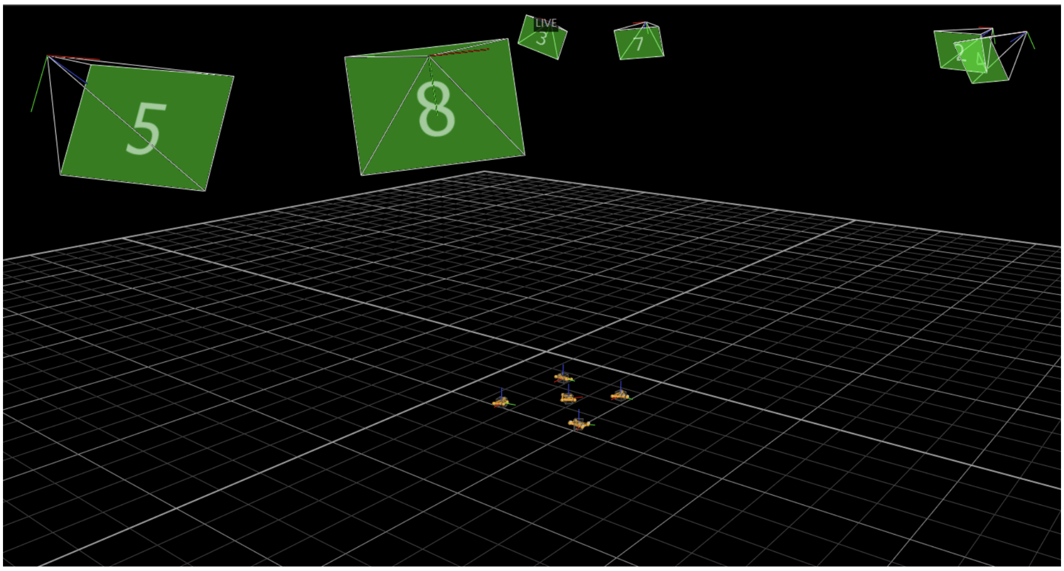


Figure 3.5: The robots as visualized in the Vicon Motion Capture System's user interface

3.2.3 Zoom Video Conferencing

One of the primary objectives of this thesis is to study remote HSI. In order to do this, it is important for the participants to be able to control the robots remotely. To enable this, we use the Zoom video conferencing software. Zoom was selected for the following reasons: Zoom allows for screen sharing and remote control making it possible for participants to interact with the MATLAB App that runs on the laboratory system. In recent times, especially with the COVID-19 pandemic, the popularity of Zoom has increased [17] as a tool for remote work and education . This makes Zoom an attractive option for running experiments as it is likely that participants are already familiar with this platform and comfortable using it.

Chapter 4

EXPERIMENT DESCRIPTION

This chapter describes the experiment design, setup, and procedures. It details the participant selection criteria, the tasks that were performed by the participants, and the data collection methods. It also provides a summary of the results of the experiments.

4.1 Participant Recruitment and Selection

Participants were recruited through email and word of mouth. Email advertisements were sent to University of Maryland, College Park students and interested volunteers were asked to sign up by filling out a screening questionnaire. The volunteers were screened to fit the following criteria:

- Healthy adults between ages 18-35.
- Have no vision impairments.
- Have no medical impairments that may interfere with the ability to operate a mouse, use a computer, or a laptop.

The number of participants was determined by running a priori power analysis for a significance level of 0.05,power of 0.95, and an effect size of 0.7, using the G*Power3 power analysis software [18]. The sample size thus obtained was 24. The number of participants used for similar studies in the areas of HRI and HSI also fall around this range [11], [19], [13], [20]. A total of 26 participants were recruited to participate in the research study.

4.2 Experiment Design

The purpose of this study was to determine whether remote human swarm interaction can benefit from the use of Augmented Reality. In order to this two interfaces were used - one basic, unaugmented interface that only showed the robot and its environment, and the second, an augmented reality interface that would display additional information. The augmented information must include those that are not physical elements that are present in the real world, and rather those that provide additional knowledge of swarm behavior or the environment to the user. The task to be performed had to be one that would have division of responsibilities between the human operator and the robot swarm, thus comprising human swarm interaction.

The task chosen for the experiment was for the robot swarms to navigate a cluttered environment to arrive at and cover a sequence of goal spaces. The robot swarm would be responsible for the coverage aspect, through the use of coverage control algorithms. The human operator, on the other hand, would be responsible for navigating the cluttered environment and successfully directing the swarm to the goal spaces. To aid this task, the augmented interface showed the swarm boundary (as well as a Voronoi tessellation corresponding to the agents within the boundary) that would change color from black to red when colliding with obstacles. The interface also showed the shortest feasible path to the goal spaces as red dotted lines, as well as the current heading of the swarm as a blue cross mark.

