

Augmented Reality 3D Display and Light Field Imaging Systems Based on Passive Optical Surfaces

by

Shoaib Rehman Soomro

A Dissertation Submitted to the
Graduate School of Sciences and Engineering
in Partial Fulfillment of the Requirements for
the Degree of
Doctor of Philosophy

in

Electrical and Electronics Engineering



**KOÇ
UNIVERSITY**

February 2018

Augmented Reality 3D Display and Light Field Imaging Systems Based on Passive Optical Surfaces

Koç University

Graduate School of Sciences and Engineering

This is to certify that I have examined this copy of a doctoral dissertation by

Shoaib Rehman Soomro

and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
examining committee have been made.

Committee Members:

Prof. Dr. Hakan Ürey

Prof. Dr. Murat Tekalp

Asst. Prof. Dr. Sedat Nizamoğlu

Prof. Dr. Levent Onural

Asst. Prof. Dr. Onur Ferhanoğlu

Date: _____



*To my lovely mother (Late) Hameeda Bano
‡ caring father Muhammad Saleh*

ABSTRACT

This dissertation presents new display and imaging techniques where a number of micro-structured passive optical surfaces are developed and then combined with mobile projectors and cameras to achieve novel display and imaging modalities. Three types of novel optical surfaces are developed: (i) a transparent AR screen, which is a transparent retroreflective surface developed for augmented reality and automotive head-up display (HUD) applications, (ii) a 3D imaging surface, which is a handheld lens array sheet used for mobile light-field capture when combined with a regular camera, and (iii) an integrated dual-purpose screen, which combines the first two surfaces to achieve 3D display and 3D imaging on the same screen simultaneously.

The transparent AR screen provides high optical gain within a small viewing window and enables the use of low lumen output head-mounted laser projectors to produce a bright content. Higher see-through performance is achieved through partial covering of a clear substrate with retroreflective microspheres. The screen transparency and optical gain is varied by changing the retroreflective fill factor, and three versions of the screen providing 50%, 75% and 90% transparency are developed. The transparent retroreflective AR screen was first used with a pair of head-mounted laser projectors (pico-projectors) for 3D vision. We achieved good stereoscopic vision providing down-to 1% crosstalk between two eyes and up-to $1,000 \text{ cd/m}^2$ brightness using 30 *lumen* projectors. For automotive 3D head-up-display applications, we performed a user study to test the simulated collimation and provide the virtual image perception at different screen distances. The user study focused on the visual acuity response under the see-through condition and the simulated collimation condition that shows the relation of visual acuity with the distance of HUD screen and amount of accommodation-convergence (AC) conflict. We showed that the visual acuity is slightly dropped (from 20/20 to 20/25) when the HUD screen is placed between the driver/user and a real-scene. For the simulated collimation condition, an inverse relationship between the amount of AC conflict and the visual acuity is observed, which shows the minimum effect on the visual acuity and viewing comfort when AC conflict is less than 0.85 *diopters* or when the screen distance is $>100 \text{ cm}$.

The 3D imaging surface introduces a light-field imaging platform that can turn a regular camera into a multi-perspective 3D capture system. The 3D imaging surface contains an array of lenses and tracking markers to capture the 3D perspective views of a scene. The camera image provides an array of sub-images; each corresponding to a different perspective view. The location of the mobile surface is determined by tracking the distinct markers attached to the corners of the surface. A computational ray tracing tool is developed using OpenGL to perform the real-time light-field reconstruction and demonstrate digital image refocusing and partial occlusion capture.

Lastly, a novel integrated dual-purpose screen is introduced for simultaneous display and imaging. The screen mainly consists of patterned retroreflective microspheres as the top layer and an array of curved mirrors as the bottom layer for 3D display and multi-perspective imaging, respectively. The simultaneous display and imaging are performed by using an intermediate polarization selective layer and performing polarization multiplexing to separate the projected and captured light. A telepresence demonstrator is built where user-1 uses a pair of head-mounted projectors and a camera while across the integrated dual-purpose screen and user-2 uses a VR headset, where user-2 can watch user-1 in real-time and from arbitrary perspectives. The display and imaging characteristics of the developed prototype are also evaluated. While mobile 3D telepresence is not possible using existing head-mounted AR and VR displays, our proposed solution offers a unique alternative and can be the future of mobile telepresence.

Keywords: 3D Displays; 3D Imaging; Augmented Reality; Light Field; Optical Surfaces; Retroreflective Screens; Head-Up-Displays.

ÖZETÇE

Bu tezde geliştirilen bir takım mikro yapılı pasif optik yüzeylerin, mobil projektörler ve kameralarla birleştirilmesiyle tasarlanan özgün ekran ve görüntüleme teknikleri sunulmaktadır. Üç farklı yeni optik yüzey geliştirilmiştir: (i) arttırılmış gerçeklik ve otomotiv sanal gösterge paneli (HUD) uygulamaları için geliştirilmiş şeffaf bir retro-reflektif yüzey olan şeffaf AR ekranı, (ii) standart bir kamera yardımıyla ışık alanını yakalanmasını sağlayan bir taşınabilir lens dizisi olan 3B görüntüleme yüzeyi (iii) iki farklı yüzeyi birleştirerek aynı yüzeyde 3B ekran ve 3B görüntüleme sağlayan bütünleşik çift amaçlı ekran.

Şeffaf AR ekranı, küçük bir görüntüleme penceresinde yüksek optik kazanç sağlayarak, parlak içeriği üretmek için düşük lümenli çıkışa, örneğin kafaya monte lazer projektörlerinin kullanılmasına olanak tanımaktadır. Yüzeyin, retro-reflektif mikro kürecikler ile kısmen örtülmesi yoluyla yüksek görme oranı elde edilmiştir. Ekran yansıması ve optik kazanç, retro-reflektif dolgu faktörünün değiştirilmesi ile değiştirilebilmektedir. Bu çalışmada % 50, % 75 ve % 90 şeffaflık sağlayan ekranın üç versiyonu geliştirilmiştir. Çalışmanın ilk aşamasında şeffaf retro-reflektörlü AR ekranı, 3B görme için bir çift kafaya monteli lazer projektörüyle (piko projektörler olarak) kullanılmıştır. İki göz arasında % 1 sızıntıyla (crosstalk), 30 lümenli projektör kullanarak 1.000 cd/m^2 parlaklık sağlayan bir stereoskopik görüntü elde edilmiştir. Otomotiv 3B sanal gösterge paneli uygulamaları için, benzetimi yapılmış kolimasyon koşullarını test etmek ve farklı ekran mesafelerinde sanal görüntü algısı için bir kullanıcı çalışması yapılmıştır. Kullanıcı deneyinde arka planın görülebildiği durumdaki görsel keskinlik yanıtına ve görme keskinliğinin sanal gösterge panelinin mesafesi ile Konaklama-Yakınsaklık (AC) çatışmasının miktarı arasındaki ilişki ölçülmeye çalışılmıştır. Sanal gösterge panelinin (HUD) sürücü / kullanıcı ile gerçek sahne arasına yerleştirildiğinde görme keskinliğinin hafifçe düştüğünü (20/20'dan 20/25'e) gösterilmiştir. Benzetimi yapılan kolimasyon koşulları için, AC çatışması miktarı ile görme keskinliği arasında ters bir ilişki gözlenmiş olup AC çatışması 0,87 dioplerden daha az olduğunda veya ekran mesafesi > 100 cm olduğunda görme keskinliği ve izleme konforunda minimum etkisi olduğu gözlenmiştir.

3B görüntüleme yüzeyi, sıradan bir kamerayı farklı açılardan görüntüleri bir seferde kaydedebilen ışıksal-alan tabanlı 3B kamera sistemine dönüştürmektedir. 3B görüntüleme yüzeyi üzerinde bulunan takip etiketleri ve lens dizisi sayesinde ortamın farklı açılardan 3 boyutlu görüntüsünü sunmaktadır. Sıradan bir kamera ile 3B görüntüleme yüzeyinin fotoğrafı çekildiğinde 3B görüntüleme yüzeyinin üzerinde ortamın farklı açılardan görüntüleri kaydedilebilmektedir. 3B görüntüleme yüzeyinin çekilen kamera görüntüsündeki pozisyonu 4 köşesinde bulunan etiketler sayesinde bulunabilmektedir. Gerçek zamanlı bir şekilde ortamın ışıksal-alan kaydını yapan bir hesaplamalı görüntüleme aracı geliştirdik ve görüntüleme yüzeyi ile dijital olarak çekimden sonra çekilen görüntünün odağını değiştirebildiğimizi ve görüntü içerisindeki kısmi perdelenme problemlerini çözebildiğimizi gösterdik.

Son olarak, aynı anda hem 3B ekran olarak kullanılabilen hem de üzerindeki yansımalarla ortamın görüntüsü kaydedilebilen yeni çok amaçlı entegre ekran oluşturduk. Ekranın üst katmanı 3B ekran olarak kullanmak için özel yerleştirilmiş retro-yansıtıcılardan, alt katmanı ise 3B görüntüleme için konveks lens dizisinden oluşmaktadır. İki katman arasına yerleştirilen polarize ara yüz sayesinde ekrana yansıtılan görüntü ve ekran üzerinden kaydedilen görüntü ayrıştırılabilmektedir ve böylelikle geliştirilen çok amaçlı entegre ekran aynı anda hem ekran hem görüntüleme sistemi olarak kullanılabilir. Sistemin çalıştığı, “Telepresence” (karşılıklı kişilere aynı anda 3boyutlu görüntünün ve sesin aktarıldığı iletişim sistemi) uygulaması gerçekleştirilerek gösterildi. Telepresence uygulamasında bir kullanıcı (kullanıcı A) geliştirdiğimiz çok amaçlı entegre ekranı kullanırken diğer bir kullanıcı (kullanıcı B) sanal gerçeklik başlığını kullanarak birbiriyle iletişime geçti. Böylelikle kullanıcı B, kullanıcı A’yı istediği bir açıdan 3 boyutlu olarak görebilmekte ve iletişime geçebilmektedir. Geliştirilen entegre ekranın, görüntüleme ve ekran karakteristikleri incelendi. Mobil telepresence uygulamaları artırılmış gerçeklik (AR) ve sanal gerçeklik (VR) başlıkları ile mümkün değil iken bizim geliştirdiğimiz çok amaçlı entegre ekran sayesinde mümkün olmaktadır ve geliştirilen ekran telepresence ile iletişimin geleceği olmaya en önemli adaydır.

Anahtar Kelimeler: 3B Ekranlar; 3B Görüntüleme; Arttırılmış Gerçeklik; Işık Alan; Optik Yüzeyler; Retroreflektif Ekranlar; Sanal Gösterge Panelinin.

ACKNOWLEDGMENTS

My sincere gratitude to Prof. Hakan Urey for providing me the opportunity to become a member of Optical Microsystems Laboratory (OML) and advising me during my PhD studies. I feel extremely lucky to have had the chance to work under his supervision and be part of this dynamic research group.

I would also like to thank Prof. Murat Tekalp and Assoc. Prof. Goksenin G. Yaralioglu for serving as the members of my research progress committee and providing valuable inputs during the meetings.

Special thanks to my colleagues at OML for a great time. I would especially thank Dr. Ulaş Adıyan for refreshing conversations and healthy discussions, Sven Holmström for reviewing my manuscripts and helping me with the screen fabrication ideas, Dr. Erdem Ulusoy and Dr. Muhsin Eralp for helpful discussions on different parts of the project. I am also thankful to Vahid, Mahdi, Uğur, Yusuf, Burak, Amir and Deniz for being friendly colleagues, Osman Eldes for helping in the imaging part, and Gamze Yilmaz and Selim Ölçer for helping me with project purchases and Turkish language.

I would also like to thank Higher Education Commission (HEC) of Pakistan for providing me a fully funded PhD scholarship under HRDI/UESTP Program, and European Research Council (ERC) for providing the financial support for my research under ERC advanced grant no. 340200.

I must also acknowledge Dr. Kaan Akşit from NVIDIA Research for his help and guidance on the computational framework of light field imaging, and Prof. Yusuf Leblebici for inviting me to EPFL, Switzerland as a visiting researcher.

Special thanks to my friends from Pakistani community at Koç University for the wonderful time, particularly Shadi, Sultan, Nabeel, Adeel, Talha, Zaheer, Zeeshan, Umair, Rizwan, Sarmad, Anwar, Akmal bhai, Rehan and Zakwan for gatherings and fun.

Finally, I am grateful to my parents for their love, support and sacrifices over the years for my education, and my brother Zohaib and sister for their love.

TABLE OF CONTENTS

List of Tables	xiii
List of Figures	xiv
Nomenclature	xx
Chap. 1: Introduction	1
1.1 Human Visual System	2
1.2 Three-Dimensional Display and Imaging	3
1.3 Augmented Reality	5
1.4 Scanning Laser Pico-Projectors for Wearable Displays	6
1.5 Structure of the Dissertation	8
1.6 Contribution to the Literature during PhD Studies	9
Chap. 2: Transparent Retroreflective Screens	11
2.1 Introduction	11
2.2 Previous Work	12
2.3 Theory of Retroreflective Materials	13
2.3.1 Glass-microspheres Retroreflectors	13
2.3.2 Corner-cube Retroreflectors	14
2.4 Screen Design	14
2.5 Fabrication Flow	16
2.6 Retroreflective Characteristics	19
2.7 Results and Discussions	21
2.7.1 Brightness and Optical Gain	21
2.7.2 Entrance Angle	23
2.7.3 Transmission Properties	24

2.8	Conclusion	26
Chap. 3: 3D Display Applications using Transparent Retroreflective Screens		28
3.1	Augmented Reality 3D Display	28
3.1.1	Introduction.....	28
3.1.2	Concept of The Display	29
3.1.3	Test Prototype.....	31
3.1.4	Retroreflective and Polarization Characteristics	32
3.1.5	Results and Discussion	35
3.1.5.1	Eye-box Analysis	35
3.1.5.2	Stereo Crosstalk.....	37
3.1.5.3	Brightness and Optical Gain.....	39
3.1.6	Conclusion	41
3.2	Windshield 3D Head-Up-Display using Simulated Collimation.....	42
3.2.1	Introduction.....	42
3.2.2	Background.....	43
3.2.2.1	Accommodation-convergence Conflict.....	43
3.2.2.2	Simulated Collimation.....	44
3.2.3	See-through Retroreflective Screen as windshield 3D HUD	45
3.2.4	User Study	46
3.2.4.1	Apparatus.....	46
3.2.4.2	Participants	47
3.2.4.3	Procedure.....	47
3.2.5	Results and Discussion	49
3.2.5.1	Experiment-1: See-through Condition	49
3.2.5.2	Experiment-2: Simulated Collimation Condition.....	50
3.2.5.3	Difficulty Level and Discomfort	51

3.2.5.4	Key Findings	52
3.2.6	Conclusion	52
Chap. 4: Light Field Imaging Using Handheld Lens Array Surfaces		54
4.1	Introduction	55
4.1.1	Light Field versus Integral Imaging	55
4.1.2	Light field Representation	56
4.1.3	Handheld Surfaces for Light Field Capture.....	57
4.2	Previous Work.....	58
4.3	Geometry of Image Formation.....	59
4.4	Spatial-Angular Resolution Tradeoff.....	61
4.5	Optimizing Resolution	64
4.6	Surface Detection and Tracking.....	66
4.7	Test Experiments.....	68
4.8	Results and Discussion.....	69
4.8.1	Image Reconstruction	69
4.8.2	Field-of-view and Camera-to-Surface Distance	72
4.9	Conclusion	74
Chap. 5: Integrated 3D Display and Imaging Using Dual Purpose Passive Screen .75		
5.1	Introduction.....	75
5.2	Previous Work.....	76
5.3	Concept of the System	78
5.4	Screen Fabrication.....	80
5.5	Simultaneous Imaging and Display	81
5.5.1	Time Multiplexing.....	81
5.5.2	Polarization Multiplexing	83
5.6	Experimental Prototype.....	84

5.7	Demonstration of 3D Telepresence.....	86
5.8	Results and Discussion.....	87
5.8.1	Display Characteristics	87
5.8.2	Image Capture and Visualization.....	91
5.8.3	Capture Quality.....	92
5.8.4	Capture Light Efficiency	94
5.9	Conclusion	95
Chap. 6: Conclusion.....		97
Appendices.....		101
	Appendix I: MATLAB Script for MTF Measurement	101
	Appendix II: MATLAB Script for Light Field Reconstruction.....	102
	Appendix III: Script for Light Field Reconstruction on GLSL Shader Language	111
Publication Record		113
Bibliography		115

LIST OF TABLES

Table 4.1. Comparison of different light field imaging techniques	58
Table 4.2. Specifications of the state-of-the-art smartphone cameras	62
Table 4.3. Parameters of the prototype surfaces used in test experiments	69
Table 5.1. Polarization state of the projected and the ambient light at different surfaces of the screen	84
Table 5.2. Loss of transmitted light for different interfaces of the system	95

LIST OF FIGURES

Chapter 1

Figure 1.1. Basic anatomy of the human eye.	2
Figure 1.2. The first ever stereoscopic display invented by Sir Charles Wheatstone in 1852 [3]... 4	
Figure 1.3. (a) Micro-mirror based MEMS scanner used in pico-projectors, (b) Illustration of image scanning using three laser sources, beam combining optics and MEMS scanner [16], and (c) Commercial laser scanning pico-projectors by Microvision (top), Celluon (middle) and Sony (bottom) [13–15].	7
Figure 1.4. (a) The optical module of the early version of the laser scanning pico-projector from Microvision, and (b) stripped version of the optical module of laser scanning pico-projector from Sony [15].	7
Figure 1.5. Contribution and structure of this dissertation.	8

Chapter 2

Figure 2.1. Difference between diffusion, specular reflection, and retroreflection.	13
Figure 2.2. Ray propagation through a microsphere retroreflector (a) and a corner-cube retroreflector (b), and (c) shows microscopic images of microspheres and corner-cub based retroreflective surfaces.	14
Figure 2.3. Steel stencil used as patterning shadow mask during the screen fabrication.	16
Figure 2.4. The fabrication process of transparent retroreflective screen, (i) optically clear substrate (200 μm) preparation, (ii) thin (<20 μm) adhesive coating, (iii) flexible mask (steel stencil) bonding and alignment, (iv) retroreflective microspheres deposition, (v) mask removal, and (vi) transferred periodic pattern with retroreflective microspheres.	17
Figure 2.5. (a) The virtual content displayed on the screen as perceived by the viewer close to the projector, (b) A user wearing an HMPD and using the transparent retroreflective screen, and (c) microscopic view of the screen (75% transparent) showing the active and inactive retroreflective microspheres.	18

Figure 2.6. (a) The viewing angle formed by viewer's eye with respect to screen and projector, and (b) Illustration of the photometric setup used to measure the retroreflective coefficient of the transparent screen..... 19

Figure 2.7. Experimentally recorded retroreflective coefficient for three different screen samples. The coefficient value decreases with increasing screen transparency, while the shape of the retroreflective cone is unaffected. 20

Figure 2.8. The brightness performance (a), and optical gain (b), of three different versions of the screen (50%, 75%, and 90% transparency) when the eye-projector distance (s) is 2 cm and 5 cm. 22

Figure 2.9. The entrance angle of different versions of the transparent retroreflective screen. The intensity of the retroreflected light remains nearly constant within the wide range of incident angles (-75 to $+75$ degrees). 24

Figure 2.10 The experimental setup used to measure transmission MTF of the screen, (b) the captured edge profile through 75% transparent screen, (c) the recovered edge spread function (ESF), and (d) corresponding point spread function (PSF). 25

Figure 2.11. Measured transmission MTF for three screen samples. MTF₅₀ (50% cutoff) is reduced from 18 cyc/degree to 8 cyc/deg and MTF₁₀ (10% cutoff) is reduced from 37 cyc/deg to 30 cyc/deg when screen transparency is decreased by 50%. 26

Chapter 3

Figure 3.1. A projector pair illuminates the screen with stereoscopic content, the light from each projector is returned to the associated projector and perceived by the eye closer to the projector. Each projector (represented by red and blue) displays the full-color images. 30

Figure 3.2. (a) The desktop size experimental prototype (b) The content as projected using one of the two projectors and perceived by eye closer to the associated projector. 31

Figure 3.3. The experimentally measured retroreflective coefficient, the microspheres buried in screen create a 100 mrad wide retroreflective cone, the diffraction minima are observed due to the aperture diffraction of microspheres. 33

Figure 3.4. The polarization maintaining ability of the see-through retroreflective screen. a) Normalized captured intensity as a function of polarization orientation measured with a photometric setup, b) and c) the screen surface illuminated with horizontally polarized light and captured by placing a horizontal polarizer (b) and, a vertical polarizer (c) in front of the camera. 34

Figure 3.5. The different eye-projector configurations, (a) bare eye configuration, where projection beam is folded towards screen using mirrors, (b) polarizer based configuration, where

additional polarizer films are used to separate two views and, (c) Beam-splitters based configuration, where eye-to projector gap is minimized.....	35
Figure 3.6. The eye-box size and overlap for different eye-projector settings at distance of 100 cm from the screen. a) Screen viewed with bare eyes, b) projectors are polarized in different directions having the matching polarizer in front of each eye and, c) 50/50 beam splitters used to align the respective eye and the projector.	36
Figure 3.7. Crosstalk per eye in stereo mode plotted as a function of the screen to viewer distance for three viewing configurations. Higher stereo crosstalk is observed when viewing the display with bare eyes, while negligible crosstalk is observed when polarizer or beam splitter is placed in front of the eye.	38
Figure 3.8. The left and right views as seen by the viewer at 125 cm from the screen and viewed, a) with bare eye, b) through polarizer films and, c) beam splitters. The same camera settings were used in all the pictures. A printed visual acuity chart on the other side of the display can also be seen.....	39
Figure 3.9. Brightness and optical gain as the distance between viewer/projector and screen is varied. Maximum brightness with an exponential decrease is perceived when eye and projector are aligned using beam-splitter, while nearly constant brightness is perceived when the screen is viewed with bare eye or through the polarizer. Higher optical gain is observed with bare eye configuration at the larger working distance.	40
Figure 3.10. Accommodation-convergence conflict, natural viewing mode, where accommodation and convergence distances are matched (left) and, stereo 3D display, where accommodation and convergence distances are different (right).	43
Figure 3.11. The principle of simulated optical collimation using stereoscopy, the collimation is provided by adjusting the parallax between stereoscopic views.	44
Figure 3.12. A virtual dashboard displayed on a see-through retroreflective screen.	45
Figure 3.13. The prototype setup used for the user study. The Snellen acuity chart is placed at the distance of 7 meters from the user.	46
Figure 3.14. The experimental setting for see-through condition (a), and simulated collimation condition (b). Both projectors show full-color images, left and right eye projected images on the screen are shown with red and green colors for illustration purposes.....	48
Figure 3.15. Average visual acuity in see-through condition and its comparison with direct viewing. The acuity response is slightly reduced when the screen is placed between user and acuity chart.	49
Figure 3.16. (a) The average visual acuity for different screen distances under simulated collimation condition and, (b) the average accuracy at different accommodation-vergence	

differences, when smaller size characters (20/70 and 20/50) are displayed on the screen. The error bars show the minimum and maximum accuracy achieved during the test. 51

Chapter 4

Figure 4.1. Parameterization of the light field using two parallel planes [69]. 56

Figure 4.2. The concept of mobile light field capture using a handheld lens array surface and regular camera. The tracking markers are used to find the location of the surface with respect to the camera. 57

Figure 4.3. The process of image formation using the lens array surface. The ray tracing geometry is based on the paraxial geometric optics and ignores the high order abbreviations of the lenses. 60

Figure 4.4. The diffraction limited resolution of the single camera and lens array surface based light field capture system. 61

Figure 4.5. The trade-off between spatial and angular resolution for a smartphone camera. (a) Maximum number of pixels per view, and (b) the maximum number of sub-images/views that can be captured along the width of a 12MP smartphone camera sensor. 63

Figure 4.6. Maximum achievable spatial resolution for three different camera settings, when f-number for camera is (a) $f/4$, (b) $f/1.7$, and (c) $f/1$. The resolution is improved if the lens size is larger and FOV per view is narrower. 65

Figure 4.7. The implementation of the surface detection tracking module on two different images. The captured image is processed to detect the corner of the surface and extract the captured perspective views. 67

Figure 4.8. Two versions of the lens array surface providing (a) 24 perspective views, (b) 72 perspective views, and (c) shows the lens array surface used with a smartphone camera in outdoor settings. 68

Figure 4.9. The process of image reconstruction. The pixels are traced through each lens and their cumulative contribution at each output pixel is calculated. 70

Figure 4.10. The reconstruction results for digital refocusing, (a) Outdoor scene captured with S1, (b) and (c) the reconstructed images at different depths, parking sign and car respectively, (d) An indoor scene captured using S2, (e) and (f) shows refocused images at toy train and printed OML text respectively. 71

Figure 4.11. Demonstration of image capture through the partial occlusion, (a) One of the captured sub-images from the lens array surface, and (b) reconstructed image. 72

Figure 4.12. Change in the field-of-view of the imaging system, when the distance between the camera and the lens array surface is varied. The higher field-of-view at a closer distance is the result of the change in the direction of the lens chief rays. 73

Chapter 5

Figure 5.1. Conceptual illustration showing the working principle of the integrated 3D display and imaging system for a 3D telepresence application. The stereo-3D views of a remote person are displayed on the screen, while the perspective views of the local user are recorded using the head-mounted camera at the same time. 79

Figure 5.2. (a) Fabrication of the dual-purpose screen showing the arrangement of different layers of the screen, (b) the images of the developed handheld screen, (c), and (d) the close-ups of a mirror in the screen when the camera is focused on retroreflective pattern and reflected image respectively..... 80

Figure 5.3. The procedure of time multiplexing between rolling shutter camera and scanning laser pico-projector to separate the captured and projected content on the screen. The camera shutter release is delayed with respect to starting time of the scanning period of the pico-projector. 82

Figure 5.4. The principle of the polarization multiplexing of projected and captured light. The ambient scene is seen only by the camera, while the projected images are only perceived by the eyes..... 83

Figure 5.5. (a) Tabletop experimental prototype, (b) close view of the head-mounted unit with two pico-projectors, placed in a 3D printed housing, and a camera. 85

Figure 5.6. The 3D telepresence architecture using dual-purpose screens and head-mounted units. 86

Figure 5.7. (a) A local user with the developed setup, (b) remote user with a VR headset, (c) 3D content seen by the local user on the dual-purpose screen, and (d) 3D content seen by remote-user on the VR headset..... 87

Figure 5.8. (a) Eye-box size and overlap between the left/right eye-box at a 70 cm working distance, (b) brightness, optical gain and crosstalk per eye when the distance between the screen and the viewer is changed. 89

Figure 5.9. (a) and (b) A stereo 3D content displayed on the screen when viewed through the polarizer or without polarizer respectively, (c) the perceived views captured by the camera from the left eye, right eye and center positions respectively..... 90

Figure 5.10. (a) The perspective views of the scene captured in a single shot, (b) and (c) two different reconstructed viewpoints relayed to a stereo display. 92

Figure 5.11. (a) Experimental setup for MTF measurement, (b) captured edge profile on the camera sensor for different configurations, and (c) measured MTF. With 10% cutoff limit, the imaging quality is reduced to one-third when a polarizer sheet is placed on top of mirror surface while 50% additional loss is observed when the retroreflective microspheres are patterned on the polarizer. 93



NOMENCLATURE

3D	Three Dimensional
AC	Accommodation-Convergence
AR	Augmented Reality
ERC	European Research Council
ESF	Edge Spread Function
FOV	Field-of-view
GPU	Graphical Processing Unit
HCI	Human-Computer Interaction
HEC	Higher Education Commission
HMD	Head Mounted Display
HMPD	Head Mounted Projection Display
HUD	Head-Up-Display
IP	Integral Photography
IPD	Inter-pupillary Distance
LCD	Liquid Crystal Display
MEMS	Micro-Electro-Mechanical Systems
MLA	Micro-Lens Array
MTF	Modulation Transfer Function
OLED	Organic Light Emitting Diode
OML	Optical Microsystems Laboratory
PSF	Point Spread Function

CHAPTER 1

INTRODUCTION

This dissertation introduces and explores new 3D display and light field imaging techniques for next-generation augmented reality display and imaging applications. The driving force behind this research is the innovation in the passive optical surfaces to offer mobility, light efficiency, and improved 3D experience when combined with low power pico-projectors and regular cameras. We show that specially designed passive optical surfaces can enable new ways to perceive and interact with the digital world and capture the real world efficiently. A significant part of this research uses the micro-structured retroreflective materials, which provide bright imagery using low power projectors. The laser scanning pico-projectors are used as image source to provide focus-free images, higher contrast, and prominent resolution. The miniature size of the optical module makes the pico-projector a suitable candidate for the head-mounted devices and wearable displays, where minimum power consumption, lightweight, and ergonomic comfort are the top priorities.

This chapter discusses the basics and fundamental principles needed to better understand this research and emphasizes on the contribution and structure of this dissertation. Since all display and imaging technologies depend on the understanding of the human vision, a brief introduction of the human visual system is presented. An overview of 3D display and imaging technologies is also presented. The basic concept and major types of augmented reality are also discussed. Finally, the scanning laser pico-projector, which is used as the image source during the significant part of this research, is briefly discussed,

1.1 Human Visual System

Vision is one of the complicated sensory systems of the human body, which provides the sight of the surroundings. The pair of eyes is separated by a fixed distance called interpupillary distance (IPD). An adult human being has an average IPD of 6.5 *cm*. The eyes behave like two cameras and capture this World from two different positions. The images from each eye are fused by the brain to have a better understanding of the scene. The field-of-view (FOV) of a human eye is about $150^{\circ} \times 120^{\circ}$ providing the total FOV of $200^{\circ} \times 120^{\circ}$ with $100^{\circ} \times 120^{\circ}$ FOV overlap between both eyes [1].

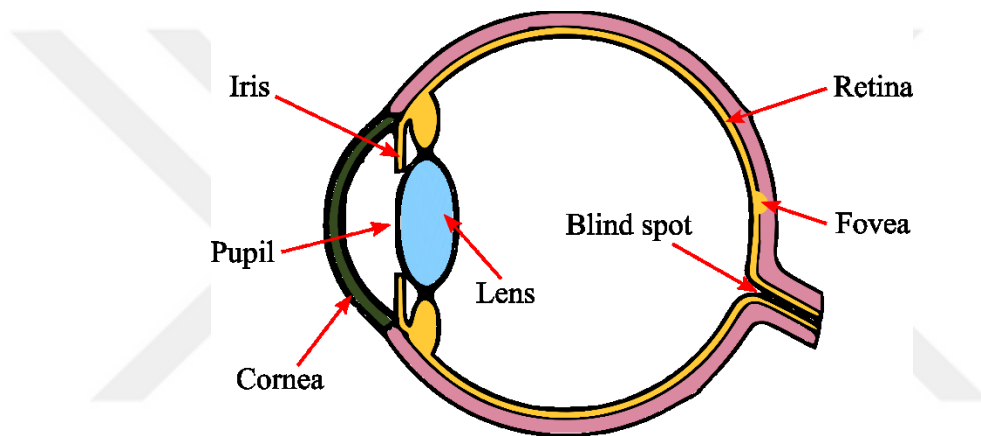


Figure 1.1. Basic anatomy of the human eye.

To understand the principles of display technologies and 3D perception its necessity to be familiar with some terminologies related to the eye. Following are few important terms related to the human visual system.

- **Accommodation:** The ability of the eyes to change its focal length and accommodate at different distances. When the eye is focused at infinity, the eye lens muscles are relaxed and have minimum lens thickness. As the eye tries to create a blur-free image of close by objects, the eye muscles are stressed to thicken the lens and change its focal length.
- **Vergence:** The horizontal rotation of eyeballs in either same or opposite direction. The eye rotation is linked to the disparity. The brain forces the eye rotation to converge on the same point in space and draw its corresponding images on the same positions in both retinas.

- **Fovea:** The innermost region of the eye covering about 1.7° diameter is called fovea. The visual acuity drops drastically outside this region, and our eyes and head move to fixate and compensate for the acuity loss.
- **Iris:** The aperture diaphragm of the eye defining eye pupil size and controlling the amount of light entered to the eye. The human eye has the pupil size of 2 – 8 mm, which is changed adaptively based on the illumination conditions of the surroundings.
- **Stereopsis:** A binocular depth cue based on the literal disparity between the left and right images on the retinas. The stereopsis is one of the most powerful depth cues and can be effective up to a few hundred meters [1].
- **Motion parallax:** A monocular depth cue that provides the sense of closer objects moving faster than distant objects. The motion parallax is perceived during the head or body motion.
- **Resolution:** The minimum angular size of the feature resolved by the eye. Rayleigh resolution criteria suggest changing resolution with varying size of the eye pupil. The typical angular resolution of the human eye is about 1 arc minute ($\approx 0.02^\circ$) when eye pupil is 4 mm. The actual resolution depends on the modulation transfer function (MTF) curves of the human eye [2].

Depth perception in human vision is facilitated by monocular and/or binocular cues. The monocular cues include accommodation, motion parallax, size, perspective, occlusion, texture, and shading, while the convergence and stereopsis are related to binocular cues. The stereopsis is one of the important depth cues of human visual systems and has been widely used by different display technologies to provide the sense of depth.

1.2 Three-Dimensional Display and Imaging

The primary source of depth extraction and 3D perception for the human brain is the stereoscopy, which is the fusion of two images each acquired by only one eye. The amount of horizontal displacement (disparity) for each of the objects appearing in those two images is widely used in a variety of stereo display technologies to provide the 3D effect. The first device to provide stereoscopic vision (called stereoscope) was invented by Sir Charles Wheatstone in 1852 [3]. His device composed of two perspective images

and a pair of the mirror to relay each image to one eye as shown in Figure 1.2 The basic principle of the majority of existing 3D displays in the consumer market is still based on this idea.

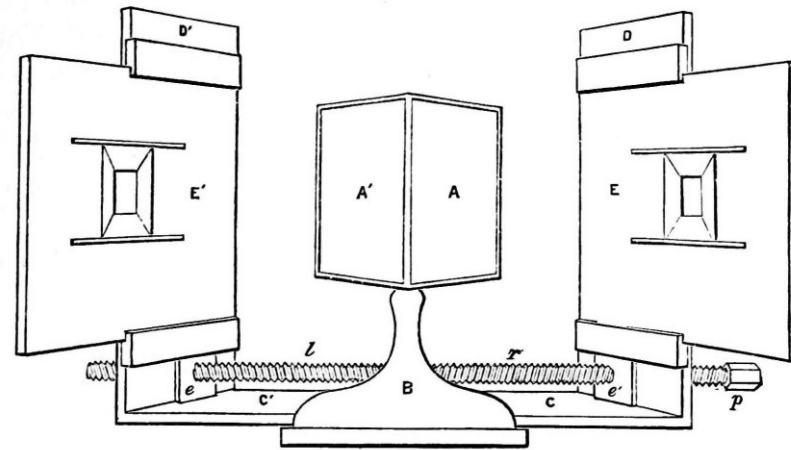


Figure 1.2. The first ever stereoscopic display invented by Sir Charles Wheatstone in 1852 [3].

Stereo 3D displays used today, range from direct-view stereoscopic displays, which require eyewear to autostereoscopic (glass-free) displays. The eyewear based stereo displays mainly use one of three different techniques 1) color multiplexing, 2) polarization multiplexing and 3) time multiplexing [4,5]. A color multiplexed stereo display separates two images by color coding the left and right views, which are then perceived by a viewer wearing the matching color filter based glasses. The anaglyph color coding based glasses and displays are the best examples of color multiplexed displays. In the polarization multiplexed stereo displays, the polarization direction of light for stereo views is mutually perpendicular, while the screen is viewed with polarization matched glasses, which transmit the light (image) intended for a particular eye only. The time multiplexed displays on the other hand use high refresh rate displays to display stereo views in the sequence, which are then separated using the active shutters based synchronized eyewear. The near-to-eye and head-worn type 3D displays (i.e. virtual reality displays) on the other hand use pair of micro-displays or LCD each dedicated to one eye. The autostereoscopic and multi-view displays have been realized using parallax barriers, lenticular sheets, multiple projectors and integral 3D displays. A parallax barrier display uses the aperture mask pattern on top a display screen, such that

the portions of the screen are invisible from particular viewing direction [5]. The lenticular sheets contain the array of lenses called “lenticules” whose purpose is similar to parallax barrier but provides higher light efficiency. The projectors base systems use multiple projectors together with lenticular sheets and diffusing screens to provide autostereoscopic of multi-view effect. Compared to parallax barrier and lenticular screen, the multi-projector approach can provide enhanced resolution. The integral 3D display, on the other hand, provides both horizontal and vertical parallax by using spherical lens arrays instead of lenticular sheet [5].

On the other hand, 3D imaging is facilitated by capturing the scene/object from a different perspective. The simplest 3D imaging technique is based on the stereoscopy, where two horizontally spaced cameras are used to record stereoscopic views. The advanced 3D imaging systems either use one or multiple cameras and additional optics to record the 3D information of the scene, which include distributed camera arrays, plenoptic cameras, integral imaging pickup systems and catadioptric cameras [6–9]. The 3D depth map is usually recorded using active imaging techniques, which include time-of-flight and structured light cameras [10,11].

