Building a Motion-Aware, Networked Do-It-Yourself Holographic Display

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***Abstract*—The COVID-19 pandemic has motivated a shift from physical interaction, approaches, or procedures due to social distancing. More people are at home using digital displays for real-time communication and engagement. With recent innovations in computational hardware for spatial applications, such as extended reality technologies, entry barriers for hosting intimate, interpersonal, virtual events continue to fall. The barrier falls at such a rate that the production or manufacturing of an extended reality system for different and simultaneous, practical scenarios may be built to solve communication issues resulting from COVID-19. This paper aims to describe a low-cost networked holographic system that can be used for various purposes such as communication, education, and gaming. We created three different applications to show the cross-compatibility, effectiveness, and usability of our system.**

***Keywords*-AR/VR, Human Centered, Remoted/Networked Application**

I. Introduction

The COVID-19 Pandemic has altered our society to stay cautious while engaging in physical events and social environments. Orders for social distancing have prompted businesses or schools to close and have dramatically shifted norms. Thus, there is a clear need to invent practical and technical solutions that may solve problems resulting from COVID-19. In this work, we research how extended reality technology can be used as an effective counter to the communication issues resulting from the pandemic. Technology from virtual and augmented reality devices may be able to create immersive environments or house robust, high-fidelity events and entertainment. One of the most compelling reasons to investigate extended reality technology may stem from the ability to manufacture alternative and engaging communication methods.

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Due to the limitations of current virtual and augmented reality hardware, only a fraction of users may enjoy their choice of entertainment, if at all join a virtual, immersive event. The hardships are further compounded when including the costs in modifying the popular types of extended reality devices. Changes may result in a decrease in affordability and accessibility of the experience overall. This work developed a low-cost networked holographic display that finds a balance between the immersive content and the conveniences brought from recent innovations in computational hardware.

Our goal is to develop a motion-aware experience such that users may translate locomotion to a virtual environment in an engaging way. One innovation we introduce in our system is a practical application of point-cloud technology for in-depth video capture. Current point-cloud technology uses a video feed to capture: real-time movements, light, and depth data. This system could be used to generate similar immersive experiences, such as from other extended reality technology via holography. Our system tracks real-world coordinates and transposes the data to a digital plane.

Alongside creating motion-aware experiences, another goal we aim to achieve is ensuring our system to be built cost-effectively with simple materials and existing hardware. Our system's networking capabilities are based on supporting the development of applications for housing cooperative experiences for users that build similar extended reality systems. Simultaneously, the simple approach may enable more users to access the content as a whole. It may be done via the production of similar, affordable prototypes, which may allow for virtual experiences to be created for a broader audience.

As our research aims to resolve the communication issues stemming from the pandemic, we will be developing three unique use cases for our holographic system: communication,

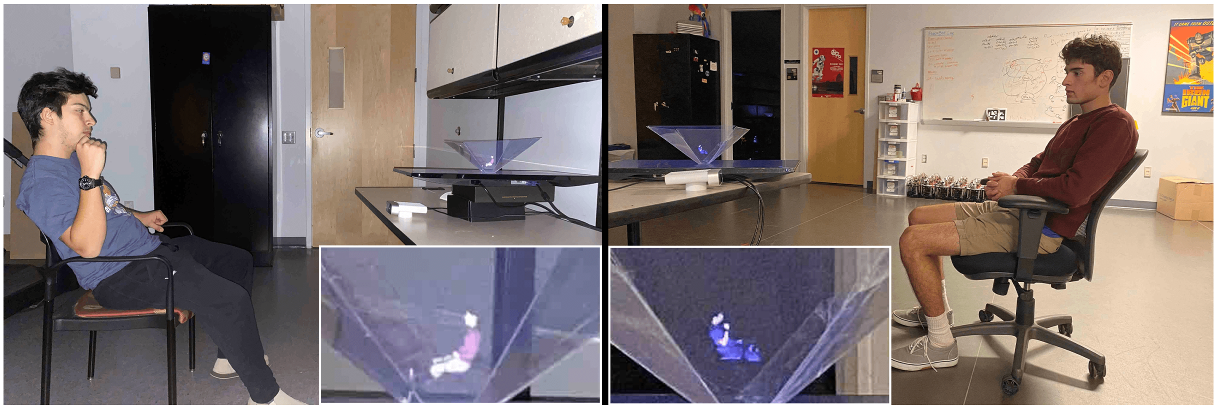


Figure 1. We presented a simple holographic setup capable of capturing 3d models of physical objects then transferring the data for the holographic view. The approach first creates a simple holographic display using the Pepper's ghost. Then we use Microsoft Azure Kinect to capture point cloud data of a 3d physical object. Finally, we project the captured 3d models to our holographic setup. This example shows two users holding a a holographic teleconference using their networked holographic setups.

education, and gaming. Each case will demonstrate how our holographic system may be employed for different applications or integrated into an enduring or post-pandemic society.