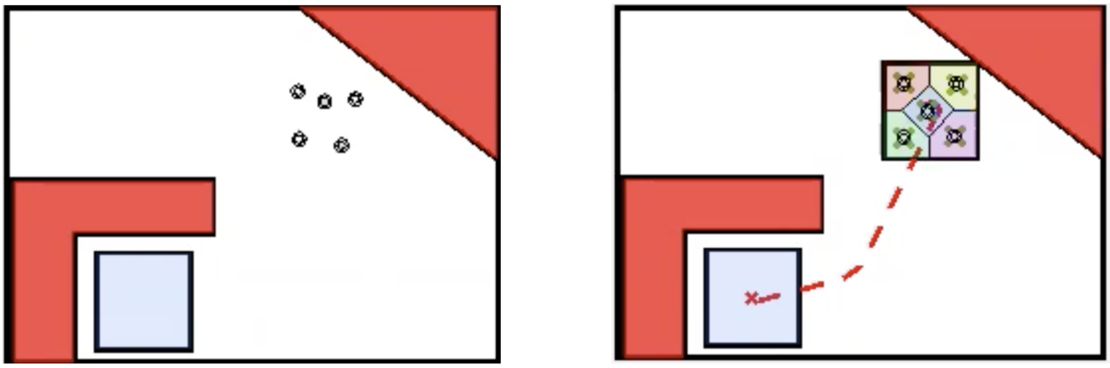


Figure 4.1: Screenshots of the unaugmented (a) and augmented (b) versions of the interface. The unaugmented version shows the robots in the workspace, the obstacles, and the goal. The augmented version shows the same but also includes swarm boundary, Voronoi Tesselation, shortest path to goal and current heading.

To accommodate for the learning curve that participants may experience when using the interface for the first time, the participants were given a trial run with a single robot. The environment and the behavior of the robot were kept the same as those for the swarm scenarios that would be used for actual testing. The participants had to drive the robot to the same goal spaces as the actual scenario, and were encouraged to try using the various control modes available to find what works best for them. Once the participants were comfortable with the controls and the interface the actual experiments were commenced. To avoid possible bias in the results that may appear based on the order in which the participants used the unaugmented and augmented interfaces for the tasks, the order was also randomized. One half of the participants used the augmented interface first, while the other used the unaugmented interface first.

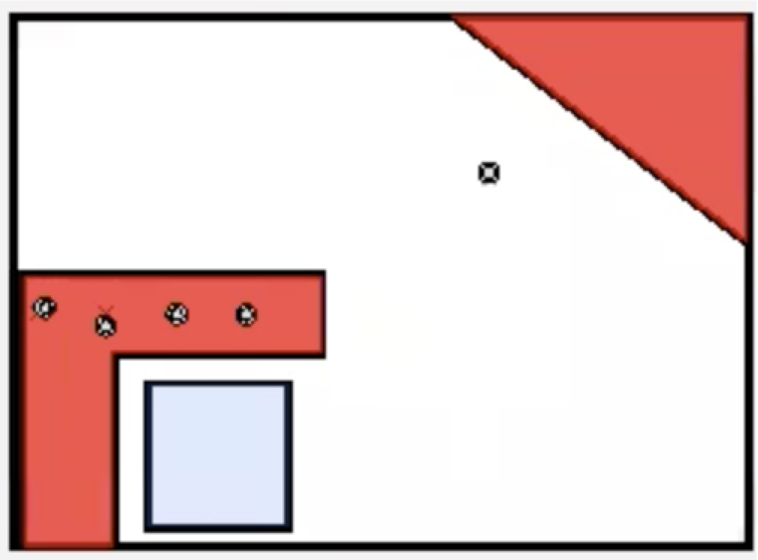
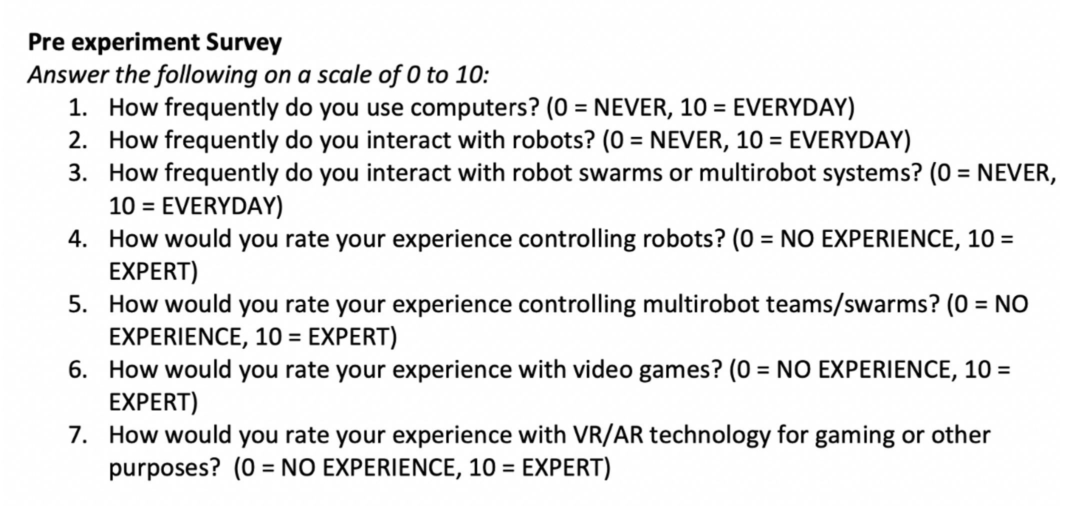