1.3 Augmented Reality

The augmented reality (AR) is defined as an enhanced version of the physical world/existing reality. The live view of the real-world is augmented with virtual/computer-generated information to enhance the perception of the existing reality. The virtual information can be a video, sound, graphics or haptic feedback, but the AR is usually referred for augmented images and graphics. Unlike virtual reality where the user is disconnected from the real-world and fully immersed in the virtual world, the AR allows the users to perceive and interact with virtual objects without losing the view of the real-world. The AR experience provides the perception of an improved world with virtual information, which can be used to assist the users in the everyday activities. The augmented reality can be used for a variety of applications including education, training, visual arts, architecture, archeology, digital marketing, videos games, industrial design development, medical visualization and surgery, navigation and military.

The AR devices and technologies can be categorized into several types each developed for different usage scenario. The simplest AR implementation is based on handheld display devices (i.e. smartphones, tablets), which offer the video see-through AR. The real-world in this case is captured with the device camera and the live view of the scene is populated with the digital information and shown on the device display [1]. On the other hand, head-mounted displays (HMD) are the helmet or headband type AR devices, which provide the superimposed views of both real-world and virtual objects over the field-of-view (FOV) of the user [12]. A compact version of the HMDs is the smart glasses resembling the regular eyeglasses, which show the real-world and augmented information on the eyepiece. Another type of AR devices is the head-up-displays (HUD), which has the transparent display to show the virtual information within the direct view of the user. Before the AR applications, the HUDs were developed for pilots to display flight information directly in front of their eyes [12]. The spatial augmented reality (SAR) is another type that augments the digital information directly on the real objects. SAR use multimedia projectors to overlay virtual content on the real objects and are usually used in multi-user environments.

1.4 Scanning Laser Pico-Projectors for Wearable Displays

One of the main elements used during this research is the laser scanning pico-projector, which is an off-the-shelf device initially produced by Microvision [13] and later developed and sold by Sony and Celluon as a consumer product [14,15]. The device consists of 3-5 laser light sources corresponding to red, green and blue color wavelengths. The light from different lasers is combined to create a single full-color beam, which is directed to a micromirror-based MEMS scanner. The scanner is an electromagnetic actuator scanning the beam in two axes in a raster scan pattern to generate the projected image on a surface. Due to the collimated nature of the laser sources, the laser scanning pico-projectors do not need focusing optics and a focus-free image is projected. The lasers from the projector are collimated and possess a Gaussian beam profile with a beam waist of $<0.5\text{ mm}$. The beam waist is reached when the beam travels 50 cm from the projector.

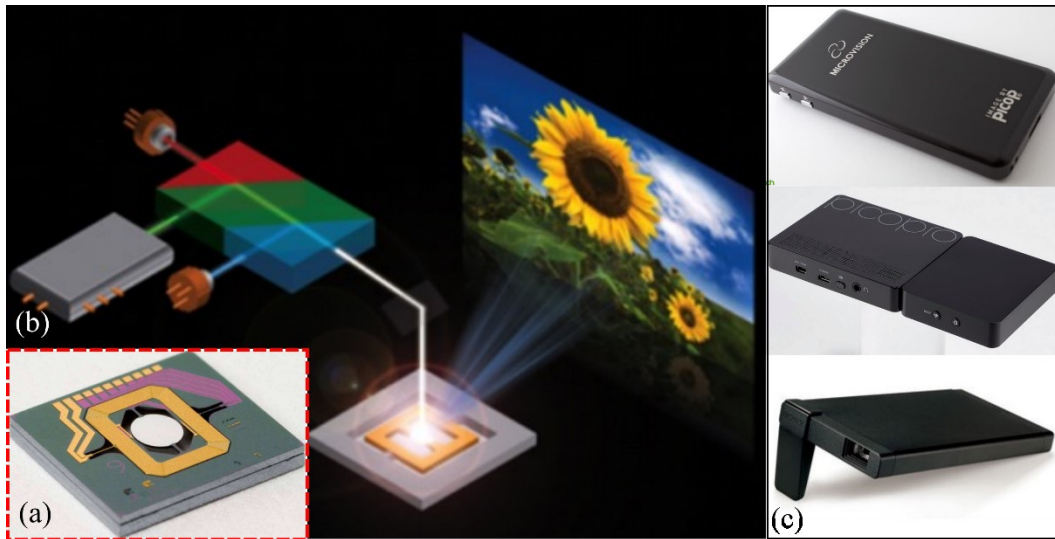


Figure 1.3. (a) Micro-mirror based MEMS scanner used in pico-projectors, (b) Illustration of image scanning using three laser sources, beam combining optics and MEMS scanner [16], and (c) Commercial laser scanning pico-projectors by Microvision (top), Celluon (middle) and Sony (bottom) [13–15].

The high contrast, focus-free projection and small size make the pico-projector the best resource for augmented reality applications. Over the past decade, our laboratory, optical microsystems laboratory (OML) have been involved in the innovation and development of the wearable 3D displays and augmented reality technologies using the laser scanning pico-projectors, which included low refresh rate flicker-free 3D displays, rotating screen based autostereoscopic displays and multi-view 3D displays [16–18].

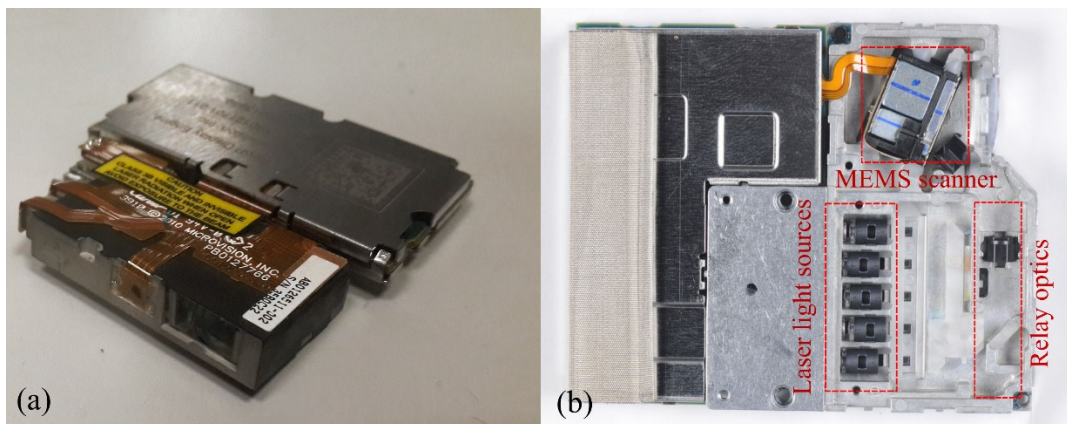


Figure 1.4. (a) The optical module of the early version of the laser scanning pico-projector from Microvision, and (b) stripped version of the optical module of laser scanning pico-projector from Sony [15].

1.5 Structure of the Dissertation

The content of this dissertation can be divided into three parts and is distributed into four chapters as illustrated in Figure 1.5. The first part presents our work in the field of AR displays, where we present a novel transparent retroreflective screen and its implementation for 3D augmented reality and head-up-display applications. The second part introduces a new light field imaging technique to capture the 3D information of the scene in mobile settings. The last part presents an integrated 3D display and imaging technique using the head-mounted device and a dual-purpose screen.

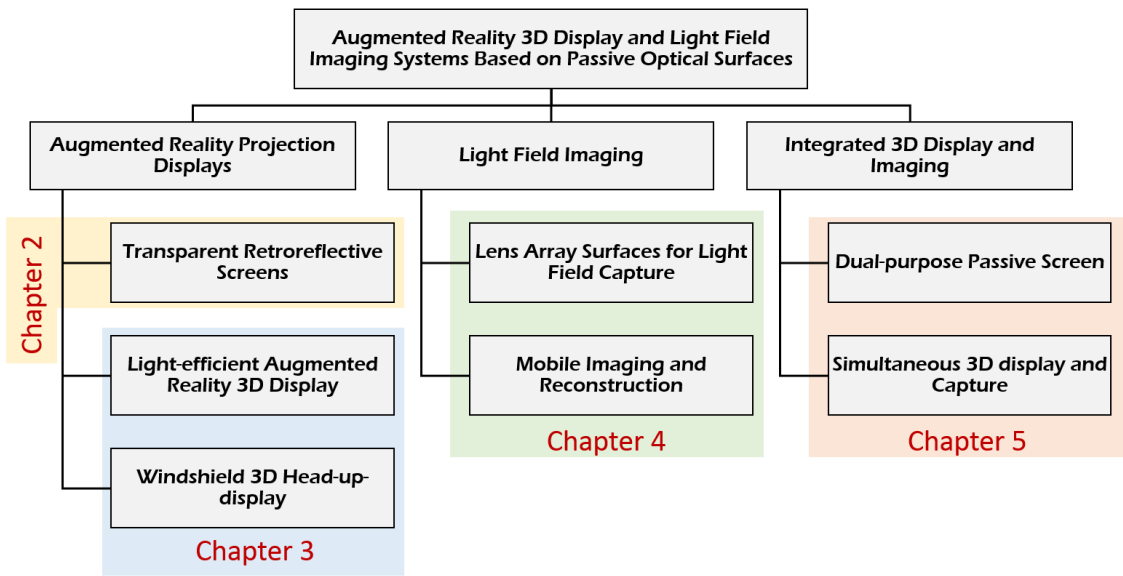


Figure 1.5. Contribution and structure of this dissertation.

In Chapter 2, a novel transparent screen, which provides higher brightness and optical gain using retroreflective microspheres while maintaining the high optical transparency, is introduced. The optical design and fabrication flow of the screen are presented, and key properties of the developed screens are examined.

Chapter 3 presents two implementations of the transparent retroreflective screen when combined with the head-mounted pico-projectors. The first technique is an AR 3D display to provide bright and crosstalk-free stereo imagery on a highly transparent screen using a pair of head-worn pico-projectors. The test prototype is demonstrated and display characteristics such as brightness and crosstalk per eye are evaluated. The second

application presents an experimental user study on the transparent retroreflective screen when used as a windshield 3D head-up-display under simulated optical collimation. The study investigates the effects of simulated collimation and screen transparency on the human vision and devises a relationship between accommodation-convergence conflict and visual acuity response of human eyes.

Chapter 4 introduces a new light field imaging technique using handheld lens array surfaces and a regular camera. The technique provides a mobile and scalable solution for light field capture using regular cameras and provides a real-time image reconstruction using a backend processing module.

In Chapter 5, a novel integrated 3D display and imaging system is introduced that provides simultaneous 3D display and 3D imaging using a head-mounted device and a dual-purpose passive screen. The tabletop test prototype is developed to demonstrate the combined operation for 3D telepresence applications and important display and imaging characteristics of the system are studied.

1.6 Contribution to the Literature during PhD Studies

This section provides the summary of the contribution of this dissertation to the literature. The details of the publications within my PhD studies can be found in the bibliography section entitled as “Publication Record” at the end of this dissertation.

The transparent retroreflective screen introduced in Chapter 2 was published as a journal paper [P5]. The paper presents the design, fabrication, and characterization of the transparent retroreflective screen for augmented reality applications. The idea of the transparent screen was also presented at different conferences [P9,P10]. The augmented reality 3D display introduced in Section 3.1 was published as a journal paper [P4]. The paper presents the demonstration and evaluation of augmented reality 3D display using head-mounted projectors and large size transparent retroreflective screen. Various aspects of the developed 3D display were also presented at different conferences [P11-P13]. The implementation and the user study of a windshield 3D head-up-display introduced in Section 3.2 is submitted as a journal paper and is currently under review [P2]. The light field imaging technique introduced in Chapter 4 is not published yet and is under preparation for a journal submission [P1], though it was recently presented at a

conference [P14]. The integrated 3D display and imaging technique introduced in Chapter 5 is published as a journal paper [P3]. Two patents are also filed on the similar subject [P7,P8]. An early demonstration of the dual-purpose screen was also presented at a conference [P15].

Apart from this dissertation, a crosstalk-free time multiplexed imaging scheme for projection-based augmented reality systems that was presented at a conference and was also published in the special issue of a journal [P6] was also developed. The technique is briefly introduced in Section 5.5.1. A user study on the visual attenuation in head-mounted projection displays, which was the result of collaboration between Koç university Design lab and OML was also presented at a conference [P16]. My contribution in this work was mainly on the content development for user tests and hardware support for the HMPD.

Overall four first author journal papers were published, two patents were filed and eight conference presentations were made. Also, one journal paper is under review and an additional journal manuscript is in preparation.

CHAPTER 2

TRANSPARENT RETROREFLECTIVE SCREENS

This chapter presents the design, fabrication, and characterization of a novel transparent retroreflective projection screen for augmented reality applications, which we have published under [19]. The screen provides higher light efficiency when used with the low power pico-projectors. Section 2.1 presents the introduction of the transparent screen, Section 2.2 provides an overview of the previous work on the transparent screens. Section 2.3 presents the theory of retroreflective materials. Section 2.4 explains the design of the screen, Section 2.5 presents the fabrication process, Section 2.6 explores the retroreflective characteristics of the developed screens and Section 2.7 evaluates various display and transmission properties of the screen.

2.1 Introduction

Transparent display surfaces are explored for many useful applications. Their ability to display virtual content without obstructing the real-world scene make them a suitable choice for augmented reality hardware and applications. The applications of the transparent screens range from 2D/3D head-up-displays for vehicular windshields to the large see-through screens for augmented reality display systems.

In this work, we present a novel transparent retroreflective screen designed for 2D/3D head-mounted projection display and head-up-display applications. The proposed screen can be used to display bright content using the low power wearable pico-projectors while maintaining significant transparency. The screen has a micro-pattern providing the partial filling of the retroreflective microspheres. The retroreflective microspheres reflect the incident light back towards source with narrow-angle scattering, which makes the screen light efficient for the working scenarios where the viewer has limited movement

with respect to the light source (projector). We designed and developed different versions of the screen providing different levels of optical gain and transparency.

2.2 Previous Work

The transparent displays have been explored in several ways using both active and passive optical surfaces. The active transparent displays using transparent liquid crystal displays (LCD) have been demonstrated with light-box and as a door for fridges and microwaves [20,21]. However, the transparent LCDs are not self-emissive and transmit only 17% of light through color filters and polarizer, which provides poor transparency. The self-emissive transparent organic light Emitting diodes (OLEDs) using transparent thin film transistors are promising but they also suffer from lower transparency [22]. The alternative of the active transparent displays are the passive screens illuminated by projectors. For applications with large working spaces, the diffusive transparent back-projection screens have been demonstrated by several companies. The back-projection transparent screen technologies are divided into two types [23], 1) anisotropic, which diffuse the light coming from explicit direction [24], and 2) isotropic, which diffuses the projection light coming from any direction [25]. The anisotropic screens are realized by using the holographic gratings, while the isotropic screens are developed by embedding the particles or droplets in a clear material. The back-projection screens can provide enhanced transparency but require very high-power projectors to achieve reasonable brightness.

A non-transparent diffused screen (i.e. Lambertian scattering screen) scatters the incoming light in a hemispherical volume and is considered to have an optical gain of 1. High optical gain is important for transparent screens, especially when used for mobile applications and high ambient environments due to their inherent transmission loss. The optical gain can be enhanced by either performing resonant scattering or diffusing the projected light within a restricted zone. The wavelength selective scattering screens are developed by embedding the resonant nano-particles into a clear glass [26], the nano-particles scatter only selected color wavelength and transmit other colors. Index-matched partially reflective micro-lens arrays (MLA) have been used to build the transparent screens where micro-lenses scatter the part of incident light and create the eye-box for

the viewer while the remaining light is transmitted through partial coating [27,28]. Although the resonant particles and MLAs can enhance the brightness of the screen, achieving a full-color display with wavelength selective scattering and reasonable brightness with MLAs using the low power pico-projectors is still not possible. Transparent screens using lens arrays recorded on a holographic material film have also been demonstrated [29]. However, recording the hologram on the large surfaces is practically difficult.

2.3 Theory of Retroreflective Materials

A retroreflective surface reflects an incident light ray such that it travels back to the direction it's coming from. Reflection of the ray back to the source makes the retroreflective surfaces different from specular surfaces and diffusing surfaces as shown in Figure 2.1. There are two types of retroreflective materials, which are used for road safety applications, (i) glass microspheres retroreflectors (also known as cat's eye retroreflectors), and (ii) corner-cube retroreflectors.

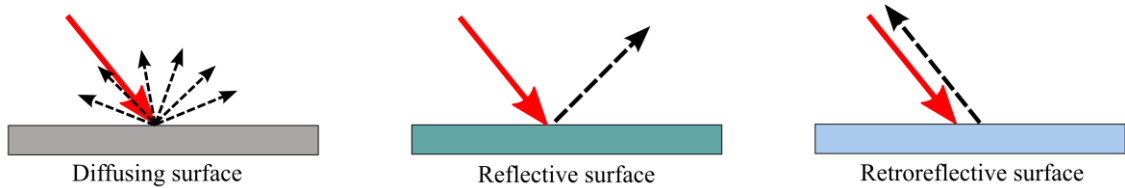


Figure 2.1. Difference between diffusion, specular reflection, and retroreflection.

2.3.1 Glass-microspheres Retroreflectors

The microsphere is a simple and common retroreflector used for road safety applications for about a century. When a light ray is directed on the microspheres, the significant amount of light passes into microsphere and is bent or refracted towards the center of the back side of the microsphere as shown in Figure 2.2(a). The back side of the microsphere is covered with a reflective coating, which reflects the ray inside the microsphere and the ray travel parallel to the direction it came from [30].

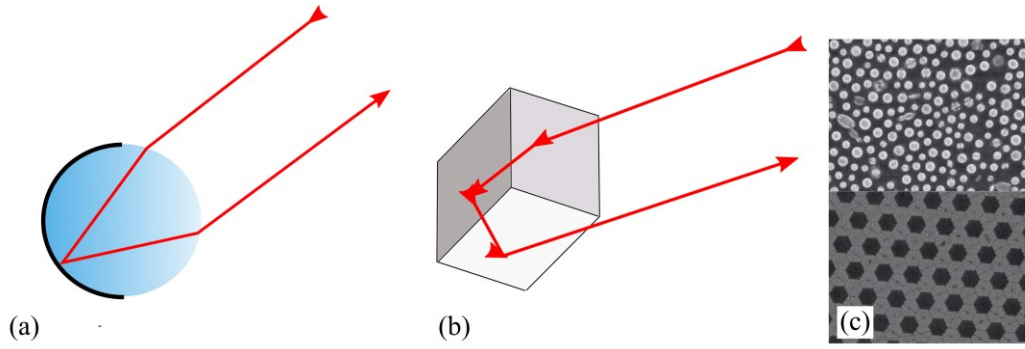


Figure 2.2. Ray propagation through a microsphere retroreflector (a) and a corner-cube retroreflector (b), and (c) shows microscopic images of microspheres and corner-cub based retroreflective surfaces.

2.3.2 Corner-cube Retroreflectors

In a corner-cube retroreflector, the light ray is reflected from three inter-perpendicular reflective surfaces making the corner of a solid cube as shown in Figure 2.2(b). The corner-cube retroreflector is more efficient when compared to glass microspheres but has some limitations. The light entering at the edge is only reflected by two sides and misses the third reflection, which creates about 35% loss of incoming light [31]. The entrance angle of corner-cube reflectors is also shallow and any ray incident at a higher angle is bounced off the surface.

2.4 Screen Design

The proposed screen makes use of the retroreflective microspheres in the form of perforated micro-patterns to direct the light back towards projector. A regular retroreflective surface can provide several times higher brightness than a diffused screen in a particular viewing setting [32,33]. The transparency is introduced by controlling the amount of the retroreflective material on a clear surface (i.e. glass) in the shape of distributed micro-pattern. Significant display gain and enhanced transparency can be achieved by optimizing the surface filling. We minimize the visibility of the structural artifacts on the screen surface by making the feature size of the micro-pattern small enough to be irresolvable by a naked eye at a typical working distance from the screen.

Assuming 1 *arc-minute* angular resolution for the human eye and a working distance of $> 40\text{ cm}$, the feature size below $100\text{-}150\text{ }\mu\text{m}$ is not visible. Since the small pattern features are not visible to the human eye, different geometric shapes including circular, triangular and hexagonal can be used to make the retroreflective micro-pattern. In the presented implementation, we use the square shaped patches of size (x) $100\text{ }\mu\text{m}$ to create micro-patterns as shown in Figure 2.3.

To investigate the impact of surface filling on the retro-reflectivity and transparency, we developed three different versions of the screen having the retroreflective fill factor of 50%, 25% and 10% providing the screen transparencies of 50%, 75%, and 90%, respectively. Since the $100\text{ }\mu\text{m}$ feature size was the minimum achieved with the laser micromachining tool used for mask production, we keep the feature size (x) fixed and change the gap (y) between the retroreflective islands to vary the screen transparency (T) as shown in Figure 2.3, which is expressed as,

$$T = 1 - \frac{x^2}{(x + y)^2} \quad (2.1)$$

Our design utilizes the cat's eye retroreflectors. We used high refractive index microspheres, which had a half-shell coating of aluminum, to create retroreflective patterns. Compared to an ideal retroreflector, which retroreflects incident light without diverging, the retroreflective microspheres spread the incident light towards source by creating a narrow angular cone, which defines the eye-box of the display. The width of the cone depends on the refractive index and size of the microspheres where lower refractive index and smaller size of microspheres lead to an expanded cone (due to geometric optics and diffraction effects). We use titanium dioxide glass microspheres having the refractive index of ≈ 1.93 . The size distribution of microspheres is $35\text{-}45\text{ }\mu\text{m}$ with a mean diameter of $40\text{ }\mu\text{m}$ [34]. The perceived brightness of the display increases significantly when the viewer moves closer to the projector. The detailed retroreflective properties of the screen are discussed later.

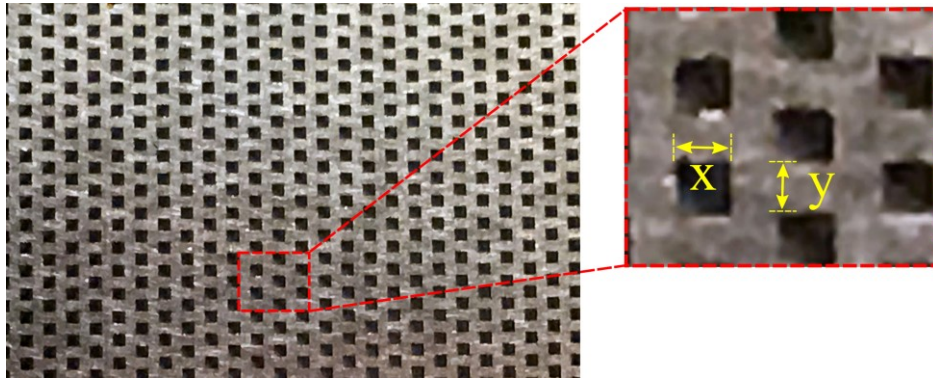


Figure 2.3. Steel stencil used as patterning shadow mask during the screen fabrication.

2.5 Fabrication Flow

Figure 2.4 illustrates the fabrication process of the transparent retroreflective screen. First, an optically clear thin ($200\ \mu\text{m}$) flexible acrylic substrate (Polymethyl methacrylate used as LCD protection film) was cleaned and prepared. In the second step, a $<20\ \mu\text{m}$ thick uniform coating of optical adhesive was applied to the substrate. Both pressure sensitive optically clear adhesive films (used for smartphone LCD glass repair) and UV curable liquid adhesive (Norland adhesives) were tested. The pressure sensitive adhesive was applied to the substrate in the form of thin film, while a substrate with pre-coated adhesive was also used. Both types of adhesive performed up to the mark, while the pressure sensitive adhesive was preferred due to its better mask alignment and release. In the third step, a thin mask (steel stencil) with perforated square holes was bonded to the substrate as a shadow mask. The stencil (shown in Figure 2.3) was designed in-house and was produced using the laser micromachining tools by availing the services from standard PCB stencil manufacturing companies.

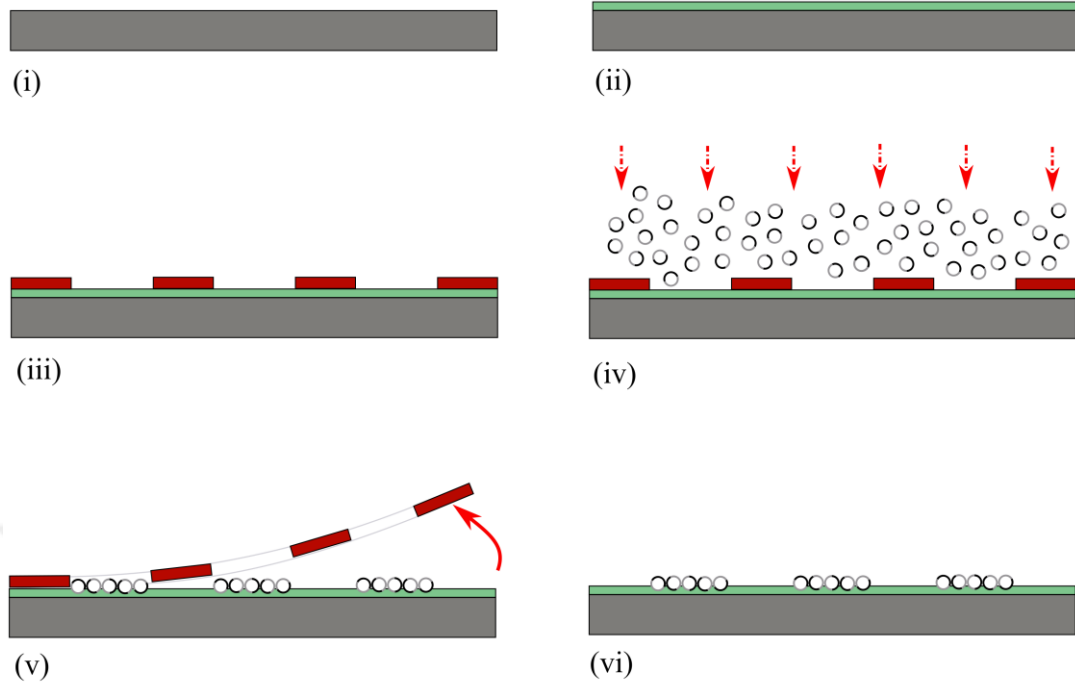


Figure 2.4. The fabrication process of transparent retroreflective screen, (i) optically clear substrate ($200\ \mu\text{m}$) preparation, (ii) thin ($<20\ \mu\text{m}$) adhesive coating, (iii) flexible mask (steel stencil) bonding and alignment, (iv) retroreflective microspheres deposition, (v) mask removal, and (vi) transferred periodic pattern with retroreflective microspheres.

In the next step, the retroreflective microspheres having hemispherical (half-shell) aluminum coating were randomly sprinkled on to the mask using a powder shaker container to fill perforations, and then microspheres were bonded to substrate by applying external pressure using a hand roller (typically used for LCD polarizer lamination). In the last step, the mask was peeled-off from the substrate by separating the substrate and the stencil and the retroreflective microspheres remained on the surface providing a transparent retroreflective screen as shown in Figure 2.5(a). For pressure sensitive adhesive, we did not notice any visible traces of adhesive transferred to stencil and the retroreflective pattern was neatly transferred to the substrate as seen in the microscopic image in Figure 2.5(a). For the UV curable liquid adhesive, a small gap between stencil and substrate was maintained by attaching scotch tape on the stencil boundaries to separate the mask and adhesive.

In the earlier implementations, the masks (stencils) of size $8\ \text{cm} \times 8\ \text{cm}$ and $16\ \text{cm} \times 16\ \text{cm}$ were used for fabrication and the large-sized screen (up to $30\ \text{cm} \times 20\ \text{cm}$) was

constructed by fabricating the screen segments individually and then tiling them together. In the later versions, larger mask sizes (up to $30\text{ cm} \times 30\text{ cm}$) with the feature size of $<300\text{ }\mu\text{m}$ were also used. To increase the transparency of the screen, a different stencil mask with reduced fill factor was used, while the fabrication process was same. The screens of larger size and variable aspect-ratio can be constructed by tiling higher number of segments together.

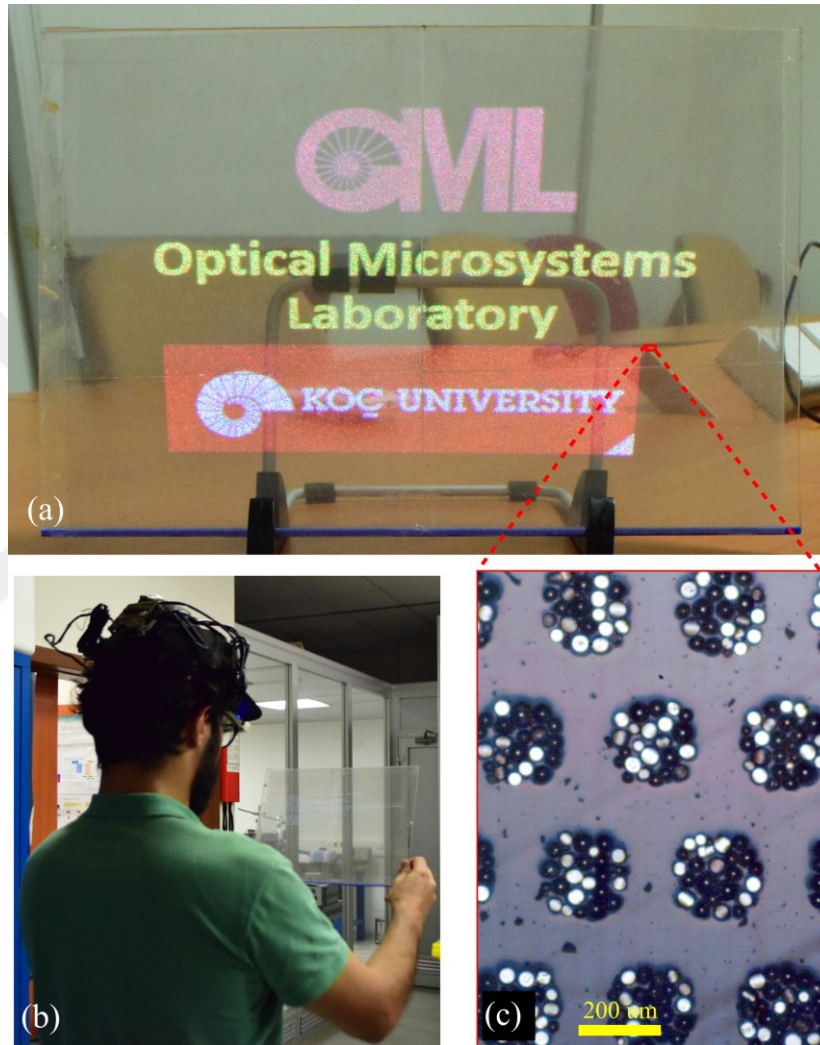


Figure 2.5. (a) The virtual content displayed on the screen as perceived by the viewer close to the projector, (b) A user wearing an HMPD and using the transparent retroreflective screen, and (c) microscopic view of the screen (75% transparent) showing the active and inactive retroreflective microspheres.

2.6 Retroreflective Characteristics

The display properties of the developed screen are determined by measuring the retroreflective coefficient of the screen. The retroreflective coefficient is defined as the amount of retroreflected light as a function of viewing angle. The transparent retroreflective screen reflects incident light towards source in the shape of an angular cone. With an eye to projector distance s , and the viewer to screen distance d , the viewing angle α can be expressed as,

$$\alpha = \tan^{-1} \left(\frac{s}{d} \right) \quad (2.2)$$

Equation 2.2 indicates that viewing angle decreases with increasing viewer-to-screen distance and decreasing eye-to-projector distance. When the viewing angle is minimized, the viewers' eye moves towards the peak of the retroreflective cone and the perceived brightness is significantly increased.

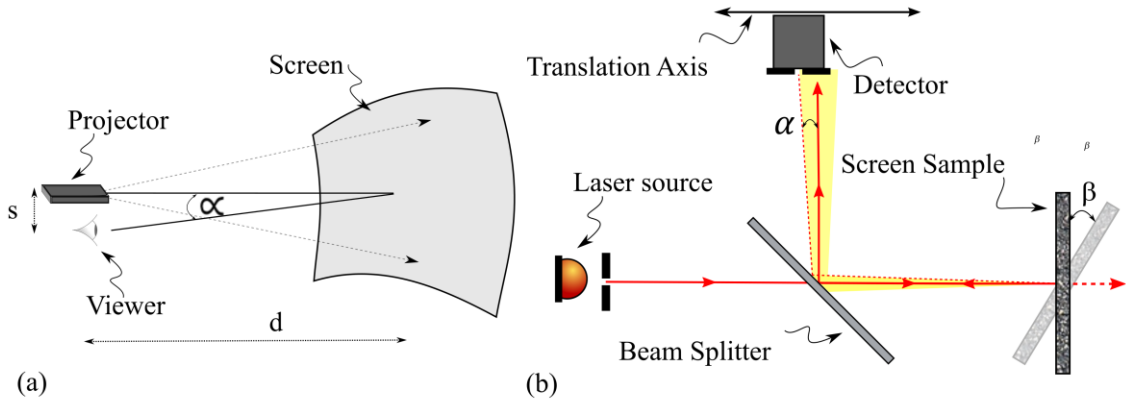


Figure 2.6. (a) The viewing angle formed by viewer's eye with respect to screen and projector, and (b) Illustration of the photometric setup used to measure the retroreflective coefficient of the transparent screen.

In order to determine the coefficient of reflectivity of the developed screen, a photometric setup was constructed as illustrated in Figure 2.6(b). The sample of the transparent retroreflective screen was illuminated with a collimated 632.8 nm HeNe laser with a 0° angle of incidence ($\beta=0$). The occlusion due to the detector was prevented by using a 50/50 beam-splitter between the screen and the detector. To limit the size of collimated laser beam, a 1 mm diameter aperture was placed in front of the laser source.

The retroreflected intensity at different angular positions is measured using a power meter (PM100A Thorlabs). The distance between the screen sample and the detector was kept as 21 cm to record the detected power within $\pm 3^\circ$ viewing angle. The detector having a diameter of 1.5 mm was placed on a translation stage to allow precise movement across the retroreflective cone. An angular step size of 0.14° was achieved by moving the detector with 500 μm steps. The retroreflective coefficient of the transparent screen is calculated as,

$$R_c(\alpha) = \frac{P_d(\alpha)}{0.5 \times P_s} \quad (2.3)$$

where P_d is the detected power at viewing angle α , P_s is the input beam power measured at sample position and R_c is the resultant retroreflective coefficient. Figure 2.7 shows the measured retroreflective coefficient for three different versions of transparent screens, providing 50%, 75%, and 90% transparency. The amount of retroreflection is decreased as the transparency of the screen is increased. Due to the use of same microspheres, all screen samples provide identical cone shapes having approximately 2° angular width. All three curves show slight side lobes, which are the result of the diffraction due to the small size of microspheres.

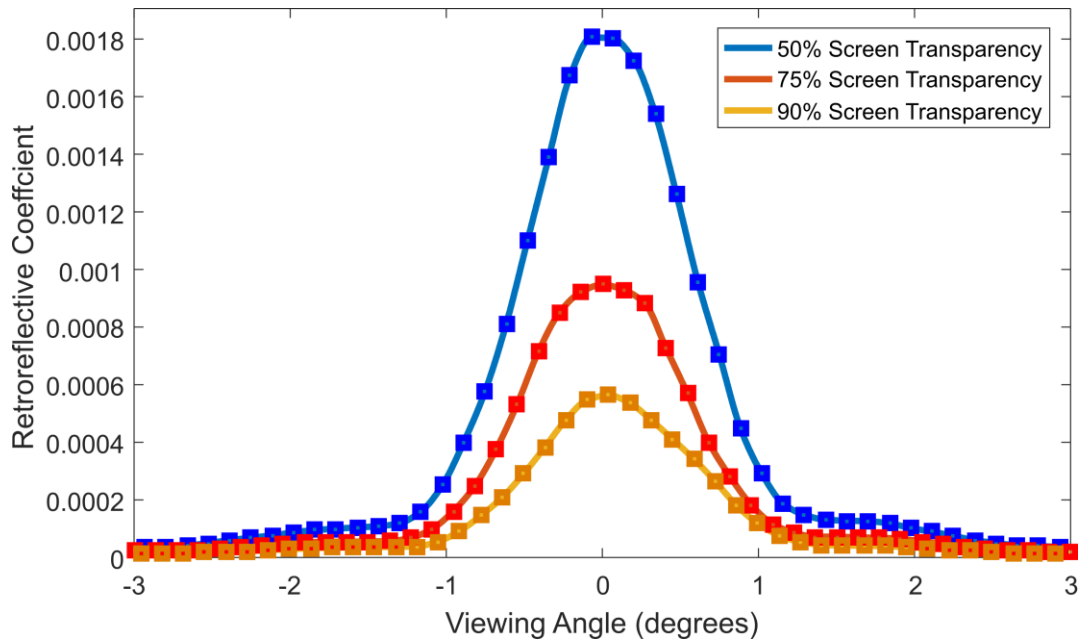


Figure 2.7. Experimentally recorded retroreflective coefficient for three different screen samples. The coefficient value decreases with increasing screen transparency, while the shape of the retroreflective cone is unaffected.

