Mid-air Imaging for a Collaborative Spatial Augmented Reality System

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Keywords: Spatial Augmented Reality, Mid-air Image, Collaboration, User Evaluation, Quality of Experience.

Abstract: Aerial imaging can be used to deliver mid-air imagining in a collaborative Spatial Augmented Reality system. This research aimed to overcome the current disadvantages of Augmented Reality headsets, which include physical discomfort, visual discomfort, high cost and its single user operation. The concept design presented delivered multiple user interaction simultaneously while delivering an increased field of view. This was done through the ASKA3D aerial imaging plate used to deliver mid-air projection, in conjunction with a camera used for view dependant rendering of mid-air images. This design delivered an Augmented Reality experience without the need for robust technology and solely focused on the method of mid-air image projection. The system was successful in delivering a high-quality mid-air image. A Quality of Experience model was found to be the most suited method for user-assessment of this multimedia device. The overall average percentage rating for the system was 69.4% which was considered successful given that what was evaluated was only one part of a whole system to be built.

1 INTRODUCTION

To improve the state of technology in our time there are a variety of approaches that one can take but none have received as much interest as Augmented Reality (AR). Augmented Reality brings the real world and the digital world together. This is done through overlaying digital information onto the world around us. This should not be confused with Virtual Reality (VR) which brings the user to a digital environment isolating the user from the real world (Marr, 2019). Augmented reality can be used in numerous ways within different fields.

In the field of design, AR is commonly used at the end of the design process, it is never used to obtain the final design solution. In the case of mechanical design, the systems are developed so that they can be viewed in 3D using a phone, tablet or a Head Mounted Display (HMD). Inspecting the object in 3D can help the designer identify possible faults with the design so that they can implement a corrective procedure before construction of the part. In civil design AR has been used give the designers the ability to preview the inside of a building before construction is finished. This way designers can walk through a building while it is just brick and mortar and preview what the inside of the building will look like using AR.

This research presents a comparative study on current methods of holographic projection using the half-slivered mirror approach. It then suggests a new method of projection. This new method of projection will increase the number of possible users interacting with the system simultaneously while delivering a greater field of view. The focus of the design is one of user collaboration.

2 RELATED WORK

Common AR systems have the display for the system situated on the user, either through a HMD or a hand-held device. There is another type of AR system that promotes multiple user collaboration unlike common AR devices, these systems are called Spatial Augmented Reality (SAR) systems. To create this collaborative system SAR separates the display from the user of the system thus allowing multiple users on a single device (IGI Global, n.d.). Unlike common AR systems, SAR systems are not commercially available. SAR systems are still undergoing research and development, this is the main reason behind its unavailability to the public.

AR is more commonly used on hand-held devices; since most hand-held devices are equipped with a

Naidoo, D., Bright, G. and Collins, J.
Mid-air Imaging for a Collaborative Spatial Augmented Reality System.
DOI: 10.5220/0009779103850393
In *Proceedings of the 17th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2020)*, pages 385-393
ISBN: 978-989-758-442-8

display, sensor technology and a camera it makes it a perfect platform for AR applications (Kim, Takahashi, Yamamoto, Maekawa, and Naemura, 2014). AR is perceived as using an HMD that will let us see digital images that are not there. HMD's do have their own weaknesses such as incorrect focus cues, small field of view, tracking inaccuracies and inherent latency as presented by Hilliges, Kim, Izadi, Weiss and Wilson (2012), all of which result in user discomfort.

Radkowski and Oliver (2014) present a discussion about natural visual perception not being present in some AR devices. This means that virtual content can only be viewed at a specific position and if viewed any other way the delivered image would be distorted. Overcoming this requires view dependent rendering, this is a method that will adapt the perspective of the virtual information to the viewing position of the user (Radkowski & Oliver, 2014). This method is based on head tracking.

Deering M (1993) writes that without headtracking present in the system the result will be a fixed viewing system. Using headtracking as a possible solution will allow corrective viewing but will limit the number of users on the system.

