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Design and Development of a Multi-Sided Tabletop Augmented Reality 3D Display Coupled with Remote 3D Imaging Module

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Highlights:

- A novel stand-alone augmented reality 3D display system was developed that can provide three-dimensional visualization of captured objects in real time.
- The system layout and optical geometry of the system is presented, and an experimental prototype was developed using off-the-shelf components and a customized assembly.
- The developed prototype was tested and characterized for different performance parameters, such as viewing angle, stereo crosstalk, transmission framerate.

Abstract. This paper proposes a tabletop augmented reality (AR) 3D display paired with a remote 3D image capture setup that can provide three-dimensional AR visualization of remote objects or persons in real-time. The front-side view is presented in stereo-3D format, while the left-side and right-side views are visualized in 2D format. Transparent glass surfaces are used to demonstrate the volumetric 3D augmentation of the captured object. The developed AR display prototype mainly consists of four 40 × 30 cm^2 LCD panels, 54% partially reflective glass, an in-house developed housing assembly, and a processing unit. The capture setup consists of four 720p cameras to capture the front-side stereo view and both the left- and right-side views. The real-time remote operation is demonstrated by connecting the display and imaging units through the Internet. Various system characteristics, such as range of viewing angle, stereo crosstalk, polarization perseverance, frame rate, and amount of reflected and transmitted light through partially reflective glass, were examined. The demonstrated system provided 35% optical transparency and less than 4% stereo crosstalk within a viewing angle of ±20 degrees. An average frame rate of 7.5 frames per second was achieved when the resolution per view was 240 × 240 pixels.

Keywords: *3D displays; 3D imaging; augmented reality systems; optical engineering; stereoscopy; systems engineering.*

1 Introduction

The fast-track exploration of 3D display and imaging technologies has revolutionized augmented reality (AR) applications. AR display systems have the

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ability to blend the real and the virtual world together to enhance the experience of existing reality [1-3]. AR systems require sophisticated displays and imaging systems to facilitate realistic 3D visualization and an immersive interactive user experience [4-6]. A typical AR display system consists of one or more image sources and optically transparent surfaces to overlay recorded or virtual information directly onto a real-world scene. On the other hand, a typical 3D imaging system consists of multiple cameras and associated optical elements to capture multiple perspectives of a real object or scene.

Some of the most well-known AR applications are used for entertainment, medical visualization, education, and telepresence [1,2]. Interactive remote education and 3D telepresence applications are among the core potential applications of AR technologies, especially for developing countries where access to sophisticated educational tools in remote areas is limited [7,8]. However, large-scale implementation of modern AR systems in such countries is very limited due to high costs and scarcity of technological resources.

In this paper, we present a large-size augmented reality 3D display system in a tabletop arrangement paired with a remote 3D image capture setup to demonstrate real-time image capture, processing, streaming, and 3D visualization. Compared to existing systems, the proposed system provides an easy way to implement a platform for remote learning and 3D telepresence applications by using off-the-shelf components and a relatively simple optical assembly, which enables large-scale implementation, especially in developing countries. The system provides three views (front-side, left-side and right side) of the object or person simultaneously, where the front-side view is presented in polarization multiplexed stereo-3D format. The multi-view 3D display and large-size setup offer the realistic perception required for 3D telepresence applications. The arrangement of partially reflective glass surfaces facilitates concurrent perception of the real-world scene on the other side of the display. The rest of this paper is organized as follows. Section 2 presents a review of the existing related literature. Section 3 explains the concept and configuration of the system, including the software applications. Section 4 presents the hardware of the developed test prototype, and Section 5 discusses the experimental results.

2 Related Work

3D display technologies developed for AR applications can be broadly divided into two categories: head-mounted or near-eye AR systems, and fixed setup or tabletop AR 3D display systems. Below is an overview of the techniques and systems associated with both categories.