2.7 Results and Discussions

2.7.1 Brightness and Optical Gain

The brightness of a non-transparent diffusing screen providing equal light in all directions can be calculated as [35],

$$B_D = \frac{P_L}{\pi(k \times d^2)} \quad (2.4)$$

where B_D is the brightness of the diffusing screen illuminated by a projector having power P_L lumen across the screen area $A=kd^2$. For the retroreflective screen, Equation 2.4 can be modified by considering the retroreflective coefficient information $R_c(\alpha)$ and the detector solid angle (ψ) with respect to the screen [33]. The modified relation can be expressed as,

$$B_R = R_c(\alpha) \frac{P_L}{\psi(k \times d^2)} \quad (2.5)$$

The brightness profile of the transparent retroreflective screen was obtained by inserting experimental measurement of $R_c(\alpha)$ in Equation 2.5 and assuming a 15 lumen projector having 49° field of view ($k=0.538$). Figure 2.8(a) shows the brightness curves as a function of the viewer-to-screen distance for three versions of the screen (50%, 75%, and 90% transparency) and two different eye-to-projector distance (s) values (2 cm and 5 cm).

Figure 2.8(a) shows the increased brightness at the cost of lower transparency. The screen brightness of 280 cd/m^2 is achieved with the 50% transparent screen and 2 cm eye-to-projector distance. The brightness is significantly reduced as viewer's eye moves away from the projector (compare $s=2$, and $s=5$). Each brightness curve shows a valley, which is the result of the diffraction minima in the retroreflective cone as seen in Figure 2.7. Additionally, the figure also shows that the screen brightness does not have an exponential drop (as in diffusing screens) when the viewer/projector moves away from the screen. This is due to the decline in the viewing angle with the increasing viewer-to-screen distance.

The optical gain of the screen is determined by calculating the ratio of the brightness of the developed screen (B_R) to the brightness of a regular non-transparent diffused screen (B_D), which can be expressed,

$$G = \frac{B_R}{B_D} \quad (2.6)$$

Figure 2.8(b) shows the optical gain of the screen as the screen-to-viewer distance is increased. In contrast with a diffusing screen, the brightness of the screen remains constant as the viewer moves away from the screen; this provides an increased optical gain for higher viewer-to-screen distances. The screen shows an optical gain of up to 100 at a working distance of 3 meters.

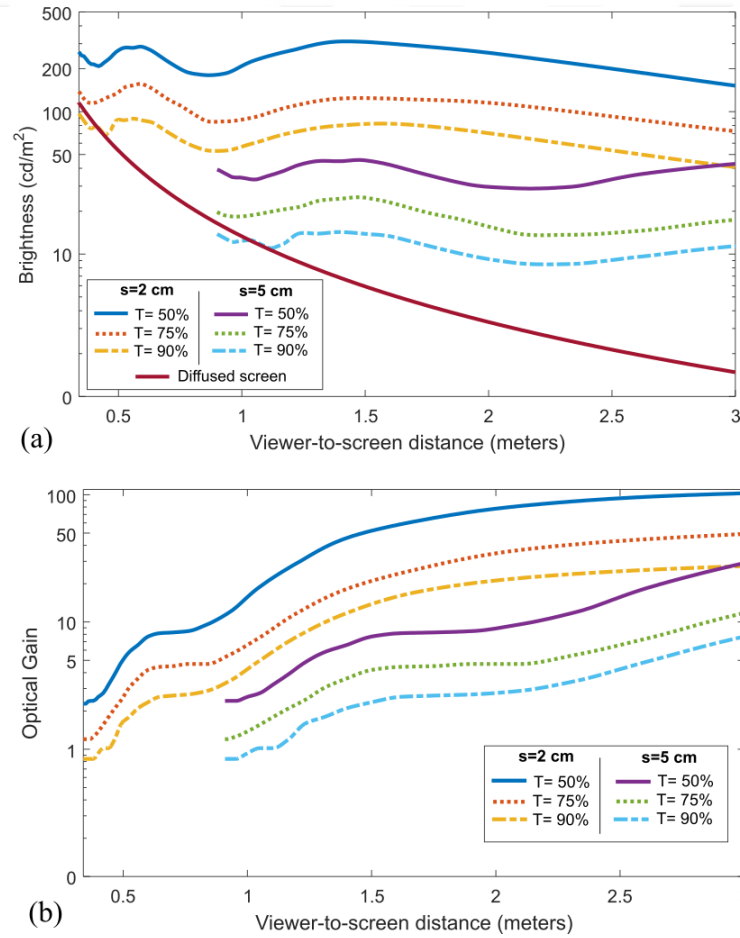


Figure 2.8. The brightness performance (a), and optical gain (b), of three different versions of the screen (50%, 75%, and 90% transparency) when the eye-projector distance (s) is 2 cm and 5 cm.

Due to the limited movement of the photometric setup, no power is detected beyond $\pm 3^\circ$ viewing angles and the brightness for larger eye-to-projector distance and closer viewer-to-screen distance is not measured. Since we use the microspheres having half-shell aluminum coating already, the coated side of microspheres is randomly oriented after they are bonded to the substrate, and only a fraction (about 30-35%) of microspheres having the aluminum coating on rear side behave as retroreflective, which can also be seen in Figure 2.8. The bright microspheres seen in Figure 2.5(c) are correctly oriented and retroreflect the incident light successfully, while the dark microspheres are oriented incorrectly and behave as dead spots. The retroreflective efficiency, brightness, and optical gain can be further enhanced by refining the fabrication process of the screen and ensuring the precise orientation of all the microspheres.

2.7.2 Entrance Angle

Brightness uniformity across the screen area is an important parameter for a display screen. For retroreflective screens, it can be characterized by the entrance angle [32]. Entrance angle is defined as the range of incident angles at which the screen remains highly retroreflective. For uniform brightness, the entrance angle of the transparent retroreflective screen should be greater than the field of view of the projector.

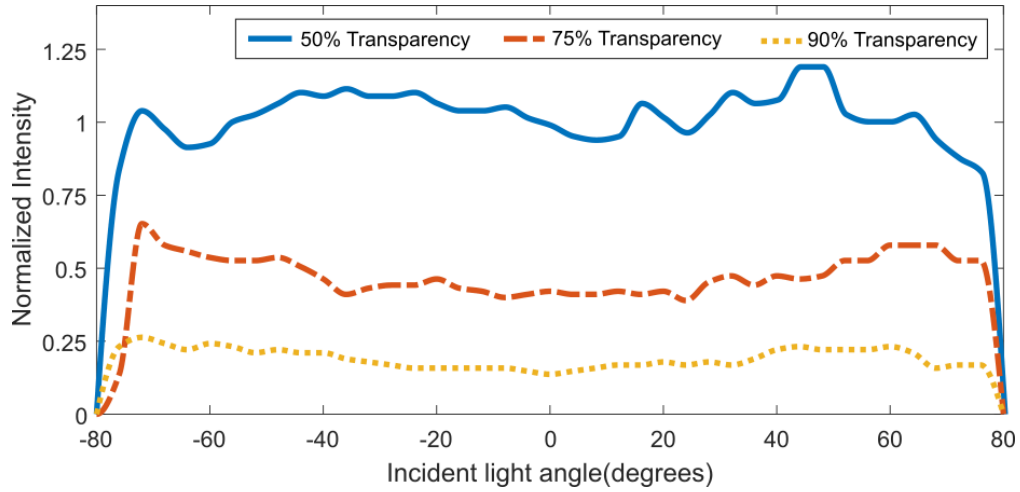


Figure 2.9. The entrance angle of different versions of the transparent retroreflective screen. The intensity of the retroreflected light remains nearly constant within the wide range of incident angles (-75 to $+75$ degrees).

The entrance angle was measured by modifying the photometric the setup shown in Figure 2.6(b). The detector was fixed at 0° viewing angle ($\alpha=0$), while the screen sample was placed on a variable angular stage to vary the incident angle (β) of the incoming beam. Figure 2.9 shows the detected power (mean normalized to the 50% transparent screen) as a function of incident angle. The figure shows wider acceptance angles (-75° to $+75^\circ$) within the intensity variation of $\pm 15\%$. The effect of wider entrance angle can also be observed in Figure 2.5(a), where the brightness uniformity from the center to the edges of the screen shows that the entrance angle of the screen is wider than the field of view of the projector. The wider acceptance angle guarantees the unprecedented brightness performance, even when the screen has a sharp tilt with respect to the projector.

2.7.3 Transmission Properties

To evaluate the transparency of the developed screen, the modulation transfer function (MTF) for the light transmitted through the screen was measured. Slant edge technique was used to measure the experimental MTF [36]. Figure 2.10(a) illustrates the experimental setup. A slanted edge object with 3° tilt was placed at 50 cm from the

transparent screen. The image of the edge was captured by a camera located on the other side of the screen at the distance of 100 cm .

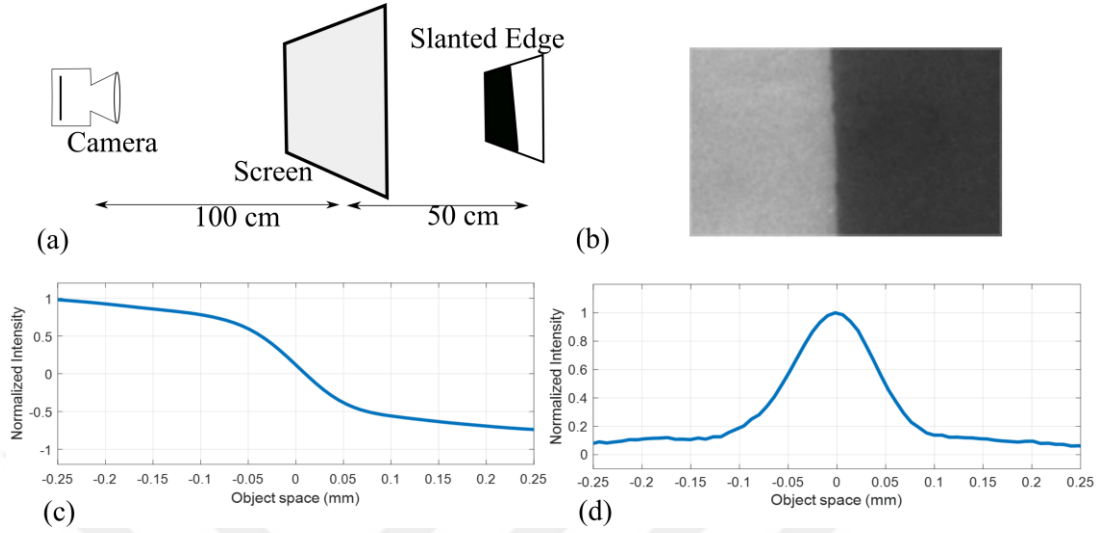


Figure 2.10 The experimental setup used to measure transmission MTF of the screen, (b) the captured edge profile through 75% transparent screen, (c) the recovered edge spread function (ESF), and (d) corresponding point spread function (PSF).

Figure 2.10(b) shows the captured edge on the camera through the 75% transparent screen. First Canny edge detection technique was applied to detect the edge [37]. The angle of the slanted edge was estimated by fitting a line to the detected edge; the image was then up-sampled by a factor of four and the edge was straightened by applying an affine transformation using the computed edge angle. From the column average of the subsequent image, an over-sampled edge profile was calculated as the one-dimensional edge spread function (ESF) shown in Figure 2.10(c). The point spread function (PSF) shown in Figure 2.10(d) was further calculated using the derivative of ESF. Finally, the transmission MTF of the screen was measured by calculating the absolute value of the Fourier transform of the PSF.

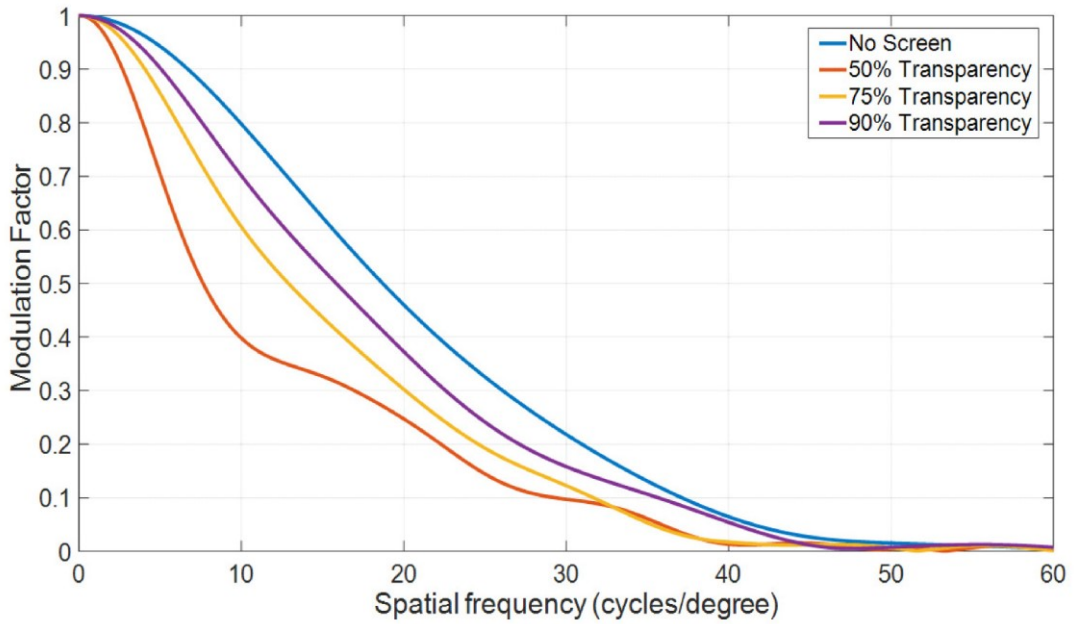


Figure 2.11. Measured transmission MTF for three screen samples. MTF50 (50% cutoff) is reduced from 18 cyc/degree to 8 cyc/deg and MTF10 (10% cutoff) is reduced from 37 cyc/deg to 30 cyc/deg when screen transparency is decreased by 50%.

With this method, the MTF curves for three transparent retroreflective screens with different transparency levels were obtained as shown in Figure 2.11. The ‘no screen’ MTF curve shows the MTF of the camera without having a screen in between for reference. The camera f-number was configured to provide 20% cut-off at 30 *cycles/degree* to make it consistent with the normal human vision. The figure shows reduced see-through resolution with increased fill factor. Increasing retroreflective fill factor reduces the amount of transmitted light, and this results in a contrast loss when looking through the screen. The 90% transparent screen performs closer to reference MTF. The MTF50 (50% cutoff) is reduced to 16 *cycles/degree* for the 90% transparent screen, 13 *cycles/degree* for the 75% transparent screen and 8 *cycles/degree* for the 50% transparent screen, when compared to the reference MTF (18 *cycles/degree*).

2.8 Conclusion

This chapter discussed the design method, fabrication process, display and transmission characteristics of the transparent retroreflective screen. A clear surface with micro-patterned retroreflective microspheres was demonstrated as a highly transparent screen

that can project very bright content. The retroreflective properties of the screen were measured by constructing a photometric setup that was later used to measure the screen brightness and uniformity. The optical transmission of the screen was evaluated by measuring the MTF of the screen in transmission. Different levels of the screen transparencies and optical gain can be achieved by controlling the proportion of the retroreflective material on the substrate. We fabricated the screen on a thin flexible substrate, which enables it to be flexible and easily installable on any surface (i.e. car windshields, home windows). The retroreflective cone can be widened, and retroreflective efficiency can be improved by using the smaller sized microspheres and refining the fabrication process.

In the next chapter, we will present the implementation of the transparent retroreflective screen for 3D display applications. The large size transparent retroreflective screen coupled with head-mounted pico-projectors is presented and evaluated as an augmented reality 3D display. Also, the implementation and psychophysical experimental study of the transparent retroreflective screen is presented when used as a windshield 3D HUD.

CHAPTER 3

3D DISPLAY APPLICATIONS USING TRANSPARENT RETROREFLECTIVE SCREENS

This chapter presents the implementation and evaluation of transparent retroreflective screen for 3D augmented reality and automotive 3D HUD applications. Two different techniques are introduced to demonstrate augmented reality 3D display and a windshield 3D head-up-display.

3.1 Augmented Reality 3D Display

This section introduces a new 3D display technique for augmented reality using a couple of pico-projectors and a large size transparent retroreflective screen that we have published under [38]. Section 3.1.1 introduces the proposed system and provides a brief overview of the augmented reality 3D displays. In Section 3.1.2, we present the concept of the proposed display. The experimental prototype is presented in Section 3.1.3. The retroreflective and polarization characteristics of the display are discussed in Section 3.1.4, while the eye-box analysis and experiment results on the stereo crosstalk and display brightness are discussed in Section 3.1.5.

3.1.1 Introduction

The augmented reality systems are seen as an integral part of the futuristic human-computer interaction. The augmented reality displays are investigated to blend the virtual and real word in an efficient way and are explored for a variety of applications including entertainment, medical visualization, and education. Most of the augmented reality systems are based on one or more image sources and optically transparent surfaces [39–

44]. Several techniques have been proposed to realize the augmented reality displays, where most of the effort has been focused on the development of near-to-eye augmented reality displays [41,42]. A typical near-to-eye augmented reality display utilizes an image projector or a micro-display as source and a holographic optical element (HOEs) or a half-silvered mirror together with the related optical components to relay the image to the eye. The 3D capability is added by providing separate views to each eye. With the availability of high-resolution micro-displays, the current near-to-eye display can produce decent image quality and resolution, but often involve bulky optics and have a limited field of view. The alternative approaches include the integral imaging [43], holographic recorded micro-lens arrays [44] and plasmonic nano-cubes [45] based AR displays where image projectors are combined with the distant transfer screens to overlay virtual content [27,43,44]. However, such displays are hard to fabricate in large size and suffer from lower transparency and/or brightness. The retroreflective materials have also been demonstrated as a transfer screen for the head-mounted projection based bright personalized displays [46,47]. However, due to the non-transparent nature of retroreflective materials, they have not been explored to be used in augmented reality displays.

This work presents an augmented reality 3D display, which can provide bright 3D content together with higher optical transparency. The foundation of our display is based on the low power pico-projectors and a special transparent screen partially filled with the retroreflective microspheres. The retroreflective nature of the screen delivers light-efficiency and separates stereo views by reflecting the incident light back towards source with minimum scattering, while partial filling of the retroreflective material provides the optical transparency needed for augmented reality applications. This section focuses on the design, implementation, and evaluation of the large size light efficient augmented reality 3D display using a transparent retroreflective screen.

3.1.2 Concept of The Display

The proposed display consists of two pico-projectors and a see-through retroreflective screen as illustrated in Figure 3.1. The retroreflective material deposited on the screen reflects incident light back towards the source in the shape of narrow angular cone

providing the peak reflectance at the exit pupil of the projector. The projectors are placed close to the viewer's head and the horizontal baseline distance between the projectors is matched with the inter-pupillary distance (IPD) of the viewer. The stereo content is projected on the see-through screen using the projector pair placed at distance d from the screen, where each projector illuminates the screen with one of the two channels of a stereo 3D content. The light from each projector is turned back to the projector and provides bright content to the eye positioned close to the associated projector. By utilizing the high contrast of laser pico-projectors, the floating 3D content can be displayed by projecting the content with a black background.

We use a specially designed and in-house fabricated transparent retroreflective surface presented in Chapter 2 as the transfer screen. The screen is an optically clear sheet consisting of finely patterned retroreflective microspheres. Since a full retroreflective surface (i.e. retro-fabric, retro-sticker sheet) can provide higher light efficiency [19,48], we optimize the amount of transparency and retro-reflectivity by partially depositing retroreflective glass microspheres on the clear substrate as square-shaped tiny islands. To balance the amount of brightness and optical transparency, the 25% of total screen area was filled with the microspheres, while 75% of screen area was left see-through.

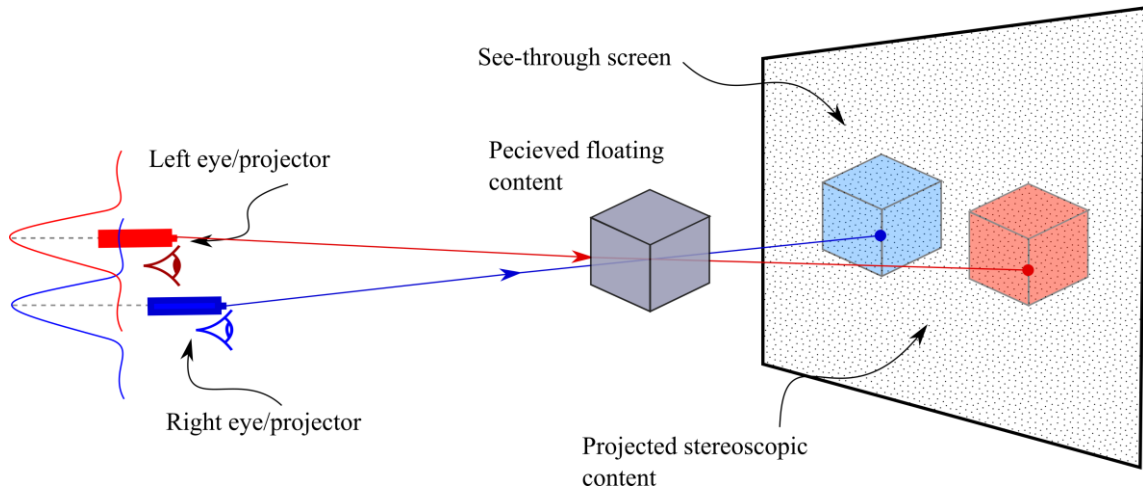


Figure 3.1. A projector pair illuminates the screen with stereoscopic content, the light from each projector is returned to the associated projector and perceived by the eye closer to the projector. Each projector (represented by red and blue) displays the full-color images.

3.1.3 Test Prototype

The tabletop experimental prototype was built to demonstrate the augmented reality 3D display as shown in Figure 3.2(a). Our setup consists of two 30 *lumen* laser sourced pico-projectors from Sony [15] and an in-house fabricated see-through screen. A pair of 3D printed projector housings together with folding mirror/beam-splitters were used to minimize the distance between the eye and the projector. Each projector has the resolution of 1280×720 *pixels* (720p HD) and covers the $42^\circ \times 24^\circ$ field of view of each eye. The screen was placed within the distance of $d=50$ -200 *cm* from the viewer and the display was tested under normal indoor ambient lighting. The horizontal distance between the projectors' exit pupils was varied to match the IPD distance of a specific viewer, while an average IPD of 6.5 *cm* was used during display characterization. The minimum achievable gap (*s*) between the eye and the projector was 2 *cm* and 0.5 *cm* for folding mirrors and beam-splitters, respectively.

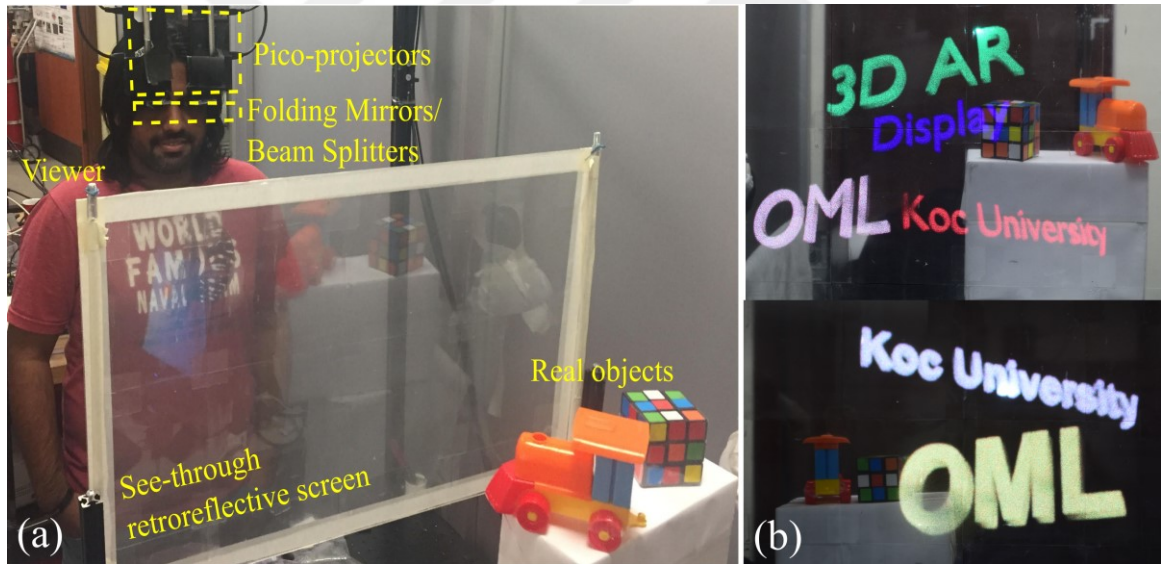


Figure 3.2. (a) The desktop size experimental prototype (b) The content as projected using one of the two projectors and perceived by eye closer to the associated projector.

The screen fabrication involved the use of half-shell aluminum coated glass microspheres, where an acrylic sheet with thin adhesive coating was used as a base substrate and the retroreflective microspheres were patterned and deposited using a negative shadow mask made of stainless steel. The full-size screen (60 *cm* $\times$ 40 *cm*) shown in Figure 3.2(b) was constructed by tiling together multiple segments of the

fabricated screen on a clear Plexiglas sheet, where the size of each screen segment was $16\text{ cm} \times 16\text{ cm}$. To have full field overlap between the projected images, both projectors were tilted inward slightly, that resulted in the keystone distortion. To provide a comfortable viewing experience, the distortion was corrected by projecting a checkerboard image on both projectors and adjusting the horizontal keystone manually.

3.1.4 Retroreflective and Polarization Characteristics

Since the proposed display uses the retro-reflectivity for image display, the quality and performance of the display depend on the retroreflective characteristics of the screen and the configuration of image source with respect to the screen. The retro-reflectivity of the screen was determined by measuring the retroreflective coefficient (intensity of retro-reflected light and the angular width of the retroreflective cone).

The retroreflective coefficient was measured with a photometric setup presented in Chapter 2, where a portion of the screen was illuminated with 632.8 nm collimated laser beam and amount of retroreflected light was measured as a function of viewing angle. To record the coefficient value for the higher viewing angles, the power was measured from the center to the edge of the retroreflective cone. Figure 3.3 shows the measured retroreflective coefficient as a function of viewing angle (angular difference between the eye and the projector with respect to the screen). The coefficient value in Figure 3.3 shows the amount of light returned within that small solid angle at different angular positions and a maximum of 0.35% of input light is returned at 0 mrad , which is the exit pupil location of the source/projector. The measured retroreflective coefficient is only about 8 times lower than the best available retroreflector (i.e. retroreflective fabric). The factor of four reduction is due to the fill factor (screen is 75% transmissive and 25% retroreflective) and an additional factor of two is due to manufacturing process and can be improved by properly orienting the microspheres on the substrate. Compared to a typical projection screen (i.e. diffused surfaces, which scatter light within the solid angle of $2\pi\text{ steradian}$), the proposed screen provides increased light efficiency, which is evident by the higher brightness offered by the screen as discussed later in Section 3.1.5.3.

The coefficient value is proportionally increased as the angle between viewer's eye and the projector is decreased. The retroreflective cone also shows the diffraction orders due to the aperture diffraction of microspheres [49]. The aperture diffraction affects the angular width and peak coefficient value of retroreflective cone. The smaller microspheres result in a wider retroreflective cone, while larger microspheres (such as the ones used in airport runways) create extremely narrow angular cones. Since the size of microspheres is at least 10 times smaller ($35\text{-}45\text{ }\mu\text{m}$) than the projected pixel size ($>400\text{ }\mu\text{m}$) the image quality is not affected. A constant coefficient value was observed outside the $\pm 50\text{ mrad}$ viewing angle that corresponds to the diffused scattering due to geometric and material imperfections of microspheres and substrate.

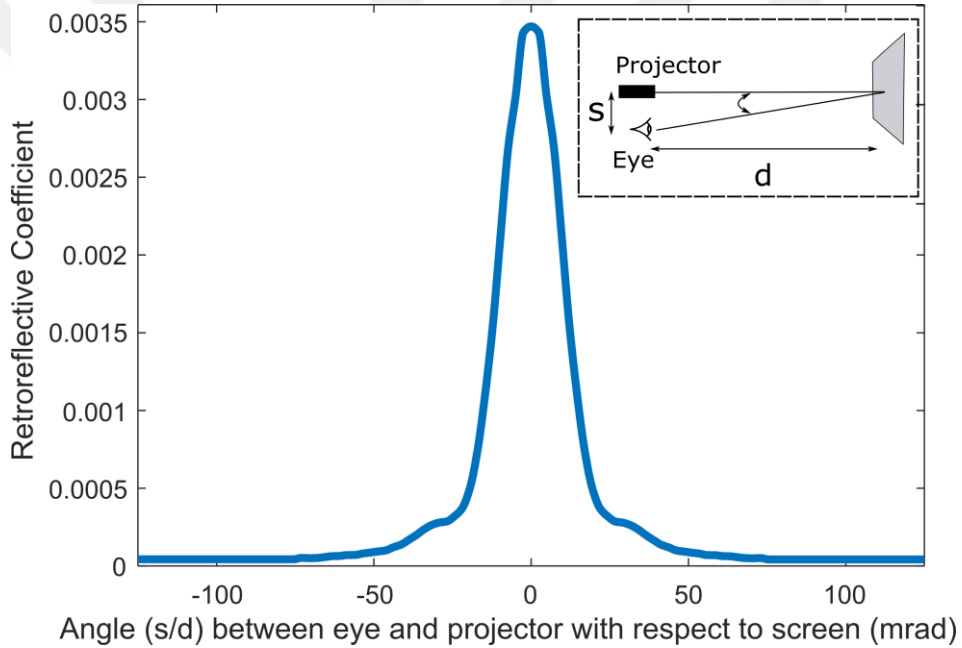


Figure 3.3. The experimentally measured retroreflective coefficient, the microspheres buried in screen create a 100 mrad wide retroreflective cone, the diffraction minima are observed due to the aperture diffraction of microspheres.

Due to the high refractive index of glass microspheres and back aluminum coating, the incident ray is refracted at the air-microsphere interface and goes through specular reflection at aluminum-microsphere interface. The specular reflection and metal coating facilitate the incident light to preserve its polarization after going through retroreflection. We measured the ability of the screen to preserve polarization by using a photometric setup (Figure 3.4(a) inset). We illuminated the screen with a linear horizontal polarized

light and captured the retroreflected light using the detector positioned at 0 mrad angle. The polarization maintainability was further measured by placing an analyzer (linear polarizer film) before the detector and changing its transmission axis orientation. Figure 2.4(a) shows the normalized intensity when the analyzer was rotated between 0 - 90° with respect to the polarization direction of the incident light. The figure shows the maximum light intensity when the angle between the polarization direction of incident light and transmission axis of the analyzer is the same. Due to the retained polarization state after retro-reflection, the light intensity is decreased as the orientation of analyzer is changed. The normalized intensity of $<2\%$ is detected at 90° orientation due to the absorption efficiency of the analyzer. Figure 3.4(b) and Figure 3.4(c) show the photos of the illuminated screen captured with the camera placed next to the projector when, the polarizer placed in front of the camera is oriented in horizontal and vertical directions, respectively.

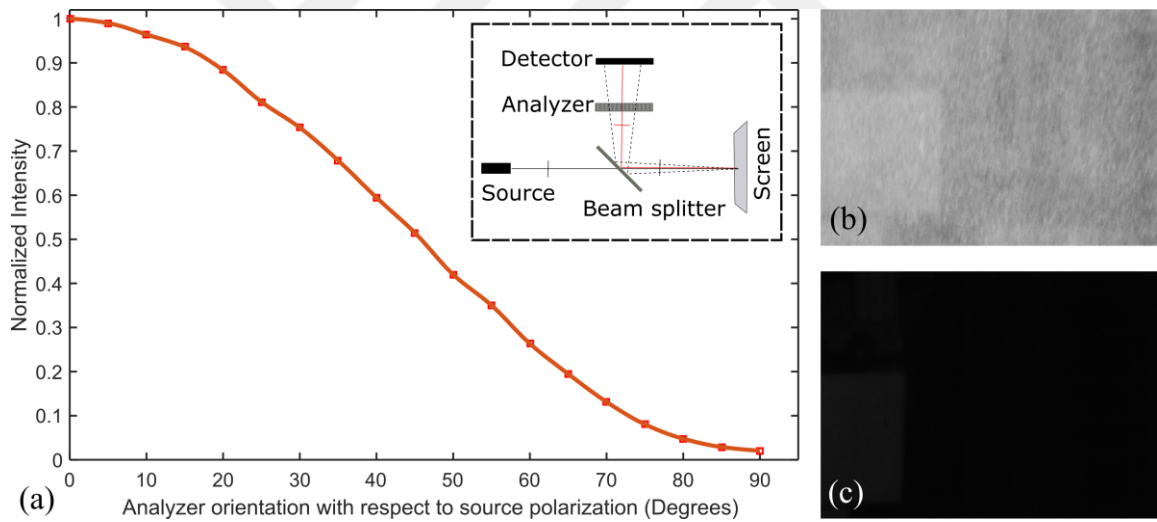


Figure 3.4. The polarization maintaining ability of the see-through retroreflective screen. a) Normalized captured intensity as a function of polarization orientation measured with a photometric setup, b) and c) the screen surface illuminated with horizontally polarized light and captured by placing a horizontal polarizer (b) and, a vertical polarizer (c) in front of the camera.

3.1.5 Results and Discussion

3.1.5.1 Eye-box Analysis

As shown in Figure 3.3, the intensity distribution of retroreflective cone was measured in only one direction. Since the retroreflective cone is circularly symmetric around 0 mrad viewing angle, the 2D representation of the retroreflective cone was obtained by circularly rotating the right side of the retroreflective cone. The retroreflective cone has an angular spread and actual eye-box size for each eye and overlap between left and right eye-box depend on the angular width of the retroreflective cone and the distance between the viewer/projector and the screen. For a defined eye-projector gap, as the distance between the screen and the viewer/projector changes, the size and amount of overlap between left and right eye box also change, which in result changes the stereo crosstalk and perceived brightness.

To minimize the overlap between left and right eye-boxes and eye-to-projector distance, we tested three different viewing configurations as illustrated in Figure 3.5, where the screen is viewed, 1) with bare eyes below each projector, 2) through additional polarizer films in front of eyes and, 3) through beam-splitters.

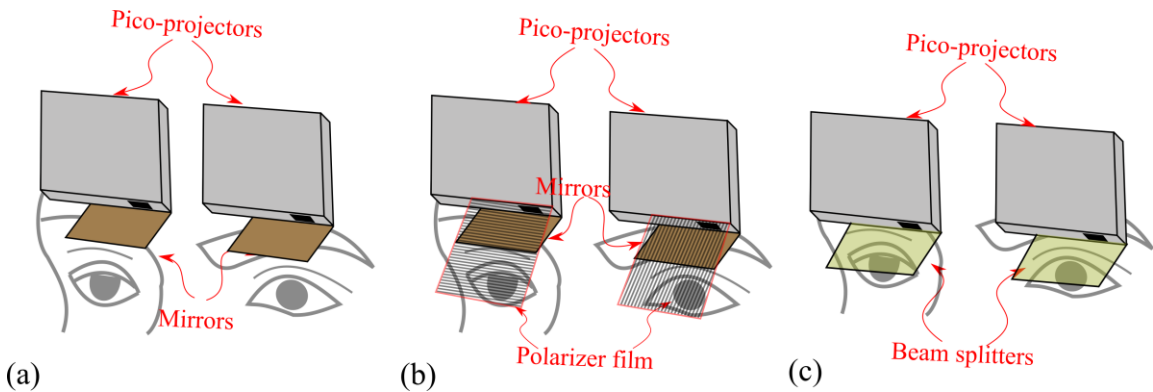


Figure 3.5. The different eye-projector configurations, (a) bare eye configuration, where projection beam is folded towards screen using mirrors, (b) polarizer based configuration, where additional polarizer films are used to separate two views and, (c) Beam-splitters based configuration, where eye-to projector gap is minimized.

Figure 3.6 shows the normalized coefficient values, eye-box size and overlap for all three configurations at 100 cm from the screen. The location of left/right projectors and

eyes are P_L , P_R , and E_L , E_R respectively. For each eye, the distance to closer and farther projector is s and u respectively.