Figure 4.2: Screenshot showing the trial run scenario. The robot used for the trial run is shown present in the white space. All other robots move to obstacle spaces.

4.3 Experiment Protocol

The experiment session would begin with the participant reviewing and signing an Institutional Review Board (IRB) approved consent form, that detailed the procedures, risks, benefits and other information pertaining to the study (see Appendix).

Once the participant has completed the consent process the session would begin with a pre-experiment survey. The survey covered questions about familiarity with computers, robots, swarm robotics, video games, AR/VR technology. Self-reported scores from the survey were used to gauge the level of comfort that the participants felt with technology similar to that used in the study.



Pre experiment Survey

Answer the following on a scale of 0 to 10:

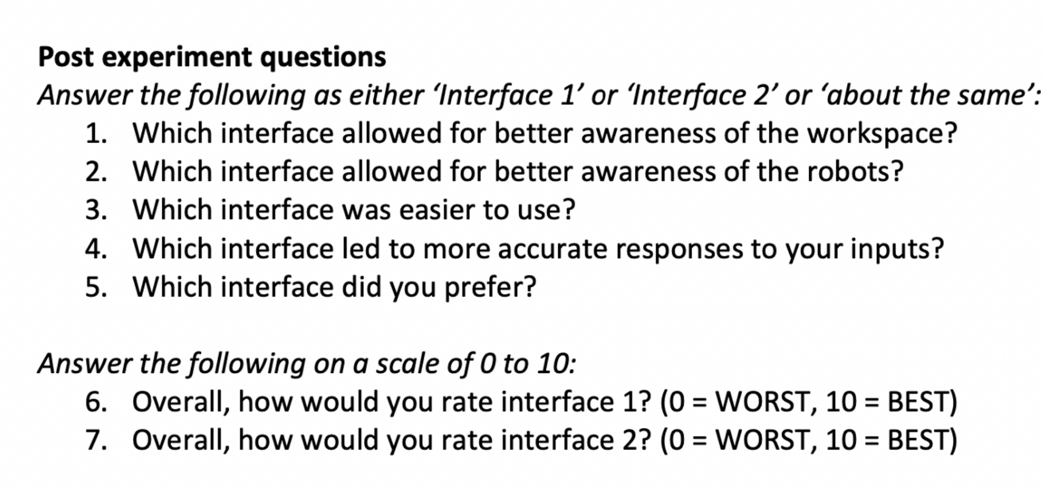
1. How frequently do you use computers? (0 = NEVER, 10 = EVERYDAY)
2. How frequently do you interact with robots? (0 = NEVER, 10 = EVERYDAY)
3. How frequently do you interact with robot swarms or multirobot systems? (0 = NEVER, 10 = EVERYDAY)
4. How would you rate your experience controlling robots? (0 = NO EXPERIENCE, 10 = EXPERT)
5. How would you rate your experience controlling multirobot teams/swarms? (0 = NO EXPERIENCE, 10 = EXPERT)
6. How would you rate your experience with video games? (0 = NO EXPERIENCE, 10 = EXPERT)
7. How would you rate your experience with VR/AR technology for gaming or other purposes? (0 = NO EXPERIENCE, 10 = EXPERT)

Figure 4.3: A screenshot of the pre-experiment survey that was provided to participants

Following the survey, the trial run would be initiated and the participant would be allowed to practise using the various controls until they feel comfortable.

After the completion of the trial run one of either the augmented or unaugmented interface would be presented to the participant. The participant would be asked to direct the swarm to the goal spaces while taking the shortest path they can, and avoiding obstacles.The process would then be repeated with the other interface (augmented or unaugmented).

Finally, participants would be asked to fill a post-experiment survey where they would state their preferred interface based on various criteria such as workspace awareness, robot awareness, ease of use, response accuracy etc. They were also asked to rate each interface on a scale of 0 to 10.