II. Related Work

A. Holographic Display

Holographic displays can pixelate color and depth for 3D models. Generally, stereoscopic displays appear as an affordable technique in holography. The display would only use a combination of color-interrailing images that, when polarized or examined through specialized lens [1], may generate a holographic effect. The effect may display a 3D image or object with some perceived depth. That said, a specialized stereoscopic hologram may contain visual conflicts that create discomfort for potential users [1] [2].

In the case of laser-based holographic displays, a hologram would be produced using a medium of ionized gas or a collection of particles to reflect a light source [3]. Techniques in laser holography for the reflective particles include suspending the medium in mid-air [4], rotated [5], condensed into high-viscous solutions like liquids [6], or arrayed [1], so when illuminated and refracted create a 3D avatar. That said, laser holography would require a medium with precise density and laser frequency [1] that would induce high production costs.

For our research, we needed a cost-effective holographic display that may be modified to enable a wide range of users to view the 3D effects. Luo et al. proposed an approach in displaying a 3D model in a holographic setup [7]. Pepper's ghost display takes light and projects an image onto glass panels [8]. Therefore, instead of glasses, lasers, or lenses needed for stereoscopic displays, the entire hologram may be built from just reflective surfaces. In Luo et al.'s work, the illusion needed: a plastic surface as the reflective material, a coin for stabilizing the reflective surface, and a light source displaying the content.

In short, Luo et al. demonstrated one method to efficiently show a 3D avatar in a thin hollow plastic cone, enabling more users to participate and view content. Our work will diverge from Luo et al.'s work to research applications for a motion-aware version of such a holographic display. By combining a system for interactivity with Pepper's ghost Display, we will incorporate more diverse use cases than a non-interactive display. Figure 1 shows the instruction for making Pepper's ghost Display.

B. Networked VR/AR Hardware

VR headsets and AR networked devices enable communication between people and engage in shareable content. Both VR and AR devices support user interaction by tracking the user's body, head, or hand movement [9]. The head-mount displays (HMDs) for both extended reality systems may come in a standalone headset, handheld device, or tethered model. Due to recent computational advancements, both kinds of devices may network with each other for cooperative experiences [10] [11].

However, due to the unbalanced weight of HMDs and limited hardware solutions for issues, such as discrepancies related to interpupillary distance, specific models of HMDs may cause users to experience discomfort, which may come in the form of experiencing nausea or eye-strain [12] [10].

For addressing the discomfort directly, our system will allow users to view the content without the need for an HMD or handheld unit by creating a stationary system, minimizing any discomfort that may result from the risk of dizziness and nausea. Such a problem can be minimized by building the holographic system's reflect surfaces explicitly placed to view the content.

In addition to resolving the issues mentioned above, we can design experiences that are found by using VR and AR hardware by using the depth camera. The depth camera captures the movement and position of our user. We can use the system to develop applications that enable people to interact in virtual spaces. Coupled with our system, we can build similar and alternative methods of interactivity that AR and VR systems may not be able to provide [13].

C. Remote Collaboration

We focus on remote augmented reality applications that create virtual spaces to bridge people together during the pandemic. Our applications need to be functional and practical, immersing users within a virtual environment. The ability to stay immersed in a virtual space may be defined through applications that give users a sense of presence (SoP). “Presence” may be defined as a response people have from human interaction [14]. Overall, presence is affected by VR/AR technology [15], [16]. Thus, while designing the holographic system’s applications, our team looked into how 3D avatars and images may be turned into novel communication forms with SoP in mind. We would like to explore current VR and AR Applications and build in a similar vein of use cases for our system.

VR and AR may be used as a tool for education purposes. The ability to retain information due to a user being more involved in a virtual environment [17] is attractive. So the ability to both engage and apply training in a safe environment leads to VR/AR technology efforts to be used for effectively communicating hypothetical scenarios or theoretical situations. Use cases include sports therapy and training, where the virtual instructor may be able to illustrate the effects of specific exercises and provide detailed instruction on how to execute training [18]. The extended reality was also used to express the necessity of dire or life-saving situations [19] as the technology. It is demonstrated to have led trainees to become competent and ready to perform [20]. Education also extended into comprehending the effect of ecosystems and respective conservation efforts/disaster prevention [21]. Thus, it is clear that the potential for more applications of networked VR/AR in education continues as the technology develops [22]. Furthermore, this field may be condensed as an appropriate application for our holographic system to demonstrate how holography may be utilized in society.

The second area of interest for our system is sharing and interacting with information in large groups. Certain extended reality apps have built a virtual desktop to efficiently collaborate or hold discussions [23] [24] and to communicate detail with precision and clarity. The spatial features of VR and AR technology were employed for use in medical study and the visualization of remote surgery [25]. Some cases combined the technology with assisting applications [26]. Thus, our system will feature an application that hosts both video and audio communication with enough clarity to serve as a viable solution for multi-user teleconferences in virtual space. Our application allows users to reference videos or interact with other users via a hologram for a shared experience.