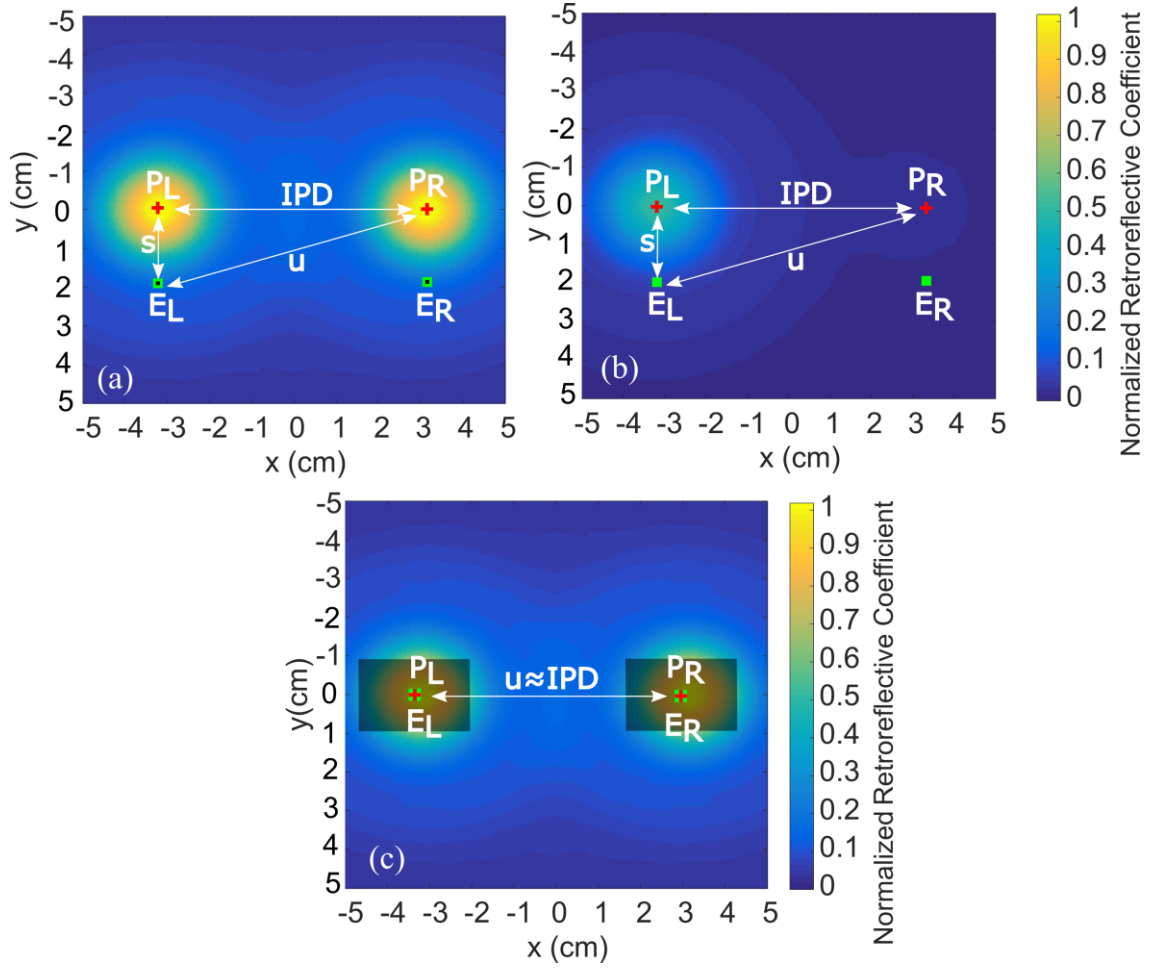


Figure 3.6. The eye-box size and overlap for different eye-projector settings at distance of 100 cm from the screen. a) Screen viewed with bare eyes, b) projectors are polarized in different directions having the matching polarizer in front of each eye and, c) 50/50 beam splitters used to align the respective eye and the projector.

For the bare eye configuration as shown in Figure 3.6(a), we use $3\text{ cm} \times 3\text{ cm}$ mirrors oriented at 45° to bend the projector light towards the screen and the viewer's eyes are positioned below the mirrors. The presence of mirrors restricts the separation of the eye and the projector, and a minimum gap of $s=2\text{ cm}$ is achieved. The bare eye configuration provides significant brightness and facilitates ergonomic comfort, but results in a higher stereo crosstalk due to the distance-dependent eye-box size as discussed in the following section. In the next configuration, we utilize the polarization maintaining property of the screen by cross-polarizing the projector's light and by placing matching polarizer films in

front of the eyes. Figure 3.6(b) shows the eye-box and normalized coefficient for the left eye when viewed through the polarizer. The polarization difference between the left and right projectors effectively separates both views and facilitates minimum crosstalk.

The eye-projector gap is reduced by replacing the folding mirrors with 50/50 beam-splitters as shown in Figure 3.6(c). The use of beam-splitter eliminates the distance between eye and projector and helps to align the eye with the exit pupil of the respective projector. The beam-splitter enables the eye to lie at the peak of the retroreflective cone, while the overall coefficient value is affected by a factor of four due to the beam splitter.

3.1.5.2 Stereo Crosstalk

As discussed previously, for each configuration, the eye closer to the projector perceives high brightness than the farther eye due to the higher coefficient value. Considering the eye-box analysis in Fig. 6 and retroreflective coefficient values, the crosstalk for the left eye can be expressed as,

$$Crosstalk_L = \frac{C_R\left(\frac{u}{d}\right)}{C_L\left(\frac{s}{d}\right)} \times 100\%, \quad (3.1)$$

where $C_R(u/d)$ and $C_L(s/d)$ are the coefficient value of right and left projectors at the viewing angle of u/d and s/d radians respectively. The values of s and u depend on the eye-projector distance. For the bare eye and polarized projectors configuration, $s=2 \text{ cm}$ and $u = \sqrt{s^2 + IPD^2} \text{ cm}$ are used, while beam splitter configuration provided $s \approx 0.5 \text{ cm}$ and $u \approx IPD$. An additional scaling factor is used when considering the polarizer configuration. As the setup is symmetric for both eyes, the crosstalk for the right eye is the same as the left eye.

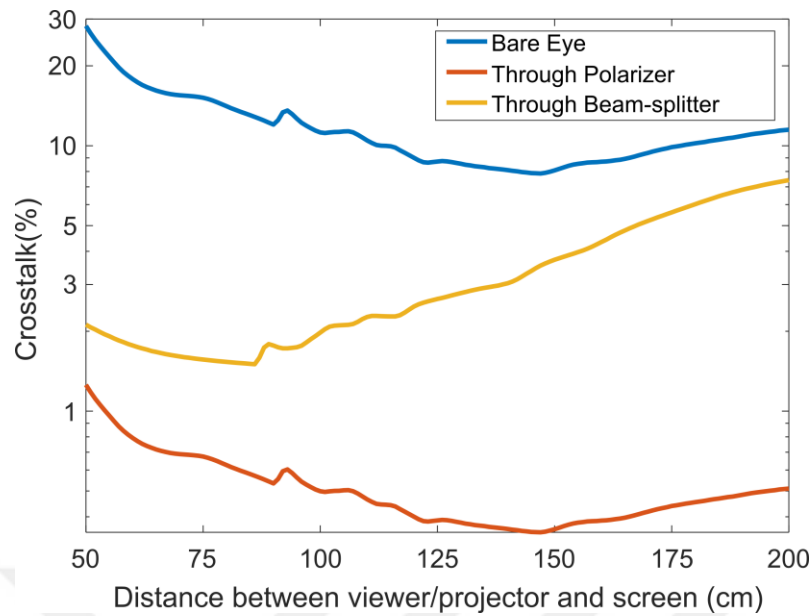


Figure 3.7. Crosstalk per eye in stereo mode plotted as a function of the screen to viewer distance for three viewing configurations. Higher stereo crosstalk is observed when viewing the display with bare eyes, while negligible crosstalk is observed when polarizer or beam splitter is placed in front of the eye.

Figure 3.7 shows the crosstalk of the system as a function of the screen to viewer distance for each one of configurations. For the bare eye, a higher crosstalk is observed at closer distances due to the small eye-box size. The crosstalk is decreased as the viewer moves towards the intermediate distance (125-175 cm) from the screen and increases again as the distance further increases due to severe eye-box expansion and overlap. The crosstalk is sharply decreased as the mirrors are replaced with beam-splitters and crosstalk of $<5\%$ is measured for a wide range of distances from the screen. The minimum crosstalk ($<1\%$) is observed when the polarizer film is placed in front of the eye and projector. Since the absorption efficiency of a typical polarizer film is limited to 98%, the crosstalk, in this case, is mainly due to the light blocking efficiency of the polarizer film.

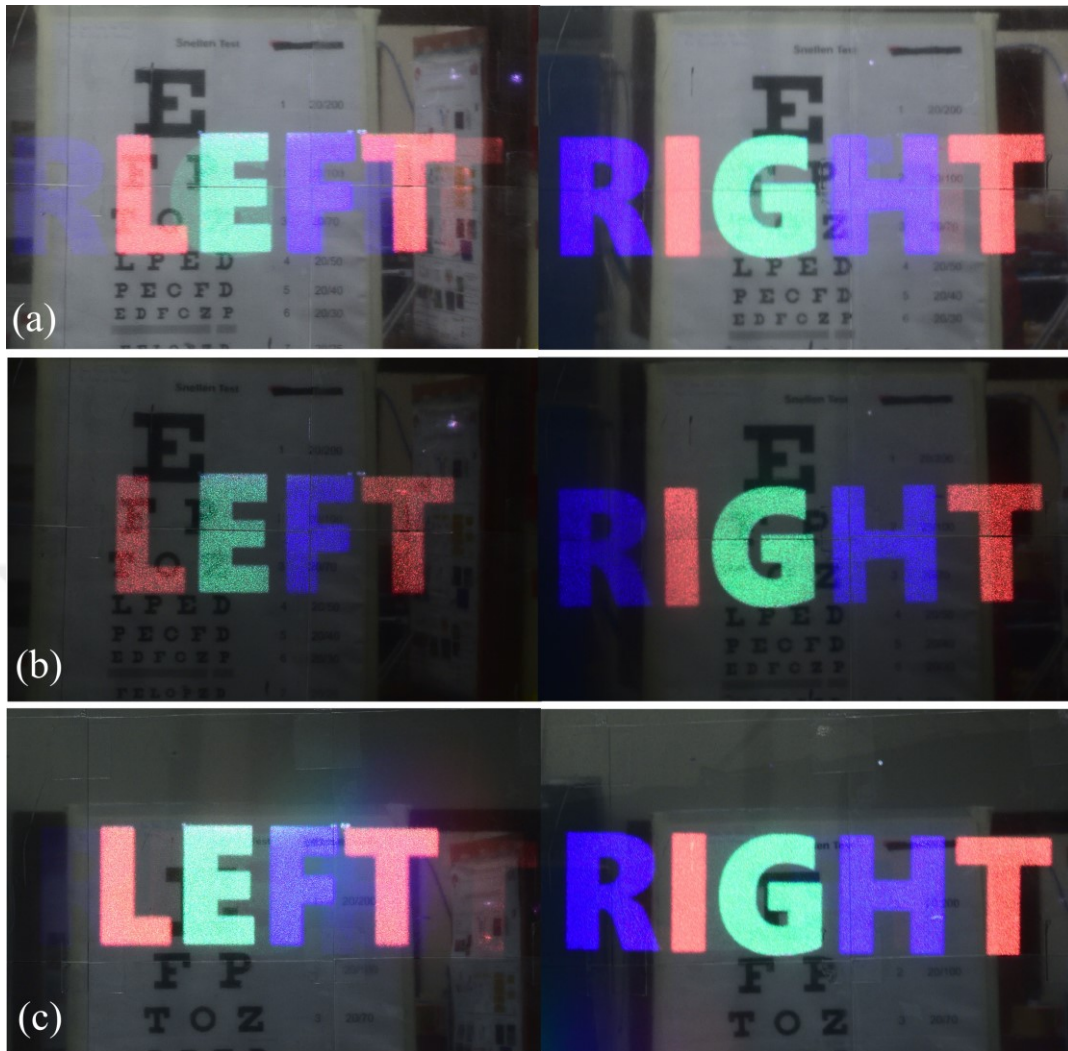


Figure 3.8. The left and right views as seen by the viewer at 125 cm from the screen and viewed, a) with bare eye, b) through polarizer films and, c) beam splitters. The same camera settings were used in all the pictures. A printed visual acuity chart on the other side of the display can also be seen.

3.1.5.3 Brightness and Optical Gain

The amount of brightness perceived by each eye was measured using experimental values of retroreflective coefficient as discussed in Section 2.7.1. When a projector illuminates the diffused screens, the incident light is scattered in the full hemisphere. On the other hand, a retroreflective screen provides varying brightness based on the distance between the projector and the screen and the distance between the eye and the projector. The brightness of the retroreflective screen can be measured using,

$$B(d) = C\left(\frac{s}{d}\right) \frac{k.L}{\Omega A}, \quad (3.2)$$

where $C(s/d)$ is the value of retroreflective coefficient at s/d viewing angle, L is the lumen power of the projector, Ω is the angle subtended by detector in the photometric setup, A is the illuminated screen area and k is the constant for different eye-projector configurations. The values for k are 1, 0.45 and 0.25 for the bare eye, polarizer and beam-splitter based configurations, respectively. The optical gain was calculated as the ratio of brightness of the proposed display and the regular diffused screen.

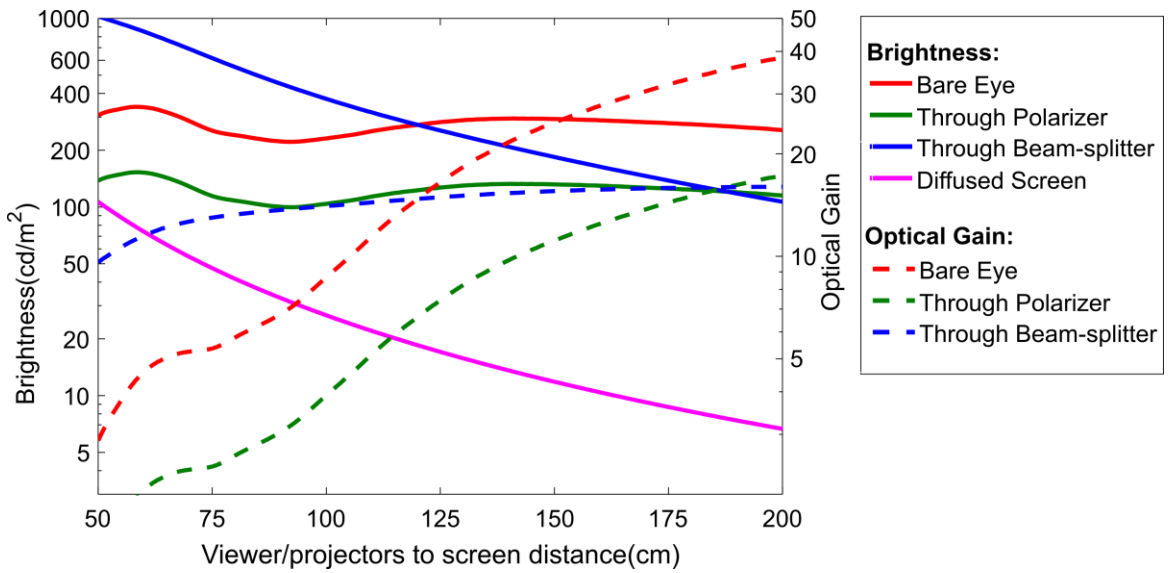


Figure 3.9. Brightness and optical gain as the distance between viewer/projector and screen is varied. Maximum brightness with an exponential decrease is perceived when eye and projector are aligned using beam-splitter, while nearly constant brightness is perceived when the screen is viewed with bare eye or through the polarizer. Higher optical gain is observed with bare eye configuration at the larger working distance.

The brightness of the display as a function of the screen to viewer distance was obtained by using Equation 3.2 and the experimentally measured retroreflective coefficient is shown in Figure 3.9. The beam-splitter configuration shows significant brightness (up to 1000 cd/m^2) due to the proper alignment of the eye with the peak of the retroreflective cone. As the distance increases, the retroreflective coefficient in Equation 3.2 remains constant while illuminated screen area increases with distance, and as a result, the brightness decay proportional to the inverse square is observed. For the

mirrors and polarizer configurations, the retroreflective coefficient also changes with the distance and result in an almost constant brightness for the wide range of the screen to viewer distance. As the distance increases, the angle (s/d) between the eye and associated projector decreases and therefore, the angular position of the eye moves towards the peak of the retroreflective coefficient. For the polarized projector configuration, the additional decrease in the brightness is observed due to the placement of the linear polarizer film in front of projectors and eyes. Compared to a diffused screen, the AR display provides 10 times more brightness at the closer distances when the beam-splitter configuration is used, while the 40 times more brightness is observed at larger distances using the bare eye configuration.

3.1.6 Conclusion

We proposed and demonstrated a light efficient augmented reality 3D display using a 75% see-through retroreflective screen and a pair of low power mobile projectors. The stereo 3D feature was added by utilizing the retroreflective property of the screen. The retroreflective and polarization characteristics of the display were experimentally measured and later used to characterize and assess the quality of the display. Several viewing configurations (bare eye, polarizers, and beam-splitter) were tested, evaluated and compared. Our results showed excellent brightness (up to 1000 cd/m^2). The minimum crosstalk (down to 1%) was achieved using both beam-splitters and polarizers.

The proposed display is currently limited to the fixed arrangement of projectors with respect to viewer's head. The positioning restriction of the display can be relaxed by stripping the projector modules and building a head-worn setup. The proposed display can be used for a variety of augmented reality applications (i.e. gaming, training/education, medical visualization, 3D head-up-display). The motion parallax can be added by tracking the viewer with respect to the screen. Due to the extended working distance and modular assembly of the screen, the display size can be easily increased by using an increased number of the screen segments. The light efficiency and display transparency can also be enhanced by refining the fabrication process.

3.2 Windshield 3D Head-Up-Display using Simulated Collimation

This section presents the study of a windshield 3D head-up-display (HUD) based on the transparent retroreflective screen for automotive applications. We investigate the impact of optical transparency and simulated collimation in stereoscopic 3D HUD on the human vision by conducting a user study, where we explore the relationship between the accommodation-convergence (AC) conflict and the screen transparency on the visual acuity of the user/driver.

3.2.1 Introduction

The see-through screens and augmented reality (AR) displays have been extensively explored as automotive applications in order to provide navigation and other driver assistance information without causing a distraction. There are different types of HUDs but most of them provide an image at a fixed depth. The simplest HUD is an LCD lying flat on the dashboard and a partially reflective beam combiner oriented at 45° angle. More sophisticated HUDs use viewing optics to provide a virtual image ahead of the car but the field-of-view (FOV) is limited (typ. $<10^\circ$) due to small etendue of the projection system. Waveguide type combiners and self-emissive high-brightness displays developed in recent years show promise for HUDs [50]. Holographic optical elements based HUDs has also been demonstrated to provide asymmetric FOV [51]. On the other hand, the development of 3D HUDs is usually limited to lenticular screen based multi-view displays [52], bandpass filters based wavelength multiplexed systems[53], and transparent screens based stereo 3D HUDs [54,55].

The visual discomfort and fatigue in stereoscopic 3D displays and their relationship with the amount of accommodation-convergence (AC) conflict has been studied in various ways. In [56], a new stereoscopic display was developed and both disparity and focus cues were provided to study the visual effect and fatigue in the absence of focus cues. The effect of viewing distance and direction on discomfort have also been investigated [57]. The importance of accommodation and presence of AC conflict in head-mounted displays have also been studied [58]. However, the impact on visual acuity when using 3D HUDs in the presence of AC conflict is unknown.

In this work, we investigate and evaluate the impact of using large-size 3D HUDs on the human vision by measuring the visual acuity under see-through and simulated colimitation conditions. The optical collimation feature of the typical HUD is simulated by using stereoscopy and controlling the parallax between the stereo views. We present the results of the two different user test experiments conducted using a see-through retroreflective screen presented in Chapter 2. The results are extendable to any type of stereo 3D HUD where the 3D content is displayed at a fixed distance from the user.

3.2.2 Background

3.2.2.1 Accommodation-convergence Conflict

All stereoscopic 3D displays are affected by AC mismatch. The accommodation is the ability of the eye lens to change its focal length to focus on the different objects at different depths and draw a sharp image on the retina [4,59]. On the other hand, convergence is the rotation of both eyeballs in opposite direction to converge on the single object (depth) to produce a brain fused single image [5,60]. Under the natural conditions, the accommodation and convergence are coupled and change together when the viewer looks at the different objects at different depths (Figure 3.10 left).

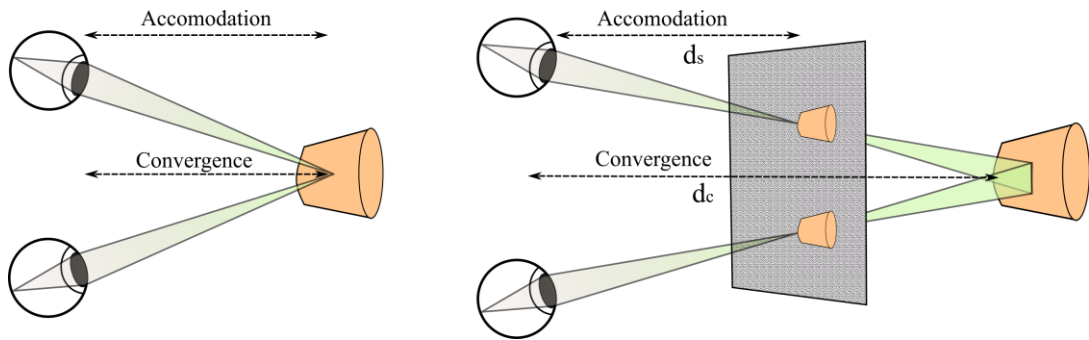


Figure 3.10. Accommodation-convergence conflict, natural viewing mode, where accommodation and convergence distances are matched (left) and, stereo 3D display, where accommodation and convergence distances are different (right).

In the stereoscopic 3D displays, accommodation-convergence relation is violated when the images are displayed on the screen at a fixed distance, but the amount of convergence varies with the level of disparity provided (Figure 3.10 right). The

mismatch forces the eyes to focus on the fixed screen distance but converge at a different distance and in result sharpness of the perceived image is reduced and visual discomfort is observed. The amount of discomfort can increase further when head-mounted displays are involved [58]. The amount of AC conflict in *diopters* can be calculated as the difference of reciprocal of accommodation distance (d_a) and convergence distance (d_c), and can be expressed as,

$$Confilct = \frac{1}{d_a} - \frac{1}{d_c} \quad (\text{diopters}). \quad (3.3)$$

3.2.2.2 Simulated Collimation

A typical HUD superimposes the virtual information on top of the real-world scene, such that the user/driver is not required to have additional accommodation and convergence efforts to perceive the virtual content. The optical collimation is mostly achieved by using additional optics with a projector, but it usually limits the field-of-view/size and eye-box of the display and provides limited brightness. To provide the similar HUD experience, we simulate the optical collimation using stereoscopy [61,62]. When the parallax between the two images matches with IPD, the depth of virtual image appears at the infinity and the driver looking at the road through the windshield screen perceives a single image as illustrated in Figure 3.11. The simulated collimation has been explored in the past using transparent (dot patterned) diffused projection screens [61], LCD screens with partially coated glasses [55,62], and computer graphic based simulated environments[63].

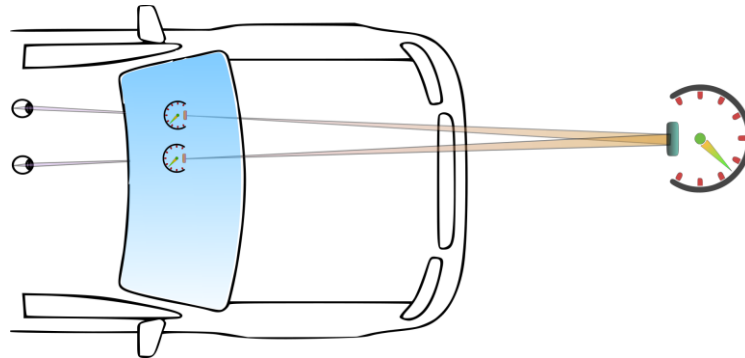


Figure 3.11. The principle of simulated optical collimation using stereoscopy, the collimation is provided by adjusting the parallax between stereoscopic views.

3.2.3 See-through Retroreflective Screen as windshield 3D HUD

A retroreflective surface contains microstructures, which refract and/or reflect incoming light ray such that it is turned back towards the source with narrow scattering angle and provides high brightness to the viewer standing close to light source. The retroreflective materials are used for road safety applications and airport runways since long time [30,64]. Over the past two decades, they have also been explored as light efficient personalized screens for wearable/head-worn projection display applications [46,47]. With a controlled fill factor of the retroreflective material, the screen provides 75% transparency and up to 10 times the brightness compared to a regular non-transparent diffused screen. As discussed in Section 3.1, the stereo views projected by two pico-projectors are separated through the retroreflective property of the screen, while stereo crosstalk is eliminated by polarization maintainability of the screen.

Compared to existing HUDs, which cover only a small portion of the driver's view and suffer from poor brightness, a transparent retroreflective screen can be adapted as a 3D HUD to cover the full windshield of the vehicle. The modular fabrication process and higher entrance angle allow the development of large size screen, while the light efficiency of the screen provides high brightness to the driver. Figure 3.12 shows a virtual dashboard displayed on the transparent retroreflective screen using a pico-projector.

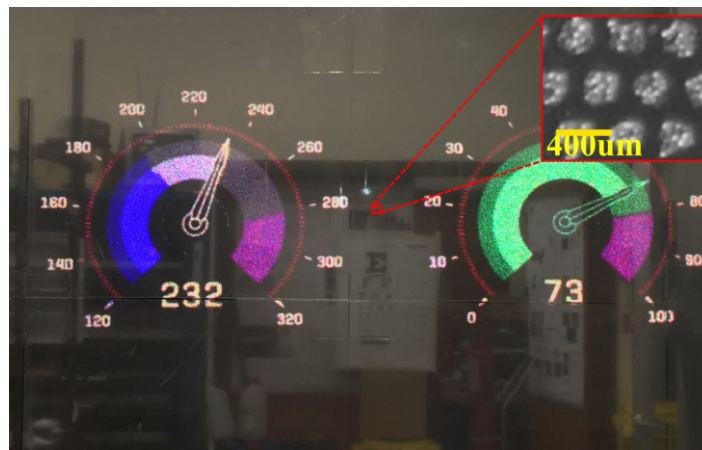


Figure 3.12. A virtual dashboard displayed on a see-through retroreflective screen.

3.2.4 User Study

To investigate the effect of screen transparency and AC conflict on the visual acuity of the user, we conducted a user study where we determined the average visual acuity using the Snellen visual acuity chart [65,66], which is widely used for the said purpose.

3.2.4.1 Apparatus

Our test apparatus, which consisted an in-house fabricated see-through retroreflective screen coupled with two pico-projectors positioned close to viewer's head was same as the experimental prototype presented in Section 3.1.3 and as shown in Figure 3.13. The pico-projectors are based on MEMS scanner and five laser sources that provided 60 *Hz* refresh rate and 30 *lumen* power. The laser sourced projectors provided focus-free image at variable distances. Each projector had the pixel resolution of 1280×720 (720p HD) and covered 42°×24° field of view [38].

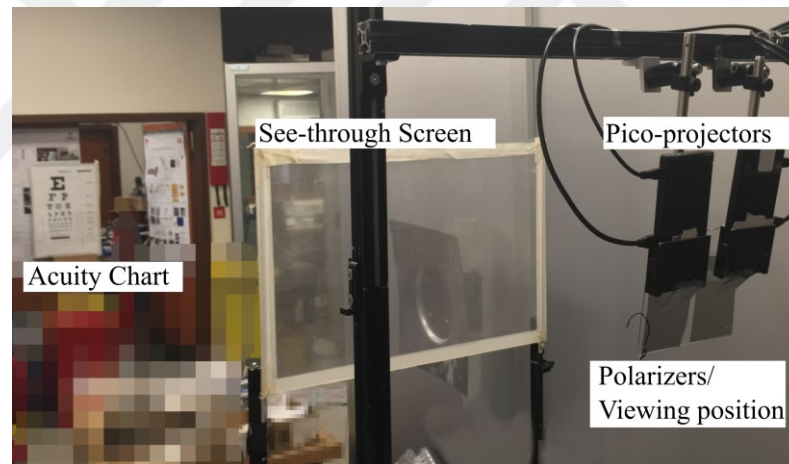


Figure 3.13. The prototype setup used for the user study. The Snellen acuity chart is placed at the distance of 7 meters from the user.

The screen consisted of square-shaped micro-patterns of half shell aluminum-coated retroreflective microspheres deposited on clear acrylic sheet/glass using perforated steel mask (stencil) [19]. The custom 3D printed projector housings and mirrors were used to minimize the distance between the eye and the projector. A pair of linear polarizer films was also used in front of the eyes and the projectors to eliminate the stereo crosstalk, where each eye/projector used mutually perpendicular polarization orientation [38]. The brightness of virtual content was 150 cd/m^2 per eye.

3.2.4.2 Participants

We recruited 11 volunteers (7 male and 4 female) from the Koç University campus (students and staff). The participants aged between 22 and 33 years ($Mean=29$ and $SD=3.12$). The participants were of several nationalities but all reported fluent English proficiency. 60% participants reported 20/20 bare eye vision while remaining participants used their vision correction glasses during the test.

3.2.4.3 Procedure

The participants signed an informed consent form before starting the experiments. After being instructed, the participants were asked to stand close to the projectors. The height and inter-pupillary distance (IPD) of the projectors were adjusted to match with the height and IPD of the participant.

3.2.4.3.1 Experiment-1: See-through Condition

In this experiment, the acuity chart was placed at a distance of 7 meters and the screen was placed at a distance of 75 cm from the user as illustrated in Figure 3.14(a). The chart was printed as black and white and was scaled for the calibrated viewing distance of 7 meters. The chart represented the characters of different sizes corresponding to the visual acuity of 20/200 to 20/20 (3 to 30 cycles/degree).

The test for the see-through condition was divided into two parts. In the first part, the participants were directed to look at the acuity chart having a see-through retroreflective screen in between and read the characters on the chart from line 1-8, the answers were simultaneously recorded by the researcher. In the second part of the experiment, the see-through retroreflective screen was removed and the users were asked to look at the chart directly and read the characters. Both parts were repeated for each participant. To avoid the learning effect, the recorded data was not shown to the users during the test.

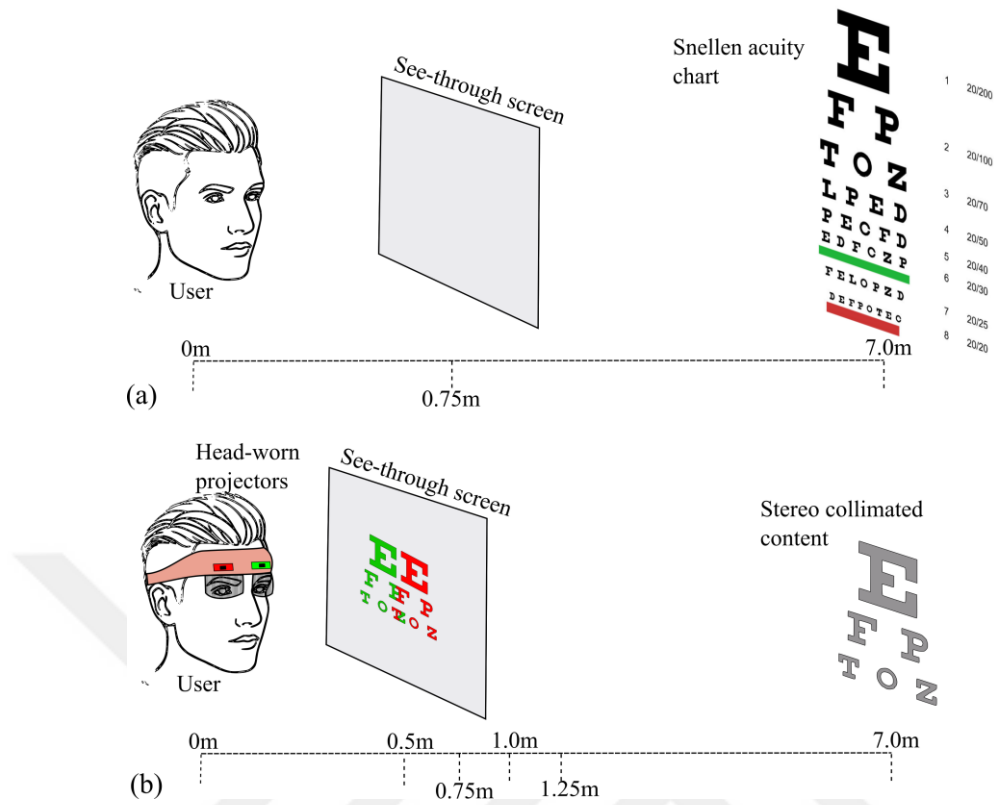


Figure 3.14. The experimental setting for see-through condition (a), and simulated collimation condition (b). Both projectors show full-color images, left and right eye projected images on the screen are shown with red and green colors for illustration purposes.

3.2.4.3.2 Experiment-2: Simulated Collimation Condition

In the simulated collimation condition, the characters from the Snellen chart with defined visual acuity were displayed on the 3D HUD. The stereoscopic views for a line of five characters corresponding to specific visual resolution was displayed on the screen. We used the acuity scale from 20/200 to 20/50 (3 to 12 *cycles/degree*). The polarizers were mounted together with projectors (as shown in Figure 3.13); therefore, the users did not have to wear separate 3D glasses. The parallax between the views was adjusted such that the characters appeared at the depth of distance of 7 *meters* from the viewer as illustrated in Figure 3.14(b). The stereo parallax and size of characters at a specific distance were determined by calculating the angular size of the projected pixel. The subjects were instructed to keep both eyes open during the test, converge and focus the eyes on the

distant real scene (at 7 meters) and read the line of superimposed text. The character pronounced by users were recorded by the researcher.

3.2.5 Results and Discussion

3.2.5.1 Experiment-1: See-through Condition

The visual acuity for the see-through condition was determined by calculating the number of characters recognized by participants accurately, when reading the acuity chart directly and through the screen. Figure 3.15 shows the average number of characters correctly read/resolved by participants as a function of visual acuity/spatial frequency and is compared to the condition when user see the chart directly without having an intermediate screen. Since all the characters larger than 20/50 were read accurately (with and without having the screen in between), the results are plotted from 20/50 scale (12 cycles/degree).

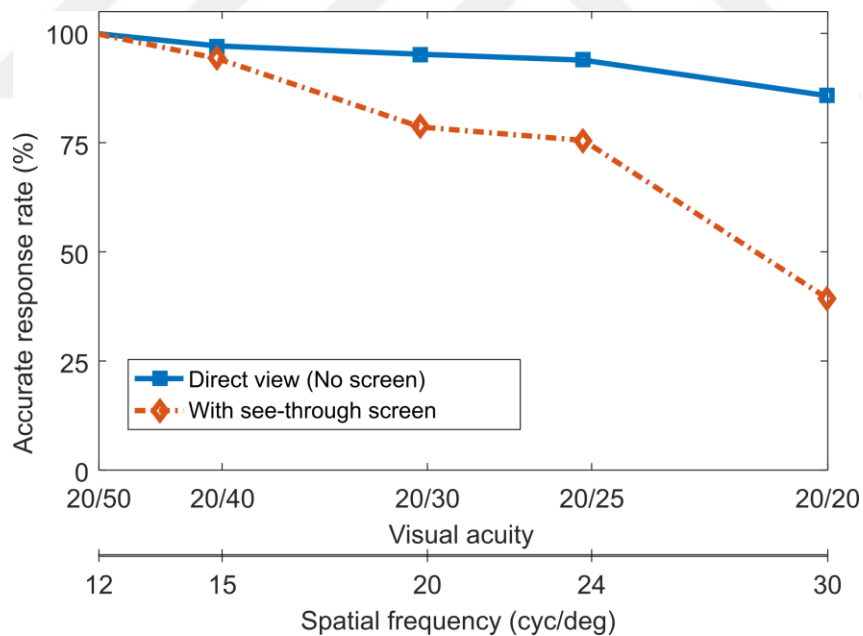


Figure 3.15. Average visual acuity in see-through condition and its comparison with direct viewing. The acuity response is slightly reduced when the screen is placed between user and acuity chart.

The Figure 3.15 shows the drop in visual acuity when the chart is viewed through the screen. An average human eye can resolve the spatial frequency of around 30 *cycles/degree*, which corresponds to 20/20 visual acuity. Since the all the participants reported normal visual acuity (with/without prescription glasses) before the experiment, the character size corresponding to 20/20 visual acuity were recognized with 90% average accuracy. Reduced visual acuity was observed when the screen was placed in between the user and the chart, where the accuracy rate was decreased to 40% for 20/20 visual acuity, while the average response for the large character size was also slightly lower than the direct view (no screen). The reduction in visual acuity is due to the micro-pattern on the screen surface and decreased the amount of transmitted ambient light. Figure 3.15 also shows higher response rate for the visual acuity of <20/25 (<24 *cycles/degree*). Negligible change in see-through performance suggests that the transparent retroreflective screen based 3D HUDs can be used as an automotive display without introducing the significant effects on the normal vision of user/driver.

3.2.5.2 Experiment-2: Simulated Collimation Condition

The visual acuity in simulated collimation condition was determined by calculating the number of characters recognized by the user accurately at each screen distance (50 *cm*, 75 *cm*, 100 *cm* and 125 *cm*). Figure 3.16(a) shows the average number of correctly recognized characters for the different visual acuity scales. The result shows the poor visual acuity when the distance between the screen and the viewer is closer (50 *cm*). The amount of content blur due to the AC mismatch, which decreases the ability of the user to resolve small size characters is significant when the screen is placed close to the viewer. The large size characters (20/200 to 20/100) are resolved correctly for all screen distances except for 50cm. The significant improvement in acuity is observed when the distance to the screen is increased. As the distance between user and screen is changed, the difference between accommodation and convergence is also changed. Figure 3.16(b) shows the accurate response rate for the 20/50 and 20/70 size characters displayed on the screen for different levels of AC conflict. The figure shows the inverse relationship between the visual acuity and amount of AC conflict. Higher AC conflict (closely positioned screen) results in poor visual acuity and vice versa. The error bars in Figure 3.16(b) show maximum and minimum accuracy achieved during the tests.