The development of head-mounted AR 3D display technologies can be divided into two groups: near-eye AR displays, where the image is displayed close to the eye using micro-displays and wearable optics, and head-mounted projection displays, where a mini-projector mounted on the head illuminates a transparent or non-transparent screen at an intermediate distance. Most recent developments have been focused on near-eye AR displays, using a variety of design approaches [9]. One of the first efforts towards consumer-grade near-eye AR displays was Google Glass, which was a monocular narrow field-of-view display in the form of smart glasses. Later developments include the use of integral imaging, semi-reflective screens, and holographic optical elements [10-12]. The most recent efforts have been focused on multi-focal and focus-free near-eye AR displays, using light field [13], free-form optics [14], and computational holography [15,16]. Projection-based head-mounted AR displays, using pico-projectors combined with microlens-array screens and retro-reflective surfaces, have been presented [17,18]. Head-mounted and wearable 3D AR displays have a small size and a portable form-factor. However, due to the wearable nature of head-mounted AR systems, they are only intended for single users and cannot be used in multi-user application scenarios with low resource settings. Another major bottleneck associated with head-mounted AR systems is their narrow field-of-view and limited range of stereo depth.

Tabletop or fixed setup AR 3D displays have been developed for both single-user and multi-user application setups, where the user can move around the system to see a 3D visualization [19]. Tabletop AR displays have been presented using lens arrays, integral imaging, light field, multi-projector arrays, and holography. Chen, *et al.* [20] proposed a small monochromatic tabletop 3D display based on a metamaterial designed to redirect the incident light in two sixteen converging points in the form of circular viewing zones. Yu, *et al.* [21] proposed a light-field tabletop 3D display based on conical lens arrays and a holographic functional screen. Shim, *et al.* [22] proposed the use of a projection-based light-field system as a scalable tabletop 3D display. An interactive collaborative tabletop 3D display was proposed using an array of sixty projectors and a 360-degree camera [23]. He, *et al.* [24] demonstrated an integral imaging-based dual-view-zone tabletop 3D display using a multiplexed holographic optical element that had the functions and properties of two different lens arrays. Luo, *et al.*[25] proposed a 360-degree viewable tabletop 3D display consisting of a 2D display, a perspective-oriented layer, a large pitch lens array, and a light-shaping diffusion screen. Date, *et al.* [26] presented a full parallax tabletop light-field 3D display based on the principles of optical interpolation using barriers with a customized aperture. On the other hand, holographic tabletop displays using spatial light modulators have also been demonstrated [27]. Tabletop 3D displays that are covered on top are sophisticated and provide unique features. However, most of the discussed tabletop 3D AR systems use a higher number of projectors or cameras and have

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a complex optical system, which results in higher setup costs and limited practicality for large-scale implementation. In contrast, the system proposed here has a simplified and easy implementable end-to-end 3D capture and display system that is easy to reproduce and can be widely used in developing countries using easily available off-the-shelf components.

3 Methodology

3.1 System Layout

The proposed system consists of two modules: (1) a tabletop AR 3D display, and (2) a 3D image capture setup. Both modules consist of dedicated processing units and are connected through the Internet. Figure 1 shows a block diagram representation of the complete system. The capture module consists of four cameras, all connected to a local processing unit. The object or person to be captured is positioned in the center of the setup with one camera each on the left and the right side to record the left-side and right-side views. Another pair of cameras, configured similar to human eyes, is placed in front to capture the stereoscopic front-side view. The translation distance between the stereo camera pair is set to 6.5 cm, which is equal to the average inter pupillary distance (IPD) of human eyes. All four cameras capture the object information simultaneously, which is recorded and transmitted by the processing unit. A single-color backdrop is placed on three sides to facilitate real-time background removal during pre-processing.

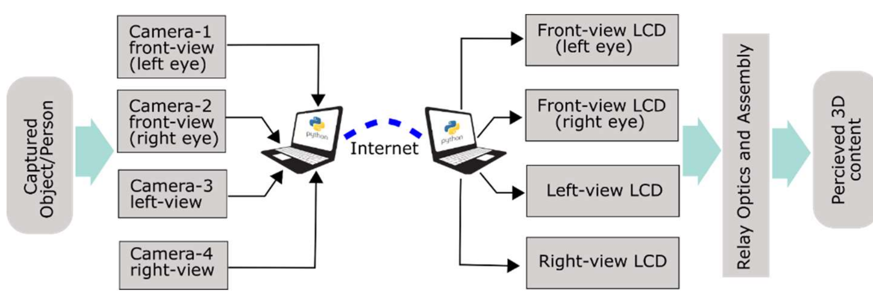

Figure 1 Block diagram of the system showing the AR display and capture modules and their major elements. Both modules operate in real time and are connected via the Internet.