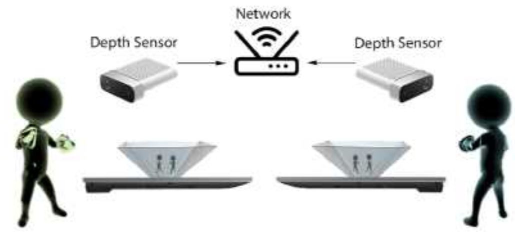


Figure 2. Overview of our system.

Finally, we would like to explore a remote application that may benefit users during this pandemic season. Games are a popular field of VR and AR applications. Applying external reality technology to the genre of gaming allows for a unique blend between entertainment [27], communication [28], and education [29]. Specific genres of games in extended reality applications, such as first-person perspective games, rely on an HMD or handheld camera to offer a uniquely immersive experience [16];. In contrast, other games may use location-based services and are designed for exploration, or physical activity [30]. Applications running on our device do not require an HMD or a location-based service. However, our device supports games that require the user to remain physically active akin to other VR and AR games.

III. Overview

As shown in Figure 2, we propose a way to stream the images over a network to holographic displays. In order to do this, we used the Microsoft Azure Kinect to capture point cloud data which is then displayed in the holographic set up. As the point cloud data received from the Kinect is very large with over a million points we applied different techniques to allow for real time streaming over the network. Data is initially captured from one client by the Microsoft Azure Kinect camera and converted to point cloud data. This information is then parsed and the RGB color, depth, and position data for the points is passed over the network. Photon Unity Networking 2 servers are used to transfer this data to the clients to allow this data to be displayed on other holographic displays. To showcase the techniques used, we developed three different applications to demonstrate the streaming of the point cloud data to be displayed in the hologram.

IV. System Design

A. Azure Kinect

To capture the point cloud data of physical objects, we used the Microsoft Azure Kinect in Figure 3. The Microsoft Azure Kinect has different resolutions for its color camera and depth camera operating modes.

Figure 3. Microsoft Azure Kinect.

The depth camera operating model supports a range of different resolutions from $320 \times$

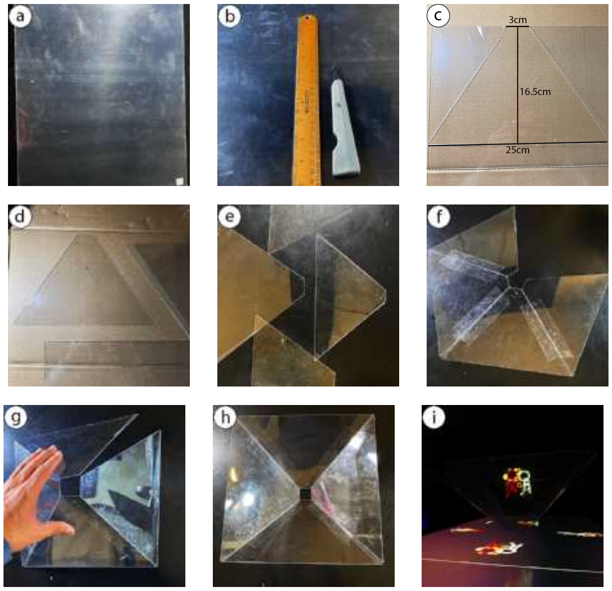


Figure 4. Steps to create the holographic display. (a) We first start off using a 16”x20” Plexiglass sheet. (b) An acrylic plastic cutter and ruler, as shown, will be used to measure the size of the pieces to be cut. (c) We take our ruler, and each piece is measured with a height of 16.5 cm, a base of 25 cm, and a top section of 3 cm. (d) These measurements are outlined on the Plexiglass, and the acrylic plastic cutter is used to score the outline of the shape applying a medium amount of pressure with the cutter. (e) We repeat this step three more times to be left with four plastic pieces of the same shape and size as the first. (f) The four pieces are taped side by side as shown. (g) They are then pushed together so that the edges meet each other. (h) The last side is tapped together to form the pyramid shape, as shown. (i) We now have a cheap and straightforward completed hologram setup that can now be placed on a monitor to visualize what we want, e.g., a networked boxing game, as shown.

288 to 1024×1024. There is a trade-off for using the higher resolution modes with a reduced FPS from a max of 30 FPS to a max of 15 FPS. The field of view for the lower resolution modes is 75 degrees $\times$ 65 degrees, while that of the higher resolution camera mode is 120 degrees $\times$ 120 degrees. As one moves higher on the resolution scale, the operating range (the camera records range) adjusts from .5-3.86m to .25-2.21 meters. Exposure time is increased for higher resolution operating modes. All these factors played a part in how we decided to optimize and implement the point cloud data transfer.