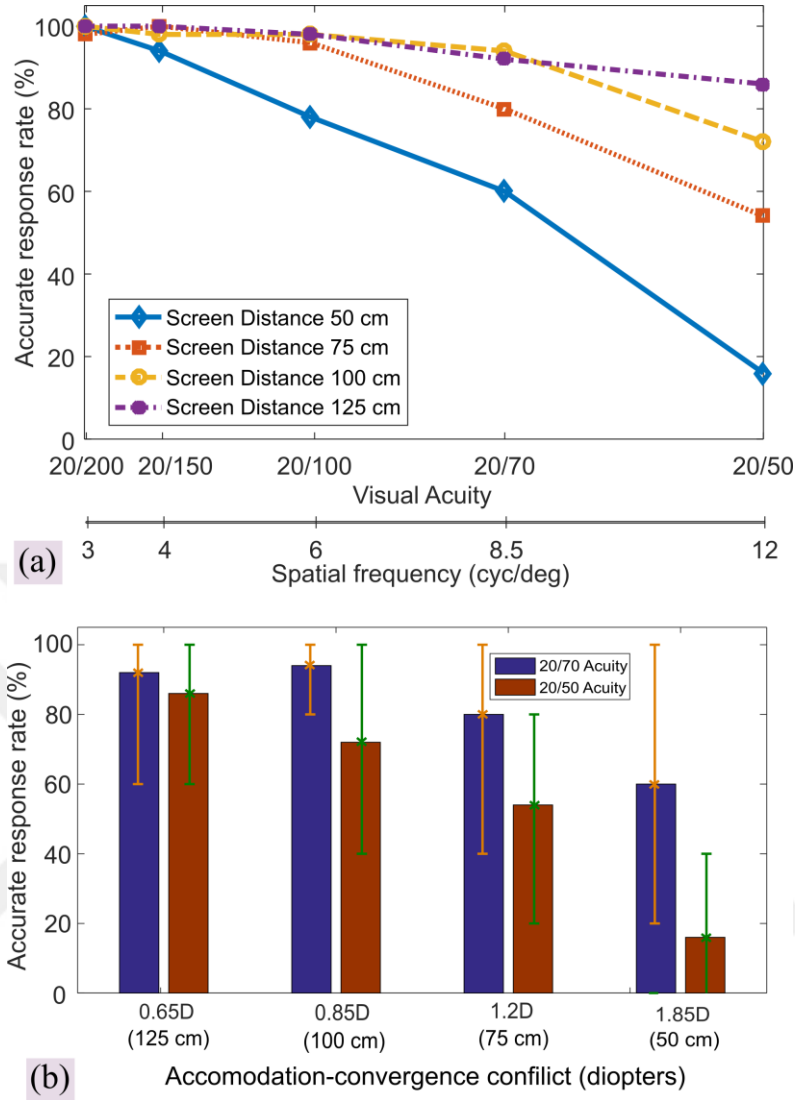


Figure 3.16. (a) The average visual acuity for different screen distances under simulated collimation condition and, (b) the average accuracy at different accommodation-vergence differences, when smaller size characters (20/70 and 20/50) are displayed on the screen. The error bars show the minimum and maximum accuracy achieved during the test.

3.2.5.3 Difficulty Level and Discomfort

In the post-test questionnaire, we asked the participants to report the relative difficulty for each screen distance in the simulated collimation condition. All the participants reported the close distance screen (50 cm) as most difficult, while the distance of 125 cm was reported as least difficult. The collimation was simulated using stereoscopy, which has the possibility of causing discomfort like, eye strain, nausea, and headache. We asked the participants to report such conditions experienced during the test experiments.

About 40% participants reported the eye-strain when using the screen at the 50 *cm* distance, while no discomfort or other effects were reported for remaining parts of tests.

3.2.5.4 Key Findings

The first experiment of the user tests showed that placement of a see-through retroreflective screen as 3D HUD has minimum effect on the visual acuity of the user/driver, where 75% transparent screen affects the visual acuity with small margin only (reduced from 20/20 to 20/25). The second part of the experiments showed an inverse relation between AC conflict/screen distance and acuity response; that suggests >100 *cm* screen distance (an AC mismatch of <0.85 *diopeters*) as better for the HUD applications. The results showed poor acuity at close screen distance (higher AC conflict). However, it was also noted that the amount of AC conflict or screen distance have a minimum effect when large size objects are displayed on the HUD screen, this result provides the guidelines for the optimum size of objects when designing the virtual interfaces of such applications.

3.2.6 Conclusion

We evaluated the visual acuity response of a 3D HUD based on the retroreflective see-through screen. Stereo parallax was used to simulate the optical collimation needed for HUD applications. Two different user tests were conducted to measure the effect of reduced light transmission (compared to clear windshield glass) of the screen and stereoscopic simulated optical collimation on the visual acuity response. Additionally, the relationship of AC conflict and screen distance with acuity response was analyzed in simulated collimation mode. We used a 75% transparent screen developed in-house coupled with two pico-projectors as our test setup. Our results showed a minor reduction in visual acuity (20/20 to 20/25) when the clear vision of the user is covered with a retroreflective HUD screen. In simulated collimation condition, the results showed opposite relation between the acuity response and amount of AC conflict (user to screen distance), where the average accuracy rate for recognizing the 20/50 (12 *cycles/degree*) sized characters decreased from 86% to 16%, when the screen distance changed from 125 *cm* (1.85 *D*) to 50 *cm* (0.65 *D*). While the see-through performance of HUD is

dependent on the type of screen and its transmission characteristics, the presented test results for the simulated collimation (stereo collimation) condition can be extended to other 3D HUDs and wearable AR glasses, where the virtual image is displayed at a fixed distance and the depth cue is provided by adjusting the stereo parallax. In the current study, participants used the display for a brief duration (15-20 *mins*), the study can be extended to assess the visual performance, when the 3D HUD is tested for longer durations.



CHAPTER 4

LIGHT FIELD IMAGING USING HANDHELD LENS ARRAY SURFACES

This chapter presents a new method for light field 3D imaging using passive optical surfaces. The method allows mobile light field capture and reconstruction by recording the multi-perspective views using a handheld lens array surface and a single camera. The position of the handheld surface is determined by detecting and tracking the surface in real-time. We present this lens array surface as an accessory that can turn a regular camera (i.e. smartphones, digital cameras) into a light field capture system. The lens array surface captures the scene from different directions, which is otherwise only possible with large camera arrays. The simple and scalable imaging architecture facilitates the lens array surface to have adjustable size and number of lenses to capture the desired number of views and resolution. The chapter is organized as follow: Section 4.1 provides the theory of light field and integral imaging and introduces the concept of light field capture with lens array surface. Section 4.2 presents the overview of the existing light field imaging techniques. Section 4.3 presents the geometry of image formation using the lens array surface. Section 4.4 discusses the spatial-angular resolution tradeoff, Section 4.5 analyzes the spatial resolution per view. Section 4.6 discusses the computer vision algorithm used to detect and track the handheld surface with respect to the camera. Section 4.7 presents the demonstrated prototype and test settings, while Section 4.8 presents and discusses the reconstruction results.

4.1 Introduction

The widespread availability of 3D displays for virtual and augmented reality applications is increasing the demand for advanced imaging systems to capture the 3D information of the scenes/objects. Among many other techniques, the light field capture is seen as one of the promising methods for capturing information rich in details. In the following part of this section, we explain the theory of light field and integral imaging followed the concept of capturing light field with handheld lens array surfaces.

4.1.1 *Light Field versus Integral Imaging*

The spatial-angular information of the 3D scenes was first captured by Gabriel Lippmann in 1908, who coined the term *Integral Photography* (IP) or *Integral Imaging* [67]. Lippmann replaced the camera lens with a micro-lens array (MLA) and placed the photographic film at the focal plane of the MLA. With this technique, he recorded the collection of small elemental images of a 3D scene known as the integral image. The initial idea of Lippmann was to use the recorded information to build an integral imaging display. With the availability of digital sensors and display devices in recent years, significant contributions emerged in integral imaging [68].

On the other hand, the term '*Light field*', which refers to the simplification of the plenoptic function from 7D to 4D was introduced by Marc Levoy from computer graphic community [69]. It should be noted here that, the light field referred here is different from the light field term used for electromagnetics and illumination engineering [70]. Over the time, the spatial-angular capturing techniques have been studied by three different and somehow isolated communities: electrical engineers, computer graphics, and physical optics communities. For that reason, different names: plenoptic, light field and integral imaging/integral photography have been used to refer the same 3D imaging concept and technology [71].

4.1.2 Light field Representation

Assuming the captured light as incoherent and propagating around the objects much larger than the wavelength, the light propagation can be represented as rays parametrized by positions and directions. The method of dealing light as rays is called ray optics or geometric optics. On macro scale, the light field is modeled using ray optics, while the microscopic light field imaging uses both ray optics and wave optics. In early 1990, Adelson and Bergen introduced a 7D plenoptic function to parametrize the information contained by the light rays [72], which is represented as,

$$P(\theta, \phi, \lambda, t, x, y, z), \quad (4.1)$$

where (θ, ϕ) represent the direction of the ray, λ and t represent wavelength and time, while (x, y, z) is the spatial coordinate points of the ray. The word plenoptic here is derived from the “plenus” in Latin, which means complete or full and therefore this plenoptic function may contain complete information about the object [70].

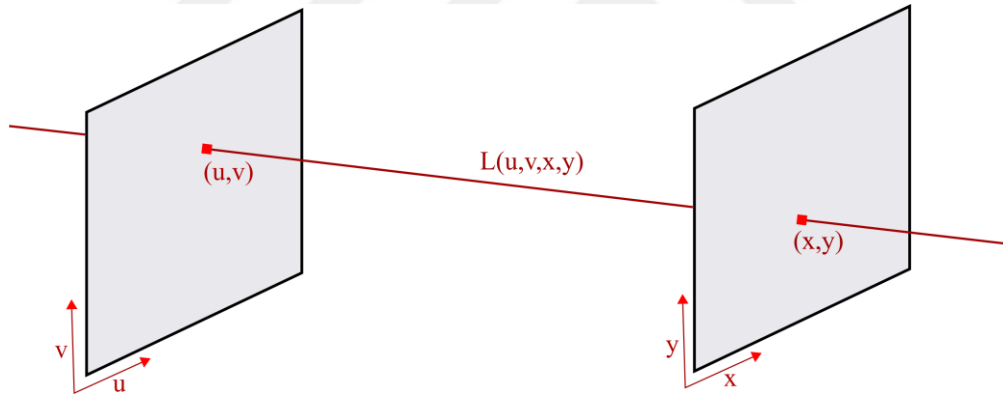


Figure 4.1. Parameterization of the light field using two parallel planes [69].

The plenoptic function is further simplified by making three important assumptions, 1) The function does not vary with time (eliminating t), 2) The ray represents monochromatic light (removing λ), and 3) the radiance along the propagation path is constant (removing z). Further, the angular coordinates are replaced with Cartesian coordinates (u, v) and assuming that the rays travel from left to right passing through two parallel planes as illustrated in Figure 4.1. With above assumptions, the 7D plenoptic function is simplified to a 4D function and represented as,

$$L(u, v, x, y). \quad (4.2)$$

This 4D simplification was referred as the light field by Levoy [69] and is sometimes called as lumigraph by the computer graphics community. (u, v) coordinates in the first plane and (x, y) in the second plane define the location and direction respectively. Based on the light field theory, any regular image can be stated as a 2D slice (sample) of the 4D light field, thus different imaging techniques can be used to capture the 2D slices and record sampled light field.

4.1.3 Handheld Surfaces for Light Field Capture

The proposed imaging technique consists of three elements: 1) handheld lens array surface, 2) a regular camera, and 3) backend processing module. The light field is captured by placing the surface at the arm length from the camera as illustrated in Figure 4.2. The surface contains an array of identical lenses with square apertures, where each lens generates the virtual perspective view of the scene/object called sub-image close to its focal plane. Due to the distributed arrangement of lenses, each lens sees the scene from a different angle where each sub-image represents a different perspective view. The views are then captured by the camera in a single shot and are processed for computational reconstruction and visualization using the backend processing module.

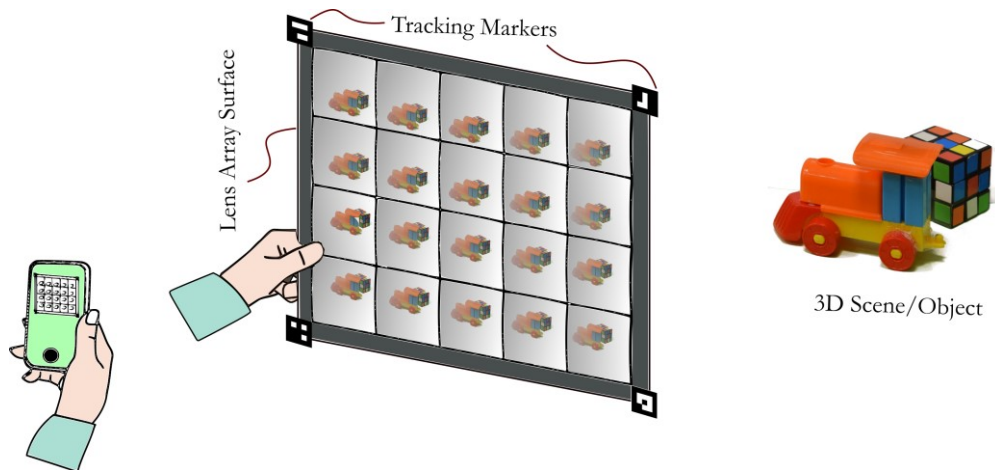


Figure 4.2. The concept of mobile light field capture using a handheld lens array surface and regular camera. The tracking markers are used to find the location of the surface with respect to the camera.

To allow mobility, the lens array surface is used as a handheld and arbitrarily positioned within the camera view. The exact position of the surface with respect to the camera is determined by performing the feature detection of distinct tracking markers attached to the corners of the surface and using intrinsic parameters of the surface and the camera.

4.2 Previous Work

The first demonstration of light field capture can be credited to Gabriel Lippmann, who laid the foundations of the integral photography in 1908 [67]. In recent years, the readily availability of the digital image sensors, lens arrays, and processing power brought various new light field capturing techniques by both applied optics and computer graphics communities.

Table 4.1. Comparison of different light field imaging techniques

Item	Camera Array	Axial/Transverse Moving Camera	Portable Plenoptic Camera	Near-field Integral Imaging	Handheld Lens Array Surface
Mobile	No	No	Yes	No	Yes
Perspective views	Sparse	Sparse	Dense	Dense	Sparse
One shot capture	No	No	Yes	Yes	Yes
Scalability	Hard	Hard	Hard	Hard	Easy
Resolution	High	High	Low	Low	Low
FOV	Large	Large	Moderate	Narrow	Large

One of the famous light field imaging architecture is based on camera arrays where a 2D grid of synchronized cameras are used to capture the scene/object from multiple perspectives [6,73]. The camera array systems can achieve high resolution, large synthetic aperture to see through partial occlusions and provide multi-view rendering. However, their fixed installations and inter-camera color mismatching and calibration have limited their applications. The alternative of the camera arrays has been demonstrated using single moving image sensor where the camera is translated along transverse and/or axial direction and multiple shots of the object are recorded from

different positions [74,75]. However, such techniques have longer capture times and are limited to static scenes/objects.

The compact size light field imaging systems have been demonstrated using a portable plenoptic camera [7] and far-field integral imaging techniques [76]. Such techniques use an additional MLA placed at the focal plane of the main lens and the image sensor is positioned at the focal plane of the MLA. The main lens (also known as depth control lens) in this case creates the conjugate image of the far object close to the MLA and facilitates the capture of the light field. The plenoptic camera and far-field integral imaging approaches offer a mobile solution to provide scene depth and focus blur, however, they cannot provide multi-perspective views or handle occlusions due to the small aperture of the main lens.

Recently, the catadioptric light field imaging techniques have also been proposed using an array of mirrors and a camera where either a curved mirror is modeled as a set of axial cone cameras [77] or faced flat mirror is used as a virtual camera [78]. However, the modeling of each mirror as hundreds of cone cameras is computationally expensive, while the flat mirror array provides a very narrow field of view. The closest imaging approach to our proposed technique is the integral photography with a lens-prism array, which uses the lens array surface where each lens is paired with the prism to provide the optical equivalent of a shifted lens [79]. However, the prism-lens array is introduced as a lens gear for photography cameras and is mounted on top of the main lens of the camera to fix the prism-lens array; that makes the imaging scheme different from the proposed approach where the lens array surface is handheld and detached from the camera. Table 4.1 provides the comparison of handheld light field capture with other famous techniques.

4.3 Geometry of Image Formation

To understand the image formation of a point in 3D space with its multi-perspective ray projections on the camera sensor when passing through a lens array surface, we formulate the geometric representation of the rays. The higher order lens aberrations are ignored by assuming the pinhole camera model and imaging lenses. Besides, the optical axis of the camera is used as the reference axis with origin at the camera pinhole. Figure

4.3 illustrates the cross-section of the imaging system. For simplicity, only 2D representation of rays (vertical component and propagation direction) is shown.

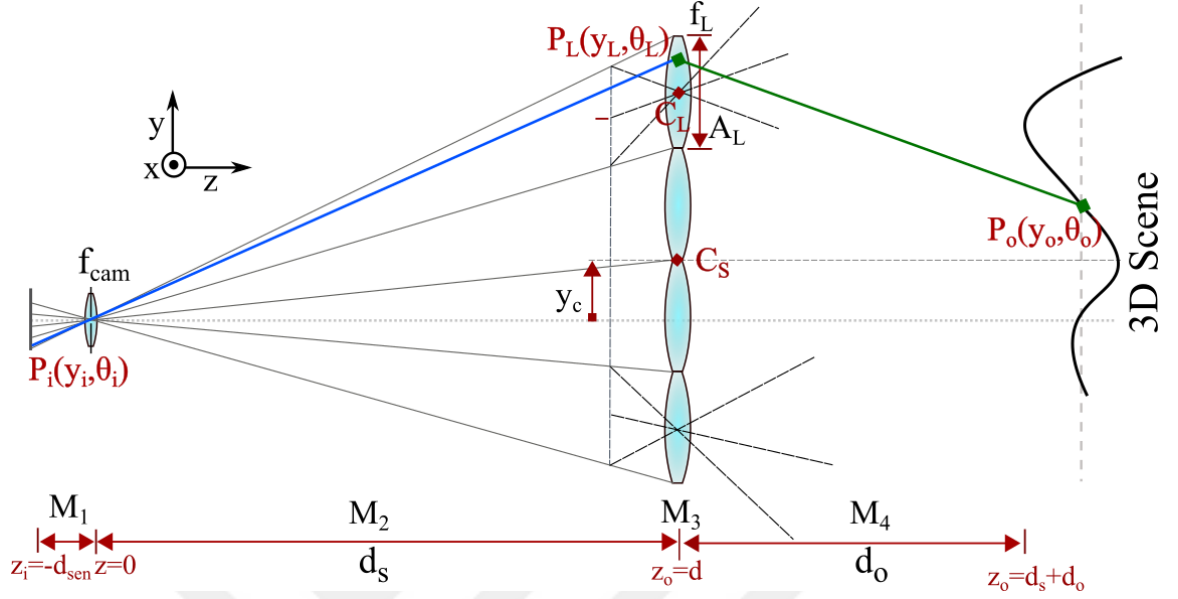


Figure 4.3. The process of image formation using the lens array surface. The ray tracing geometry is based on the paraxial geometric optics and ignores the high order abbreviations of the lenses.

For a handheld surface having $M \times N$ lenses, where focal length and aperture size of each lens is f_L and A_L respectively, the center of the surface is C_S , and is placed at the distance d_s from the camera, and the real object is placed at a distance d_o on the other side of the surface. Assuming a pixel/part of the pixel represented by a ray $P_i(y, \theta)^T$ on the camera sensor, where y and θ represent the position and direction (slope) of the ray respectively. The propagation of the ray from the camera sensor to the surface can be expressed as,

$$P_L = M_2 \times M_1 \times P_i = \begin{bmatrix} 1 & d_s \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & d_{sen} \\ 0 & 1 \end{bmatrix} \times P_i. \quad (4.3)$$

M_1 and M_2 in Equation 4.3 are the free-space ray transfer matrices from sensor to pinhole, and pinhole to surface respectively. Depending on the position and direction of the traveling ray, each ray passes through one of the lenses in the surface. Since the optical axis of the individual lens is different than reference axis, the ray coordinates are first translated to the local axis of the lens using the lens center $C_{L(m,n)}$ and shifted back to

reference axis after passing through the lens. The resultant ray is then transferred to the object plane of interest as,

$$P_o = M_4 \left(M_3 \times (P_L - C_{L(m,n)}) + C_{L(m,n)} \right) = \begin{bmatrix} 1 & d_o \\ 0 & 1 \end{bmatrix} \left(\begin{bmatrix} 1 & 0 \\ \frac{1}{f_L} & 1 \end{bmatrix} \times (P_L - C_{L(m,n)}) + C_{L(m,n)} \right). \quad (4.4)$$

M_3 in Equation 4.4 represents the ray transfer matrix of the lens on the surface, while M_4 refers to the free space propagation from the lens array surface to the object plane. The lens center $C_{L(m,n)}$ for $(m,n)^{th}$ lens on the surface is defined as,

$$C_{L(m,n)} = \begin{bmatrix} \frac{M-1}{2} - m \\ \frac{N-1}{2} - n \end{bmatrix} A_L + C_s \quad (4.5)$$

Once the path of the rays from the camera sensor to the object plane is known, the pixels are back-projected to reconstruct the captured scene at the desired depth.

4.4 Spatial-Angular Resolution Tradeoff

The proposed technique uses a single camera for light field capture where the spatial resolution (number of pixels per sub-image) is traded with angular resolution (total number of captured sub-images). The spatial-angular resolution tradeoff is a common issue of light field capture systems and integral imaging systems and has been studied for different 3D image capturing modalities [79].

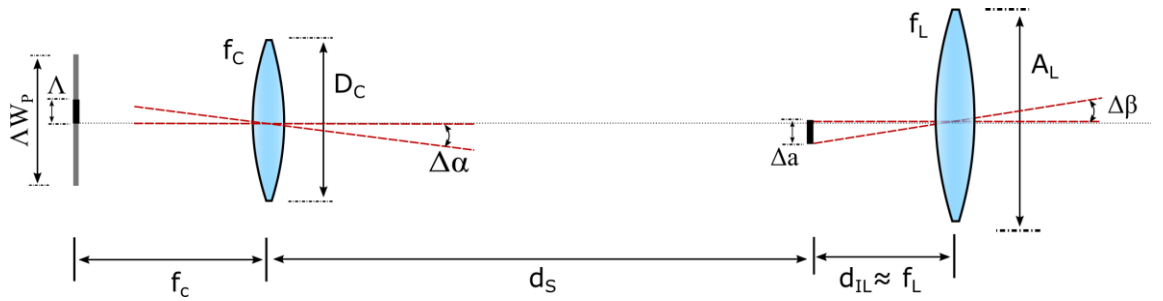


Figure 4.4. The diffraction limited resolution of the single camera and lens array surface based light field capture system.

We identify the limits of spatial and angular resolutions in mobile settings by considering the specifications of the state-of-the-art smartphone cameras as mentioned in

Table 4.2. Assuming the diffraction limited image resolution, the pixel size (Λ) of the image sensor can be estimated using the Rayleigh criterion for resolvable objects as,

$$\Lambda = \frac{1.22\lambda}{D_c} f_c, \quad (4.6)$$

where D_c is the aperture size and f_c is the focal length of the smartphone camera. Using the distance between the camera and the focal plane of the handheld surface (d_s), the minimum resolvable feature (Δa) on the focal plane of the lens array surface becomes,

$$\Delta a = \frac{d_s}{f_c} \Lambda, \quad (4.7)$$

The resolution at this plane can be through as pixel size for each sub-image (perspective view). The number of pixel per sub-image (N_p) can be calculated using Equation 4.7 and aperture size of the lens in the surface (A_L) as,

$$N_p = \frac{A_L}{\Delta a} = \frac{A_L f_c}{d_s \Lambda} = \frac{A_L D_c}{1.22 \lambda d_s}. \quad (4.8)$$

Additionally, knowing the number of pixels captured per sub-image, the total pixel count and the aspect ratio of the image sensor, and the maximum number of sub-images (N_s) that can be captured along the sensor width (W_p) in one shot can be calculated as,

$$N_s = \frac{W_p \Lambda d_s}{f_c A_L}. \quad (4.9)$$

Table 4.2. Specifications of the state-of-the-art smartphone cameras

Smartphone	F#	Pixel Size (um)	MP
iPhone X	1.8	1.12	12
Galaxy Note 8	1.7	1.4	12
iPhone 8/8 plus	1.8		12
Galaxy S8	1.7	1.4	12
LG V30	1.6	1	16
Google Pixel 2	1.8	1.4	12.2
Huawei Mate 10 Pro	1.6		20
HTC U11	1.7	1.4	12
Sony Xperia XZ P	2		19

Assuming a fixed wavelength $\lambda=600\text{ nm}$, and using the average parameters for the smartphone cameras ($fn=1.7$, *number of camera pixels*=12 MP and *aspect ratio*=4:3) from Table 4.2, we plot the number of pixels per sub-image (N_p) and maximum number captured sub-images (N_s) along the sensor width as a function of aperture size (A_L) of each lens in the handheld surface as shown in Figure 4.5.

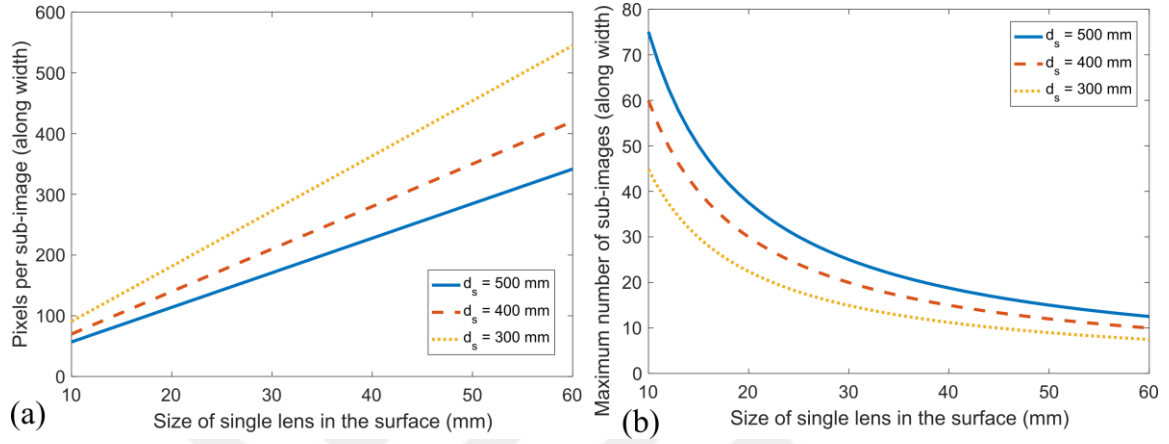


Figure 4.5. The trade-off between spatial and angular resolution for a smartphone camera. (a) Maximum number of pixels per view, and (b) the maximum number of sub-images/views that can be captured along the width of a 12MP smartphone camera sensor.

Figure 4.5 shows the direct relationship between the size of the lens and the number of pixel per sub-image and an inverse relation with the total number of sub-images. Figure 4.5(a) and Figure 4.5(b) show the level of compromise between spatial and angular resolution. The angular resolution can be increased by sacrificing the spatial resolution and vice versa. Since the surface is mobile and handheld, the distance between the camera and the surface can also change. Figure 4.5(a) shows improvement in spatial resolution when the surface is closer to the surface. On the other hand, Figure 4.5(b) shows a reduction in the number of captured sub-images if the surface is moved closer to the camera. It should be noted here that Figure 4.5(b) shows the maximum number of lenses that can be accommodated within the full FOV of the camera. Due to the mobile and handled nature of the surface, the actual number of lenses may be lower than this limit. Also, Figure 4.5 only shows the resolution tradeoff in one direction (along the width of camera sensor).

4.5 Optimizing Resolution

Although the number of pixels captured per sub-image primarily depends on the resolution limit of the camera, the spatial resolution achieved per view depends on both the camera and the properties of the lenses in the handheld surface. Consider ϕ as the required FOV per view/lens; the focal length for the lens (f_L) can be calculated as,

$$f_L = \frac{D_L}{2 \tan(\phi / 2)}, \quad (4.10)$$

Further, considering the resolution limit of the camera from Equation 4.7, we determine the minimum spatial resolution ($\Delta\beta$ in degrees) achieved per view as,

$$\Delta\beta = \tan^{-1} \left(\frac{\Delta\alpha}{f_L} \right) = \tan^{-1} \left(\frac{ds}{f_c} \Lambda \times \frac{2 \tan(\phi / 2)}{D_L} \right), \quad (4.11)$$

Using Equation 4.11, we plot the maximum achievable spatial frequency as the function of FOV of each perspective view for different aperture sizes of the lenses in the lens array surface (30-60 mm) and the fixed distance between the camera and image plane of the surface ($d_s=500$ mm). Figure 4.6(a) to Figure 4.6(c) show the achievable spatial resolution for three different cameras, where the camera f-number and pixel size are changed from 1.0 to 4 and $0.73 \mu m$ to $2.9 \mu m$, respectively.

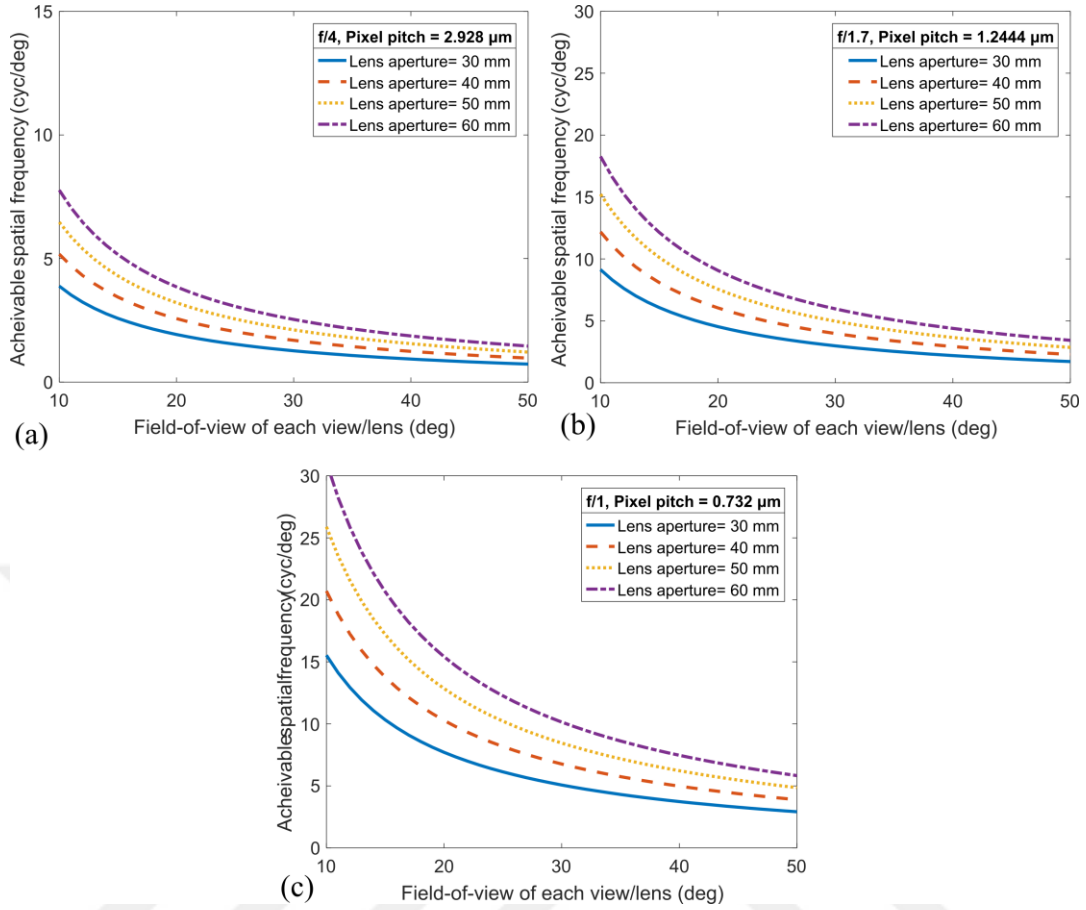


Figure 4.6. Maximum achievable spatial resolution for three different camera settings, when f-number for camera is (a) $f/4$, (b) $f/1.7$, and (c) $f/1$. The resolution is improved if the lens size is larger and FOV per view is narrower.

The figure shows an inverse relation between the spatial resolution and FOV of each sub-image, where increasing the FOV by five times in one direction decreases the resolvable spatial frequency by the same factor. The reduction in spatial resolution is due to the magnification factor, which further depends on the FOV of each lens in the array. The size of the lens also affects the resolution, where lower spatial resolution is observed if the aperture size of the lens is small. This is mainly due to the lower number of resolved features (pixels) in each lens, which as seen in Figure 4.6(a). The f-number of the camera also plays an important role; decreasing the f-number improves the overall spatial resolution.

Figure 4.6(b) shows the close match ($f/1.7$ and pixel size $1.25 \mu\text{m}$) with existing smartphone cameras (Table 4.2), where the spatial resolution of up to 20 *cycles/degrees* can be achieved if the lens aperture is 60 *mm* and FOV is 10° . With the availability of

advanced smartphones with improved cameras (i.e. $f/1.0$ as shown in Figure 4.6(c)), the spatial resolution can be further increased up to 30 *cycles/degree* in each view, which can provide the resolution equivalent to the normal human vision [2].

To capture the scene properly and provide enough overlap between the views, higher FOV per view is needed. The spatial resolution and FOV per view can be improved by constructing the lens array surface tiled with lenses of different focal lengths. A possible lens array design can be inspired by the human eye, where the center of the eye (fovea) has much higher visual acuity than the periphery. The lens array surface can be designed to have long focal length lenses at the center to provide narrow FOV and higher spatial resolution at the center and short focal length lenses at the surroundings to provide higher FOV. The light field captured from the center and surrounding lenses can be combined computationally to reconstruct the images with improved spatial and angular resolution.

4.6 Surface Detection and Tracking

Since the lens array surface is handheld and arbitrarily positioned within the FOV of the camera, it is important to locate the surface boundaries, camera to surface distance and center of the surface with respect to the reference axis. For that purpose, we added a computer vision sub-module at the front end of our computational reconstruction module. The surface tracking is divided into two parts; 1) extraction of the sub-images (perspective views) from the captured image, and 2) estimation of the location of the surface with respect to the camera. We track the handheld surface using Python and OpenCV based augmented reality library ‘*Aruco*’ [80]. An Aruco marker is composed of the wide black border and an inner binary matrix where each binary pattern is represented by a unique identification number. The inner binary matrix can differ from 2×2 *bits* to 7×7 *bits* [80]. We use four 4×4 *bits* Aruco markers, each attached at the corner of the surface, and find its pixel position using Aruco library. After the corners are detected, the projective geometric transformation is applied to the captured image to correct the surface rotation and extract the sub-images as shown in Figure 4.7.



Figure 4.7. The implementation of the surface detection tracking module on two different images. The captured image is processed to detect the corner of the surface and extract the captured perspective views.

The distance between the camera and the surface ($d_s=z_c$) is determined by using detected corners, and already known size of the surface ($W \times H$), and pixel size (Λ) and focal length of the camera as,

$$d_s = \frac{f_{cam}}{M_{cam}} = \frac{H}{H_p \Lambda} f_{cam}, \quad (4.12)$$

where H_p is the height of the surface in pixels. The center position of the surface (x_c, y_c) is further determined by using the camera magnification and the pixel size of image sensor and, the center position of surface in pixels (x_{cp}, y_{cp}) as,

$$C_s = \frac{\Lambda}{M_{cam}} \begin{bmatrix} x_{cp} \\ y_{cp} \end{bmatrix}. \quad (4.13)$$

The extracted perspective views, distance and amount of translation of the surface with respect to the camera are used by the image reconstruction module to project rays correctly. To provide the reliable surface detection and tracking, the surface is assumed to be inside the captured frame at all the times.

4.7 Test Experiments

We developed and tested two lens array surfaces of different sizes as shown in Figure 4.8(a) and Figure 4.8(b). A smartphone camera (iPhone SE, 12 MP) and a photography camera (Nikon, 24 MP) were used for image capture to test the imaging scheme. We used off-the-shelf sheets of Fresnel lens array sheet made of acrylic material using injection molding and tiled multiple segments of 4×3 lens arrays to create the desired surface.