Post experiment questions

Answer the following as either 'Interface 1' or 'Interface 2' or 'about the same':

1. Which interface allowed for better awareness of the workspace?
2. Which interface allowed for better awareness of the robots?
3. Which interface was easier to use?
4. Which interface led to more accurate responses to your inputs?
5. Which interface did you prefer?

Answer the following on a scale of 0 to 10:

6. Overall, how would you rate interface 1? (0 = WORST, 10 = BEST)
7. Overall, how would you rate interface 2? (0 = WORST, 10 = BEST)

Figure 4.4: A screenshot of the post-experiment survey that was provided to participants

4.4 Results

This section provides a summary of the results of the experiments. The results are categorized as qualitative and quantitative. Qualitative results obtained are those based on responses received from the surveys. These give a picture of user experience and preference. Quantitative results, on the other hand, are obtained from robot trajectory and related information. These serve as performance metrics that tell us whether there is an actual difference in how well the participants performed, between interfaces.

4.4.1 Qualitative Results Summary

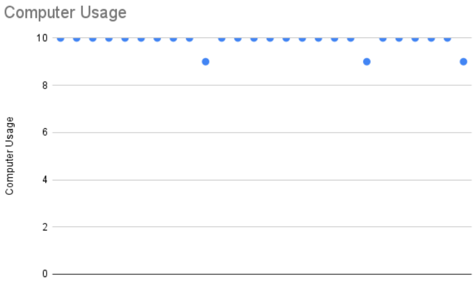
This section summarizes the participant response to the pre-experiment and post-experiment surveys.

4.4.1.1 Pre-Experiment Survey

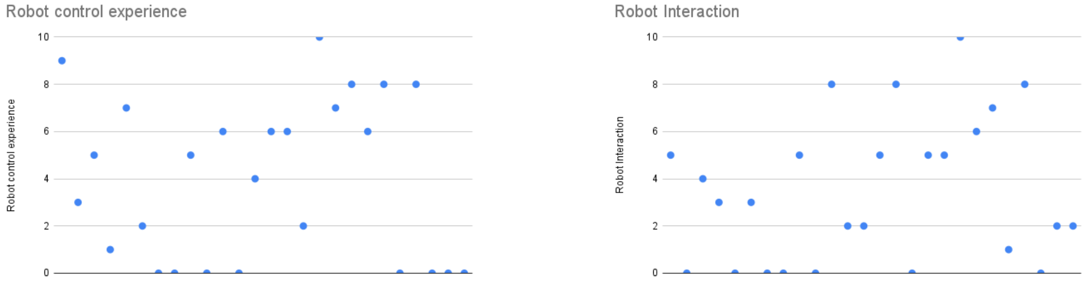
The pre-experiment survey helps us understand the extent to which the participants are comfortable with technology related to the study. Participants rates their familiarity and experience with each type of system on a scale of 0 to 10.

A score of 0 represents no experience while a score of 10 represents expert level experience. Below is a table that shows the mean and standard deviation of the self-reported scores for each question on the pre-experiment survey.

From the scatter plots in Figure 4.5 and the histograms in Figure 4.6 it can be seen that most of the participants used computers nearly on a daily basis, and a good number were at least moderately familiar with video games. However, experience with robots and VR/AR technology was more distributed showing participants with varying degrees of familiarity. Familiarity with multi-robot systems and swarm robotics was more limited with most participants reporting little to no interaction or experience with these systems. Hence it can be said that the results of the survey may apply to people that do not necessarily have experience with multi robot systems or robot swarms, but are very comfortable with using computers.

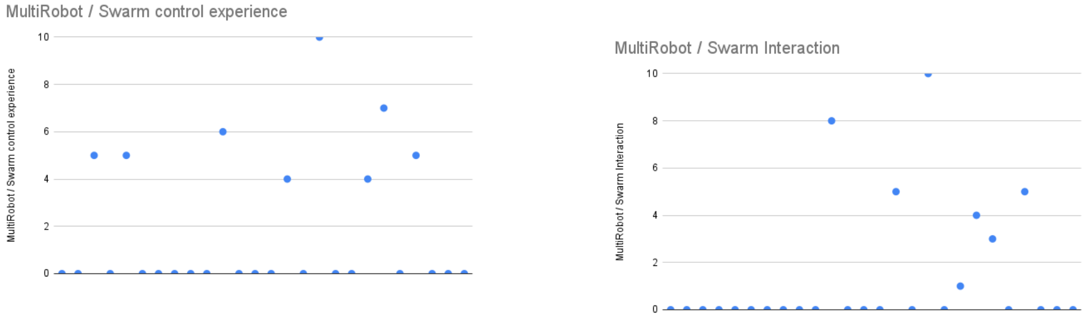


(a) Computer Usage.