2.1 Mid-air Imaging

The half-slivered mirror approach to mid-air imaging was selected as the foundation for the proposed system. The half-slivered mirror approach involves using a light source (an LCD screen) and a beam splitter. The light source is what the system desires to project into a hologram while the beam splitter reflects the image from the light source as the desired hologram. The characteristics of a beam splitter can be seen illustrated in Fig 1 where "a" is the light source, "b" is the reflected light and "c" is the transmitted light (Aspect & Brune, 2017).

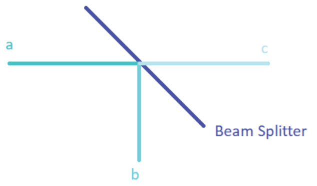

Figure 1: Diagram of beam splitter behaviour.

The Mid-air Augmented Reality Interaction with Objects (MARIO) (Kim et al, 2014) and HoloDesk (Hilliges et al., 2012) are two systems that achieve their projection using half-slivered mirrors, but their implementation is different.

The HoloDesk is a system that allowed users precise 3D interaction with holograms without the need of any wearables. The precise interaction was due to their new proposed technique for understanding raw Kinect data to approximate and track objects while supporting physics inspired interactions between virtual and real objects (Hilliges et al., 2012). Hilliges et al. (2012) used a Kinect sensor for the hand and object tracking, an LCD screen as a light source, an RGB webcam to track the users head position and a half-slivered mirror beam splitter. The purpose of head tracking in this system is to allow viewpoint corrected rendering of the hologram. This gives the users a sense of reality of the virtual object as the scene changes the objects to different depths depending on how the user views the scene. The system set-up of the HoloDesk can be seen in Fig 2, the systems' design is unique due to the position of the beam splitter. The HoloDesk system has the light source projected at an angle of 45 degrees with the beam splitter at an angle of 0 degrees. Due to the beam splitter used, it only allowed the user to view the digital images so long as the user was looking through the beam splitter. In this way the area underneath the beam splitter would be the interaction volume which they ensured had a black background in order to view the projected images clearly.

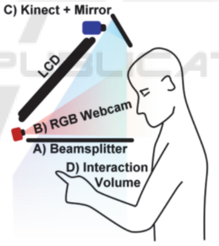

Figure 2: HoloDesk system overview (Hilliges et al., 2012).

The MARIO system proposed by Kim et al. (2014) was a novel design that overcame the limitations of half-slivered mirror designs while enabling users to control mid-air images with their hands or objects. The interaction permitted on the MARIO system allows the user to influence the position of the mid-air image by placing an object or the users hand in the interaction volume. This does not allow precise interactions with holograms like what is delivered on the HoloDesk. Kim et al. (2014) performs an analysis on the type of beam splitter to use for their system without losing the advantage of distortion free imaging that a half-slivered mirror design gives. One of the main limitations of a half-slivered mirror design is that virtual images can only be placed behind the half-slivered mirror and not in front, resulting in design limitations (Kim et al., 2014). The MARIO system overcomes this limitation by analysing different types of beam splitters that either deliver distortion free imaging or imaging in-front of the beam splitter. From the analysis, two types of beam splitters were found to deliver both above mention properties; the first was the Dihedral Corner Reflector Array (DCRA) the second was the Arial Imaging Plate (AIP).

The AIP was selected as the beam splitter for the MARIO design and its implementation has the light source at 0 degrees with the AIP angled at 45 degrees to deliver the image directly in front of the AIP, as seen in Fig 3. Kim et al. (2014) further went on to define a geometric relation between the AIP and the display, this relationship was given as equations describing the horizontal and vertical viewing angles of the AIP. Kim et al. (2014) expected that the closer the light source ("z") the greater the viewing angle both horizontally and vertically.

The system overview of MARIO can be seen in Fig 3, the overall system comprises of three sub-systems namely object detection, mid-air imaging display and shadow projection (Kim et al., 2014). The object detection system has a Kinect depth sensor mounted directly above the interaction volume to track user interaction within the mid-air image. The mid-air imaging display has an LED backlit display as the light source mounted on a linear actuator that changes the distance between the AIP and the light source, this will affect the position of the mid-air image. The shadow projection system gives the users of MARIO a sense of 3D since the MARIO system only displays 2D mid-air images, shadows are placed underneath the mid-air images displayed in real time using a projector.

