AIAA SciTech Forum
23-27 January 2023, National Harbor, MD & Online
AIAA SCITECH 2023 Forum

10.2514/6.2023-0156

Robot Guided Emergency Evacuation from a Simulated Space Station

Brett P. Sheeran[1], Alan R. Wagner[2], Colin Holbrook[3], Daniel Holman[4]
[1] *Pennsylvania State University, State College, PA, 16802, United States*
[2] *University of California, Merced, Merced, CA, 95343, United States*

Our research investigates the potential use of free-flying robots as guides during emergency evacuation in future space stations. Building from prior research investigating if and how people follow evacuation directions given by an autonomous robot, we now apply these ideas to managing evacuations from a space station. Our research uses an immersive virtual reality (VR) simulation of the International Space Station (ISS) to evaluate 1) if nonexpert human subjects will follow an evacuation guidance robot in the form of an Astrobee to an escape module and 2) how an Astrobee robot should communicate its guidance instructions to an evacuee onboard a space station. Objective and subjective data were collected during human subject testing in the virtual reality simulation. In spite of a small sample size (9 subjects), the results indicated that 100% of subjects followed the robot's guidance. Selfreports also show that the virtual reality environment was effective in creating a strong sense of presence and affecting the subject's emotional and psychological state. The Astrobee was reported as a competent guide. This research provides important and novel data related to how non-experts evacuate from a space station and how a free-flying robot such as an Astrobee can be of assistance during a space station evacuation.

I. Introduction

Our research seeks to develop robots capable of guiding people to exits during an emergency [1,4]. Evaluating the effectiveness of such systems, however, is difficult. We have recently developed a system that uses virtual reality to create immersive experiences. The research presented here uses a simulated model of the International Space Station (ISS) to investigate robot guided emergency evacuation of non-expert humans from a space station.

Recently researchers have focused on the development of caretaker robots, such as the Astrobee, capable of manning space stations for long periods of time [2, 3]. Eventually these caretaking robots will be expected to monitor, maintain, inspect, and repair spacecraft and space stations. We believe that, as part of the monitoring functionality, caretaker robots could also serve to guide space station inhabitants to escape modules during an emergency. Yet it is unclear how an Astrobee robot should communicate guidance directions and whether people will follow a robot during an emergency evacuation of a space station. Our research thus intends to examine how an Astrobee robot might be used to guide human subjects to escape modules. The system that we have developed to evaluate robot guided evacuation from offices and schools, was used to investigate robot guided emergency evacuation from a space station. Our work does not focus on well-trained astronauts, simply because we do not have access to these individuals as human subjects. Rather, our focus looks forward to a day when space stations are populated with lightly trained tourists. We hope that this work will one day inform spacecraft and space station evacuation procedures.

The paper is organized as follows: Section 2 discusses the experimental platform. Section 3 presents the robot guided evacuation from the space station. Section 4 presents the results from the experiments. Section 5 discusses results of the experiments and future work. Section 6 concludes the paper.

II. Experimental Platform

Our experimental platform uses virtual reality to immerse human subjects in a virtual environment. We use an HTC Vive Pro headset to immerse subjects in the virtual environment, two Valve Index controllers and Cybershoes (Figure 1) to allow the person to interact with the virtual environment. We use the Cybershoes to allow the human subject to move in the environment by making walking motions. The Cybershoes have a cylindrical wheel on the bottom of them that, when rotated, sends movement data which is interpreted as translational movement by the subject in virtual reality.

Figure 1. Cybershoes (left). Displaying how they are worn by the subject (right).

In collaboration with the University of California Merced, we have developed an experimental paradigm for investigating robot guided emergency evacuation in virtual reality. Our experimental paradigm first introduces the human subject to a physical guide robot prior to having them put on the virtual reality headset. Once they put on the headset, in order to maintain immersion, they find themselves in a virtual room that is an exact replica of the actual room they are sitting in. The virtual environment includes a replica of the guide robot (Figure 2). This collaborative work explores robot guided emergency evacuation from a university environment. This virtual environment is also populated with realistic Non-Player Characters (NPCs) that can move, talk, and perform simple tasks. The NPCs are used to create a type of social atmosphere in the simulation (Figure 3).

Figure 2. Real emergency guide robot (left) and virtual guide robot (right).

Figure 3. University environment populated with NPCs. The NPCs arms are out because the image was taken in developer mode. During the actual simulation runs, the NPCs take on predefined poses.