Using the point cloud data that we collected, we can then reconstruct models in the scene for later holographic display. The Azure Kinect also includes body tracking features that allow developers to build interactive games and simulations based on user movement. The Azure Kinect depth map is generally around 3MB, and the color map is around 36MB. We capitalize on this feature in our game application.

B. *Holographic Displays*

Our holographic display mimics Pepper’s ghost illumination effect. Figure 4 shows the steps to create our holographic display. The holographic display is set up using four clear transparent reflectors and a monitor. Four identical triangles

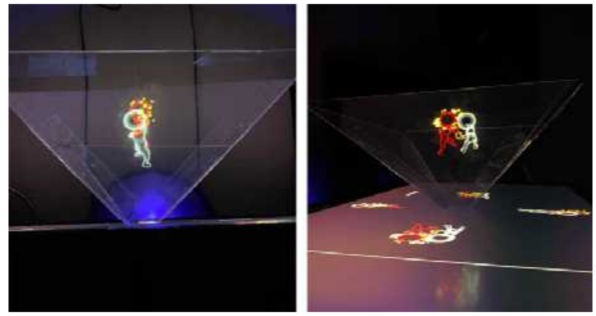


Figure 5. We used Pepper’s ghost to illuminate images to the center of the hologram. The user could view the illuminate images from different views: front, back, and two rear views. Each view gives a different perspective.

of plastic sheets are put together side by side so that it forms a square base. The setup resembles a four-sided pyramid where each side will represent different angles of the model or scene. Pepper’s ghost effect employs a reflective transparent surface to reflect the image towards the user. The optical illusion takes advantage of the user’s inability to see the transparent surface. It only looks like the model’s projection and not an image being projected onto a physical surface.

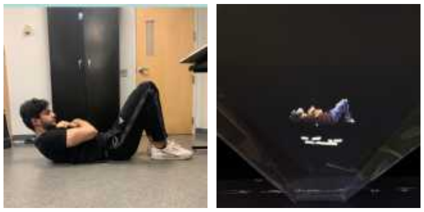
Four separate images showing different perspectives (front, back, right, and left sides) are displayed on a separate monitor for showcase models in the hologram setup. The transparent pyramid display is placed on the monitor with the sides lined up so that each of the four images is under one side of the holographic display. It allows for a pyramid holographic representation showing each side of the model as physically in the room. Our finished holographic display is shown in Figure 5.

C. *Network*

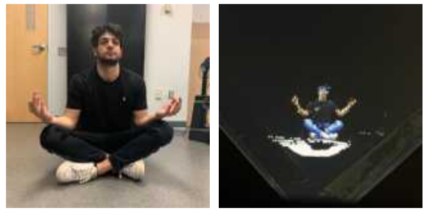
The network transmission is done by a Photon Unity Networking 2 (PUN 2), a network tool for Unity created by Photon [1].

PUN 2 is a Unity-specific networking solution that we use to synchronize game objects, point cloud data, and procedure calls over a global network. PUN 2 wraps its API into three main structures. The highest level is implementing Unity features like passing Game objects over the network or remote procedure calls (RPC’s) and similar commands. The following API layer focuses on talking to the Photon servers to do room and matchmaking setups and the real-time API. The final layer contains the different protocols, serialization, and deserialization of data through DLL files. The network transmission capability of the network load depends on the network condition. Our experiment found that for keeping the network transmission stable, the network load should be smaller than 1 MBps, or each network call should be smaller than 5 Kb.

[1]Photon, https://www.photonengine.com, an independent networking engine, and multiplayer platform.



(a) Sit Up



(b) Meditate

(c) Push Up

Figure 6. Workout exercises visualized via our holographic display.

D. Performance Optimization

Based on the data structure used by the Azure Kinect, the size of the point cloud could be up to 36 MB using the 32 bits for the color channels and the 64 bits for the vertex channels. The higher the point cloud quality is, the larger the size is, and the slower the transmission frame rate is. Due to the networking limitation, it is difficult for large amounts of data to be transmitted in real-time. We have to limit the network load to 0.5 MBps to get a real-time data transmission.

In order to maximize the point cloud quality and the transmission frame rate, we compress the point cloud by *Gzip* [31] in *C#* before sending it to the server. Moreover, we decompress the receiving data by *Gzip* [31] in order to get the complete point cloud. In our experiment, the compressed point cloud size is 15% of the original size, which gives us much space to improve the point cloud quality and transmission frame rate.

We also tried to lower the load on each network call to 3 Kb or smaller to ensure that the connection was stable and the data transmission can be completed in real-time. To achieve this goal, we split the point cloud into 4 data blocks and sent the data to use the UDP protocol. Each data block comes with a *ID* number to identify the order the blocks were sent and a magic number that the sender randomly generates to identify a specific point cloud. The receiving end puts the passed data into the proper offset of the buffer by the *ID* number and the previously received data's length.