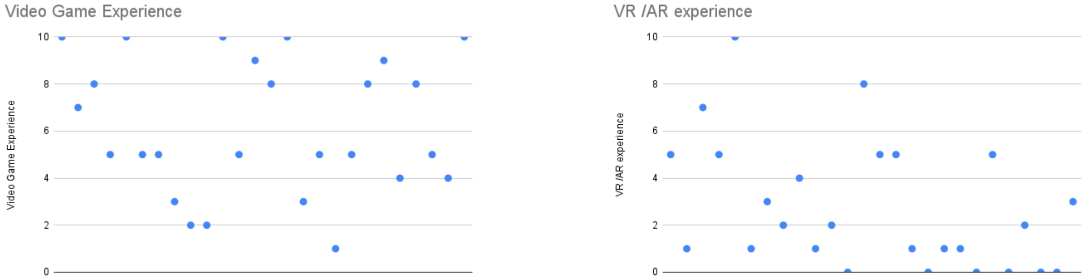
(b) Robot Control Experience.

(c) Robot Interaction.



(d) Multi-Robot/Swarm Control Experience.

(e) Multi-Robot/Swarm Interaction.



(f) Video Game Experience.

(g) VR/AR Experience.

Figure 4.5: Scatter plots showing distribution of participant familiarity and/or experience with different technology, based on self-reported scores from the pre-experiment survey.

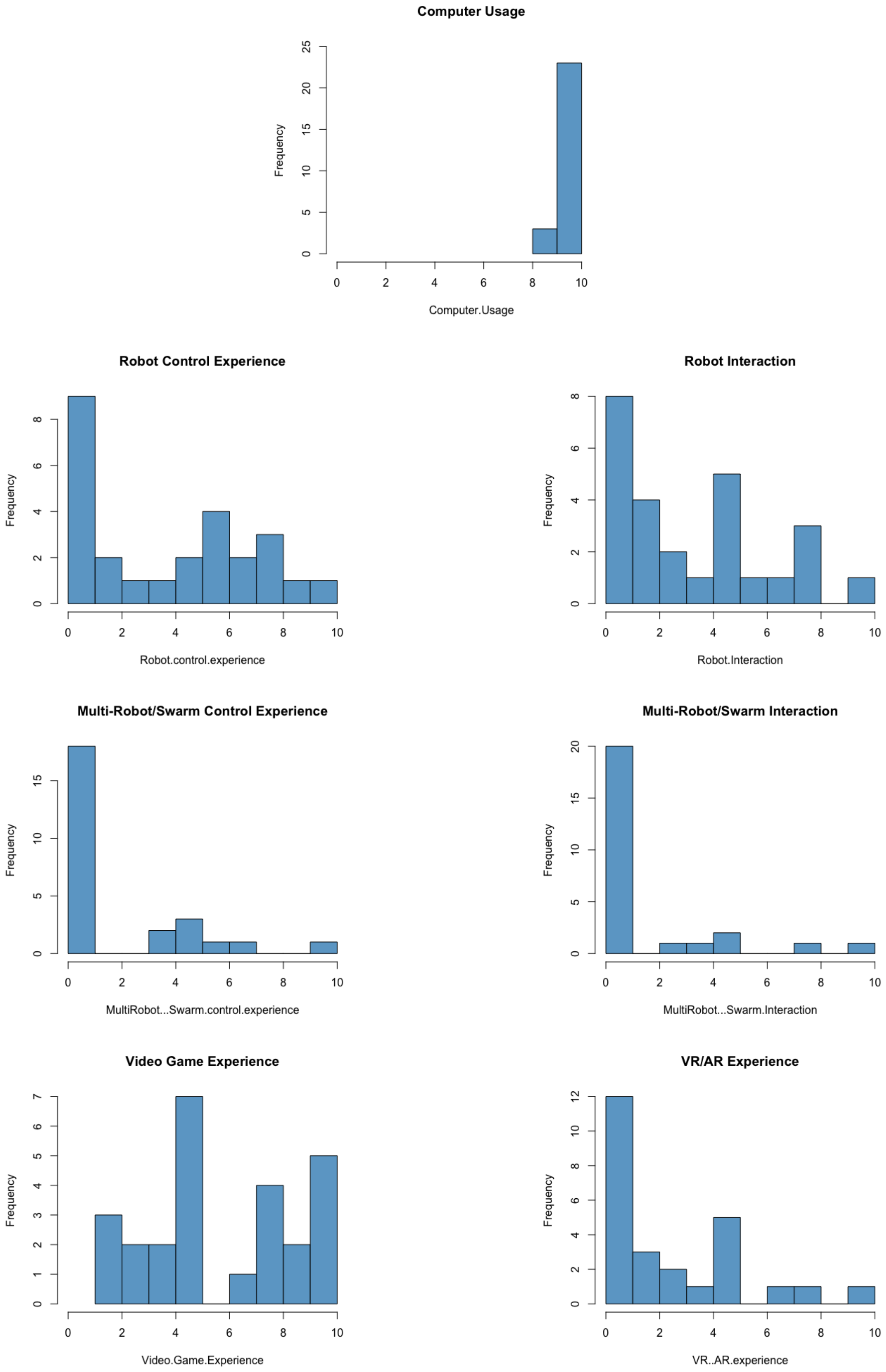


Figure 4.6: Histogram showing distribution of participant familiarity and/or experience with different technology, based on self-reported scores from the pre-experiment survey.