The AR 3D display module consists of a tabletop setup based on four LCD panels, relay optics, a customized assembly, and a processing unit. The processed image frames received from the capture module are separated, processed, and relayed to the corresponding LCD panels, which are further reflected through partially reflective glasses before reaching the user.

3.2 Optical Configuration of AR 3D Display

The display module is composed of four LCD panels, named L1 to L4, relaying four different views. Each LCD panel is paired with a partially reflective glass surface, labeled M1 to M4. The display system as a whole covers three sides, while the fourth side (back-side view) is left open. Since the front-side view is presented in stereo 3D, two LCDs panels and glass surfaces are dedicated for this purpose, as illustrated in Figure 2. For the left eye image of the front stereo-view, the light ray from L1 is reflected through M1, which is placed at distance d1 from L1 at an angle of 45 degrees. M1 reflects a portion of the incident light towards the viewer.

The image displayed through L1 is perceived at distance d1 directly in front of the user. Similarly, for the right eye image, the light ray from L2 is partially reflected through M2 and transmitted through M1 before reaching the user's eye. Distance d3 between L2 and M2, and distance d2 between M1 and M2 are matched to make sure that both the left and the right eye images appear in the same depth plane. The polarization multiplexing technique is used to separate the left and right views. The light rays from L1 and L2 are linearly polarized with a mutually perpendicular polarization direction and are perceived by the user through polarization-matched glasses.

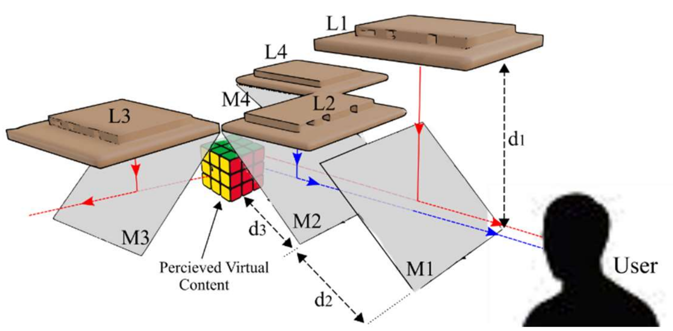

Figure 2 Conceptual illustration of the AR 3D setup, showing the optical arrangement and the transfer of light rays through different elements.

Moreover, both the left-side and right-side views are presented by L3 and L4 and relayed in their corresponding directions through M3 and M4, respectively. The user can move around the tabletop setup to perceive a volumetric 3D representation of the displayed content.

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3.3 Content Processing and Software Implementation

The AR 3D display and the 3D capture setups are both connected to dedicated computers serving as processing units. Separate software applications are developed for the image capture and display modules. Both applications were developed in Python with support of OpenCV and socket libraries. Figure 3(a) and Figure 3(b) show the flowcharts of the applications running at the capture and display ends, respectively.