We also checked the total length and the magic number of the received data to verify the transmitted data's integrity. If any data block is lost due to network errors, the entire buffer would be discarded to ensure the point cloud's integrity and to avoid crashing the program due to a decompression failure. Once a complete point cloud is received, it will be immediately rendered onto the screen.

In our experiment, we can transmit a 60×60 point cloud at 30 FPS for the high-speed motion needs or a 80×80 point cloud at 12 FPS for the low-speed motion but high-quality needs.

V. Applications

Three applications have been designed to showcase the functionality of the Hologram. These applications ran on a desktop equipped with an Intel Core i7-7700K CPU, an NVIDIA GeForce GTX 1080 8GB graphics card, and 48GB of RAM. The foundation of these applications was developed in Unity. The network transmission is done by PUN 2, which is a network tool for Unity. The network is supported by a $1,000$ MBps fiber-optic network and indoor WiFi. The downlink/uplink is at least 450/90 MBps, and the ping is 10 ms on average. The three applications are described in the following sections.

A. Workout Instructor

Due to the recent outbreak of COVID-19, many institutes shifted their education to online seminars. We created *Workout* to fit the needs of an online class. Figure 6 shows a workout instructor performing some workout exercises via the holographic setup.

Our application allows a user to stream their point cloud captured from the Azure Kinect to whoever is on the other side via a one-way stream. The first person to join the application becomes the host of the network. All other users who join the application will serve as a spectator of the host user's stream. In such a manner, we allow different users to switch between watching or streaming as the host user.

With real-time voice, all the users who participate in the application may join a public channel. In the public channel, all the users can talk and discuss with one another in real-time.

We use a one-way stream application for the workout instructor. Those who opt-in to participate in the workout can watch and practice with the instructor performing various workouts via hologram. With multiple angles of the instructor due to the holographic system's nature and the public channel to allow voice interaction in real-time, the one-way workout application allows for a new method of instructions. As it is a high-speed motion application, we used 60×60 at 30 FPS. Figure 6 shows a user following a workout routine that his instructor is streaming via the hologram system.

B. Holographic Teleconference

The second application, *Holographic Teleconference*, mimics the idea of traditional video and audio communication. It allows two users to see and communicate with each other using our system.

Unlike the *Workout* application, the *Holographic Teleconference* is a two-way stream application. It allows two different users to stream each other's point clouds in real-time.

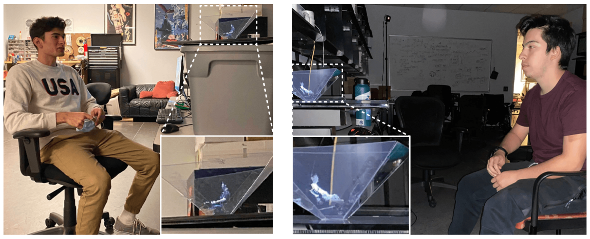


Figure 7. We developed an application to allow two users to communicate via holographic displays. Two users see each other's holograms while chatting online.

While our prototype enables two users to stay connected and watch each other's hologram in real-time, it could also be extended to support more users' teleconferencing.

The two users in the *Holographic Teleconference* application are also linked with real-time voice. Both users will join the public channel and discuss with each other in real-time. As this application requires a higher resolution, we used 80×80 at 12 FPS. Figure 7 shows two users communicating with the hologram system.

C. Boxing Mini-Game

The Azure Kinect has body-tracking features that enable the player to interact with our system. We created a mini-game called *Boxing*, which allows two players to box each other through our system. We deployed a virtual camera in each of the playing areas' four directions: front, back, left, and right. All of the virtual cameras must aim at the playing area to construct a holographic projection image. Figure 8 shows the camera setup for the boxing mini-game.

When starting the *Boxing* mini-game, the adaptive reality mode allows only the first two players that join to become designated boxers. All other players who join will be a spectator to watch the boxing match via the holographic display.

The boxing game functions as a multi-way streaming application; the players and spectators can stream their skeletons. Figure 9 shows a player playing the game via the holographic display.

The visual effects of the boxing mini-game make the game visually appealing and fun. The players start with an initial color. Player 1 is light blue, and Player 2 is light green. The colors contrast to make the two characters look distinct to the players. Each character in the boxing game will have their name displayed above their avatar to allow spectators to see who is fighting.