4.4.1.2 Post-Experiment Survey

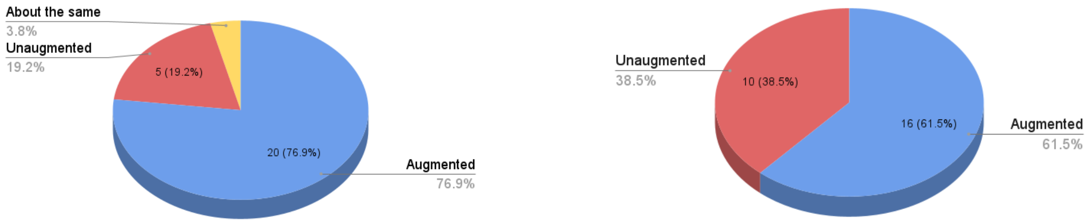
In the post-experiment survey participants stated their preferred interface, between the unaugmented and augmented interfaces, for each criterion. The criteria were workspace awareness, robot awareness, ease of use, system response accuracy, and overall preference. Table 4.1 shows the number of participants that voted for each interface, as well as the average overall score for the augmented and unaugmented interfaces.

Q.No.	Question	Augmented	Unaugmented	About the same
1.	Workspace Awareness	20	5	1
2.	Robot Awareness	16	10	0
3.	Ease of Use	19	3	4
4.	Response accuracy	19	3	4
5.	Overall Preference	22	4	0
6.	Overall Average Rating	8.3846	6.2692	-

Table 4.1: Summary of Post-Experiment Survey Responses.

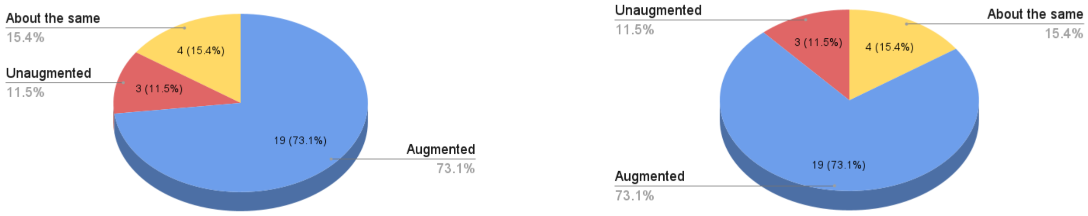
The set of pie charts in Figure 4.7 show the distribution of participant interface preference for each one of these criteria. In each of the pie charts the blue slices indicate preference for the augmented interface, the red slices indicate preference for the unaugmented interface, and the yellow slices indicate no preference.

As can be seen from the pie charts the augmented interface performed better than the unaugmented interface in all of the criteria. Apart from the robot awareness question, where only 61.5 % of participants preferred the augmented interface, under all other criteria over 70 %of the participants favored the augmented interface. In the overall preference criteria, about 85 % of the participants stated that the augmented interface was their interface of choice.



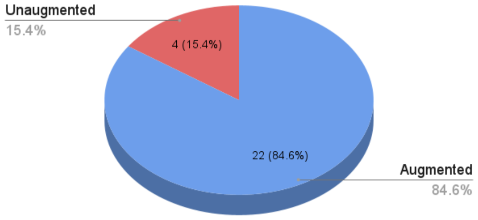
(a) Workspace Awareness.

(b) Robot Control Experience.



(c) Ease of Use.

(d) System Responsiveness.



(e) Overall Preference.

Figure 4.7: Pie charts showing distribution of participant preference between the augmented and unaugmented interfaces for each criterion based on the post-experiment survey.

4.4.2 Quantitative Results Summary

In this section we summarize the quantitative results obtained from the study. The quantitative data were obtained by recording task completion time, swarm trajectory, collision count, and other related data from MATLAB for each participant's solution to the task, for each interface. The data was then run through paired t-tests to determine whether there was any variation in participant performance, based on the interface. The process was also repeated for data that was stratified based on previous experience, particularly robot control experience and video game experience, to determine whether these factors had any effect on the results. The criteria used for stratification are shown in Table 4.2. These numbers were arrived at based on median values, as well as the distribution of data observed from the histograms in Figure 4.6.