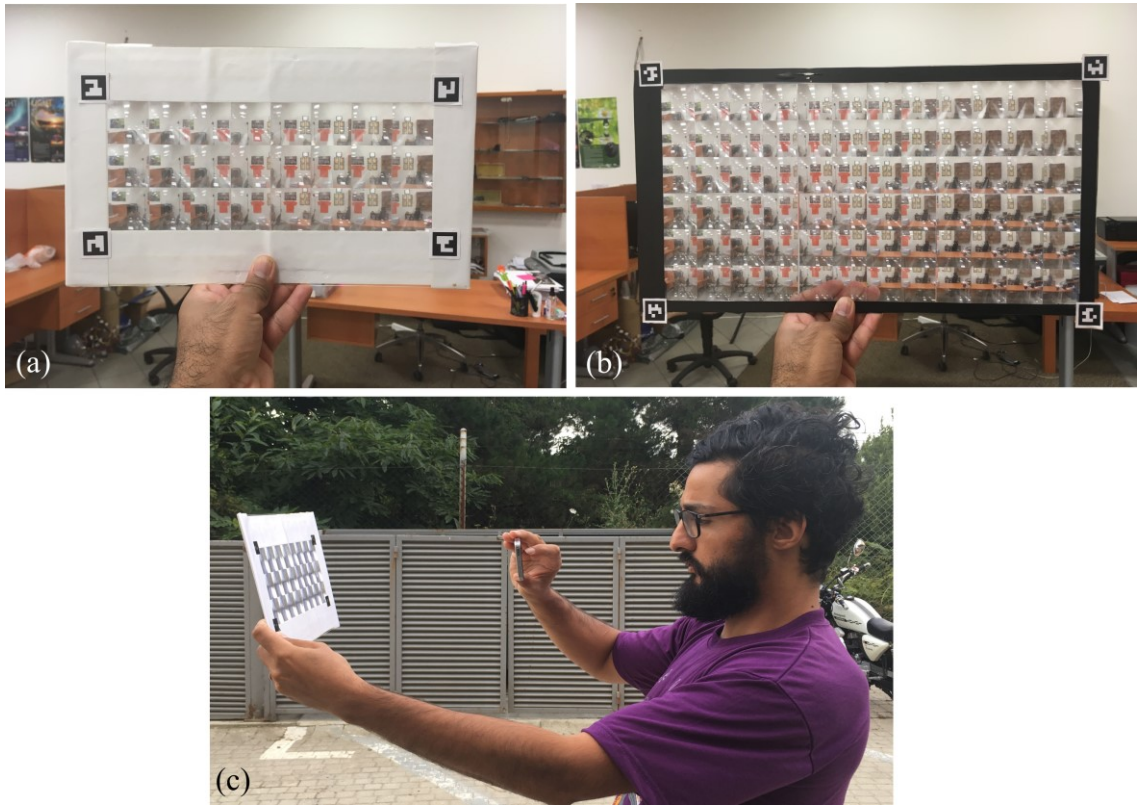


Figure 4.8. Two versions of the lens array surface providing (a) 24 perspective views, (b) 72 perspective views, and (c) shows the lens array surface used with a smartphone camera in outdoor settings.

The Fresnel lenses explored here have diffractive structures and are typically used for illumination optics (i.e. solar light concentration), therefore provide poor resolution when compared to the refractive imaging lenses. The reason for using Fresnel lenses is the thin and flexible form factor of the surface to facilitate handheld operation and mobility. The capture resolution can be further improved by using high quality Fresnel lenses or using

refractive lenses. Table 4.3 lists different parameters of both surfaces. The difference between S1 and S2 is the number of lenses and size that justify the tradeoff between the spatial-angular resolution discussed in the previous section. The number or size of the lenses (views) in the handheld surface can be increased/decreased by customizing the surface without changing the imaging architecture or reconstruction scheme of the imaging system.

Table 4.3. Parameters of the prototype surfaces used in test experiments

Item	Symbol	S1	S2
No. of perspective views (lenses)	$M \times N$	$8 \times 3 = 24$	$12 \times 6 = 72$
Aperture size of each lens	A_L	$34 \times 34 \text{ mm}^2$	$34 \times 34 \text{ mm}^2$
Focal length of each lens	f_L	-40 mm	-40 mm
FOV single view	FOV_{per}	$\approx 46^\circ$	$\approx 46^\circ$
FOV total	FOV_{tot}	$90^\circ - 120^\circ$	$110^\circ - 150^\circ$
Size of the surface	$W \times H$	$272 \times 102 \text{ mm}^2$	$408 \times 204 \text{ mm}^2$
Thickness of the surface	t	1 mm	1 mm

4.8 Results and Discussion

4.8.1 Image Reconstruction

The image reconstruction was accomplished by tracing the light field rays from the camera sensor to the object plane using Equations 4.3 through 4.5. To limit the size and resolution of the reconstructed image, a finite size output window with specific pixel resolution was defined as reconstruction plane as illustrated in Figure 4.9. The size and placement of the object plane was changed interactively to sweep through different depth distances. After the captured raw image is processed through the surface tracking module and the geometric corrections are performed, the rays for each perspective view are propagated through the camera lens (pinhole) and the lens array surface to the targeted object plane. The estimated distance and location of the surface with respect to camera is used by reconstruction module to reconstruct the image with a correct depth.

The projection of the pixel values is performed by considering the input and output positions of the rays. Since a point in the object plane is captured by multiple lenses in the handheld surface, the color value for each output pixel is determined by calculating the average contribution from all views as,

$$P_{out} = \sum_{i=1}^U \frac{P_{input}(i)}{U}, \quad (4.14)$$

where U is the number of views (lenses) contributing to the value of the pixel P_{out} at the object plane, while $P_{input}(i)$ is the value of the input image pixel in the i^{th} sub-image.

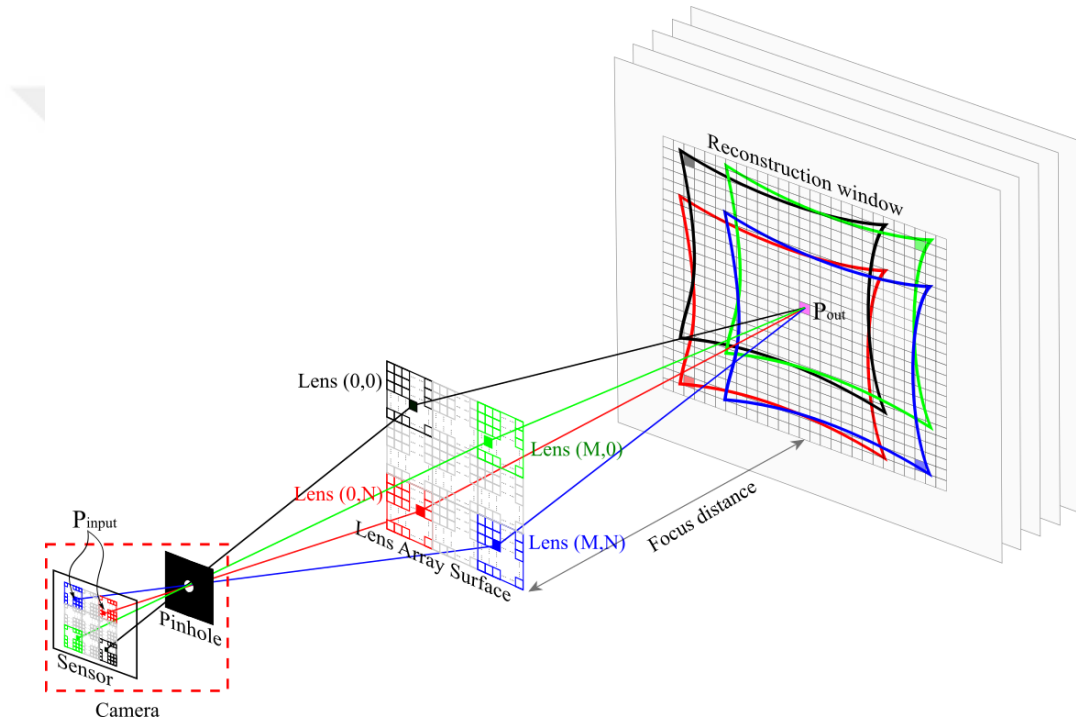


Figure 4.9. The process of image reconstruction. The pixels are traced through each lens and their cumulative contribution at each output pixel is calculated.

By using the above-mentioned reconstruction scheme, we implemented the digital refocusing, which is the famous application of light field imaging. The refocusing was performed by capturing the scene having objects at different depths and reconstructing the image at the selected depth (object plane). The distance of the object plane was interactively changed to focus/defocus different objects. Figure 4.10(a) shows an outdoor scene with a parking sign in the foreground (about 100 cm) and a car in the background (about 500 cm) captured using the surface S1 and a smartphone camera. The

refocused images rendered at the object plane distances of 100 *cm* and 500 *cm* are shown in Figure 4.10(b) and Figure 4.10(c), respectively. Figure 4.10(d) shows an indoor scene imaged using the surface S2 and a photography camera capturing a toy train and a printed text at the depth distance of 75 *cm* and 100 *cm*, respectively. The reconstruction results for two depth distances, toy train and printed text are shown in Figure 4.10(e) and Figure 4.10(f), respectively.

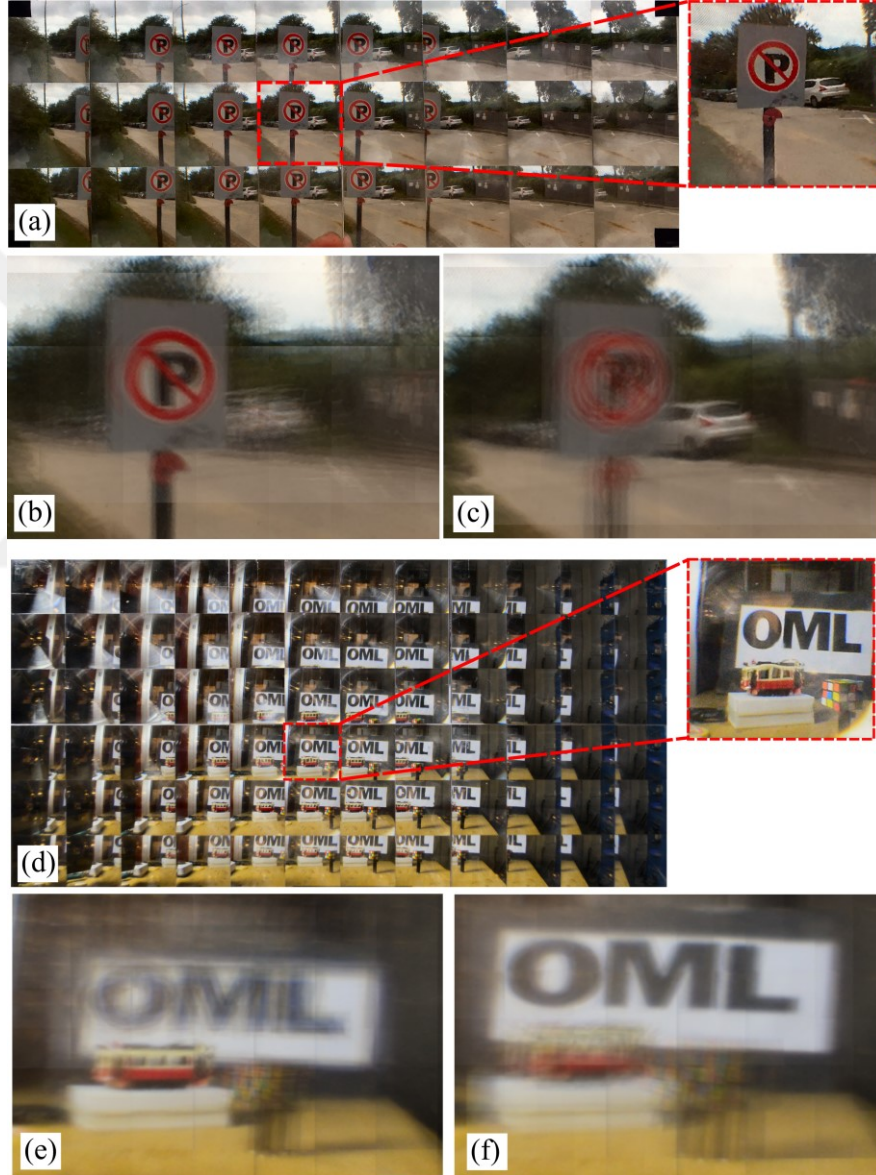


Figure 4.10. The reconstruction results for digital refocusing, (a) Outdoor scene captured with S1, (b) and (c) the reconstructed images at different depths, parking sign and car respectively, (d) An indoor scene captured using S2, (e) and (f) shows refocused images at toy train and printed OML text respectively.

The reconstruction was performed on the Graphical Processing Unit (GPU) and implemented in OpenGL using fragment shader (GLSL shader language), while the tracking of the surface and geometric transformation was performed on the CPU (Python/MATLAB). We used a standard laptop computer (i5 processor, 4GB RAM) with an integrated graphics card for processing. A refocused image with 600×600 pixels and 360000 rays was rendered in about 50 milliseconds.

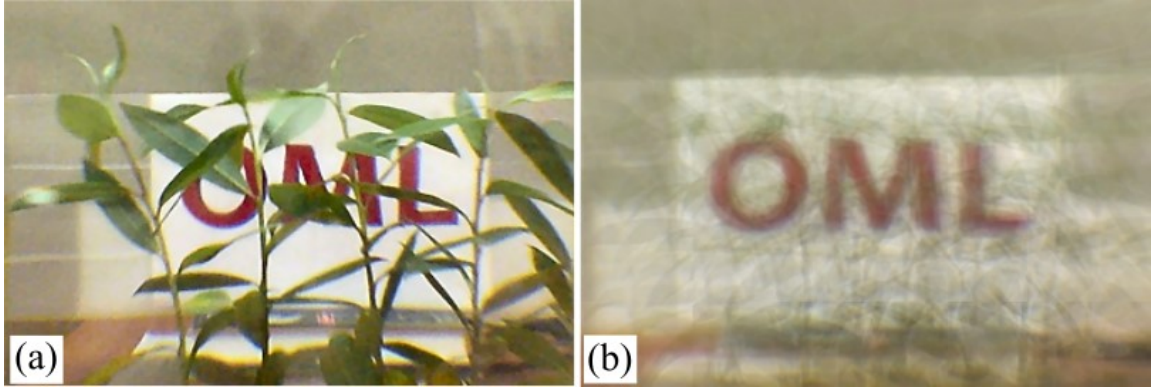


Figure 4.11. Demonstration of image capture through the partial occlusion, (a) One of the captured sub-images from the lens array surface, and (b) reconstructed image.

Similar to the camera arrays, the lens array surface can also provide wide synthetic aperture where each lens behaves as a sub-aperture. The large synthetic aperture has the capability to see-through partial occlusions and resolves the objects captured through the occlusions. To demonstrate this capability, we developed a setup where a printed text object was partially occluded with the leaves. The light field of this scene was captured with the lens array surface placed at about 40 cm from the leaves. Figure 4.11(a) shows the sub-image from the center of the surface where almost half of the text is blocked by occlusion. The object is resolved by reconstructing the refocused image at the object depth distance. Figure 4.11(b) shows the reconstructed image, where the blocked part of the text object can also be seen.

4.8.2 Field-of-view and Camera-to-Surface Distance

In a typical light field capture system, the FOV of all perspective views is considered as parallel to each other. In the proposed technique, the FOV of each perspective view

(lens) diverges depending on the angle of a chief ray passing through the lens. The total FOV of the system, amount of divergence in each view and overlap between the adjacent views depend on the intrinsic parameters of the surfaces and its distance from the camera. Using the ray tracing procedure discussed in Section 4.3, we calculated the total FOV for both S1 and S2 surfaces mentioned in Table 4.2. Figure 4.12 shows the change in total FOV (diagonal) when the surface distance from the camera is increased from 200 mm to 600 mm.

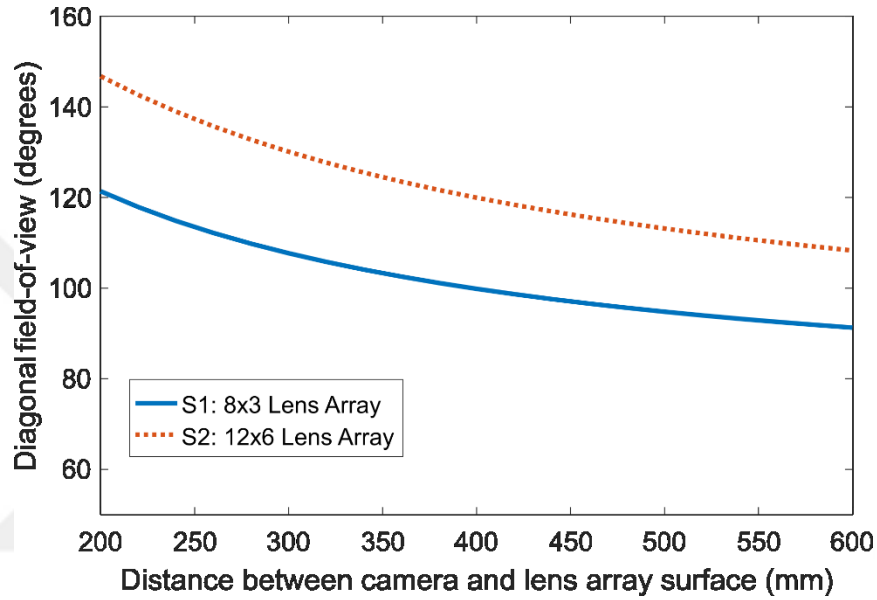


Figure 4.12. Change in the field-of-view of the imaging system, when the distance between the camera and the lens array surface is varied. The higher field-of-view at a closer distance is the result of the change in the direction of the lens chief rays.

As the distance between the camera and the surface is decreased, the angle of the chief ray for each lens in the surface is increased, this increases the total FOV of the imaging system. The change in FOV is sharper for shorter distances, while almost constant FOV is observed at larger distances (>500 mm). The change in total FOV also affects the amount of FOV overlap between the adjacent lens. The figure shows a change of about 30° when the surface is moved 40 cm.

4.9 Conclusion

A new light field imaging architecture was presented using the handheld lens array surface and a regular camera. Unlike other light field capture techniques, the proposed imaging scheme provides mobility and scalability together with multi-perspective capture capability. We presented geometric representation of multi-perspective image formation and ray projections from the camera to the scene passing through the surface. The location of the surface was determined by tracking the surface using AR markers. The computation for reconstruction was implemented on the GPU to achieve real-time operation.

The experimental tests were conducted by using two different versions of the surface providing 24 and 72 views of the scene. The handheld surfaces were based on Fresnel lens sheets. The tradeoff between angular and spatial resolution was also studied. Real-time digital refocusing was demonstrated for both indoor and outdoor settings. The current implementation limits the image quality of the reconstruction because of low-quality Fresnel lenses. The image quality and reconstruction can be improved by using high-quality imaging lenses, a high-resolution camera and, computationally correcting the lens distortions.

CHAPTER 5

INTEGRATED 3D DISPLAY AND IMAGING USING DUAL PURPOSE PASSIVE SCREEN

This chapter presents a novel integrated 3D display and imaging system using a head-mounted unit and a dual-purpose passive screen. The proposed screen has multiple layers and simultaneously acts as a high gain 3D display and multi-perspective virtual camera array when combined with the head-mounted projectors and a camera. The chapter is organized as follows: Section 5.1 provides the introduction and motivation. Section 5.2 provides a brief overview of the previous work in the domain of 3D displays, 3D imaging, and combined 3D displays and imaging, respectively. Section 5.3 explains the concept of the system, Section 5.4 presents fabrication flow of the dual-purpose screen. Section 5.5 presents the multiplexing techniques for simultaneous imaging and display. Section 5.6 presents the details of the test prototype, Section 5.7 demonstrates the real-time 3D telepresence using the developed device and Section 5.8 discusses the experimental results.

5.1 Introduction

3D content recording and visualization is an important part of the human-computer interaction (HCI). Display technologies are quite advanced but mobile displays and emerging augmented reality headsets have small screens and offer limited field-of-view. Projection displays can offer wide field-of-view using only a small display engine, but a projection surface is needed, and the brightness is limited due to low lumen output of the projectors. 3D imaging technologies, on the other hand, provide accurate depth maps but are typically limited to a single perspective view or need large installations.

Current display and imaging systems and techniques can provide enhanced 3D display experience using wearable devices and can capture the 3D scene efficiently. However, the existing head-mounted displays and smart headsets cannot use onboard cameras on the head to capture the user who is wearing the device. Therefore, such systems rely on separate fixed installations (i.e. depth cameras, camera arrays) around the user and cannot offer true mobility. The problem becomes particularly important when considering such wearable devices for 2D/3D telepresence applications where simultaneous capture and relay of the information is critical. In other words, the current wearable headsets lack the functionality of ‘3D selfie cameras’ let alone ‘multi-perspective selfie camera arrays’ to support telepresence applications in mobile settings.

In this work, we present a dual-purpose passive screen coupled with a head-mounted unit to demonstrate an integrated 3D display and multi-perspective 3D imaging system for mobile 3D telepresence applications. Compared to existing head-mounted displays, the proposed system provides an alternative platform that facilitates 3D telepresence by using a passive screen that captures the user from different perspectives. The compact size of the screen and the head-mounted device have the tendency to offer mobile operation needed for the ubiquitous 3D telepresence applications. The screen simultaneously acts as a high gain 3D display and multi-perspective virtual camera array when combined with the head-mounted projectors and camera. The stereo-3D display is facilitated by a pair of head-mounted projectors and retroreflective microspheres used a top of the screen, while multi-perspective views of the user are recorded using a head-mounted camera that captures the scene reflections using the bottom layer of the screen that contains an array of curved mirrors. An additional polarizer surface is sandwiched between display and imaging surface to separate both features and enable simultaneous operation.

5.2 Previous Work

The head-worn 3D display technologies can be classified into two groups, 1) near-eye-displays, where the image is displayed on a screen close to the eye, and 2) head-mounted projection displays, where the head-worn projectors are used to illuminate a handheld or a fixed screen at an intermediate distance. In recent years, an accelerated development in

near-eye-displays is seen using various techniques [1,39,81]. The GoogleGlass®, a monocular eye-wear display uses beam-splitter and curved reflectors [12] for image display in front the eye. The head-mounted displays using integral imaging, semi-reflective mirrors screens, and holographic optical elements have also been demonstrated [82–84]. Recently, the near-eye-displays with focused cues have been demonstrated using light-field [85], deformable membrane mirrors [86], and spatial light modulator based holographic displays [87]. On the other hand, the laser scanning pico-projectors based head-mounted displays and high gain retroreflective screens have also been demonstrated for numerous applications, including training simulations [88], mixed reality games and entertainment [89] and tele-existence [90]. The 3D version of head-mounted projection display has also been demonstrated using two head-mounted projectors and a retroreflective screen [33]. The AR display using transparent retroreflective screens has also been demonstrated [19,38].

There are various techniques available today for 3D capture and content recording. A simpler 3D imaging scheme uses stereoscopy, which consists of two cameras separated by a fixed distance. More sophisticated systems either use light field capture and integral imaging approaches or record the depth map of the scene directly using active imaging and reconstruct the 3D scene computationally. As discussed in the previous chapter, the light field capture and integral imaging systems use different techniques to record intensity, position, and direction of light rays represented by a 4D radiance function [69]. A famous technique for capturing high-resolution light field is based on multiple cameras arranged as a matrix to capture the scene from different perspectives simultaneously and then reconstructing the 3D information computationally [73,91]. The camera array based systems can capture the scene with both horizontal and vertical parallax and address occlusions, but either require computationally intensive inter-camera synchronization and fixed installation or can capture only the static scenes. The light field capture using catadioptric systems have also been demonstrated using curved mirrors [77] and array of planar mirrors [9]. 3D imaging with a single camera, a field lens, and lens-let arrays have also been demonstrated as integral imaging pick up systems, but such techniques can only provide limited field-of-view and capture the close objects [92,93]. On the other hand, the depth cameras either use structured light or time-

of-flight techniques to record the depth maps of the scene together with a single view [10,11].

There are a few combined 3D display and imaging systems demonstrated in the literature and most of them are designed for desktop settings only. In [94], the camera arrays and projector are used together to provide an autostereoscopic display of dynamic scenes. In [95], a transparent autostereoscopic display and depth cameras are used to facilitate combined capture and display for 3D telepresence. Room-size informal telepresence using a combination of depth and panoramic color cameras and wall display has also been demonstrated [96]. Recently, the 3D teleportation using Microsoft HoloLens as display and depth cameras as capture device is also demonstrated [97]. However, the need to separate capture device placed across and large installation setups have limited the usage of head-mounted-displays for telepresence applications.

5.3 Concept of the System

The proposed system consists of two elements, 1) head-mounted unit consisting of a camera and a pico-projector pair for capture and display, respectively and, 2) a multi-layered dual-purpose passive screen to display stereo 3D content and capture multi-perspective views through the reflections of mirrors buried in the screen. Figure 5.1 shows the conceptual illustration of the system where the 3D views (images of a lady) are displayed on the screen using head-mounted projectors, while the perspective reflections of the user (the boy wearing proposed head-mounted unit and holding the passive screen) are captured at the same time. The screen is composed of two primary layers, where the top and bottom layers are responsible for 3D display and 3D capture, respectively. The top layer of the screen has retroreflective microspheres, which reflect the incident projected light back towards the source with a narrow scattering angle. The microspheres are partially patterned to create tiny islands, where the spacing between the islands is used by the bottom layer for imaging. A pair of head-mounted projectors illuminates the screen with two images corresponding to a stereoscopic content, which is reflected towards the respective eyes positioned close to associated projectors. The distances between each eye and the exit-pupils of the projectors are minimized using the

beam-splitter, while the separation of the stereoscopic content for each eye is facilitated by the retroreflective property of the top layer [38].

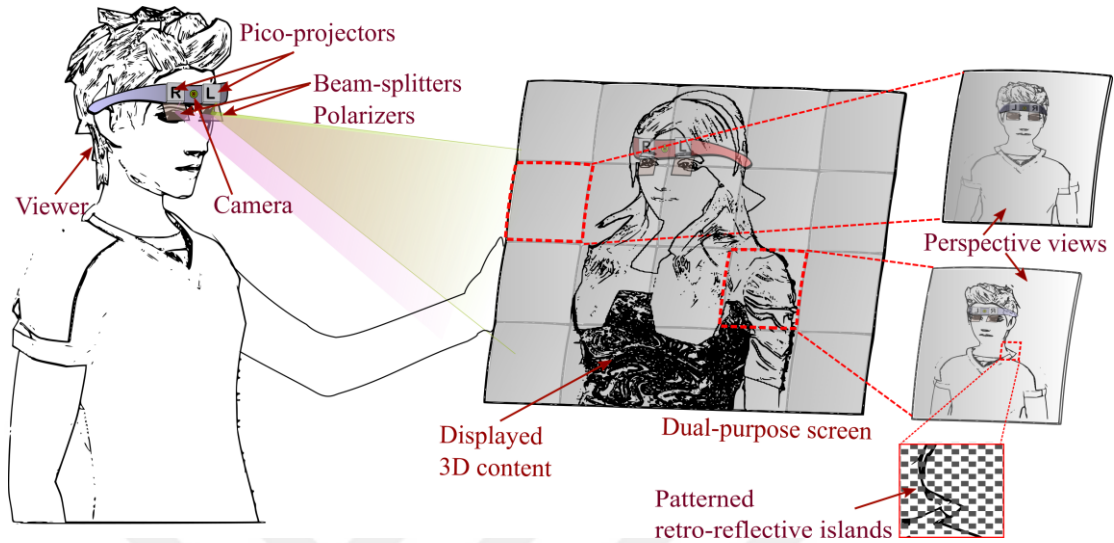


Figure 5.1. Conceptual illustration showing the working principle of the integrated 3D display and imaging system for a 3D telepresence application. The stereo-3D views of a remote person are displayed on the screen, while the perspective views of the local user are recorded using the head-mounted camera at the same time.

The bottom layer of the screen contains an array of curved mirrors. The mirrors are equally aligned and distributed over the screen area to allow a multi-perspective image capture. Each mirror in the array forms the virtual image of the user as illustrated in Figure 5.1 insets. The distribution of mirrors allows each mirror to see the user from different perspectives and the mirror array as a whole behaves as a multi-perspective virtual camera array. All perspective mirror images are captured by a single high-resolution head-mounted camera in one shot and are processed by a backend computational module to render the stereo view pairs.

An additional linear polarizer sheet is placed between the patterned retroreflective surface and the mirror array surface to facilitate simultaneous 3D display and imaging. The intermediate polarizer sheet blocks ambient reflection and projected light to be seen by the viewer and camera, respectively. The details of polarization multiplexing are discussed in Section 5.5.2.

5.4 Screen Fabrication

The screen was fabricated in three steps. First, the retroreflective microspheres were deposited on the polarizer sheet using optical adhesive. In the second step, the mirrors were tiled on the base substrate. At the end, both polarizer surface with retroreflective microspheres and tiled mirror array were bonded together. Figure 5.2(a) shows the stacking of the different layers of the screen.

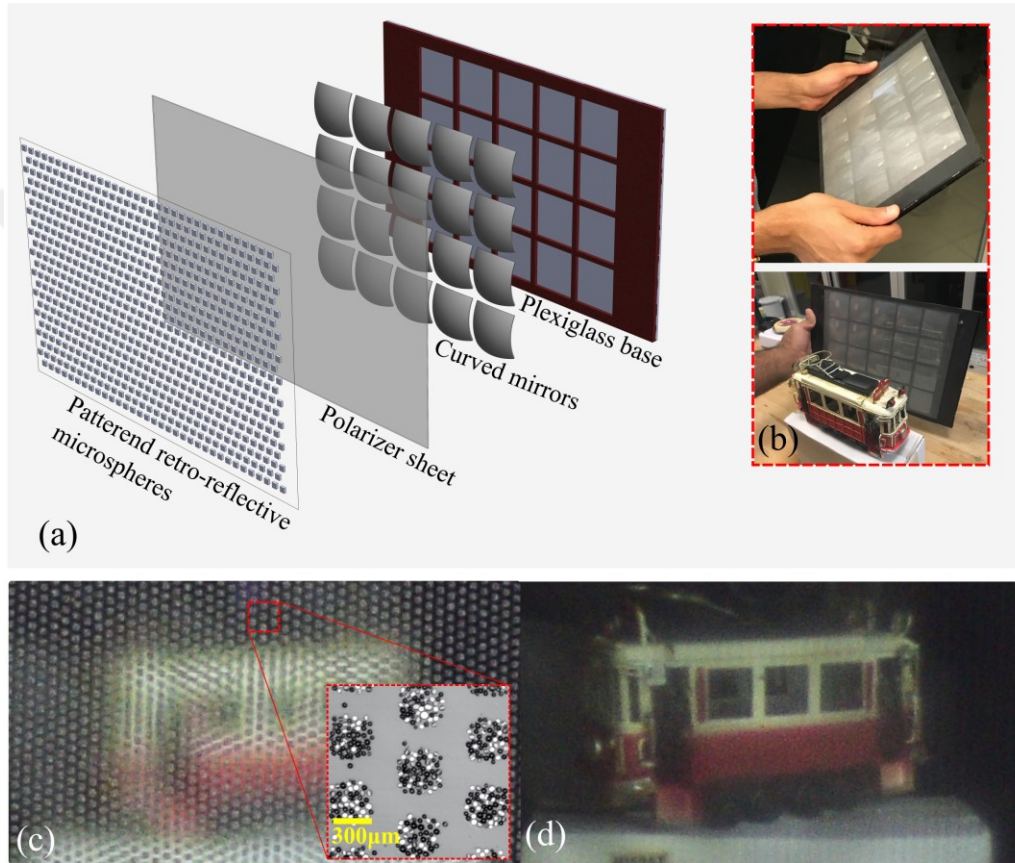


Figure 5.2. (a) Fabrication of the dual-purpose screen showing the arrangement of different layers of the screen, (b) the images of the developed handheld screen, (c), and (d) the close-ups of a mirror in the screen when the camera is focused on retroreflective pattern and reflected image respectively.

Similar to the screen presented in Chapter 2, we used the half-shell aluminum coated glass microspheres as retroreflective material. The microspheres were based on titanium dioxide (TiO_2) having the refractive index of 1.93. The diameter of microspheres was randomly distributed between 35-45 μm [19]. We used 200 μm thick linear polarizer sheet having a thin coating of pressure sensitive optical adhesive on one side [98]. To

pattern the microspheres, we used a $100\ \mu\text{m}$ thick stencil ($30\ \text{cm}\times 30\ \text{cm}$ negative mask) made of stainless steel. The stencil was designed in the lab and produced by printed circuit board (PCB) manufacturing firm using laser micromachining. The stencils had tiny square-shaped holes, covering 25% of the total area. The microspheres were transferred by attaching the stencil to the polarizer sheet and filling the stencil holes with the microspheres. The stencil was gently unwrapped, while microsphere stayed bonded to the polarizer sheet. The period of the retroreflective islands was made small enough ($<300\ \mu\text{m}$) to be irresolvable by the eye at the working distance from the screen.

We used off-the-shelf convex mirrors (used as rear-view blind-spot mirrors in vehicles) for the bottom layer of the screen. To better utilize the screen area, we cut the circular mirrors of $7\ \text{cm}$ diameter into $5\ \text{cm}\times 5\ \text{cm}$ squares using a 3D printed mold and diamond tipped glass cutting tool. The mirrors were uniformly tiled on the $1\ \text{mm}$ thick plexiglass frame. Figure 5.2(b) shows the fabricated handheld screen, while Figure 5.2(c) and Figure 5.2(d) show the closeup of a mirror in the screen showing the retroreflective pattern and reflection through the mirror.

5.5 Simultaneous Imaging and Display

To separate the displayed and captured light and enable simultaneous operation, we tested two different multiplexing techniques for projected and captured light: time multiplexing and polarization multiplexing.

5.5.1 Time Multiplexing

The time multiplexing utilized the scanning properties of the rolling shutter camera and laser pico-projector to provide simultaneous imaging and display through the dual-purpose screen. The vertical scanning signal from the projector was used to synchronously trigger the camera sensor. Figure 5.3 illustrates the running procedure: as the system starts ($t=0$), the projector generates the vertical scanning signal, which starts light beam scanning pixel-by-pixel, while the image sensor remains idle at that time. The projector's scanner signal is fetched and passed through a phase delay and amplifier circuit to introduce half a period delay. The sensor shutter is released when the delayed

signal triggers image sensor ($T_p/2$). By that time, the projection beam reaches the image center and first half of the image is already displayed. The image sensor then synchronously follows the projection beam with a constant delay. At end of the beam scanning period ($t=T_p$), the projector completes the image display and the image-sensor scanning reaches the center of the scene. At the following step, the projector's scanner rotates back to display a new frame, while the image sensor captures the remaining half of the scene. The projector keeps scanning new frames continuously, while the image-sensor takes additional time after each frame capture to allow sensor readout and memory reset. The process is repeated once the sensor is ready to capture the next frame.

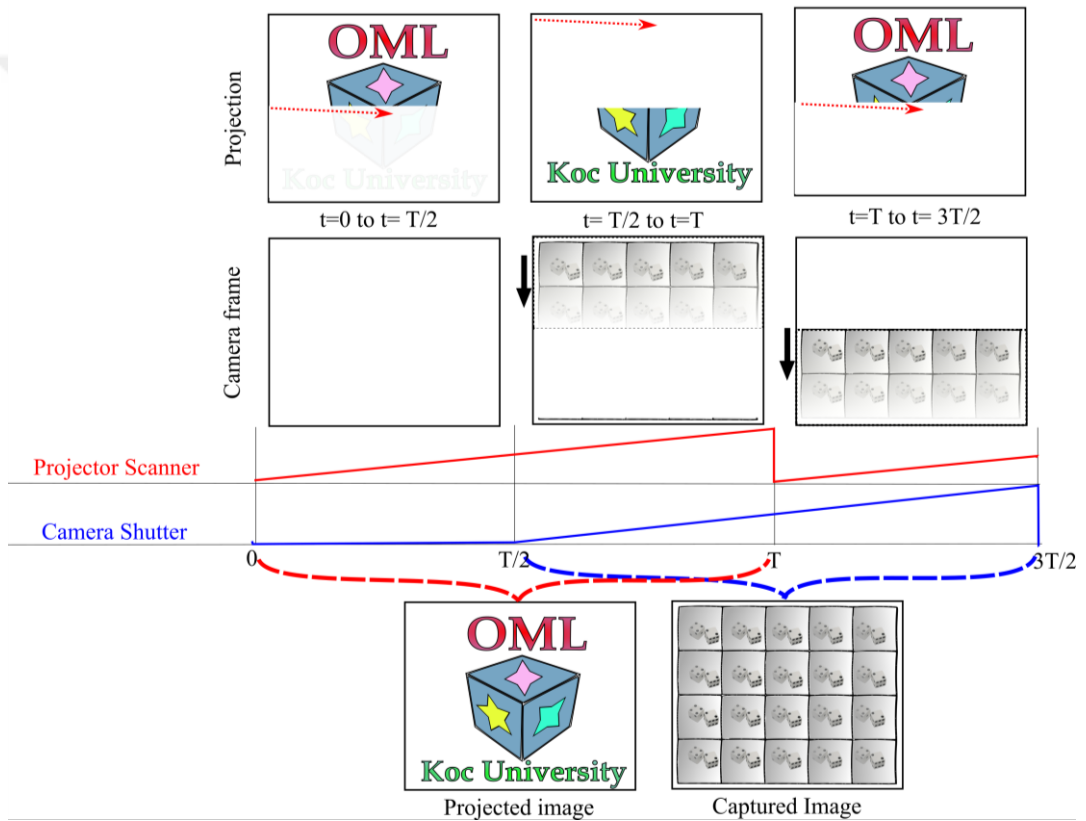


Figure 5.3. The procedure of time multiplexing between rolling shutter camera and scanning laser pico-projector to separate the captured and projected content on the screen. The camera shutter release is delayed with respect to starting time of the scanning period of the pico-projector.