When a player lands a successful hit inside the play area, the opponent's hit points will lower, and various visual cues and sounds will show and play. The visual cue will be for any glove that makes contact with the other player. The glove will turn gold for two seconds for every hit landed, and a yellow particle effect will appear. However, if a player successfully protects themselves from a hit, the gloves will turn white. As players lose hit points, their characters will

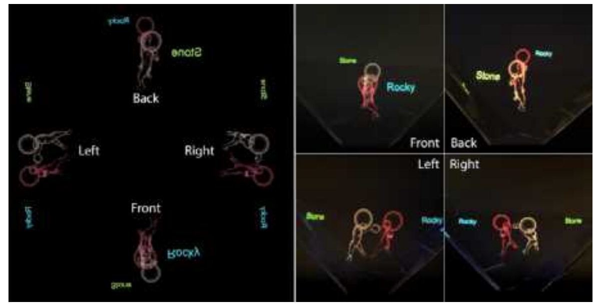


Figure 8. The camera setup for the boxing mini-game. The left image shows a screenshot of the computer screen. The right images correspond to the four viewing angles of the holographic display during the game. Because the image in the holographic display and the image on the computer screen mirror each other's vertical direction, so, we flipped the camera image vertically before rendering it on the screen.

fade to a red color. The effects coalesce to create a visually appealing boxing game for all spectators watching a game via a holographic display as Figure 8 shows.

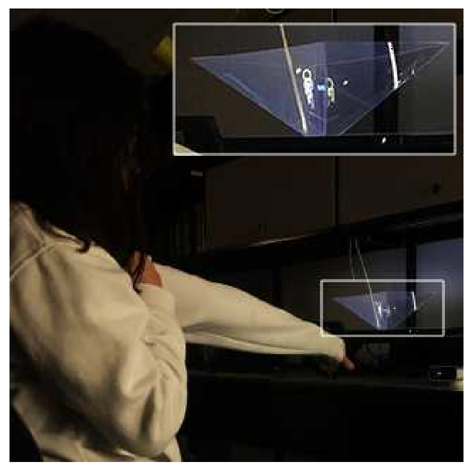


Figure 9. A player playing the boxing mini-game. The player punches in front of the Azure Kinect. The holographic display shows the character controlled by the player in real-time. Note that the player also sees the character controlled by her opponent playing the game at a remote location.

For avoiding having a player leave the screen or move outside of a player's reach, each player is fixed at a particular location to ensure the game may begin and end at any given time during proper game-play. The lower body animation is fixed for each player, while the upper body's animation is controlled by the detected skeleton data collected from the Azure Kinect. Figure 9 shows a player playing the boxing mini-game.

Each player in the real space must make a punching motion to hit the opponent in virtual space. For protecting themselves, the players must cover their head with both hands or dodge a punch by leaning their physical bodies to the left or right. Figure 10 shows the examples of the boxing actions. The player would lose 3 hit points when getting hit regardless of protecting, yet a player would only lose 1 hit point if the player protected itself successfully. When the player's hit

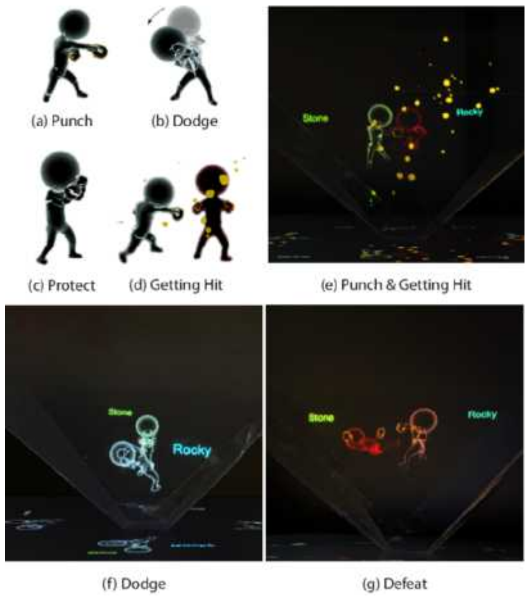


Figure 10. Examples of boxing actions. (a–d) shows the designed boxing actions. (e–g) shows the boxing actions in the holographic display during the game.

points reach 0, the player will fall to the ground. After 5 seconds, the in-game player will automatically stand up, and each player's hit points will be reset, and a new match will start.

Lastly, the *Boxing Mini-Game* also supports real-time voice communication. Like the teleconference application, each of the players in the network can discuss with each other in a public channel.

VI. Evaluation

We conducted multiple user evaluation tests to validate our system's usability using prototype applications discussed in Section V. We want to validate the performance and each user's satisfaction while using the applications on our system. To reduce the bias of preferences in applications, our user evaluation participants tested all three applications.

A. Settings

Participants. We recruited 32 university students as participants to test our system. 21 of them were males, and 11 were females. The average age was 22 ± 2 years old. All participants had experience in using mobile technologies, such as a smartphone or a tablet, at least a few times a day.