The human subject tours the environment and is led by the robot which speaks and provides information during the tour. The subject completes several surveys using a virtual tablet over the course of the experiment. During the tour an emergency occurs, either a fire or an active shooter incident, depending on the condition. The simulation environment includes data capture tools which record the person's movements, choice of whether to follow the robot or not and grip on the controllers. We are thus able to collect a significant amount of behavioral and physiological data over the course of an experiment.

III. Robot Guided Evacuation from a Space Station

For this paper we conduct a similar experiment to the experiment described in Section II. Human subjects were recruited using flyers on the Penn State campus. Institutional Review Board approval was obtained prior to the collection of data. Subjects were paid $15 for participating. A total of 9 human subjects participated in the experiment (66% male). The experimental procedure described below was designed to closely mimic our concurrent research focused on robot guided emergency evacuation in office environments. This design is meant to offer several situations in which the subject must decide whether to follow the robot.

Upon arrival at the experiment location, subjects were greeted by a graduate research assistant. The subject was read a briefing statement and asked to confirm that they agree to participate. Upon agreeing to participate a Lavalier microphone was clipped to the top of their shirt below their chin. The microphone was used to communicate with the physical robot. Next the research assistant explained that the Astrobee can speak to them. The research assistant then directs the subject to stand in the doorway and converse with the robot. The physical Astrobee explains that a simulated version of its body is being controlled by artificial intelligence software in the virtual reality simulation. The robot informs the subject that the simulated version of the robot will be guiding them on a tour of the International Space Station. The robot then asks the subject if this makes sense. The subject can respond with 'yes' or 'no' or variations such as 'yeah' or 'nah'. The robot then explains that the research assistant will help them get seated in the virtual reality chair and directs the subject to the virtual reality chair. The research assistant then helps them get the VR equipment on.

In this case, the human subject interacts with a replica of an Astrobee robot (Figures 4 and 5).

Figure 4. The Astrobee free flying robot onboard the ISS.

Figure 5. Astrobee VR Model (left) and Physical Model (right)

The robot guided emergency evacuation experiment consists of a pre-VR portion, a VR portion, and a post-VR portion. The pre-VR portion consists of the physical model of the Astrobee robot being introduced to the participant and the participant getting accustomed to its voice and movements. The VR portion consists of the VR simulation of the ISS, and the post-VR portion is the subject filling out a post-experiment survey. The experimental steps were implemented in a manner that was informed by our prior research focused on terrestrial robot guided emergency evacuation in a VR simulation. An existing model of the ISS existed in the Unity Asset Store, and the environment development skills had been honed to create an ISS evacuation simulation.

The VR simulation progresses as a series of simulation environments or scenes. The VR scene progression is depicted in Figure 6.

Figure 6. Space Station Scene Progression

The first scene is an office scene that is an exact replica of the physical office that the subject is in (Figure 7). Now in simulation, the Astrobee robot introduces itself to the subject. For the VR portion of the experiment the robot speaks to the human subject but is not capable of responding to communication from the subject. The subject is told to move around the office environment in order to get used to the VR equipment. The participant moves about the Office scene and is guided by the flying Astrobee to an adjacent office where an elevator is located (Figure 8).

Figure 7. Simulated Office (left) and Real Office (right)

Figure 8. Simulated Elevator in Office Scene

The Astrobee then directs the subject to press the elevator button to open the doors. The participant steps into the elevator and the scene fades to gray as the simulation transitions to the Space Station scene. Once the participant transitions into the ISS, the Astrobee greets them in the U.S. Lab module (Figure 9). The U.S. Lab module is labeled as point 1 in the tour layout (Figure 10).