The above-mentioned technique allows the projector and camera to share the screen space in real-time. We tested this technique in the early version of our prototype where we used a single projector and a rolling shutter camera. However, our current

implementation utilizes the polarization multiplexing technique discussed in the following section. The time multiplexing technique was also used to demonstrate the decoupling of the real and digital content in a projection based augmented reality system [99].

5.5.2 Polarization Multiplexing

We use mutually perpendicular polarization to separate the captured and displayed light as illustrated in Figure 5.4. Since both projectors use the same polarization direction, only one projector is shown in the figure for simplicity. In addition to the intermediate polarizer film in the screen, the additional linear polarizer films are used in front of the camera and the projectors/eyes.

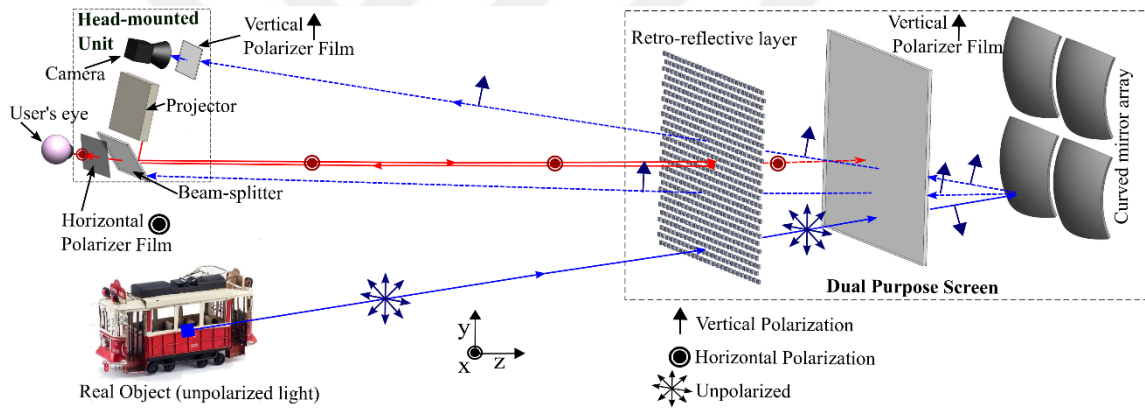


Figure 5.4. The principle of the polarization multiplexing of projected and captured light. The ambient scene is seen only by the camera, while the projected images are only perceived by the eyes.

We first use the polarizer film in front of projectors aperture to orient the polarization of the projected light along the horizontal direction. The projection beam is reflected by the beam-splitter to illuminate the screen. When the projected light rays hit the screen, the portion of the light rays is retro-reflected and is returned towards beam-splitter, while the remaining part of the projected light is transmitted through the spacing between the retroreflective islands and blocked by the intermediate vertical polarizer in the screen. Since a retroreflective surface retains the polarization orientation after the retro-reflection [38], the projected light passes through the beam-splitter and an optional polarizer in

front of the eye thus, the displayed content is perceived by the eye. The blockage of projected light after the retroreflective layer eliminates the visibility of bright spots in each mirror. Table 5.1 shows the polarization vectors of the projected light and the captured scene light at the different stages of the system.

Table 5.1. Polarization state of the projected and the ambient light at different surfaces of the screen

	Jones Matrix	Polarization Vector	
		<i>Projected Light</i>	<i>Scene Light</i>
Input		$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$	Unpolarized
Retroreflection at top layer of screen	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$	Unpolarized
Mirror array reflections after intermediate polarizer	$\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \end{bmatrix}$
Recorded on sensor (after camera polarizer)	$\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \end{bmatrix}$
Viewer's eyes (through optional polarizer)	$\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \end{bmatrix}$

On the capture side, the unpolarized ambient light is first transmitted through the patterned retroreflective layer and the vertical polarizer sheet where the horizontal component of the light is removed, the vertical component of the light is reflected off the mirrors and captured by the camera having a matching polarizer (vertically oriented) in front of the camera. The camera polarizer also guarantees the blockage of the projected light. Although our current multiplexing scheme uses linear polarization orientations, which are prone to tilts and rotations, the multiplexing scheme can be extended to circular polarizations by using additional quarter wave plate films at the system.

5.6 Experimental Prototype

The experimental prototype was developed to demonstrate the integrated 3D display and imaging system in real-time as shown in Figure 5.5(a). The setup consisted of a safety helmet type head-mounted piece and an in-house fabricated dual-purpose screen. We

used a pair of 15 *lumen* laser scanned pico-projectors from Microvision [13] providing 6.5 *lumen* effective power (in single polarization orientation). The projectors were stripped-off from original packaging and placed in a custom 3D printed housing (visible in Figure 5.5(b)). The distance between the exit-pupil of projectors was adjusted to 6.5 *cm*, which is close to the average Inter-Pupillary Distance (IPD) of human eyes. A pair of 50/50 reflective beam-splitters was used to bend the projected light towards the screen and decrease the distance between eye and projector. Each projector had 848×480 *pixels* resolution covering the $42^\circ \times 24^\circ$ field-of-view which provided 76% overlap between left and right views at the working distance of 70 *cm*.

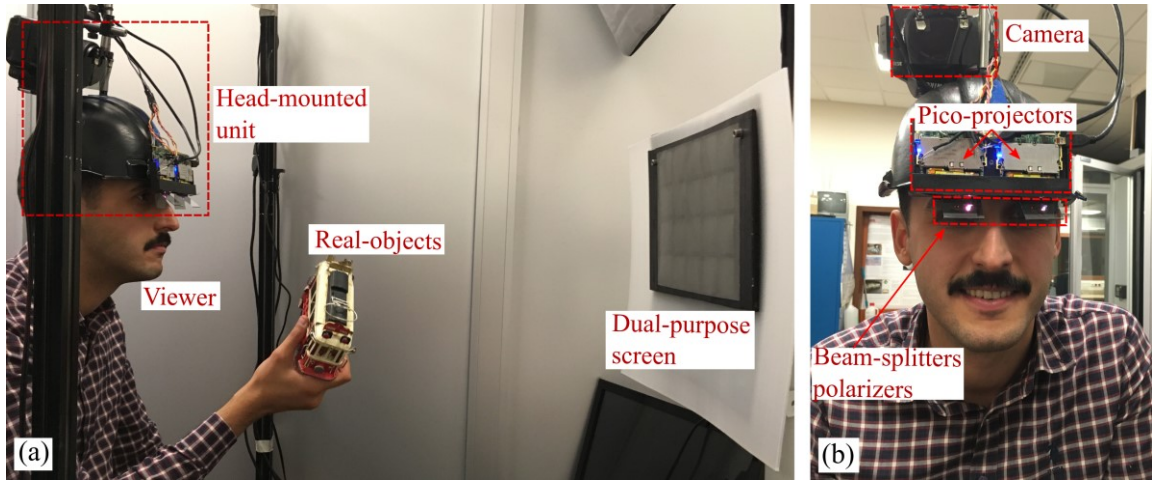


Figure 5.5. (a) Tabletop experimental prototype, (b) close view of the head-mounted unit with two pico-projectors, placed in a 3D printed housing, and a camera.

Since the mirror array layer was designed to mimic a camera array and each mirror was designed to behave like a virtual camera, we used $5\text{ cm} \times 5\text{ cm}$ mirrors with 7.5 *cm* focal length to provide $40^\circ \times 40^\circ$ field-of-view for each perspective view, which is close to the field-of-view of a typical webcam. To achieve sufficient disparity between adjacent views, the center-to-center distance between the mirrors was set to 6 *cm* that is close to average interpupillary distance IPD (6.5 *cm*) of human eyes. The current implementation provided the perspective views with a 1:1 aspect ratio. The field-of-view and aspect ratio can be modified by using the customized mirrors with different focal length and size. The total number of mirrors in the screen were limited by the size of the screen and total pixel count of the camera. Since the size of our stencil mask was limited to $30\text{ cm} \times 30$

cm, we used an array of 5×4 mirrors providing 20 perspective views to develop the $30\text{ cm} \times 24\text{ cm}$ screen. The reflections of the screen were captured using a 24 megapixels photography camera (Nikon D5300) attached to the head-mounted unit. The camera provided a resolution of $\approx 800 \times 800\text{ pixels}$ and $\approx 200 \times 200\text{ pixels}$ per view for still photos and real-time video capture, respectively.

5.7 Demonstration of 3D Telepresence

Full 3D telepresence architecture using the developed platform is envisioned by using two identical devices for local and remote users respectively as illustrated in Figure 5.6. In addition to dual-purpose screen and head-mounted device, each user side contains the processing engine to perform backend computations. The local user perceives the stereo 3D views of the remote user and at the same time the 3D perspective views of the local user are captured by the head-mounted camera, rendered into stereo pair using the local processing engine, and are relayed to the remote-viewer over the Internet. The bidirectional communication is enabled by applying the same process on the remote user side.

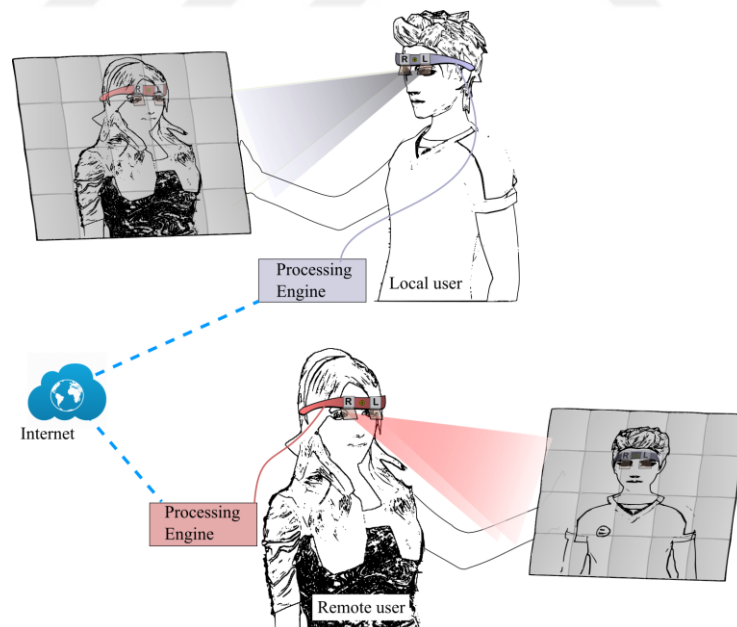


Figure 5.6. The 3D telepresence architecture using dual-purpose screens and head-mounted units.

In the current implementation, the 3D telepresence is demonstrated by using the developed system on the side of local-user and a virtual reality headset (Oculus Rift DK2) on the remote end. Figure 5.7(a) shows the local user with the developed device, while Figure 5.7(b) shows the remote user using a virtual reality headset. The local user perceives the stereo-3D views on the screen as shown in Figure 5.7(c), while at the same time the captured multi-perspective views of the local user are transmitted to the headset of the remote user as shown in Figure 5.7(d). The remote-user changes the viewpoint interactively to perceive the local user from different perspectives.

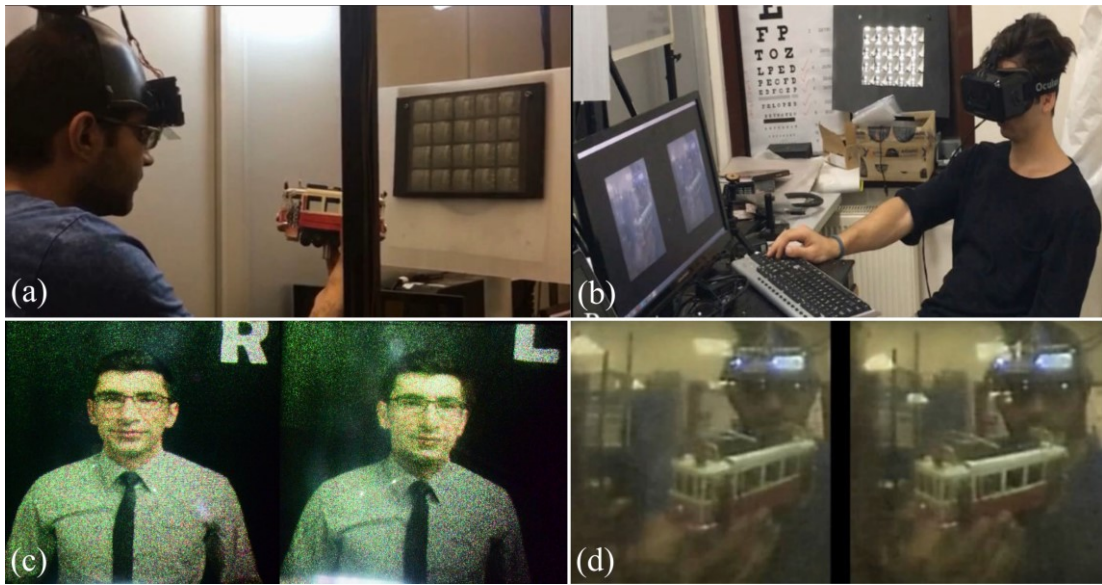


Figure 5.7. (a) A local user with the developed setup, (b) remote user with a VR headset, (c) 3D content seen by the local user on the dual-purpose screen, and (d) 3D content seen by remote-user on the VR headset.

5.8 Results and Discussion

5.8.1 Display Characteristics

The display performance of the system was evaluated by measuring the size of the eye-box, the brightness and the crosstalk per eye. Since the display layer of the screen is retroreflective, the brightness and crosstalk depend on the retroreflective properties of the screen. We used the retroreflective coefficient data measured using a photometric setup as reported in [19]. The brightness was further determined using the retroreflective

coefficient values, the projector power, eye-to-projector distance, interpupillary distance and the screen-to-viewer distance [19]. Figure 5.8(a) shows the size and overlap of the left/right eye-box and the change in perceived brightness within the eye-box at the working distance of 70 *cm*. Each projector creates a circularly shaped eye-box with a 2 *cm* diameter, which is enough for head-mounted projector scenarios where user's eyes are positioned close to the projectors. The small size of the eye-box is the result of the narrow angular expansion of retroreflected light that is about 2°. The angular width and shape of the eye-box depend on the aperture diffraction of microspheres [19]. The size of the eye-box also depends on the distance between the user and the screen. The size of the eye-box can be increased either by using the small size microspheres (providing wide diffraction angle) or by using the screen from a larger distance. A sharp change (up to 4 times reduction) in brightness is observed if the eye moves from the center to the edge of the eye-box.

Figure 5.8(b) shows the brightness and crosstalk per eye for the dual-purpose screen and brightness of a non-transparent diffused screen when viewed from the distance of 50-150 *cm*. The optical gain of the screen is calculated as the ratio of brightness of the dual-purpose screen to the brightness of an ideal diffused screen. Up to 240 *cd/m²* brightness is achieved using only a 15 *lumen* (≈ 6.5 *lumen* after polarizer) projection power. The optical gain of the dual-purpose screen shows 5.5 times more brightness compared to the diffused screen scattering light in the hemisphere volume when illuminated with a similar projector. The optical gain is further increased as the distance between the projector and the screen is increased. As the distance between the user and the screen increases, the brightness of the diffusing screen decreases more than that of the retroreflective screen due to the wide angle scattering by the diffusing surface. As a result, the ratio of the brightness of both screens is increased; this provides an increased optical gain. The mathematical expressions for the brightness of the diffusing screens and the retroreflective screens are given in [19]. The crosstalk between the left and right views was measured to close to 2% at the working distance of 70 *cm*. Overall, less than 4% crosstalk is observed for the working distance between 50 *cm* and 150 *cm*. The lower crosstalk is due to the close alignment of the eye and the projector (up to 0.5 *cm*), which facilitates the eyes to be positioned inside the eye-box of the associated projector.

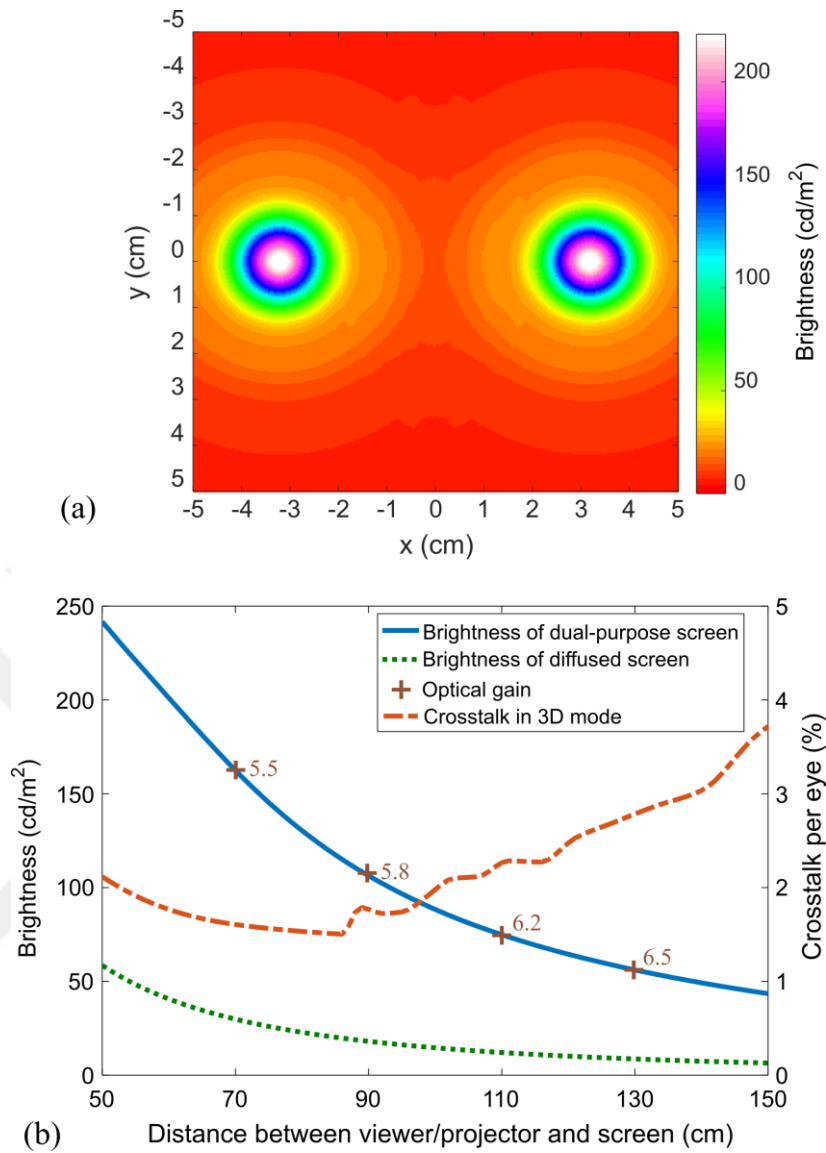


Figure 5.8. (a) Eye-box size and overlap between the left/right eye-box at a 70 cm working distance, (b) brightness, optical gain and crosstalk per eye when the distance between the screen and the viewer is changed.

The acceptable range of working distance can be assessed from Figure 5.8(b), which suggests that the screen can be viewed from 50 cm to 150 cm while providing acceptable brightness and negligible crosstalk. For a retroreflective screen, the effect of a change in position and viewing angle depends on the entrance angle of the retroreflective material. The entrance angle is defined as the range of incident angles where the screen remains highly retroreflective. The entrance angle of the microsphere type retroreflective screen was measured in Chapter 2 and showed that the screen can be used from different

viewing angles (up to 75°) without having a significant effect on the perceived brightness. Figure 5.9(a) and Figure 5.9(b) show the stereo-3D content displayed on the screen and as perceived with or without polarizer sheet in front of the eyes, respectively. With the polarizer, the screen appears black to the viewer and the mirror array become completely invisible to the eyes, while the absence of the polarizer provides slightly higher brightness making the mirrors partially visible.

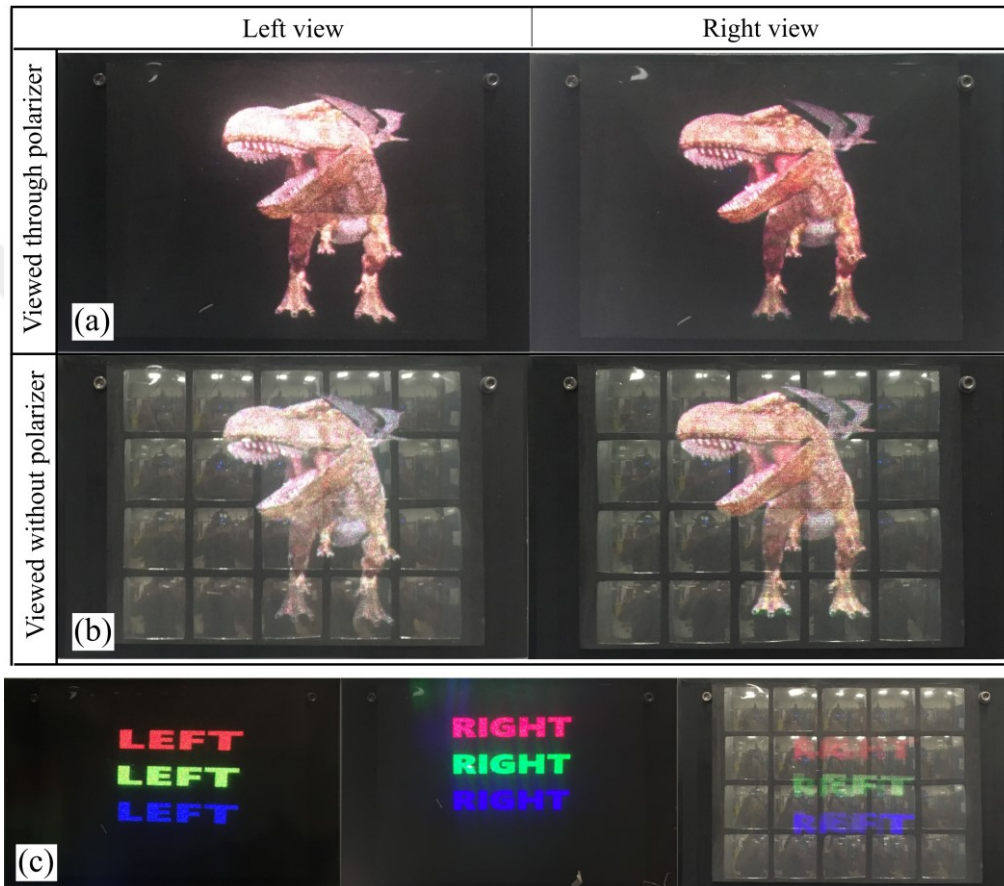


Figure 5.9. (a) and (b) A stereo 3D content displayed on the screen when viewed through the polarizer or without polarizer respectively, (c) the perceived views captured by the camera from the left eye, right eye and center positions respectively.

For full retroreflective efficiency, it is important for each microsphere to be oriented correctly with the uncoated part of the microspheres facing outward. In our implementation, the retroreflective microspheres were deposited in random orientation and about 30-35% of the total microspheres were useful. The inactive microspheres (appearing black in Figure 5.2(c) inset due to wrong orientation) produce speckle and grainy effect over the displayed content due to the coherent nature of the lasers used in

projectors. Significant improvements in display brightness and quality can be obtained with process improvements. Figure 5.9(c) shows the displayed stereo views when captured with the camera placed at the left eye-box, right eye-box and at the middle of both eyes. The left and right eye positions show unperceivable crosstalk, while the center view shows both left and right views mixed together with mirror reflections.

5.8.2 *Image Capture and Visualization*

3D image capture through the dual-purpose screen was demonstrated by performing the real-time computations on a backend processing module. First, the mirror reflections through the screen are captured using the head-mounted camera in the single shot. The field-of-view of the head-mounted camera is adjusted such that all mirrors in the screen are accommodated in the captured shot. A convex mirror creates the virtual image on the other side of the user/object, therefore, we tuned the focus of the camera close to the focal plane of the mirrors to capture the virtual views sharply. The captured image is then corrected for geometric distortion by performing the four-point projective distortion correction and the resultant image is segmented to extract the perspective views. Figure 5.10(a) shows the corrected image with all captured views. In the next phase, two horizontally adjacent perspective views are selected and processed through the geometric ray tracing procedure based on the already known geometry (i.e. screen distance, camera placement) of the system, where the pixels are computationally projected from the camera sensor to the scene to render the resultant stereo views. The ray tracing removes the none-overlapping part of each view and provides fully overlapping stereo views with approximately correct parallax that are then converted to the side-by-side stereo 3D format. Using the 20 mirrors on the screen, 16 viewpoints are generated where each viewpoint provides a stereo 3D view of the user/scene from a different angle. Figure 5.10(b) and Figure 5.10(c) shows two different viewpoints of the captured object and the user. The real-time visualization was provided by interactively selecting and relaying the desired viewpoint to a desktop or virtual reality headset (Oculus Rift). To facilitate the real-time operation, the ray tracing is performed on the Graphical Processing Unit (GPU) using fragment shader language.

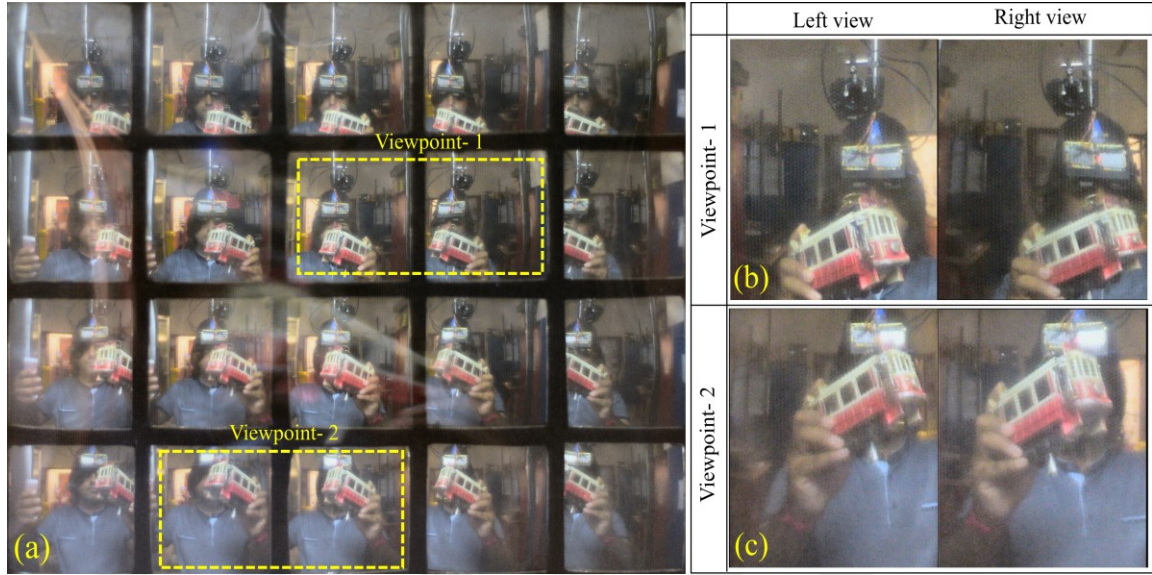


Figure 5.10. (a) The perspective views of the scene captured in a single shot, (b) and (c) two different reconstructed viewpoints relayed to a stereo display.

In the current implementation, the field-of-view and focus of the camera are set for the working distance of 70 cm. For a typical arm's length working distance (40-70 cm), the change in distance has a negligible effect on the capture quality. However, when the working distance is higher (i.e. >100 cm), the image quality is reduced due to fewer pixels per view. On the other hand, changing the viewing angle with respect to the screen has no effect on the quality of captured images but changes the viewing space and is equivalent to tilting the camera array.

5.8.3 Capture Quality

The image quality of the system was evaluated by measuring the experimental modulation transfer function (MTF) for a perspective view. We used slant edge technique to measure the MTF [36]. An experimental setup as shown in Figure 5.11(a) was constructed where a LCD screen was placed at 70 cm from the screen showing an edge with 5° tilt. The perspective views of the slanted edge were captured in a single image using the system camera attached to the head-mounted unit. The captured image was segmented into perspective views and one of the perspective views was used as an

input to slant edge MTF measuring algorithm. First, the Canny edge detection technique was applied to detect the edge [37]. The angle of the slanted edge was estimated by fitting a line to the edge, the image was up-sampled by a factor of four and the edge was straightened by applying an affine transformation by using the computed edge angle. From the column average of the subsequent image, an over-sampled edge profile was calculated to obtain one-dimensional edge spread function (ESF) as shown in Figure 5.11(b). The point spread function (PSF) was further calculated by computing the derivative of ESF. Finally, the MTF was determined by calculating the absolute value of the Fourier transform of the PSF.

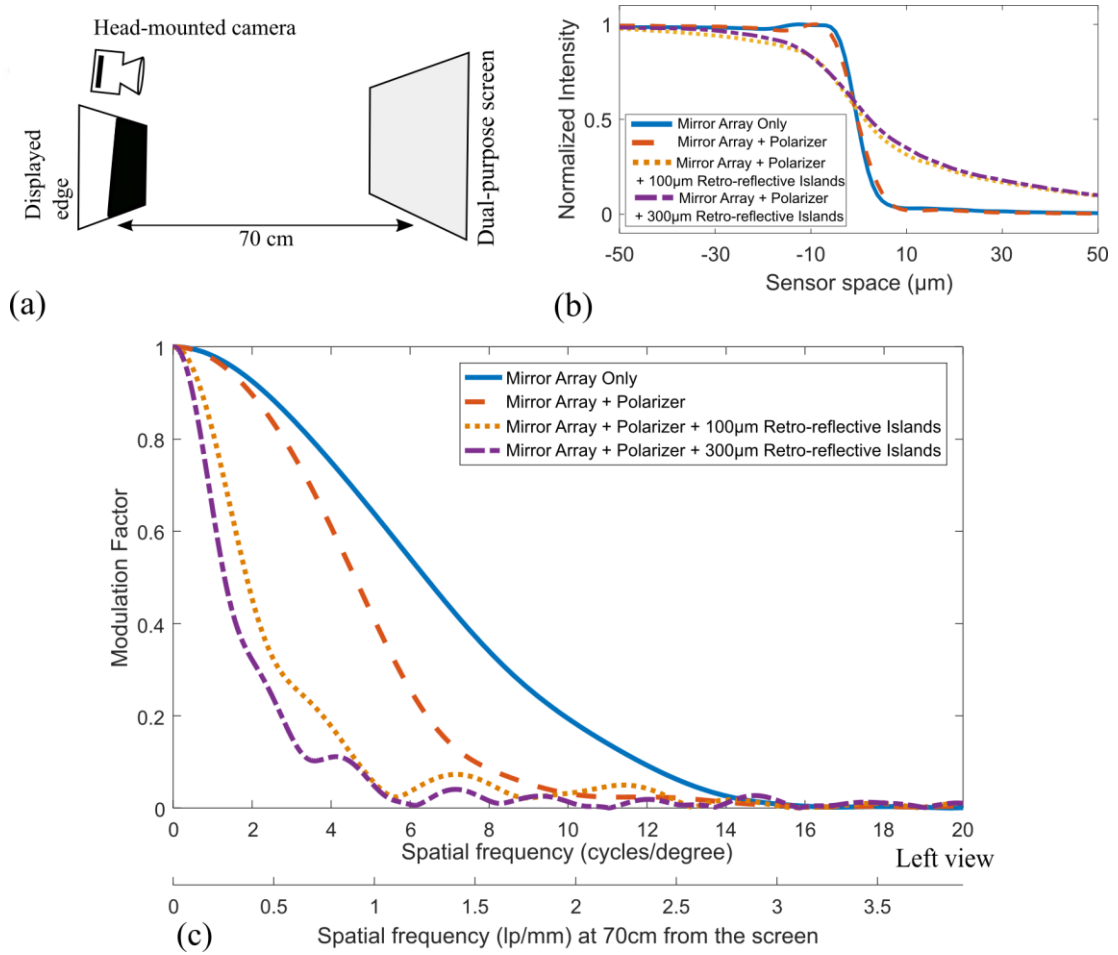


Figure 5.11. (a) Experimental setup for MTF measurement, (b) captured edge profile on the camera sensor for different configurations, and (c) measured MTF. With 10% cutoff limit, the imaging quality is reduced to one-third when a polarizer sheet is placed on top of mirror surface while 50% additional loss is observed when the retroreflective microspheres are patterned on the polarizer.

With the method discussed above, the MTF curves shown in Figure 5.11(c) were obtained for mirror array surface, mirror array surface covered with polarizer film and a dual-purpose screen having $100\ \mu\text{m}$ and $300\ \mu\text{m}$ retroreflective islands respectively. The figure shows the loss in the quality with the placement of the polarizer and the retroreflective microspheres. Considering the 10% of MTF as the limit, the resolution of mirror array surface with and without the polarizer sheet is 12 *cycles/degree* and 8 *cycles/degree* respectively. The further loss in image quality is observed after the microspheres are deposited on the polarizer sheet, where MTF is further decreased to 5 *cycles/degree*. The performance degradation can be attributed to the apparent loss in PSF due to the retroreflective surface and contrast loss introduced by the intermediate polarizer. The repeated micropattern of retroreflective microsphere behaves as a diffraction grating, which causes the PSF to expand, hence the loss in resultant MTF is observed. The effect of the diffraction grating can also be observed when comparing the MTF curves for the screen with $100\ \mu\text{m}$ and $300\ \mu\text{m}$ islands. The image quality can be improved either by using a better polarizer with increased transmission and further optimization of the retroreflective surface density or using a camera of higher quality. As seen in Figure 5.11(c), the system can resolve features of about 1 mm at 70 cm; this performance is closer to the standard midrange telepresence cameras or webcams.

5.8.4 Capture Light Efficiency

The shared use of dual-purpose screen for imaging and display, and placement of multiple polarizer films in the system reduce the amount of light captured by the camera. The capture light efficiency depends on the retroreflective fill-factor and transmittance of the polarizer film for parallel and orthogonally polarized light. Table 5.2 shows the amount of light at different stages of the system. Our screen has 25% retroreflective fill-factor, which allows 75% of ambient light to pass through. The polarizer film used in the system transmits 43% of the unpolarized light, while 87% and 0.002% transmission is achieved for parallel and orthogonal polarizations, respectively. As mentioned in the table, the camera captures only 22% of the scene light when compared to the direct imaging. The amount of captured light can be improved by replacing the intermediate

polarizer with wavelength selective notch coatings and performing wavelength multiplexing procedure.

Table 5.2. Loss of transmitted light for different interfaces of the system

	Input	Retroreflective Layer	Intermediate Polarizer (1 st Pass)	Mirror Array Reflection	Intermediate Polarizer (2 nd Pass)	Captured After Camera Polarizer
Efficiency of the interface	-----	75%	43%	90%	87%	87%
Total light transmission	I_0	$0.75I_0$	$0.323I_0$	$0.29I_0$	$0.253I_0$	$0.22I_0$
Remarks	<i>Unpolarized scene light</i>	<i>Retroreflective fill factor 25%</i>	<i>Horizontally Pol. Light Removed</i>		<i>Matched polarizer</i>	<i>Matched polarizer</i>

5.9 Conclusion

We proposed and demonstrated a combined 3D display and imaging system enabled by a head-mounted unit and a dual-purpose screen that simultaneously works as a 3D display and a multi-perspective virtual camera array. The stereoscopic 3D content was displayed using two head-mounted pico-projectors illuminating the retroreflective microspheres patterned on the screen. Perspective views of the scene/user were recorded by a head-mounted camera capturing the reflections through the mirror array embedded in the screen. The separation of imaging and display features and the simultaneous operation was facilitated using the polarization multiplexing of the captured and projected light. The display brightness and crosstalk per eye were measured through the retroreflective characteristics of the screen. Real-time 3D capture and discrete free-viewpoint stereo reconstruction were accomplished by implementing geometric ray tracing on a GPU and visualized on a head-mounted virtual reality display. Our test prototype provided high brightness (up to 240 cd/m^2) and negligible crosstalk in 3D mode ($<4\%$) using only 15 *lumen* pico-projectors and 25% retroreflective fill-factor on the screen. 5×4 mirror array provided 20 perspective views of the scene using a single high-resolution camera.

A fully mobile system can be realized by introducing a screen detection and tracking module for dynamic projection mapping and imaging. The image resolution per view is limited to 5 cycles/degree and the captured light efficiency is 22% due to polarizer layer on the screen. Further improvements in the screen fabrication and the computational

imaging aspects would make the proposed system a unique platform for mobile devices and open new directions in wearable devices, computational imaging, and human-computer interaction.



CHAPTER 6

CONCLUSION

3D imaging and display technologies can provide an enhanced experience for augmented reality applications and pave the way towards the future of human-computer interaction. The aim of this research was to explore and develop new 3D display and imaging techniques using passive optical surfaces, which can provide enhanced 3D capabilities with relatively easy implementation. The improved 3D experiences and easily adaptable technology will offer the smooth transition to the world of augmented and mixed reality for both end-users and companies.