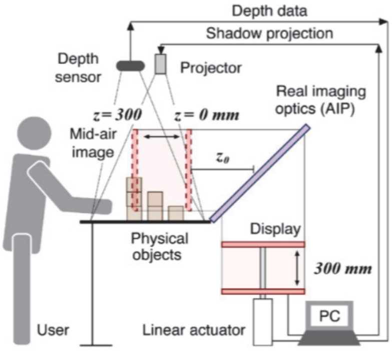

Figure 3: MARIO system overview (Kim et al., 2014).

When comparing the MARIO and HoloDesk systems each have their own strengths. The HoloDesk focuses on the precise control techniques and MARIO focused on a new type of imagine display delivering the interaction volume in front of the beam splitter.

3 SYSTEM DESIGN

The ideal system should have the strengths of the HoloDesk and MARIO systems without their weaknesses. The precise control granted by the HoloDesk for hand interaction was essential to have in the system; this was on the basis that the algorithm used to deliver the hand interaction was available. The strength of the MARIO system was its ability to deliver mid-air images in-front of the beam splitter without having to look through the beam splitter to see the virtual images.

The work presented by Kim et al. (2014) did not specify a supplier for the AIP or DCRA beam splitter. Research into possible suppliers of these beam splitters led to a company called ASKA3D. ASKA3D is a company that solely produces AIP's that deliver mid-air images. The company prides itself in creating a product that does not require any complicated equipment to deliver videos and objects projected in mid-air (ASKA3D, n.d.). Furthermore, the images are projected in such a way that allows you to interact with your hands. The company's only product is AIP's which are separated in two categories: one being Plastic ASKA3D-Plates and the other being Glass ASKA3D-Plates. The plastic plates are manufactured at one size and are rated to only have a transmittance of 20% while the glass plates come in four different sizes which are rated to have a transmittance of 50% (ASKA3D, n.d.). The company provides two methods of projection with their product, one of these methods can be seen in Fig 4 and will be the layout used in the proposed system design. Additionally, ASKA3D will provide customers with the viewing angle calculations for each layout when purchasing their product.

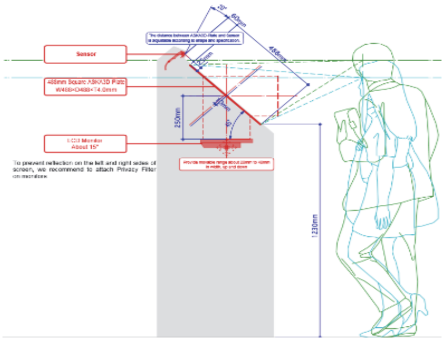

Figure 4: ASKA3D AIP Layout (ASKA3D, n.d.).

The strength of the HoloDesk system relied in its method of interaction with the virtual images, this was due to the physics enabled interaction the system provided.

The HoloDesk was able to achieve this with its sophisticated new algorithm including the use of the Kinect sensor which provided the real time depth data required to deliver the virtual scene and interaction capability (Hilliges et al., 2012). Therefore, to enable the same precise interaction the design of the new system must have a Kinect sensor position in line with the interaction volume and access to the HoloDesk system code must be requested. If the code was not accessible user interaction must be done through another algorithm for precise hand interaction or using glove technology. The MARIO system's strength was in its method of projection, using an AIP as the beam splitter which allowed front projection compared to systems like the HoloDesk which required the user to interact with the virtual scene behind the beam splitter. Therefore, the design of the new system uses an AIP from ASKA 3D.

An important point noted was that head tracking was used in the HoloDesk system and not in the MARIO system. The MARIO system was not designed for users to view 3D digital objects therefore, it lacks an element of head tracking, but the system does give the user an illusion of 3D movement of the digital objects due to its shadow projection subsystem. The new system must be an evaluative platform for users; therefore, it would need an element of head tracking allowing view corrective rendering of virtual images. The new system will use a face tracking software called OpenFace 2.2.0: a facial behaviour analysis toolkit.