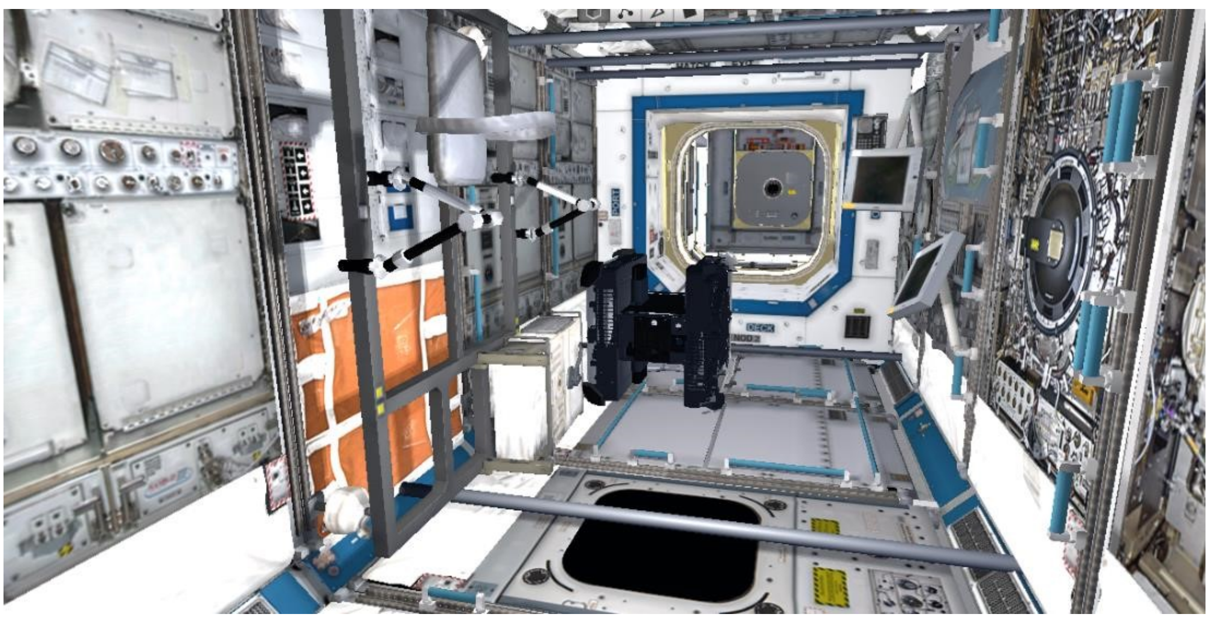

Figure 9. Astrobee VR Model in ISS U.S. Lab

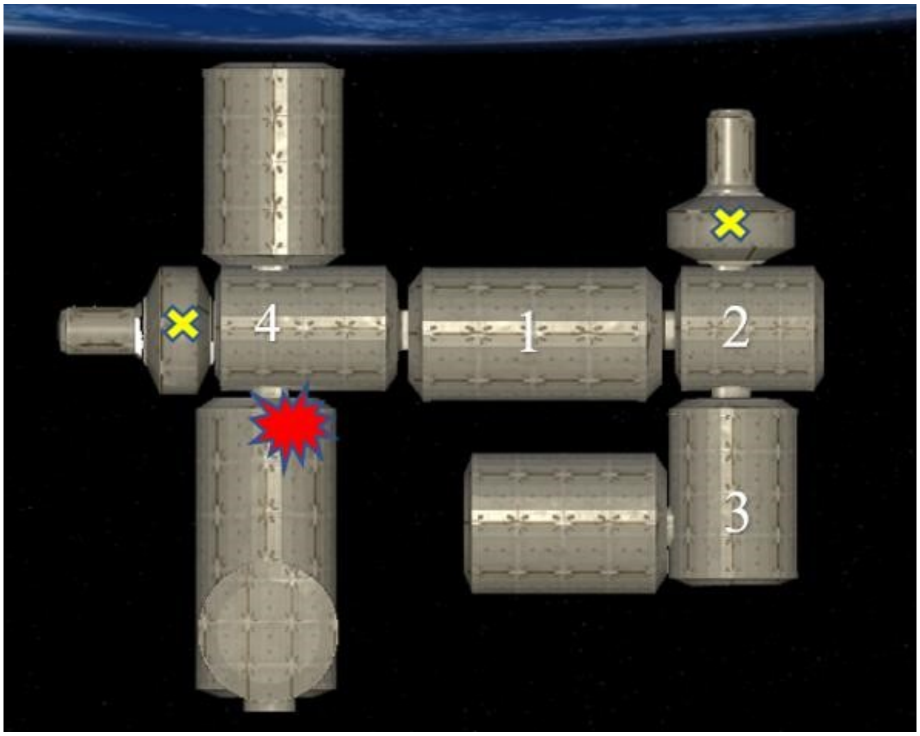

Figure 10. ISS Birds-Eye View and Tour Layout

Points 1 through 4 indicate the waypoints that the Astrobee navigates to along the tour. The tour progresses from point 1 to point 2, point 2 to point 3, then point 3 back to point 2, point 2 to point 1, and then finally from point 1 to point 4. The yellow X's are the locations of the emergency exits (airlocks). The red bang is where the fire begins after the subject completes the tablet survey. As mentioned, the subject spawns at point 1. The Astrobee greets the subject and tells them that they will be given a tour of the International Space Station but will first be given some time to get used to moving around in micro-gravity. The human subject movement is controlled by a C# script that is based off Unity's built-in physics engine. The subject must grab objects and push and pull off objects in order to move in the micro-gravity environment of the ISS. After 60 seconds of practicing how to move in the space environment, the Astrobee tells the human subject that they will tour the Bigelow Expandable Activity Module (point 3) and describes it to the subject. Astrobee guides the human subject through the U.S Lab towards point 2, but once the robot reaches point 2 it turns left instead of right. Now, the robot is in the airlock but recognizes its mistake. The Astrobee informs the subject that it has mistakenly navigated to the airlock, then guides the participant back to point 2, to head for the Bigelow Expandable Activity Module (BEAM). At point 2, Astrobee informs the subject that it has located the BEAM module then moves toward it (point 3). The Astrobee directs the subject to interact with floating objects and to look at the earth observatory, depicted in Figure 11.

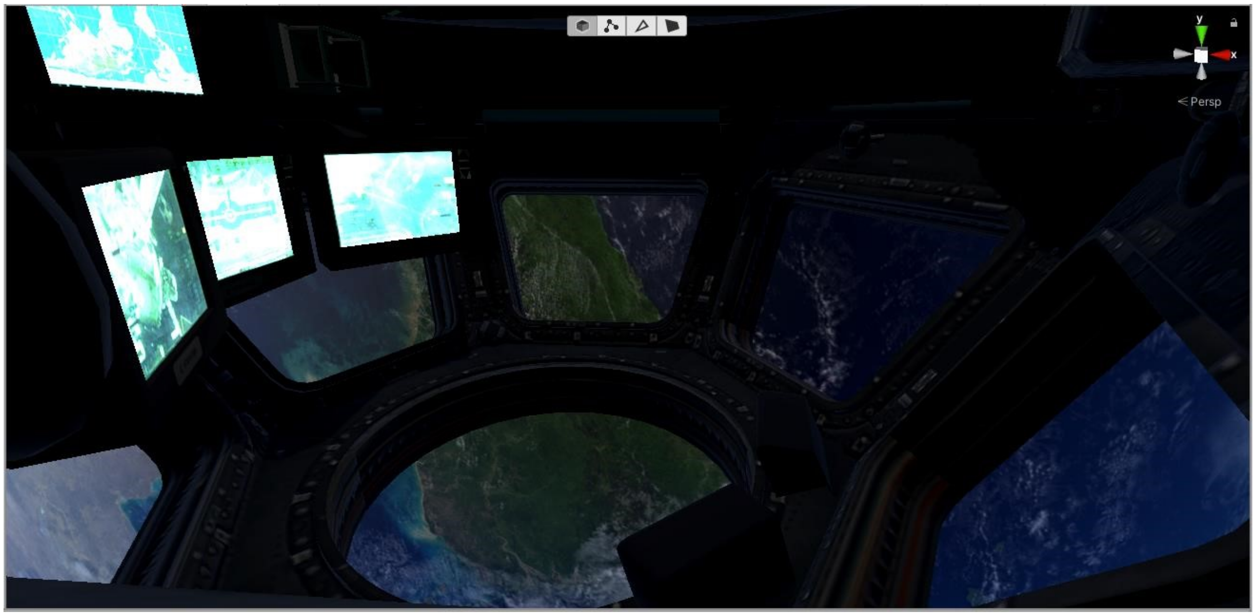

Figure 11. Earth Observatory Aboard the VR ISS

After 70 seconds, the Astrobee directs the human subject to follow it back towards the U.S. Lab by going back the way they came. While at point 2, the Astrobee tells the human that they will go back to the U.S. lab where they will fill out a survey about the experience thus far. But, first Astrobee points out the airlock and explains that the airlock is the safest place to be in the event of an emergency. Here the Astrobee is referring to the airlock nearest to point 2. The Astrobee then guides the subject back to the U.S. lab (point 1). When they arrive back at point 1, the Astrobee directs the subject to fill out the tablet on their thoughts of the environment. The subject fills out the tablet and once the survey information is submitted the Astrobee starts moving towards point 4 when a fire occurs. The Astrobee explains that there is a fire and the lights aboard the ISS go out and the emergency egress lights are activated. The emergency egress system aboard the simulated space station was modelled after the emergency egress system aboard the real ISS [5]. The Astrobee directs the subject to close the port hatch using the tablet and to follow it to the airlock (nearest point 4) to safety. The emergency egress system and hatch tablet are depicted in Figures 12 and 13.