Procedure. Our evaluation procedure was IRB-approved. We asked the participants to test 3 different applications described in Section V on our system. Each application was tested for 5 minutes. At the end of each application testing, we asked the participants to provide their feedback through the standard version of a System Usability Scale (SUS) questionnaire [32]. After finishing all three applications, the participants were asked to provide feedback or improvement advice about the system.

Analysis Methods. We used the original version of the System Usability Scale (SUS) [33] questionnaires to evaluate how convenient, and accessible our system was. The SUS uses a tested 10-items Likert scale to assess the usability of a system [34]. Table I shows all the 10 questions in the SUS.

The questions provided 5 response options from Strongly Disagree to Strongly Agree. Each option provided a score from 0 to 4. The response from each option would then be converted to a quantitative score. The even-numbered questions were negatively worded. For these questions, 0 was the highest score, and 4 was the lowest score. Then each response was summed and multiplied by 2.5. The score was then converted from the original $0-40$ to $0-100$.

According to the SUS guideline, a SUS score above 68 is considered "above average", and a score below 68 is considered "below average". We examined the SUS score's descriptive statistics; then, we used a one-sample t-test to check the difference from the average SUS score of 68.

At the end of the evaluation, we provided open-ended questions for the participants to comment on our system. We asked participants about their impressions and opinions of the system. We also collected any suggestions and the features that the participants would like to see in the future.

B. Experiment Tasks

Workout Instructor. The researcher taught a participant some stretching warm-up exercises or yoga moves. The participant viewed the demos through the holographic display. The participant was invited to try these moves with the researcher.

Holographic Teleconference. The participant was connected with our researcher through the holographic display. Our researcher had a conversation with the participant in a teleconference.

Boxing Mini-Game. The participant was asked to play the boxing game with our researcher. Two animated characters were visualized via the holographic display. The skeletons of the animated characters were associated with the participant and the researcher, respectively. The Kinect sensor detected the participant's motion, which drove the motion of the animated character correspondingly. There were a total of three-game matches. Each game match ended when the health point of a player reached zero.

C. Results and Discussion

Table I shows the results of the SUS questionnaires. The scores range from 0 to 4. In the table, 0 represents Strongly Disagree and 4 represents Strongly Agree. Note that the even-numbered questions are worded negatively, with the highest score of 0 to the lowest score of 4. Finally, the score is adjusted so that it maps to 0 to 100.

The overall SUS score of the three applications running on our system is 74.7 ± 11.2, which is above the average of 68. The *Workout Instructor* application received an average score of 71.3 ± 9.4; the *Holographic Teleconference* application received an average score of 75.5 ± 12.0, and the *Boxing Mini-Game* application received an average score of 77.3 ± 11.5. In comparison with existing mobile applications [35], Skype received an average score of 71 on the Android tablet platform, YouTube received an average score of 81 on the iPhone platform, and Twitter received an average score of 69 on the iPad platform. In general, participants favored *Holographic Teleconference* and *Boxing Mini-Game* more than *Workout Instructor*. It could be that because *Holographic Teleconference* and *Boxing Mini-Game* allowed participants to interact with the applications, so they were more fun to use.

Furthermore, we examined significant differences in our scores with the average SUS score using one-sample t-tests. The *Workout Instructor* application has $t(31) = 2.008, p = .027$, the *Holographic Teleconference* application has $t(31) = 3.565, p \ll 0.001$, and the *Boxing Mini-Game* application has $t(31) = 4.604, p \ll 0.001$. The p-values indicated that the *Holographic Teleconference* and *Boxing Mini-Game* applications have a statistically significantly higher score than the average score of 68; hence the perceived usability of our system for these applications can be considered as above the average.

On the other hand, the results of the questionnaires depicted in Table I show that most participants think our system is very convenient and easy to learn. The ratings of ”easy to use” scored 3.22 ± 0.76; ”learn to use very quickly” scored 3.47 ± 0.66; and ”confident using the system” scored 3.33 ± 0.68. In the negatively worded questions (scores are reversed), most participants do not feel that our system is complex and poorly designed. With a “unnecessarily complex” score of 0.85 ± 0.78, a “inconsistency in the system” score of 0.93 ± 0.87, and finally a “cumbersome to use” score of 1.33 ± 1.08, we believe that most participants enjoyed using the applications via our holographic setup.

Question	Mean	S.D.
1. I think that I would like to use this system frequently.	2.95	0.97
2. I found the system unnecessarily complex.	0.85	0.78
3. I thought the system was easy to use.	3.22	0.76
4. I think that I would need the support of a technical person to be able to use this system.	1.49	1.26
5. I found the various functions in this system were well integrated.	3.13	0.81
6. I thought there was too much inconsistency in this system.	0.93	0.87
7. I would imagine that most people would learn to use this system very quickly.	3.47	0.66
8. I found the system very cumbersome to use.	1.33	1.08
9. I felt very confident using the system.	3.33	0.68
10. I needed to learn a lot of things before I could get going with this system.	1.59	1.40
Total adjusted score:	74.7	11.2

Table I
SYSTEM USABILITY SCALE QUESTIONNAIRE RESULTS.