A variety of concept designs were generated for the following system all of which differed on the method and techniques they used to obtain a collaborative system. A single concept design stood out among the rest and was explained below.

3.1 Concept Design

This concept design proposed a desktop system that was not robust in size but still delivered an SAR experience to users of the system. It achieved a collaborative environment through only one viewing position. This was due to the ASKA3D plate that was used as the beam splitter of the device, while it was not stated by the company, they illustrate that more than one person can view the mid-air image at the same time so long as they are within the viewing angle of the system, this can be seen in Fig 4. This is a property that will need to be tested in order to confirm it validity. This concept has the capability to allow users to switch between the two different layouts for an ASKA3D plate, allowing users the freedom and comfort to choose how they interact with the mid-air images.

The system was designed to house an LCD screen and an ASKA3D plate in some form of mechanical linkage that changed the positions of the screen and plate to conform to the two layouts the plate can be used in. The design has a platform located at the top of the system which allowed a camera to be positioned aligned with the user. This allowed view dependent rendering of the mid-air images. In this system the view dependent rendering function was controlled by the user. In situations where there are multiple users observing the mid-air images view dependent rendering cannot take place since it is not possible to track multiple users' visions and change the scene to match every single user view. Only when there was one user on the device can view dependent rending be used. Interaction on this system took place by using an AR glove known as the CaptoGlove (CaptoGlove, n.d.), this glove allowed physical interaction with AR images.

This system was not a stand-alone system since it did not require a dedicated computer to deliver the mid-air images. The idea behind this system was to allow SAR projection without the need of robust technology or complicated requirements. This system operated by connecting a laptop to the LCD screen and duplicated or extended the laptop workspace, then the user would start the software for this AR system on their laptop. This proposed system delivered a collaborative environment with a high-quality SAR experience in a small scale, which resulted in a reduced overall workspace and a highly portable device. An example of the proposed system can be seen in Fig 5.

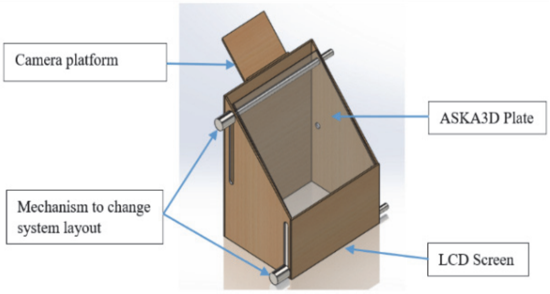

Figure 5: Conceptual design.

4 EXPERIMENT AND RESULTS

When exploring possible testing methods to evaluate AR systems, it was discovered that AR devices were tested through user interaction as these are multimedia devices. The work presented by Kim et al. (2014) and Hilliges et al. (2012), allowed users to operate their respective systems and asked the users to provide feedback on the quality of experience delivered by the AR device. A paper written by Zhang, Dong, and Saddik (2018) suggested a quality-of-experience (QoE) model can better evaluate an AR device from the user's perspective, Zhang et al. (2018) went on to present a QoE framework and modelled it with a fuzzy-interface-system to evaluate the device. The framework they proposed to evaluate a holographic AR multimedia device comprised of four major categories; Content Quality, Hardware Quality, Environment Understanding and User interaction. They allowed users to interact with a Microsoft HoloLens and play two different games, after which they asked the users to answer a questionnaire based on their experience with the system. The experiment performed by this paper will be similar to the one performed by Zhang et al. (2018) except the results obtained by the questionnaire will not be compared to a fuzzy model but rather the user responses will be depicted on a graph and evaluated to understand the current strengths and weaknesses of the system so that future changes can be made.

The focus of this paper was design of an SAR system; since the beam splitter for this system was purchased from ASKA3D there was a limitation on the layout of the system. This paper evaluated the quality of experience granted by the ASKA3D plate executed in the layout seen in Fig 4.

A test structure was constructed to fit the layout in Fig 4. It was sized to fit the ASKA3D-200NT plate. A HP Compaq LE2002x monitor screen acted as the light source for the test structure. The ASKA3D plate was purchased and the test structure was built, the test system can be seen in Fig 6. To deliver the best possible mid-air image, any solid surfaces (frame or coverings) was painted black so that the reflected light was not absorbed by bright coloured surfaces preventing the reduction of quality of the image and delivering transparent virtual images.