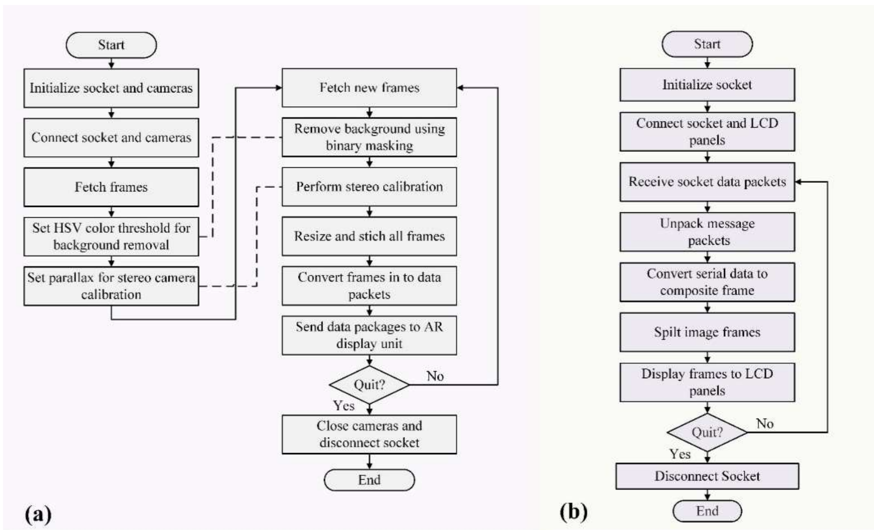

Figure 3 (a) Flowchart of the software application on the capture end, and (b) flowchart of the software application on the display end. Both applications were developed in Python.

The capture side application starts with the initialization of the socket and all four cameras connected to the computer. Network-assigned IP and port addresses are used during the initialization process. In the next step, the image frames are captured by all cameras corresponding to the left-side, right-side, and front-side views. The captured images are converted to HSV format, and the color threshold value is set for binary masking, which is later used for background removal. In the next step, the parallax value is set to clip off non-overlapping peripheral regions from the front-side camera images. A parallel camera configuration is used to obtain stereoscopic images. The color threshold and stereo camera parameters are set once during the start-up of the system. Once the parameters are set, new frames are fetched from the cameras and the background is removed from all captured views. A binary mask is generated based on a set threshold value, which is bitwise multiplied to the captured frame to remove the background. In the next step, the processed frames are stitched together in a single image frame and converted to data packets to be sent to the display unit through the Internet. The process is repeated for the next frames once the packets are ready for transmission.

Similar to the capture side, the application executed on the AR display side starts with the initialization of the socket and establishment of a connection. In the next step, the received data packets are unpacked and converted from serial data to a composite frame. The resultant frame is then split into four views, corresponding to left-side view, right-side view, and front-side stereo view, and relayed to the respective LCD panels. The LCD panels are interfaced to the computer using virtual graphics adapters and connected as secondary screens.

3.4 Experimental Prototype

An experimental prototype was developed to demonstrate a real-time implementation of the AR 3D display and capture system, as shown in Figure 4. The AR display setup comprised four LCD screens, four off-the-shelf partially reflective glass surfaces, an in-house fabricated wooden assembly, and a laptop computer. Each LCD screen had a size of 40 × 30 cm^2, 1600 × 1200 pixels, and 260 cd/m^2 luminance with a 60-Hz refresh rate. The glass surface used in the prototype was 0. 5 cm thick, regular optically clear glass. A thin reflective film was pre-deposited on one side of the glass to provide partial reflection. The glass surfaces obtained from a local market were primarily sold for household windows and doors. The wooden housing assembly was made of chip board with a solid wooden frame. The housing assembly was designed in Solidworks and constructed in the lab. The overall size of the 3D AR display setup was 125 × 105 × 66 cm^3. The processing unit for the display unit was a 10^{th}-generation 1.6 GHz Core-i5 computer with 8 GB RAM and an Nvidia MX110 graphics card. All four LCD screens were simultaneously connected to the computer using virtual display adapters interfaced through USB ports.

The capture module consisted of four cameras mounted on tripods, backdrop fabric, and a laptop computer for processing, as shown in Figure 4(b). We used off-the-shelf web-cameras, A4Tech PK-910p, for image capture unit, where each camera provided a native resolution of 1280 × 720 pixels and a frame rate of 30 fps. Two cameras were positioned at the left and right sides of the object/person, while another camera pair was placed in front to capture the stereoscopic view. All cameras were connected to the laptop computer. A backdrop fabric was used to ensure full background subtraction during processing. The 3D AR display and the capture setup were both connected to the campus Wi-Fi network and real-time content transmission and reception was handled through socket programming as discussed in the previous section.