Measure	Familiarity Criteria
Video Game Experience	≥ 6
Robot Control Experience	≥ 5

Table 4.2: Table showing familiarity criteria for video game and robot control experiences, used to stratify data.

4.4.2.1 Task Completion Time

Task completion time is defined as the total time the participant took to complete the mission, that is, to drive the swarm to both goal locations successfully. The task completion time was recorded for each interface separately. A paired or correlated sample t-test was performed to determine the relationship between task completion time using the augmented interface and that using the unaugmented interface, for each participant. Using an alpha level of 0.05, this test resulted in t = -1.1875 and p-value = 0.1231 (one-tailed), as shown in Table 4.3. The p-value being greater than 0.5 suggests that the test was inconclusive. The data was also stratified based on previous experience with robot control and video games, to see if each of these factors had any effect on the performance variations between interfaces. While the results remained inconclusive for those without robot control experience, for those with self-reported robot control experience ≥ 5, there was a statistically significant improvement in task completion time when using the augmented interface (t = -2.3282, p-value = 0.0191). On the other hand, no conclusions could be made on whether video game experience had any effect on performance variations between interfaces. These results are summarized in Table 4.4.

4.4.2.2 Normalized Path Error

We define normalized path error as the root mean square error of the path through which the participant drives the swarm and the shortest possible path to each goal. The normalized path error was recorded for each interface separately. A paired or correlated sample t-test was performed to determine the relationship between normalized path error using the augmented interface and that using the unaugmented interface, for each participant. Using an alpha level of 0.05, this test resulted in t = 0.33789, p-value = 0.6309 (one-tailed), as shown in Table 4.3. The p-value being greater than 0.5 suggests that the test was inconclusive. The data was also stratified based on previous experience with robot control and video games, to see if each of these factors had any effect on the performance variations between interfaces. No conclusions could be made on whether these factors had any effect on performance variations between interfaces. These results are summarized in Table 4.4.

4.4.2.3 Safety Barrier Violations

Another metric we used was the total number of times the safety barrier was exceeded, i.e., the domain boundary of the swarm overlaps with the boundary of an obstacle. This value was also recorded separately for each interface for each participant. A paired or correlated sample t-test was performed to determine the relationship between the number of safety barrier violations using the augmented interface and that using the unaugmented interface, for each participant. Using an alpha level of 0.05, this test was found to be statistically significant, with t = -2.6343, p-value < 0.01 (one-tailed), as shown in Table 4.3. This suggests that the participants violated the safety barrier significantly lesser using the augmented interface than the unaugmented interface. The 95 % confidence interval was between $-\infty$ and -6.1392. The data was also stratified based on previous experience with robot control and video games, to see if each of these factors had any effect on the performance variations between interfaces. While the results were inconclusive for those without robot control experience, for those with self-reported robot control experience ≥ 5, there was a statistically significant improvement in task completion time when using the augmented interface (t = -3.0183, p-value = 0.0053). On the other hand, no conclusions could be made on whether video game experience had any effect on performance variations between interfaces. These results are summarized in Table 4.4.

Measure	t	p
Time	-1.1875	0.1231
RMS Path Error	0.33789	0.6309
Safety Barrier Violations	-2.6343	0.0071*

Table 4.3: Table showing results of the paired t-tests for unstratified data. Statistically significant results (for alpha = 0.05) are indicated with an asterisk (*).

Measure	Criteria	Unfamiliar		Familiar	
		t	p	t	p
Time	Video Game Experience	-0.0972	0.462	-1.344	0.1029
	Robot Control Experience	1.7032	0.9429	-2.3282	0.0191*
RMS Path Error	Video Game Experience	0.4464	0.6687	-0.0242	0.4905
	Robot Control Experience	-0.3200	0.3772	0.7679	0.7713
Safety Barrier Violations	Video Game Experience	-2.0315	0.0316	-1.6154	0.0673
	Robot Control Experience	-0.5954	0.2813	-3.0183	0.0053*

Table 4.4: Table showing the results of the paired t-tests for the stratified data. Statistically significant results (for alpha = 0.05) are indicated with an asterisk (*).

Chapter 5

CONCLUSION

The primary objective of this thesis was to evaluate the effectiveness of augmented reality for improving remote human swarm interaction. This was accomplished in two parts. First, a simple user interface was developed that would allow human users to perceive and control a team of robots remotely. This interface was then used to run remote human user studies, in which the participants would perform navigation tasks, directing the team of robots to a sequence of goals in a cluttered environment. The participants performed these tasks using two different versions of the interface - a basic unaugmented interface that only shows the robots and their environment, and an augmented interface that provided more information such as robot swarm boundary, shortest path to goal, current heading, and indications of safety barrier violations when they occur. Quantitative data such as total task completion time, root mean square error between the participant's path and the shortest path to the goal, and total number of safety violations were also collected for each of the interfaces, to provide insights into participant performance variation with interface. Surveys were also used to gain an understanding of the participant experience with technology related to that used in the study and participant preference between the two interfaces.