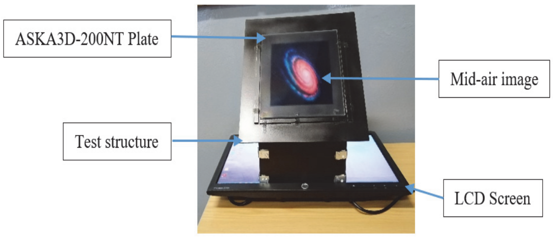

Figure 6: Test system setup.

Based on the equations provided by ASKA3D the viewing area was dependant on the viewing distance of the user, therefore, a definite value for these measurements cannot be given as users were not standing at one fixed distance when evaluating the system. Additionally, the value of the viewing angle was dependent on the size of the image show and what distance in front of the plate the image was shown.

Once the test structure was built, a questionnaire was drawn up based on the questionnaire used by Zhang et al. (2018), however, some questions that were changed to relate to the new SAR system that was being developed. This questionnaire was given to users after they interacted with the mid-air images shown to them. The questionnaire first collected basic information such as age, name, gender and whether users have previously interacted with AR or VR technology. The questions were Likert scale questions as seen in (Zhang, Dong, & Saddik, 2018) where the user responded to the questions with a number from 1 to 5 with each number representing a different response. The questionnaire was split into four sections where each section was centred on one of the four main categories in the QoE framework. Firstly, the user was asked general questions that relate to a specific category (i.e. Content Quality) before they give a final rating on the category in question. The user did this for each category before they gave an overall system rating out of 100. Finally, the users were encouraged to comment on their experience and suggest system errors or recommendations.

4.1 Experimental Method

What follows was the procedure taken to test the system seen in Fig 6.

- An HP Compaq LE2002x monitor was placed to lay flat on a table.
- The test structure was then placed on top of the monitor screen.
- The ASKA3D-200NT plate was placed onto the test structure.
- A sample group of five people was selected to evaluate this system, whose ages and experience with AR and VR technology varied.

- Individually, the users were exposed to two types of mid-air images, static images and dynamic images.
- The static images displayed varied from colourful images and scenes of sunsets, planets, galaxies and text.
- The dynamic images displayed varied from rotating planets, moving gears and internal combustion cycles.
- The users were show both static and dynamic images under two different light conditions, the first being no presence of artificial or natural light and the second being allowing natural light or artificial light.
- During the test the users could interact and move however they wanted when viewing the mid-air image.
- Once all the users underwent the test individually, they were all brought together to test the system with multiple users following the same methods used in the individual test.
- The users were then asked to complete a questionnaire about the SAR experience they had received

4.2 Results

The following data was obtained from the scores given by each user evaluating the four main categories of interest as well as the users overall score for the system:

Table 1: Evaluation data of system properties.

Participant No.:	**1**	**2**	**3**	**4**	**5**
Content Quality [5]:	4	4	4	4	4
Hardware Quality [5]:	3	4	4	3	3
Environment Understanding [5]:	3	3	4	3	2
User interaction [5]:	1	1	1	1	5
Overall system rating [100]:	60	80	80	55	72

What follows is a bar graph displaying the average percentage rating for each system property;

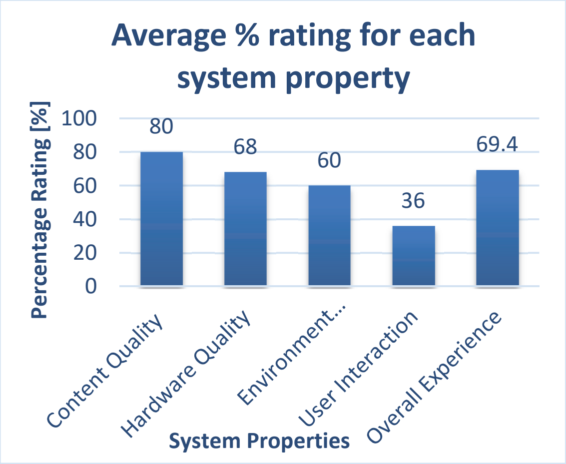

Figure 7: Bar graph of average percentage ratings.