Figure 12. Emergency Egress System in VR U.S. Lab

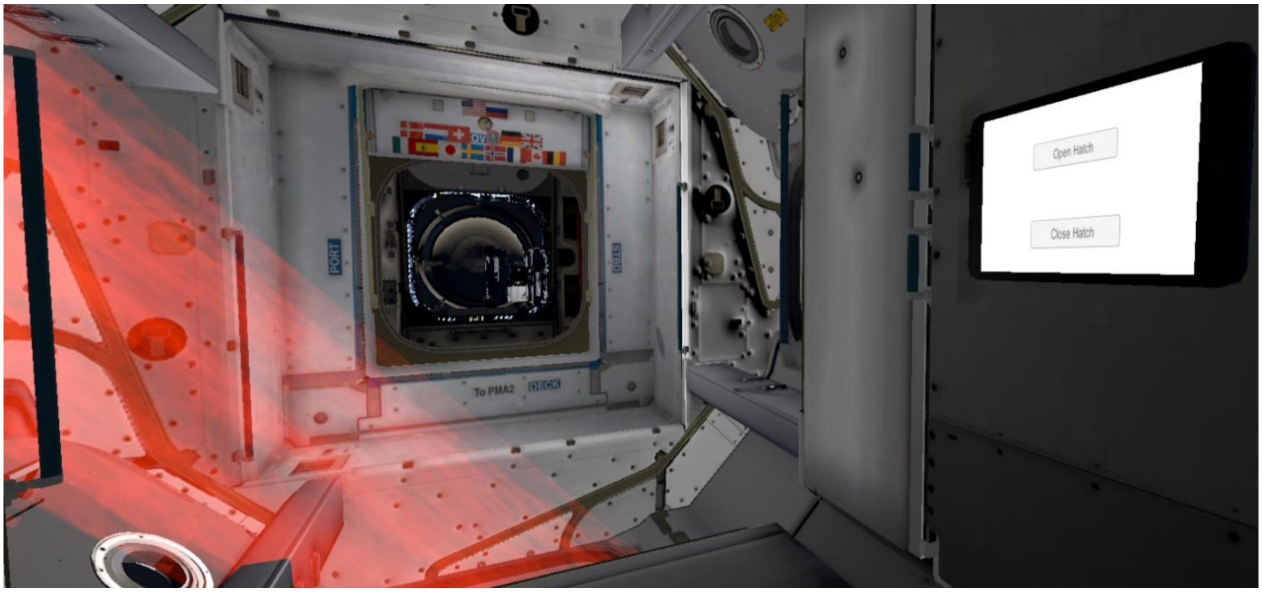

Figure 13. Hatch Tablet with Fire and Astrobee

The subject is faced with a decision. They can follow the egress system to the known exit or follow the Astrobee to the airlock through the fire. A physical heater in the office near to the human subject was triggered in order to enhance the realism of the experiment by heating the experimental space. Upon arrival at either of the airlocks the human subject is transitioned back to the elevator to the office where they fill out a final survey. The Astrobee then guides the subject back to the red chair where they are directed to wait for the human subject to help them takeoff the VR equipment. The subject is debriefed and the experiment ends.

IV. Results

Self-reported measures were collected by using a simulated tablet inside the simulation environment. Data was collected twice within the space station. Self-reported data for the ISS experiment was collected prior to the fire emergency (in the main corridor of the ISS), and directly after the fire emergency (in the elevator transitioning out of the ISS). The same survey questions were answered. The tablet questions are shown in Table 1 of the Appendix. The questions capture the subject's affective state, feeling of presence, and their appraisal of the robot. Each question uses the same 7-point Likert scale. In addition to the in-situ measures, a post-VR survey was conducted in which subjects responded to questions via a laptop. Notes were taken during the experiments, and feedback was recorded. Objective measures, such as whether the person followed the robot were also recorded.

In our experiments, all 9 subjects followed the robot's emergency evacuation guidance. This confirms our hypothesis and prior work showing that human subjects will tend to follow the guidance directions of a robot during the space station evacuation. Data from several surveys collected during the experiment are presented below. Because these experiments were exploratory and only included nine subjects, statistical hypothesis testing was not conducted. Rather, we present the descriptive statistics from the surveys. These statistics will be the basis for hypotheses for future experiments.