Based on the results of the qualitative segment of this study, we were able to conclude that most participants preferred the augmented reality interface over the unaugmented interface. Overall, from a user experience perspective, more participants reported greater ease of use, better awareness of workspace, and more accurate system responses to inputs in the augmented interface over the unaugmented interface.

From a performance metrics point of view, the task completion time reduced significantly for those with robot control experience, when using the augmented interface. There was also statistically significant reduction in the number of safety barrier violations when using the augmented interface, as compared to when using the unaugmented interface. On the other hand, the tests were inconclusive for variations between interfaces for rms path error. The stratified tests were also inconclusive for video game experience, and for those participants without robot control experience, for all three measures.

Thus, to conclude, augmented reality can aid user experience by providing better awareness of workspace and greater ease of use. It can also facilitate improvement in some aspects of performance, in this case safety. It can also aid with reduction in task completion time, for those with robot control experience. However, it is unclear whether augmented reality may aid other aspects of performance, such as rms path error.

Appendix A

IRB Consent Form

This appendix shows the IRB approved consent form, used for the purpose of the human participant experiment, with identifying information removed. The form details the procedures, risks, benefits, confidentiality information, and right to withdraw.

Initials: _______ Date: _______

Institutional Review Board
1204 Marie Mount Hall ● 7814 Regents Drive ● College Park, MD 20742 ● 301-405-4212 ● irb@umd.edu

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CONSENT TO PARTICIPATE

Project Title	*Evaluation of VR/AR for Human Swarm Interaction*
Purpose of the Study	*This research is being conducted by **Dr. Yancy Diaz-Mercado** at the University of Maryland, College Park. We are inviting you to participate in this research project because you are an adult with no known vision impairments. The purpose of this research project is to understand the effectiveness of Virtual and Augmented Reality (VR/AR) as a suitable interface to facilitate human robot swarm interactions.*
Procedures	*The procedures involve you interacting remotely with a robot swarm to perform a series of control tasks through an interface. The experiment will be conducted via video calling and is expected to take no more than 90 minutes. The interface will be screen recorded however your video footage will not be collected. You will also answer surveys regarding your previous experience with similar technology and your experience using the interface before and after the task, respectively.*
Potential Risks and Discomforts	*There may be some risks from participating in this research study. Risks associated with participation are not expected to exceed those associated with participating in everyday video calling and computer usage. You may take breaks as necessary to mitigate fatigue.*
Potential Benefits	*There are no direct benefits from participating in this research. However, possible benefits include identifying factors to be considered while developing a VR/AR interface for human swarm interaction. We hope that, in the future, other people might benefit from this study through improved understanding of the effectiveness of VR/AR as an interface for human swarm interaction and the human factors to be considered.*
Confidentiality	*Any potential loss of confidentiality will be minimized by storing data encrypted in Box. Data will be labelled using serial numbers for participants. Only the principal investigator and graduate research associates directly involved with the research will have access to the forms and documents collected. All individual data will be destroyed after a period of 5 years.* *If we write a report or article about this research project, your identity will be protected to the maximum extent possible. Your information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.*
Compensation	*You will receive an Amazon gift card worth $20 after completion of the testing session. You will be responsible for any taxes assessed*

	on the compensation. *Your name and address may be collected to receive compensation.*	
Right to Withdraw and Questions	*Your participation in this research is completely voluntary. You may choose not to take part at all. If you decide to participate in this research, you may stop participating at any time. If you decide not to participate in this study or if you stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify.* *If you are an employee or a student at the University of Maryland, your academic standing as a student or employability will not be affected by your participation or non-participation in this study.* *If you decide to stop taking part in the study, if you have questions, concerns, or complaints, or if you need to report an injury related to the research, please contact the investigator:* **REDACTED**	
Participant Rights	*If you have questions about your rights as a research participant or wish to report a research-related injury, please contact:* **REDACTED** *For more information regarding participant rights, please visit:* https://research.umd.edu/irb-research-participants *This research has been reviewed according to the University of Maryland, College Park IRB procedures for research involving human subjects.*	
Statement of Consent	*Your signature indicates that you are at least 18 years of age; you have read this consent form or have had it read to you; your questions have been answered to your satisfaction and you voluntarily agree to participate in this research study. You will receive a copy of this signed consent form.* *If you agree to participate, please sign your name below.*	
Signature and Date	**NAME OF PARTICIPANT** **[Please Print]**	

	SIGNATURE OF PARTICIPANT	
	DATE	

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