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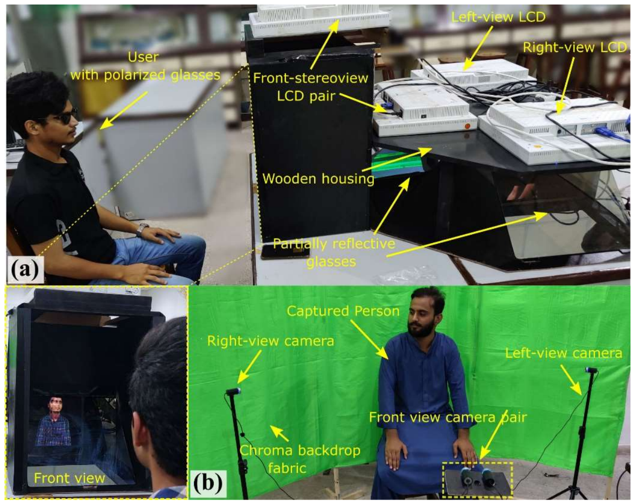

Figure 4 (a) Developed experimental prototype of the display showing a user viewing the display from the front end, and (b) the 3D image capture setup capturing a person from three different directions.

Figure 5 shows the perspective view as displayed on the test prototype. Figures 5(a) to (c) show the right-side view, front-side stereo-view, and left-side view, respectively, as seen by the user. Figures 5(d) and 5(e) show the images perceived by the left and right eye, respectively, through polarized glasses. The user can visualize the front-view from the position shown in Figure 4(a). To perceive the side views, the user can move in either direction. In addition, the developed AR display system can also be viewed by multiple users at the same time.

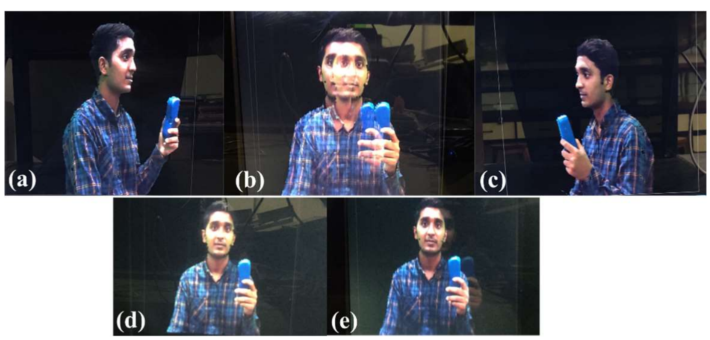

Figure 5 The display result of the AR prototype as perceived by the user: (a) right-side view, (b) stereoscopic front-side without polarized glasses, (c) left-side view, (d) left-eye front-side view through polarized glasses, and (e) right-eye front-side view through polarized glasses.

4 Results and Discussions

4.1 Viewing Angle Analysis

The viewing angle is defined as the angle between the user and the normal screen. The viewing angle range defines the acceptable range of angular positions where bright imagery can be seen. The range of viewing angles is one of the key characteristics of any display system. In the proposed system, a photometric examination was performed to evaluate the luminance of the display at various viewing angles. The normalized luminance was measured using a CMOS camera detector. A white image with uniform brightness was displayed on the system and the amount of captured light was recorded at different viewing angles.

Figure 6(a) shows the normalized luminance recorded as a function of viewing angle. The result shows very little variation in the luminance when the display was perceived from higher viewing angles. A maximum of 5% change in luminance was observed when the display was viewed within a viewing angle of ±20 degrees. The result shows that the proposed system has a viewing angle range of 40 degrees. Further, clipping of the displayed image was observed when the viewing angle was higher than 20 degrees in either direction. The width of the viewing angle is mainly limited by the eye-box size of the display, which further depends on the distance between the semi-reflective mirror and the corresponding LCD panel.