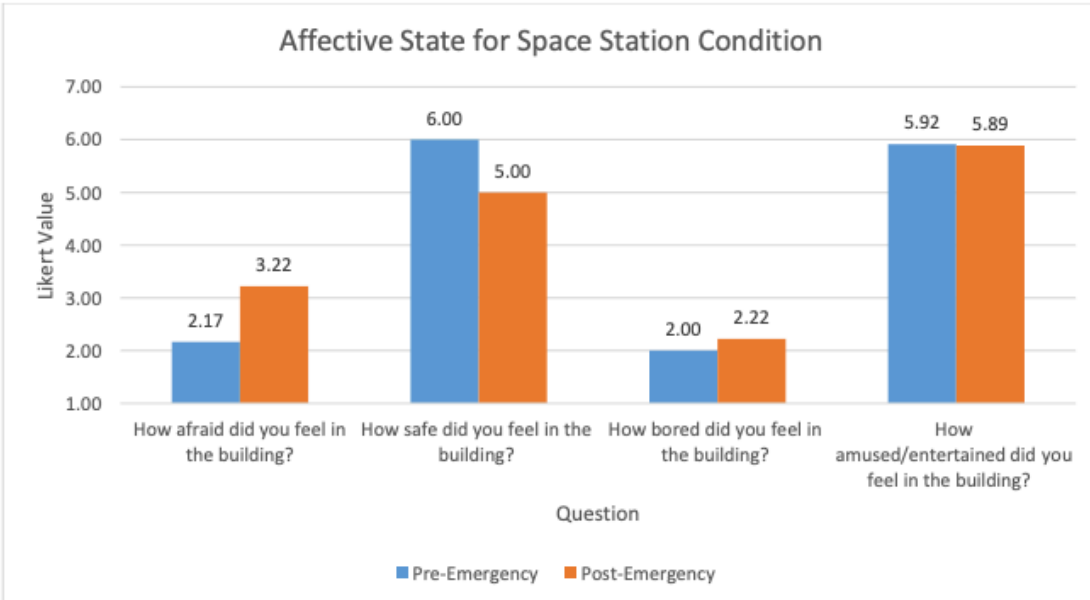

Figure 14. Human Subject Affective State before and after Space Station fire

The affective state measures show that self-reported fear increased by 48% after the space station fire. These values are low on the Likert scale, i.e., below the 'somewhat' value of 4. However, the increase was substantial which indicates that the fire emergency did heighten the subject's fear. There was a decrease in the self-reported feeling of safety, which is consistent with the increase in fear. There was a 16% drop in self-reported safety after the space station fire. These results suggest that the virtual reality fire does increase self-reported fear and reduce self-reported safety.

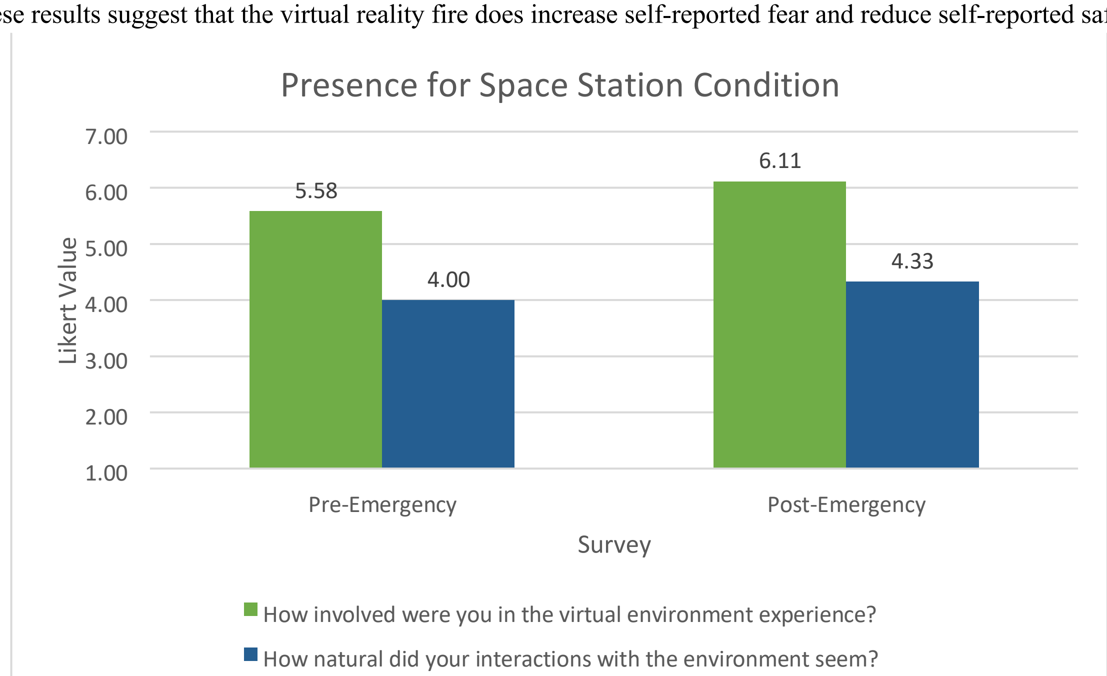

Figure 15. Human Subject Self-Reported Presence before and after Space Station fire