5 DISCUSSION

High tier AR devices such as AR headsets have been the face of AR technology and have delivery, currently the best possible AR environment for single users. Due to the advanced technology involved in building these AR headsets they have a high cost and limited availability, so even though this AR technology exists it is not accessible to most people. Furthermore, having this technology which was limited to one user at a time for a single device is an issue. Consumers should question whether this limitation was worth the price, coupled with the fact that one would need to wear these systems on their body, which results in discomfort. Physical discomfort was the not the only disadvantage of this system, in some cases users had eye discomfort due to incorrect focus cues and other visual latencies while using these headsets. Therefore, there was a need for a solution these problems. If a new AR system could be developed that could deliver mid-air projection, not only to one user but many users, without the need to wear a headset, at price consumers can afford, it may be possible to deliver an AR experience to users without the shortcomings of AR headsets.

This research presented a solution to the disadvantages of AR headsets in the form of a Collaborative Spatial Augmented Reality System. The goal of this system was to remove the need for users to wear a headset to view AR images. This new idea of AR projection is called Spatial Augmented

Reality and using SAR techniques the proposed system allowed multiple users to view AR images at the same time. The proposed system used an AIP to deliver mid-air images to users, coupled together with a Kinect sensor for hand interaction or AR glove technology it allowed users to physically influence the AR image seen in mid-air. The system contained camera that performed head tracking, allowing view corrective rending of virtual images.

A single concept design was presented in this paper although other designs were developed, they are not covered, though they differ in their implementation.

These other concept designs were intended to be a robust system that had a large workspace. This type of design was flawed due to its redundancy, there are too many components in these systems that was meant to be simple yet elegant. Furthermore, these systems heavily relied on the code presented by Hilliges et al. (2012) that would allow precise hand interaction with mid-air images. The code had been requested from the authors but there was no response.

The concept design seen in Fig 5 was created to be a simpler version of previous designs, that was more flexible in its method of projection, since it allowed both layouts granted by the ASKA3D AIP. The current design iteration (Fig 5) does make an allowance for a Kinect sensor and a web-camera to be mounted on the system. This system (Fig 5) was created as a desktop system that did not require a dedicated computer to operate the system but rather a laptop. This would make it highly accessible to everyday consumers wanting to experience AR technology. User interaction with this system (Fig 5) did not come through direct hand interaction but through glove interaction where users were able to influence the AR image, if they were wearing AR glove technology. CaptoGlove was selected as the AR glove technology to use for this system. There was an allowance for a camera to be positioned on the system to allow view dependant rendering.

This research covered a single part of a whole system, which was the physical hardware that will be required to implement a Collaborative SAR system. The concept design meets the desired goal of the system and will be the design used when building the final system. The concept will need to be redesigned after further review before it can be complete.

Since the method of projection relied on whether the ASKA3D plate performed mid-air projection as intended a test structure was created to test the mid-air image projection (Fig 6). The image projection delivered far exceeded what was expected. Since it was possible to deliver a mid-air image an experiment was created to evaluate the quality of experience granted by the projection technique. The experimented used for testing was based on the QoE evaluation framework created by Zhang et al. (2018). The experiment allowed users to view and interact with the mid-air images and evaluate their experiences through a questionnaire they had to complete. The answered questionnaires can be found by following the link provided: https://github.com/Dashlen/Questionnair-results-for-SAR-System/issues /1#issue-564724513.

The data was then tabulated (Table 1) and graph showing the average percentage rating for system properties was created (Fig 7). The feedback from users showed an average rating of 80% for the Content Quality. The high percentage of this result showed that based on user evaluation the images perceived by users were realistic and did not require intense focus from users to observe the mid-air images.

The average rating for Hardware Quality, concerning user mobility and comfort, was 68%. Users found the experience both physically and visually comfortable, since no headset was required, furthermore no eye soreness was reported. The reason behind the moderate percentage rating was due to the limited visual freedom granted by the system. This may be attributed to the users' exiting the viewing angle of the system, the size of the ASKA3D plate and how far it is situated from the LCD screen.