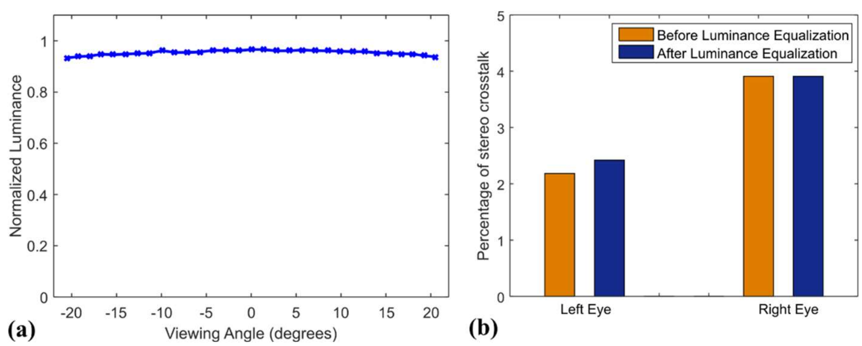

Figure 6 (a) Normalized luminance as a function of view angle, and (b) percentage of stereo crosstalk in left and right eye images before and after luminance equalization was performed.

4.2 Stereo Crosstalk

The front-side view of the proposed system is presented in stereo 3D using polarization multiplexing, which could introduce stereo crosstalk. Stereo

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crosstalk is the ghosting or leakage of the right-eye view into the left-eye, or vice versa. In the proposed system, the crosstalk was determined by measuring the normalized luminance of desired and undesired images reaching each eye.

Figure 6(b) shows the amount of crosstalk in the test prototype in two different conditions, i.e., before and after luminance equalization. The results show less than 1.9% crosstalk difference between the left-eye and right-eye images, where minor crosstalk was observed in the left-eye image compared to the right-eye image. The difference was due to the additional refraction of the right-eye image through glass surface M1, which can also be observed in Figure 2. Luminance equalization was performed for the left-eye image only. Therefore, a change of 0.3% was observed in the left-eye image while the crosstalk in the right-eye image was unchanged. The overall analysis shows less than 4% stereo crosstalk, which will not cause any noticeable sickness or discomfort during the 3D viewing experience.

4.3 Polarization Perseverance, Light Reflection and Transmission

Since the proposed system exploits the polarization multiplexing scheme for the separation of the left-eye and right-eye images, the polarization perseverance of the display system plays a vital role in providing the 3D imagery. The polarization-maintaining property of the system was measured using a photometric setup. The horizontally polarized light emitted by the LCD panels and reflected through the glass surface was recorded by an optical detector (CMOS sensor) with a linear polarizer film in front. The orientation of the linear polarization film was changed with respect to the polarization direction of the emitted light and then recorded on the detector.

Figure 7(a) shows the measured normalized intensity when the polarizer film was rotated from 0 to 90 degrees with a step size of 10 degrees. The result shows the maximum light intensity when the polarization direction of the film matched that of the incident light. Due to the polarization persistence of the light after partial reflection, the measured light intensity proportionally decreased as the orientation of the polarizer film was varied. Only 2.5% light transmission was recorded when the polarization film at the detector was rotated to 90 degrees. This small leakage of light was mainly due to imperfections in the polarization film and stray scattering of light through the partially reflective glass.

The developed prototype contained off-the-shelf partially reflective glass surfaces; therefore, the transmission and reflection properties of the glass surfaces were unknown. To evaluate the optical properties of the glass surfaces, the intensity of the light reflected and transmitted through the surface were recorded and compared to the incident light. Figure 7(b) shows the percentage of incident light reflected and transmitted through the surfaces. Experimental evaluation showed 54% reflection and 35% transmission, while the remaining 11% of light was absorbed and scattered in random directions. The absorption was due to the reflective acrylic film and the random scattering was due to fabrication imperfections in the glass surfaces.

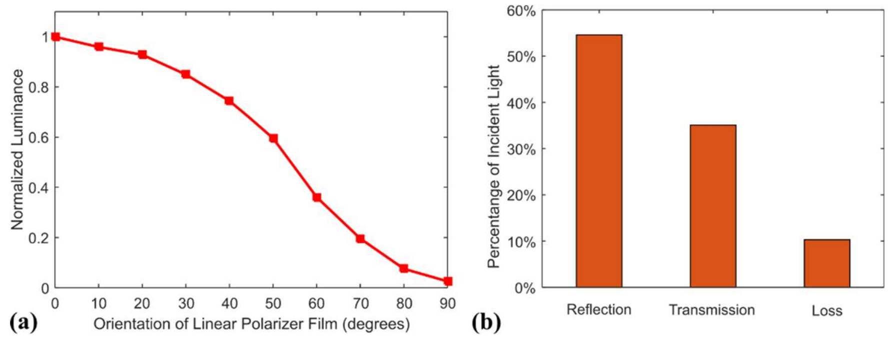

Figure 7 The polarization maintenance property of the AR display setup (a), and the reflection and transmission properties of the partially reflected glass surfaces (b).