D. User Feedback

We collected some feedback from the participants after the evaluation. A majority of them think that the system is cool and interesting. Some reported that the system is impressive, and they hope to see more applications running on this holographic display. Most participants enjoyed the *Boxing Mini-Game*; they think it is fun to interact with the system.

We also received many valuable suggestions for improvement from our participants. Some reported that the hologram screen could be bigger and brighter to enhance their viewing experiences further. Others suggested that the audio quality and the network bandwidth can be improved for the *Holographic Teleconference* application. A participant reported that they hope to see the “zoom-in and out” feature with two fingers when using the *Holographic Teleconference* application. Some participants suggested us to add more interactive games to the holographic setup.

Overall, we received a lot of positive feedback and suggestions from our system. Most critiques are on the hardware limitations, such as the display’s size or the network limitation. It can be improved using a higher-resolution and brighter display or more transparent plastic sheets. Most participants are more excited when using interactive applications such as the *Boxing Mini-Game* and *Holographic Teleconference*. Part of the reason is that they were able to see themselves interacting with another user via holograms.

VII. SUMMARY

We presented a simple networked holographic system. The system was constructed using a depth camera and four ordinary reflective materials. When combined with a network for streaming voice and images, the system enabled users to interact with a 3D avatar in a virtual environment.

In order to examine the feasibility of our system, we designed three different applications to introduce holographic technology into society: the *Workout Instructor* was built for people to remain active during the COVID-19 pandemic while providing a new approach for motion graphics and instructions in 3D; the *Holographic Teleconference* provided alternative methods in communication using holograms; finally, the *Boxing Mini-Game* demonstrated an interactive gaming application based on our networked system. We showed the usability of our system through positive evaluation and feedback. We believed our simple holographic system might work as a feasible and accessible way of enjoying extended reality content.

Limitations. Pepper’s ghost illusion is not an actual 3D display. Technically speaking, it is a pseudo 3D display composed of four 2D images. When a person views the display from a distance, it is difficult to tell that a 3D image is being presented. If one views the display closely enough, it becomes obvious that only a flat 2D image is shown.

The third-party network service that supported our applications limited the network load at a low level. Thus, if we needed to keep the frame rate at 30 FPS, the size of the workload would be smaller than 16.6 Kb.

The trade-offs continue further when looking at increasing the resolution of the holograms. Higher resolutions would reduce the system to 15 FPS. At the same time, if the FPS lowers, the field of view increases to 120 degrees $\times$ 120 degrees.

Eventually, we found that for keeping our network transmission stable, the network load would be better set as smaller than 1 MBps, or each network call would be better set as smaller than 5 Kb. However, this meant restricting how multi-stream connectivity worked. However, if we used an exclusive web server, we could relieve the above restrictions. The limitations were considered and played a part in how we decided to optimize and implement the point cloud data transfer for our networked holographic system.

Future Work. We may also look into other technologies that can expand the holographic system. For example, using four Azure Kinect cameras to form a camera array so that the holographic setup can sense and capture the user's motion in all four directions; using a cone (akin to Luo et al. [7]) instead of a pyramid to visualize the 3D model or scene in different directions.

The feedback participants gave after the evaluation also suggests looking into an opportunity to revisit our system and incorporate more applications. Work may be done to expand into practice scenarios in education, social networking, or interactive content that mirrors other genres of games.

Although some participants thought our system would be very convenient and easy to learn, some reported that the hologram's screen could be made bigger and brighter to enhance their viewing experiences further. Our prototype can be improved by upgrading to a brighter screen. Others suggested that the audio quality and the network bandwidth could be improved for the *Holographic Teleconference* application.

Some participants reported that they hope to see more user experience features, such as signaling the application to zoom in or zoom out while teleconferencing. This feature can be easily implemented using Azure Kinect's gesture recognition. Other participants suggested us to add more interactive games to the holographic setup. We implemented three different applications to demonstrate the variety of applications our system can support. Other interactive applications can be easily developed based on our system.

Besides developing more applications, future applications may test our design's streaming limits, such as finding the maximum number of users that may join an extended reality teleconference or enjoy a virtual boxing event. Future tests may include increasing the virtual environments' fidelity, perhaps by looking into further integration with extended reality head-mounted displays or hand-held devices. One test might be simultaneously broadcasting on to head-mounted displays, hand-held devices, and the holographic display to gauge preferences between the various external reality systems.

The evidence from the p-values derived from the SUS scores shows that our system's perceived usability can be considered above average. However, by comparing with other forms of extended reality devices, we may measure how preferred the holographic display is accurate. Overall, most participants enjoyed using the applications via our holographic setup. We achieved our initial goal of building a motion-aware, networked holographic display.

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