The self-reported level of involvement was high and increased after the fire. This data suggests that the fire heightened the subject's level of involvement. The self-reported naturalness of interactions in the environment remained above the "somewhat" level throughout the experiment.

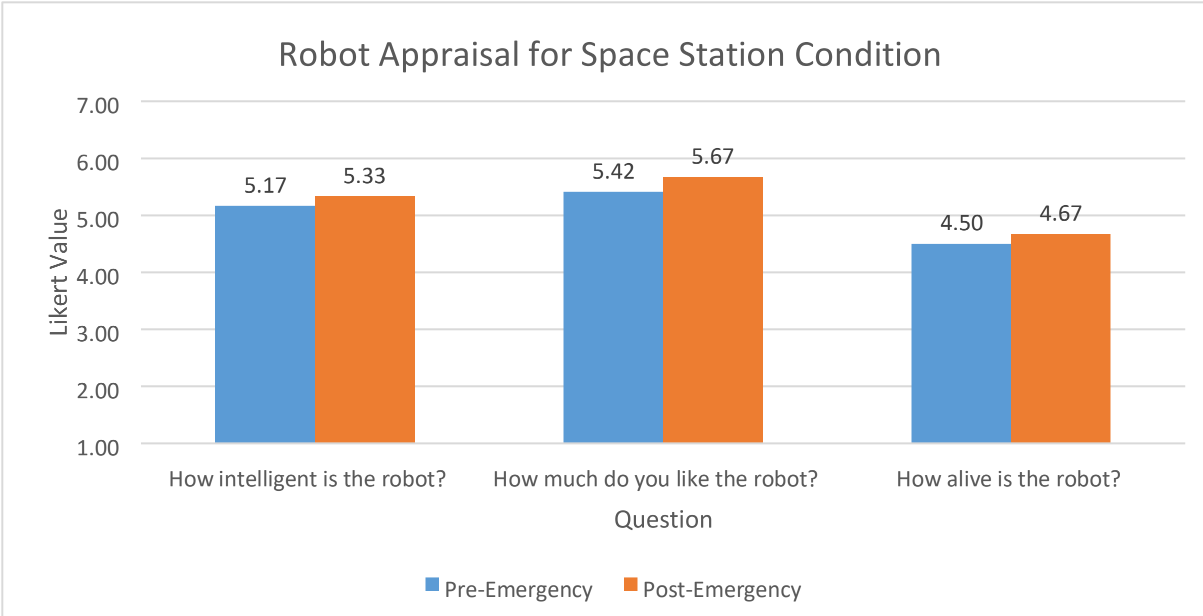

Figure 16. Human Subject Robot Appraisal before and after Space Station fire

The subjects rated the robot as intelligent and likable both before and after the emergency. They rated the robot as "somewhat" alive before and after the emergency.

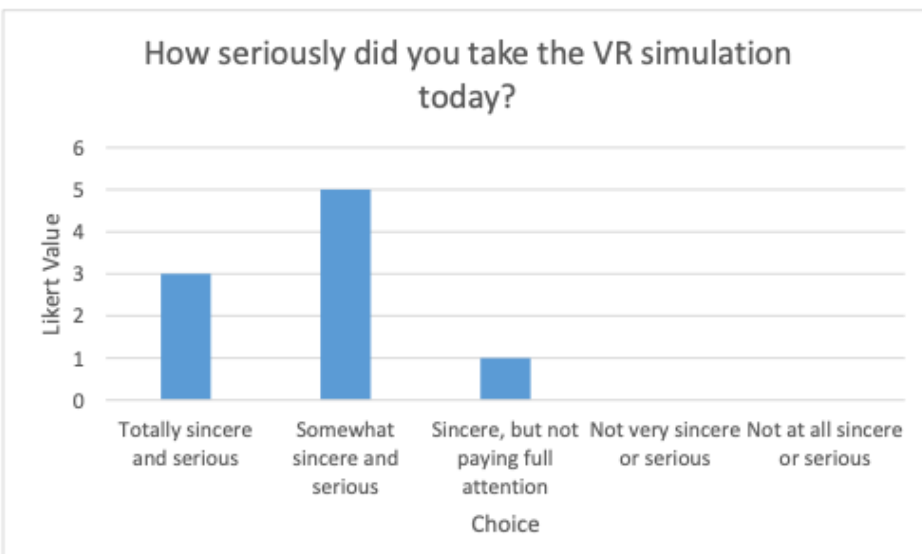

Figure 17**. Post-VR Self-Report of How Serious the Subject Took the Simulation**