4.4 Real-time Implementation

A real-time demonstration of the system was realized by performing end-to-end video rate implementation. The average frame rate of the system was estimated by calculating the average number of frames received, processed, and displayed per second. Figure 8 shows the average frame rate of the system when the resolution per view was increased from 14,400 pixels to 518,400 pixels.

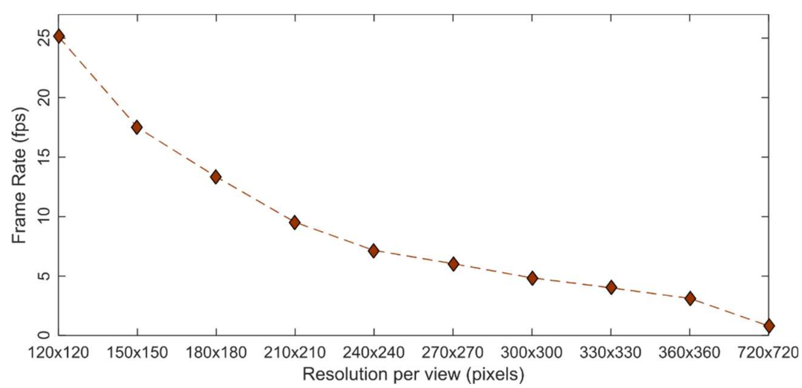

Figure 8 Average frame rate achieved at varying resolutions of the perspective view.

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The frame rate was calculated considering the system specifications mentioned in Section 4. The result shows a sharp decrease in frame rate when the resolution was increased. For practical demonstration, an optimum resolution of 240 × 240 pixels per view was used, which provided an average frame rate of 7.5 frames per second. Furthermore, a network latency of 200 milliseconds was observed during operation. The resolution per view and the frame rate are limited by two important factors: (1) unpacking and conversion of the serial data stream to the composite image and, (2) separation and relay of the perspective view images to the corresponding LCD panels.

5 Conclusion

We proposed and experimentally demonstrated a real-time AR 3D display system paired with a remote 3D capture setup. The developed system was able to capture, process and display multi-side volumetric 3D visualization of the captured content. The front-side view was presented in stereo-3D using polarization multiplexing. Real-time system operation for 3D telepresence application was realized by connecting the capture and display units through the Internet. The acceptable range of viewing angle, crosstalk per eye, and polarization maintainability were measured. The average frame rate of the system was estimated by calculating the processing time per frame. The test prototype provided a wide viewing angle range, more than 20 degrees on each side, with less than 4% stereo crosstalk using off-the shelf LCD panels and partially transparent glass surfaces. A frame rate of up to 25 fps was achieved when the resolution per view was set to 120 × 120 pixels.

The current prototype employs two LCDs for the front view and one LCD for the left and right views. The left and right views can be converted to stereoscopic 3D by employing two additional LCDs and partially reflective glasses. The image quality per view can be further improved by replacing the regular web-cameras with high-resolution image sensors. The see-through capability of the display unit can be enhanced by replacing the glass surfaces with high quality beam-splitters. The proposed system can be used for a variety of applications, including 3D telepresence, remote learning, interactive 3D visualization for education and trainings, and medical visualization. The 3D telepresence, as demonstrated in the manuscript, can be used for remote lectures, meetings, and presentations. The system can be used in classrooms and training sessions to display complex 3D illustrations and visualization. Further, the system can also be explored for medical visualization and diagnostic testing results such as X-ray and ultrasound images can be realistically visualized. Further refinements in the system assembly and add-on features, such as user interaction and voice support, can support wide-scale implementation of the proposed system for remote education and 3D telepresence applications.

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