The average rating for Environment Understanding was 60%. While the system was able to deliver images that could fit any environment the images projected could not interact with foreign objects, any interaction with physical objects would result in the mid-air image losing its holographic effect on the users.

User Interaction was given a low average rating at 36%, since the users were unable to control the image they were viewing. As a result, they could only rate the interaction granted by the system as "very bad". Originally, a software was designed to be used on the system that would allow users to change the scene of the object they were observing, but the projection of this scene was too big to be projected correctly. One of the users concluded that user interaction with regards to how precise and how fast the system responds to user input would not depend on the ASKA3D plate but rather the LCD screen being used and how good a response time and refresh rate it had. After further consideration their statement was found to be correct.

The overall experience rating was given as 69.4%, this rating was given by the users when they considered the entire experience granted by the mid-air image. This showed that even though the system was not complete and still has some errors it still made users want to interact with the system.

At the end of the questionnaire users were able to comment on what they experienced and leave recommendations.

Most users felt that the system was very effective in displaying a digital image in mid-air. One of the users commented that viewing the image slightly off centre improved the image quality, this might have been an error on the user's part since none of the other users reported such a thing. Users observed that objects surrounded by dark backgrounds were more effective in generating a floating effect and images with boarders reduced the quality of the floating effect. It was also discovered that when the image touches the edge of the viewing area the holographic qualities were lost. To ensure this does not happen in future a bigger ASKA3D plate should be used with a smaller image being displayed. One user felt that they had to be in a single position to view the image correctly. This could be addressed by increasing the size of the screen which will in turn increase the viewing angle of the image. Users observed a wider viewing capability with an increase in distance between the user and the mid-air image. This was expected as it conforms with the equations provided by ASKA3D. One major discovery made was the ability to produce a mid-air image under natural and artificial lighting. Some users noted that they were able to better identify the mid-air images while in natural and artificial light. Although they were able to better identify the mid-air image it was noted that the image loses a portion of its sharpness in artificial or natural lighting. At the end of the individual user evaluation all the users were asked to observe the mid-air image together to prove a hypothesis involving multiple user viewing. The users reported being able to see the image when being observed by five people. This was able to prove that the proposed system will allow multiple user observation.

The data obtained from QoE evaluation helped identify strengths and weaknesses in the current system. This information will help in creating the final system which will then be evaluated under the same conditions with the same questionnaire. Thereafter, the results obtained will be compared against the current results.

6 CONCLUSION

The focus of this research was to design the hardware of a collaborative SAR system based on previous AR design systems that used beam splitters to obtain their projections. Two systems were analysed in this paper, the HoloDesk and MARIO systems. Using the information drawn from these systems the current design iteration was proposed, promoting a unique approach on a collaborative system. This system (Fig 5) could deliver mid-air images, view dependant rendering and physical interacting in a simple and elegant way. Furthermore, it can be run by connecting a laptop to the system instead of a desktop computer with high processing power. The method of projection was evaluated using a quality of evaluation framework that allowed users to give feedback on their interaction with the projected images delivered by the test structure (Fig 6). This data was captured and further evaluated.

Performing this evaluation helped identify weaknesses in the system that will need to be addressed in the final system design. Currently, the system has an overall average rating of 69.4% (Fig 7), showing that users find the system interesting, and are inclined to use it.

The most important discovery that was made through user testing was not the overall quality experienced by the users but rather that multiple users could comfortable view the mid-air image at the same time without any viewing issues, in fact it was found that the further back you were the greater the viewing angle granted by the system. This discovery will affect how the system can be used which will have to be described after further testing. This ability to allow multiple users to view the mid-air image comes from using an ASKA3D AIP in the system design.

Future work on this system will involve the full software design that creates a scene allowing mid-air mechanical assembly, final mechanical design iteration and developing precise glove or hand interaction. This paper has shown the initial collaborative effect the final system will have through its method to allow multiple user viewing, the final step is to allow multiple user interaction to become a finished collaborative system.

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