Post-VR surveys asked subjects how seriously they took the VR simulation. The average subject stated that they took the simulation somewhat sincere and seriously.

V.Discussion and Future Work

The primary purpose of this work is to explore the feasibility of using VR to investigate human-robot interaction in difficult to test environments such as space. This exploratory study highlights the promise and limitations of this approach. Our work shows that subjects are engaged and immersed in the simulation, in spite of the obvious fact that the person is not in a zero g environment. Because access to real space robots, such as the Astrobee, in a space station is extremely limited, investigating robot guided emergency evacuation can only realistically be achieved in simulation.

Nevertheless, this exploratory study has shed light on some aspects of the environment that could be improved. For example, subject's reported confusion when Astrobee directed them to close the hatch to seal off the fire. The tablet to close the hatch was in front of them in the direction of the airlock. The fire was to their left, but the hatch was behind them. Six subjects reported not seeing or knowing where the hatch was that they were closing. In the future, the tablet should be positioned such that it can be seen when closing the hatch.

All subjects experienced some difficulty moving in the environment. We therefore gave subjects sixty seconds at the start of the Space Station scene to practice moving in the simulated space station. One subject resorted to pushing off of objects because "it felt easier" than grabbing handles.

Five out of nine subjects reported that they wanted to interact with the robot quite a bit. To increase the realism, it is suggested that the subjects be able to interact with Astrobee in the simulation. When a subject would touch Astrobee they were not able to move it. We believe that including realistic physics for interacting with Astrobee would increase the realism of the simulation, i.e., being able to push and touch the Astrobee.

VI. Conclusion

We recognize that virtual environments cannot be perfectly matched to conditions aboard an actual space station. Our overarching goal was to 1) evaluate whether people can become immersed enough in the simulated environment to react in a similar manner to an actual emergency; 2) evaluate methods of communication that a free-flying robot could use to guide people during an emergency; and 3) explore new methods for training and preparing non-experts for space flight. We believe that our research provides important initial data related to how people might evacuate from a space station. We believe that this work can be used as a baseline for conducting simulated robot led evacuations and feel that our work can inform those interested in developing robots that help save lives both on Earth and in space.

Appendix

Table 1. VR Survey Questions (Answered on Simulated Tablet)

Q1: How much did you like the building?	Q6: How involved were you in the virtual environment experience?
Q2: How afraid did you feel in the building?	Q7: How natural did your interactions with the environment seem?
Q3: How safe did you feel in the building?	Q8: How intelligent is the robot?
Q4: How bored did you feel in the building?	Q9: How much do you like the robot?
Q5: How amused/entertained did you feel in the building?	Q10: How alive is the robot?

Acknowledgments

This material is based upon work supported by the National Science Foundation under Grant Number IIS-2045146. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

[1] Robinette, P., Li, W., Allen, R., Howard, A. M., & Wagner, A. R. (2016). Overtrust of robots in emergency evacuation scenarios. 2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI). https://doi.org/10.1109/hri.2016.7451740.

[2] Bualat, M., Barlow, J., Fong, T., Provencher, C., & Smith, T. (2015). Astrobee: Developing a free-flying robot for the international space station. In AIAA SPACE 2015 Conference and Exposition (p. 4643).

[3] Bualat, M. G., Smith, T., Smith, E. E., Fong, T., & Wheeler, D. W. (2018). Astrobee: A new tool for ISS operations. In 2018 SpaceOps Conference (p. 2517).

[4] Robinette, P., Howard, A. M., & Wagner, A. R. (2017). Effect of robot performance on human–robot trust in time-critical situations. IEEE Transactions on Human-Machine Systems, 47(4), 425-436.

[5] Maida, J. (2014). The use of photo-luminescence as an emergency egress guidance system on ISS. NASA.gov. Retrieved October 20, 2022, from https://ntrs.nasa.gov/api/citations/20140013117/downloads/20140013117.pdf