The research work presented in this dissertation introduced three novel optical surfaces combined with the mobile projectors and cameras to demonstrate four new 3D imaging and display techniques. The first two techniques introduced and explored the transparent retroreflective screens for augmented reality 3D displays and automotive head-up-display applications. The third technique introduced a unique way of capturing and reconstructing light fields using a handheld lens array surfaces and a single camera, and the fourth technique introduced an integrated 3D display and 3D imaging platform using a dual-purpose passive screen and a head-mounted device. The technical contribution and impact of each part are concluded below.

The first part was focused on the design and development of the transparent retroreflective screens for augmented reality display applications. The design methodology and fabrication flow of the screen were presented, and the display and transmission characteristics of the developed screens were evaluated. Higher optical transparency was demonstrated by micro-patterning the retroreflective microspheres on an optically clear substrate. Different levels of transparencies were achieved by fabricating multiple screens with the controlled filling of the retroreflective material. The retroreflective properties, brightness and transmission characteristics of the screens were

measured. Three versions of the screen were demonstrated to provide the transparency levels of 50%, 75%, and 90%, respectively. Our results showed up to 280 cd/m^2 screen brightness using a 15 *lumen* pico-projector and the optical gain of 8, 4, and 2 at 60 *cm* working distance while maintaining the optical transparency of 50%, 75%, and 90%, respectively. The optical gain up to 100 was observed when the working distance increased to 300 *cm*. The acceptance angle of the screen was measured up to $\pm 75^\circ$, which enabled the screen to have a large size and provide a larger FOV. The MTF measurement indicated the slight loss in the transmission performance of the screen. The screen was fabricated on a thin flexible substrate, which offers easy installation on any surface (i.e. automotive windshields, home windows).

In the second part, an AR 3D display was proposed and demonstrated using the transparent retroreflective screen. A pair of pico-projectors and a 75% transparent retroreflective screen were used to demonstrate the 3D augmented reality. The 3D imagery was provided by using stereoscopy and utilizing the retroreflective property of the screen. The tabletop experimental prototype was developed using two 30 *lumen* head-mounted pico-projectors and a 60 *cm*×40 *cm* transparent retroreflective screen. The retroreflective and polarization characteristics of the developed display were experimentally measured, and various display parameters were assessed. To analyze the display eye-box, three different viewing configurations; bare-eye, polarizers and beam splitters were tested, evaluated and compared. The results showed excellent brightness per eye (up to 1000 cd/m^2) for beam-splitters based configurations. The crosstalk in 3D mode was also measured down-to 1% under the beam-splitter and polarizer configurations. Also, 98% retroreflected light was observed to retain the polarization. The proposed display has the potential to be used for a variety of applications including, gaming, entertainment, training, education medical visualization, and an automotive visual interface. Since the display is for a single viewer, the motion parallax can be added by either tracking the viewer with respect to the screen or vice versa. The modular assembly of the screen enables the proposed screen to have a large size by using an increased number of fabricated screen segments.

In the next part, a user study was performed to investigate the transparent retroreflective screen as an automotive 3D HUD. The simulated collimation was provided by using the stereo parallax to mimic the optical collimation provided by a

typical HUD. Two different user experiments were conducted to measure the effect of reduced light transmission of the retroreflective screen and simulated collimation on the visual acuity of the driver/user. Additionally, the relationship between AC conflict/screen distance and acuity response was explored. A 75% transparent retroreflective screen coupled with two pico-projectors was used as the test apparatus. The results showed a slight reduction in the acuity (up to 20/25) when the clear vision of the user/driver is covered with the retroreflective HUD screen. In the simulated collimation test, the results showed an inverse relationship between the visual acuity and amount AC conflict. The average response for 20/50 (12 *cycles/degree*) acuity was decreased from 86% to 16% when the screen distance changed from 125 *cm* (0.65 *diopeters*) to 50 *cm* (1.85 *diopeters*). In the current study, the 3D HUD was tested only for a brief duration (15-20 *mins*). The study can be extended to assess the visual performance when the 3D HUD is tested for longer durations.

In the fourth part, a new 3D imaging technique was introduced for mobile light field capture using a handheld lens array surfaces and a single camera. The developed imaging scheme provided the mobility and scalability, which are the important limitations of existing light field capture techniques. The geometry of the image formation was studied. The tradeoff between the spatial-angular resolution of the light field capture system was also studied. The tracking markers were used to track and locate the handheld surface with respect to the camera. The computational reconstruction was implemented on the GPU to allow real-time operation. The experimental tests were conducted by using two different versions of the handheld surface providing 24 and 72 views of the scene. The handheld surfaces were based on the Fresnel lens sheets. The light field image reconstruction was demonstrated by resolving partial occlusions and performing real-time digital refocusing for both indoor and outdoor settings. In the current implementation, the image quality is limited due to the optical quality of Fresnel lenses. The image quality and reconstruction can be improved by using higher quality imaging lenses, a high-resolution camera and by computationally correcting the lens distortions.

In the last part, an integrated 3D display and 3D imaging system based on a dual-purpose screen and head-mounted device was introduced for mobile 3D telepresence applications. The dual-purpose screen simultaneously works as a stereo 3D display and a multi-perspective virtual camera array when used together with the head-mounted

projectors and a camera. The 3D content was projected on the screen using two head-mounted projectors while the perspective 3D views of the user were captured using reflections from the mirror array buried in the screen. The separation of imaging and display features and simultaneous operation was facilitated performing the polarization multiplexing of the captured and the projected light. The prototype provided high brightness (up to 240 cd/m^2) and negligible crosstalk in 3D mode ($<4\%$) using only 15 *lumen* pico-projectors and 25% retroreflective fill-factor of the screen. The 5×4 mirror array provided 20 perspective views and 16 stereo viewpoints using single high-resolution camera. The image resolution per view is limited to 5 *cycles/degree* and the captured light efficiency is 22% due to polarizer layer in the screen. Further improvements in screen fabrication and computational imaging aspects would make the proposed system a unique platform for mobile devices and open new directions in the domain of wearable devices, computational imaging, and human-computer interaction.

APPENDICES

Appendix I: MATLAB Script for MTF Measurement

```
function [wi,wo,MTF,xspace1,ESF1,LSF1]=findMTF(image)

    p=.0039; % Camera pixel size
    fcam=50; % Camera focal length
    dcam=700;% Distance to lens array
    fs=4;     % Sampling frequency
    dobj=700; % Distance to edge profile
    fmirror=75; % Focal length mirror
    w_sample=2048; % FFT Samples
    I=image; % Input image of edge profile
    figure, imshow(I); title('original')
    Ig=(rgb2gray(I)); Iedge=edge(Ig,'canny',.8);
    figure, imshow(Iedge); title('edges');

    % Line fitting
    [y,x]=find(Iedge>0);
    P=polyfit(x,y,1)

    angle=mod(90-atan(P(1)),90)-90

    % Upsample
    Iup=imresize(Ig,fs);
    %Rotate with affine transform
    Istraight=imrotate(Iup,-angle,'nearest','crop');
    figure, imshow(Istraight); title('straight');
    %ROI selection
    rect=getrect;
    Icrop=imcrop(Istraight,rect);
    figure, imshow(Icrop); title('cropped');

    %Finding ESF and LSF
    ESF1= mean(Icrop(1:end,:));
    ESF_d1=ESF1-mean(ESF1); %DC removal
    %xspace1=(-length(ESF1)/2:(length(ESF1)/2-1))*p/fs;
    LSF1=-diff(ESF_d1/max(ESF_d1));

    [v i]=max(LSF1)
    xspace1=(0:length(LSF1))*p/fs-i*p/fs;
```

```

figure,
subplot(211);
plot(xspace1,(ESF_d1/max(ESF_d1)), 'linewidth',2); title('ESF screen');
xlabel('space in mm'); ylabel('normalized amplitude');
axis([min(xspace1),max(xspace1),-1.2,1.2]);
subplot(212);
plot(xspace1(1:end-1),LSF1/max(LSF1), 'linewidth',2); title('LSF
screen');
xlabel('space in mm'); ylabel('normalized amplitude');
axis([min(xspace1),max(xspace1),0,1.2]);

% FFT
OTF=fftshift(fft(LSF1,w_sample));
MTF=abs(OTF);
MTF_sm_sc=MTF/max(MTF);

% SENSOR PLANE
wi=(fs/p/(2*pi))*(linspace(-pi,pi,w_sample)); % Image Space frequency;
figure,
subplot(211);
plot(wi,MTF_sm_sc,'linewidth',2), title('Screen MTF @ Sensor Plan');
axis([0,150,0,1])
ylabel('Modulation');
xlabel('Spatial freq (lp/mm)');
grid

wo=wi*fcam/dcam*fmirror/dobj;
subplot(212);
plot(wo,MTF_sm_sc,'linewidth',2), title('Screen MTF @ Object Plan (40cm
from screen)');
ylabel('Modulation');
xlabel('Spatial freq (lp/mm)');
axis([0,3,0,1])
grid

MTF=MTF_sm_sc

```

Appendix II: MATLAB Script for Light Field Reconstruction

```

% Lens Array Class
classdef lensArrayABCD
    properties
        dLA=0; %Pinhole to lens array distance (mm)
        dOP=0; %Object Plan distance from lens array (mm)
    end
end

```

```

lensAper=[0,0]; % Aperture of size of lens (mm)
lensFL=0; %Lensarray focal length(mm)
dimLA=[0,0]; %Number of lens in array (M,N)
cameraF=0; %Focal length of pihole camera
ML=1 % 1 for lens and -1 for mirror

%Mapping related
szPlanWin=[1,1]; %Object plane window size in mm
outImgRes=[1,1,1]; %Resolution of output window
inImgRes=[1,1,1];
objPlanAngle=0;

%Screen Motion Related in degrees
translateX=0; % In mm
translateY=0; % In mm
rotationAngle=0; % In mm

szLA=[0,0]; %LensArray Size
dSensor=0; %Location of image sensor wrt to camera lens(should
z<0)
szSensor=[]; %size of camera sensor fitting
Mcam=10;
layout;

currLensCenter=[]; %Center of current lens wrt to Optical axis

end

methods

function obj = lensArray()
    % This is unused
end

% Function to set initial parameters
function obj=setParameters(obj,layout_flg)
    obj.szLA=obj.dimLA.*obj.lensAper;
    obj.szSensor=1/obj.Mcam*obj.szLA;
    obj.dSensor=1/obj.Mcam*obj.dLA;
    if(layout_flg==1)
        obj.layout=plot3(0,0,0); xlabel('Z'); ylabel('X');
zlabel('Y'); axis equal;
        axisArea=500;
        axis([-100,obj.dLA+obj.dOP+100,-axisArea,axisArea,-
axisArea,axisArea]);
        axis([-100,1200,-500,500,-500,500]);
        obj.drawSensor();
        obj.drawLA();
        obj.drawOP();

```

```

        view(30,30);
    end

end

%Draw sensor
function obj=drawSensor(obj)

    %Draw Sensor
    pSen_x=[-
obj.szSensor(1)/2,obj.szSensor(1)/2,obj.szSensor(1)/2,-
obj.szSensor(1)/2,-obj.szSensor(1)/2]-1/obj.Mcam*obj.translateX;
    pSen_y=[obj.szSensor(2)/2,obj.szSensor(2)/2,-
obj.szSensor(2)/2,-obj.szSensor(2)/2,obj.szSensor(2)/2]-
1/obj.Mcam*obj.translateY;
    pSen_z=[-obj.dSensor,-obj.dSensor,-obj.dSensor,-
obj.dSensor,-obj.dSensor];
    obj.layout=line(pSen_z,pSen_x,pSen_y);
    obj.layout.Color=[1,0,0]; obj.layout.LineWidth=2;
end

% Draw lens array surface
function obj=drawLA(obj)
    %Draw lens array
    M=obj.dimLA(1); N=obj.dimLA(2);
    for m=0:(M-1)
        for n=0:(N-1)

            cen=[(M-1)/2-
m)*obj.lensAper(1)+obj.translateX,(N-1)/2-
n)*obj.lensAper(2)+obj.translateY];

            pL_x=[cen(1)-
obj.lensAper(1)/2,cen(1)+obj.lensAper(1)/2,cen(1)+obj.lensAper(1)/2,cen
(1)-obj.lensAper(1)/2,cen(1)-obj.lensAper(1)/2];

            pL_y=[cen(2)+obj.lensAper(2)/2,cen(2)+obj.lensAper(2)/2,cen(2)-
obj.lensAper(2)/2,cen(2)-obj.lensAper(2)/2,cen(2)+obj.lensAper(2)/2];
            pL_z=[obj.dLA,obj.dLA,obj.dLA,obj.dLA,obj.dLA];

            obj.layout=line(pL_z,pL_x,pL_y);
            obj.layout.Color=[1,0,0]; obj.layout.LineWidth=2;
        end
    end

end

% Draw objec plan (depth slice) window
function obj=drawOP(obj)
    %Draw Obj Plan

```

```

        pOP_x=[-
obj.szPlanWin(1)/2,obj.szPlanWin(1)/2,obj.szPlanWin(1)/2,-
obj.szPlanWin(1)/2,-obj.szPlanWin(1)/2]+obj.translateX;
        pOP_y=[obj.szPlanWin(2)/2,obj.szPlanWin(2)/2,-
obj.szPlanWin(2)/2,-
obj.szPlanWin(2)/2,obj.szPlanWin(2)/2]+obj.translateY;
        zo=obj.dLA+obj.ML*obj.dOP;
        pOP_z=[zo,zo,zo,zo,zo];
        obj.layout=line(pOP_z,pOP_x,pOP_y);
        obj.layout.Color=[0,0,0]; obj.layout.LineWidth=1;

    end

    % Create a ray
    function [obj,x,y]=createRays(obj,m,n,n_rays,gap) % n_rays for
m,n th lens with gap.
        wgap=gap(1); hgap=gap(2);
        eiW=obj.szSensor(1)/obj.dimLA(1);
        eiH=obj.szSensor(2)/obj.dimLA(2);

        x=linspace(m*eiW+wgap/obj.Mcam,(m+1)*eiW-
wgap/obj.Mcam,n_rays)-obj.szSensor(1)/2-1/obj.Mcam*obj.translateX;
        y=linspace(n*eiH+hgap/obj.Mcam,(n+1)*eiH-
hgap/obj.Mcam,n_rays)-obj.szSensor(2)/2-1/obj.Mcam*obj.translateY;

        M=obj.dimLA(1); N=obj.dimLA(2);
        obj.currLensCenter=[((M-1)/2-
m)*obj.lensAper(1)+obj.translateX,((N-1)/2-
n)*obj.lensAper(2)+obj.translateY];

    end

    % Caterian cordinates to R, theta
    function [Rx,Ry]=xyTortheta(obj,x,y,d)

        Rx=[x;x/d]; Ry=[y;y/d];

    end

    % Ray transfer from snesor to lens array surface
    function [Rx_LA,Ry_LA]=senToLA(obj,Rx,Ry,layout)

        M1=[1,obj.dSensor+obj.dLA;0,1]; %Transformation to LA
        Rx_LA=M1*Rx; Ry_LA=M1*Ry;

        if(layout==1)

```

```

        obj.layout=line([-
obj.dSensor,obj.dLA],[Rx(1),Rx_LA(1)],[Ry(1),Ry_LA(1)]);
        obj.layout.Color=[0,.6,1]; obj.layout.LineWidth=1;
    end

end

% Ray transfer through lens array surface
function [Rx_PL,Ry_PL]=passLens(obj,Rx_LA,Ry_LA,m,n,layout)

    Rx_LA(1)=Rx_LA(1)-obj.currLensCenter(1); Ry_LA(1)=Ry_LA(1)-
obj.currLensCenter(2); %1 - Move Lens to Optical axis

    M2=[1,0;-1/obj.lensFL,1];
    Rx_PL=M2*Rx_LA; Ry_PL=M2*Ry_LA; % 2- Pass ray through Lens

    Rx_PL(1)=Rx_PL(1)+obj.currLensCenter(1);
Ry_PL(1)=Ry_PL(1)+obj.currLensCenter(2); %3- Move Lens back to position

    if(layout==1)
        %Can be added
    end

end

% Second order distortion correction
function [Rx_DC,Ry_DC]=undistort(obj,Rx_PL,Ry_PL,k)
    k1=k(1); k2=k(2);
    r=sqrt(Rx_PL(1)^2+(Ry_PL(1))^2);
    Rx_PL(1)=Rx_PL(1)*(1+k1*r^2+k2*r^4);
    Ry_PL(1)=Ry_PL(1)*(1+k1*r^2+k2*r^4);

    Rx_DC=Rx_PL; Ry_DC=Ry_PL;
end

% Ray transfer from the surface to object plan
function [Rx_OP,Ry_OP]=lensToOP(obj,Rx_PL,Ry_PL,layout)

    sagZ=0;
    if(obj.ML==-1)
        x=Rx_PL(1)-obj.currLensCenter(1); y=Ry_PL(1)-
obj.currLensCenter(2); %1 - Move Lens to Optical axis

        Raduis=2*obj.lensFL;
        r=sqrt((x)^2+(y)^2);
        sagZ=Raduis- sqrt(Raduis^2 - r^2);
    end

    M3=[1,obj.dOP+sagZ;0,1]; %Transformation to LA
    Rx_OP=M3*Rx_PL; Ry_OP=M3*Ry_PL;

```

```

        if(layout==1)

obj.layout=line([obj.dLA+sagZ,(obj.dLA+obj.ML*obj.dOP)],[Rx_PL(1),Rx_OP
(1)],[Ry_PL(1),Ry_OP(1)]);
        obj.layout.Color=[0,.6,1]; obj.layout.LineWidth=1;
        end
    end

    % Ray to pixel corresonding
    function [Pi,Po]=projectPixel(obj,ri,ro)

Pi(1)=round((ri(1)+obj.szSensor(1)/2)/obj.szSensor(1)*(obj.inImgRes(2)-
1));

Pi(2)=round((ri(2)+obj.szSensor(2)/2)/obj.szSensor(2)*(obj.inImgRes(1)-
1));

Po(1)=round((ro(1)+obj.szPlanWin(1)/2)/obj.szPlanWin(1)*(obj.outImgRes(
2)));

Po(2)=round((ro(2)+obj.szPlanWin(2)/2)/obj.szPlanWin(2)*(obj.outImgRes(
1)));

    end

    % Ray tranfer through curved mirror
    function [Rx_rfl,Ry_rfl]=passMirror(obj,Rx_LA,Ry_LA,m,n,layout)

        Rx_LA(1)=Rx_LA(1)-obj.currLensCenter(1); Ry_LA(1)=Ry_LA(1)-
obj.currLensCenter(2); %1 - Move Lens to Optical axis

        x=Rx_LA(1); y=Ry_LA(1);

        Raduis=2*obj.lensFL;

        r=sqrt((x)^2+(y)^2);
        sagZ=Raduis- sqrt(Raduis^2 - r^2); Msag=[1 sagZ; 0 1];

        Rx_sag=Msag*Rx_LA; Ry_sag=Msag*Ry_LA;
        if(layout==1)

obj.layout=line([obj.dLA,obj.dLA+sagZ],[Rx_LA(1),Rx_sag(1)]+obj.currLen
sCenter(1),[Ry_LA(1),Ry_sag(1)]+obj.currLensCenter(2));
        obj.layout.Color=[0,.6,1]; obj.layout.LineWidth=1;
        end

        normAngle=[asin(x/Raduis),asin(y/Raduis)];
        %normAngle=sqrt(sum(normAngle.^2));

```

```

clear all
close all
clc

res=3
n_rays=res/1; % Number of rays to trace

layout=1
if(n_rays>30) layout=0; end % 0= no layout, 1= show ray layout

%for di=1:10

freM=lensArrayABCD();
freM.outImgRes=[res,res,3];
freM.dLA=500; %Pinhole to lens array distance (mm)
freM.dOP=500%+di*200; %Object Plan distance from lens array (mm)
freM.ML=1; % 1=Lens and -1=Mirror
freM.lensAper=[34,34]; % WxH, X,Y
freM.lensFL=-40; %Lensarray focal length(mm)
freM.dimLA=[8,3]; %Number of lens in array (M,N)
freM.cameraF=35; %Focal length of pihole camera

freM.szPlanWin=[freM.dOP*1.5,freM.dOP*1.5];
freM.translateX=00;
freM.translateY=00;

inImg=imread('input/fre_60x40.jpg');
imshow(inImg)
freM.inImgRes=size(inImg);

freM=freM.setParameters(layout);

M=freM.dimLA(1); N=freM.dimLA(2);
outImg=uint8(zeros(freM.outImgRes));

m=2; n=0;
for m=0:(M-1)
    for n=0:(N-1)
        [freM,nx,ny]=freM.createRays(m,n,n_rays,[5,5]);
        for xi=1:length(nx)
            for yi=1:length(ny)
                x=nx(xi); y=ny(yi);
                [Rx,Ry]=freM.xyTortheta(x,y,-freM.dSensor);
                [Rx_LA,Ry_LA]=freM.sentToLA(Rx,Ry,layout); %From Sensor
to LA

```

```

[Rx_PL,Ry_PL]=freM.passLens(Rx_LA,Ry_LA,m,n,layout);
%Pass Lens
[Rx_PL,Ry_PL]=freM.passMirror(Rx_LA,Ry_LA,m,n,layout);
%Pass Lens
%continue
[Rx_OP,Ry_OP]=freM.lensToOP(Rx_PL,Ry_PL,layout);

%[Rx_OP,Ry_OP]=freM.undistort(Rx_OP,Ry_OP,[.0000005,0]);
ri=[Rx(1),Ry(1)]; % Ray positions X,Y
ro=[Rx_OP(1),Ry_OP(1)]; % Ray positions X,Y

if(ro(1)>-freM.szPlanWin(1)/2 && ro(1)<
freM.szPlanWin(1)/2 && ro(2)>-freM.szPlanWin(2)/2 && ro(2)<
freM.szPlanWin(2)/2 && layout==0)
    [Pi,Po]=freM.projectPixel(ri,ro);
    outImg(Po(2)+1,Po(1)+1,:)=inImg(Pi(2),Pi(1),:);
end

end
end
if(layout==0)
    %imshow(outImg)
else
    view(0,0)
end
%%%
filename=['output/' num2str(freM.dOP) 'mm_'
num2str(m),'x',num2str(n),'.tiff']
imwrite(outImg,filename);
outImg=uint8(zeros(freM.outImgRes));
end

end

if(layout==0)
    outImg=imrotate(freM.stitchSubImages(),180);
    imshow(outImg/255);
    imwrite(outImg/255,['depth slices\depth_' num2str(freM.dOP)
'.tiff']);
end
%view(0,90)

%end

```

Appendix III: Script for Light Field Reconstruction on GLSL Shader Language

```
//In values
in vec4 gl_FragColor;
in vec4 gl_FragCoord;

//Out values
out vec4 out_color;
vec4 color_sum;
//main shader

uniform sampler2D img_buffer;

uniform vec2 dimLA;
uniform vec2 szSen;
uniform vec2 outPlanWin;
uniform vec2 winPos;
uniform vec2 inImgRes;
uniform vec2 outImgRes;
uniform vec2 pCiLA[25];
uniform vec2 pCoP[25];
uniform float Mfcam;
uniform float Mla;
uniform vec2 max_points_x[25];
uniform vec2 max_points_y[25];

// Temprrory variables
float pxn,pyn; // Normalized Pixel values for right half of screen
float po_x,po_y;
float xi,yi;
float xo,yo;
float pi_x,pi_y;
int m,n;
float w=0;
float dp;
int indx=0;
vec4 singleColor=vec4(0.,0.,0.,0);
float plx,ply;
float simg_num=3/4;
void main()
{
    out_color = gl_Color;
    out_color = vec4(0,0,0,1.);
    if (gl_FragCoord.x <= 600)
    {
        plx=(gl_FragCoord.x/outImgRes[0])/dimLA[0]+2/dimLA[0];
        ply=((gl_FragCoord.y)/outImgRes[1])/dimLA[1]+1/dimLA[1];
        vec4 color1 = texture2D(img_buffer, vec2(plx,ply));
        out_color = color1;
    }
    else
    {
        pxn=1-(gl_FragCoord.x-outImgRes[0])/outImgRes[0];
        pyn=gl_FragCoord.y/outImgRes[1];
    }
}
```

```

        po_x=pxn*outImgRes[0];
        po_y=pyn*outImgRes[1];

        xo=po_x/outImgRes[0]*outPlanWin[0]-
outPlanWin[0]/2+winPos[0];
        yo=po_y/outImgRes[1]*outPlanWin[1]-
outPlanWin[1]/2+winPos[1];

        for(int m=0; m<dimLA[0]; m++)
        {
            for(int n=0; n<dimLA[1]; n++)
            {
                m=0; n=0;
                if(xo<=max_points_x[indx][0]      &&
yo>=max_points_y[indx][1])      &&
                {
                    xi=-Mfcam*(Mla)*(xo-
pCoP[indx][0])+pCiLA[indx][0]);
                    yi=Mfcam*(Mla)*(yo-
pCoP[indx][1])+pCiLA[indx][1]);

                    pi_x=(xi+szSen[0]/2)/szSen[0]*inImgRes[0];
                    pi_y=(yi+szSen[1]/2)/szSen[1]*inImgRes[1];

                    if(l==1 && l==1)
                    {
                        out_color=(out_color*w+texture2D(img_buffer,vec2(pi_x/inImgRes[0],pi_y/i
nImgRes[1])))/(w+1);
                        w=w+1;
                    }
                }
                indx=indx+1;
            }
        }

        //out_color=texture2D(img_buffer,vec2(pxn,pyn));
    }

    //gl_FragColor=vec4(1.,0.,0.,1.);
    //frag_cord=
}

```

PUBLICATION RECORD

Journal Articles

- [P1] **S. R. Soomro**, O. Eldes, K. Akşit, and H. Urey, “Real-time Mobile Light Field Imaging Using Handheld Lens Array Surfaces and Single Camera,” *Applied Optics (In-preparation)*.
- [P2] **S. R. Soomro** and H. Urey, “Visual acuity response when using 3D head-up-display in the presence of accommodation-convergence conflict,” *Journal of Society of Information Display (Under-review)*.
- [P3] **S. R. Soomro** and H. Urey, “Integrated 3D Display and Imaging Using Dual-Purpose Passive Screen and Head-Mounted Projectors and Camera,” *Optics Express*, vol. 26(2) pp. 1161-1173, 2018.
- [P4] **S. R. Soomro** and H. Urey, “Light-efficient augmented reality 3D display using highly transparent retro-reflective screen,” *Applied Optics*, vol. 56, no. 22, pp. 6108–6113, 2017.
- [P5] **S. R. Soomro** and H. Urey, “Design, fabrication and characterization of transparent retro-reflective screen,” *Optics Express*, vol. 24, no. 21, pp. 24232-24243, 2016.
- [P6] **S. R. Soomro**, E. Ulusoy, and H. Urey, “Decoupling of Real and Digital Content in Projection-based Augmented Reality Systems Using Time Multiplexed Image Capture,” *Journal of Imaging Science and Technology.*, vol. 61, no. 1, pp. 104061–104066, 2017.

Patents Filed

- [P7] H. Urey, **S. R. Soomro**, and M. Eralp, “A Dual-Function Display and Multi-View Imaging System,” PCT/TR2015/050231 (2015).
- [P8] H. Urey and **S. R. Soomro**, “Physical Object Reconstruction Through a Projection Display System,” PCT/TR2015/050227 (2015).

Conference Proceedings/Presentations

- [P9] **S. R. Soomro** and H. Urey, “Retro-reflective Characteristics of Transparent Screen for Head Mounted Projection Displays,” in *Frontiers in Optics* 2016, 2016, p. FTu5A.2.
- [P10] **S. R. Soomro** and H. Urey, “Desktop-size See-through Display for 3D Augmented Reality,” in *International OSA Network of Students (IONS) Paris*, 2017.
- [P11] **S. R. Soomro** and H. Urey, “Augmented reality 3D display using head-mounted projectors and transparent retro-reflective screen,” in *Proc. SPIE 10126, Advances in Display Technologies VII*, 2017, vol. 10126, p. 101260E.
- [P12] **S. R. Soomro** and H. Urey, “Augmented Reality 3D Display Using Head-worn Projectors and Passive Screen,” in *Fotonik Turkey*, 2017.
- [P13] H. Urey, **S. R. Soomro**, and E. Ulusoy, “Wearable Augmented Reality Displays,” in *Imaging and Applied Optics*, 2017, pp. 2016–2018.
- [P14] **S. R. Soomro**, O. Eldes, K. Akşit, and H. Urey, “Mobile 3D imaging using handheld lens array sheet and single camera,” In *Electronic Imaging, Image Sensors and Imaging Systems*, 2018.
- [P15] **S. R. Soomro**, E. Ulusoy, M. Eralp, and H. Urey, “Dual purpose passive screen for simultaneous display and imaging,” in *Proc. SPIE 10126, Advances in Display Technologies VII*, 2017, p. 101260N.
- [P16] Ç. Genç, **S.R Soomro** et al., “Head Mounted Projection Display & Visual Attention: Visual Attentional Processing of Head Referenced Static and Dynamic Displays while in Motion and Standing,” in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*, 2016, pp. 1538–1547.

BIBLIOGRAPHY

- [1] K. Kiyokawa, “Head-Mounted Display Technologies for Augmented Reality,” in *Fundamentals of Wearable Computers and Augmented Reality*, Woodrow Barfield, Ed. Tylor and Francis Group, 2016, p. Chapter 4.
- [2] A. Guirao, G. Manuel, E. Geraghty, S. Norrby, and P. Artal, “Average Optical Performance of the Human Eye as a Function of Age in a Normal Population,” *Invest. Ophthalmol. Vis. Sci.*, vol. 40, no. 1, pp. 203–213, 1998.
- [3] C. Wheatstone, “The Bakerian lecture: contributions to the physiology of vision. Part the Second. On some remarkable, and hitherto unobserved, phenomena of binocular vision (continued).,” *Philos. Trans. R. Soc. London*, vol. 142, pp. 1–17, 1852.
- [4] H. Urey, K. V. Chellappan, E. Erden, and P. Surman, “State of the art in stereoscopic and autostereoscopic displays,” *Proc. IEEE*, vol. 99, no. 4, pp. 540–555, 2011.
- [5] J. Geng, “Three-dimensional display technologies,” *Adv. Opt. Photonics*, vol. 5, no. 4, pp. 456–535, 2013.
- [6] B. Wilburn *et al.*, “High performance imaging using large camera arrays,” *ACM Trans. Graph.*, vol. 24, no. 3, p. 765, 2005.
- [7] R. Ng, M. Levoy, G. Duval, M. Horowitz, and P. Hanrahan, “Light Field Photography with a Hand-held Plenoptic Camera,” *Comput. Sci. Tech. Rep. CSTR*, vol. 2, no. 11, pp. 1–11, 2005.
- [8] J. Jang, “Three-dimensional synthetic aperture integral imaging,” *Opt. Lett.*, vol. 27, no. 13, pp. 1144–1146, 2002.
- [9] W. Song, Y. Liu, W. Li, and Y. Wang, “Light field acquisition using a planar catadioptric system,” *Opt. Express*, vol. 23, no. 24, pp. 31126–31135, 2015.
- [10] “Microsoft Kinect,” *Microsoft*. [Online]. Available: <https://developer.microsoft.com/en-us/windows/kinect>. [Accessed: 15-Dec-2017].
- [11] V. Ganapathi, C. Plagemann, D. Koller, and S. Thrun, “Real time motion capture using a single time-of-flight camera,” in *IEEE Conference on Computer Vision and Pattern Recognition*, 2010, pp. 755–762.
- [12] B. Kress and T. Starner, “A review of head-mounted displays (HMD) technologies and applications for consumer electronics,” in *SPIE Proceedings*, 2013, vol. 8720, p. 87200A–87200A–13.
- [13] “ShowWX Pico Projectors,” *Microvision*. [Online]. Available: <http://www.microvision.com/product-support/showwx/>.

-
- [14] “Celluon PicoPro and PicoAir,” *Celluon*. [Online]. Available: <https://www.celluon.com/picopro-3/>. [Accessed: 10-Jun-2016].
- [15] “MP CL-1 Sony Pico Projector,” *Sony*. [Online]. Available: <https://www.sony.com/electronics/projector/mp-cl1a>. [Accessed: 15-Oct-2017].
- [16] S. T. S. Holmström, U. Baran, and H. Urey, “MEMS laser scanners: A review,” *J. Microelectromechanical Syst.*, vol. 23, no. 2, pp. 259–275, 2014.
- [17] K. Akşit, O. Eldes, S. Viswanathan, M. O. Freeman, and H. Urey, “Portable 3D laser projector using Mixed Polarization technique,” *IEEE/OSA Journal of Display Technology*, vol. 8, no. 10, pp. 582–589, 2012.
- [18] O. Eldes, K. Akşit, and H. Urey, “Multi-view autostereoscopic projection display using rotating screen,” *Opt. Express*, vol. 21, no. 23, pp. 29043–29054, 2013.
- [19] S. R. Soomro and H. Urey, “Design, fabrication and characterization of transparent retro-reflective screen,” *Opt. Express*, vol. 24, no. 21, p. 24232, Oct. 2016.
- [20] “LG Transparent LCD,” *LG*. [Online]. Available: <http://www.lg.com/global/business/information-display/digital-signage/transparent>. [Accessed: 01-Nov-2017].
- [21] “Samsung LTI460AP01 Transparent LCD,” *Samsung*. [Online]. Available: <https://news.samsung.com/global/clearly-ahead-transparent-lcd-display-by-samsung>. [Accessed: 20-Jul-2016].
- [22] P. Görrn *et al.*, “Towards see-through displays: Fully transparent thin-film transistors driving transparent organic light-emitting diodes,” *Adv. Mater.*, vol. 18, no. 6, pp. 738–741, 2006.
- [23] N. Ranieri, H. Seifert, and M. Gross, “Transparent stereoscopic display and application,” in *IS&T/SPIE Electronic Imaging*, 2014, vol. 9011, p. 90110P.
- [24] V. Optics, “Vision Optics Holographic Screens.” [Online]. Available: <http://www.visionoptics.de/index.php?id=18&L=1>. [Accessed: 10-Oct-2017].
- [25] “Screen-Tech Projection Screens,” *ScreenTech*. [Online]. Available: screen-tech.eu/en/ST-Professional-Trans.html. [Accessed: 10-Oct-2017].
- [26] C. W. Hsu *et al.*, “Transparent displays enabled by resonant nanoparticle scattering,” *Nat. Commun.*, vol. 5, p. 3152, 2014.
- [27] M. K. Hedili, M. O. Freeman, and H. Urey, “Microlens array-based high-gain screen design for direct projection head-up displays,” *Appl. Opt.*, vol. 52, no. 6, pp. 1351–7, 2013.
- [28] M. K. Hedili, M. O. Freeman, and H. Urey, “Transmission characteristics of a bidirectional transparent screen based on reflective microlenses,” *Opt. Express*, vol. 21, no. 21, p. 24636, 2013.
- [29] K. Hong, J. Yeom, C. Jang, G. Li, J. Hong, and B. Lee, “Two-dimensional and three-dimensional transparent screens based on lens-array holographic optical elements,” *Opt. Express*, vol. 22, no. 12, p. 14363, 2014.

-
- [30] J. Lloyd, "A brief history of retroreflective sign face sheet materials," *The Retroreflective Equipment Manufacturers Association: Lancashire, UK*. .
 - [31] G. H. Seward and P. S. Cort, "Measurement and characterization of angular reflectance for cube-corners and microspheres," *Opt. Eng.*, vol. 38, no. 1, p. 164, 1999.
 - [32] H. Hua, C. Gao, and J. P. Rolland, "Study of the Imaging Properties of Retro-reflective Materials Used in Head-Mounted Projective Displays (HMPDs)," vol. 4711, pp. 194–201, 2002.
 - [33] D. Héricz, T. Sarkadi, V. Lucza, V. Kovács, and P. Koppa, "Investigation of a 3D head-mounted projection display using retro-reflective screen," *Opt. Express*, vol. 22, no. 15, p. 17823, 2014.
 - [34] "Cole Safety International Reflective Products," *Cole Safety*. [Online]. Available: <http://www.colesafetyinternational.com/>. [Accessed: 01-Mar-2016].
 - [35] Warren J. Smith, *Modern Optical Engineering*. McGraw Hill, 2000.
 - [36] M. Estriebeau and P. Magnan, "Fast MTF measurement of CMOS imagers using ISO 12333 slanted-edge methodology," in *Proc. SPIE 5251*, 2004, p. 243.
 - [37] J. Canny, "A Computational Approach to Edge Detection," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 8, no. 6, pp. 679–698, 1986.
 - [38] S. R. Soomro and H. Urey, "Light-efficient augmented reality 3D display using highly transparent retro-reflective screen," *Appl. Opt.*, vol. 56, no. 22, pp. 6108–6113, 2017.
 - [39] J. P. Rolland, K. P. Thompson, H. Urey, and M. Thomas, "See-Through Head Worn Display (HWD) Architectures," in *Handbook of Visual Display Technology*, J. Chen, W. Cranton, and M. Fihn, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2012, pp. 2145–2170.
 - [40] H. Hua and B. Javidi, "Augmented Reality : Easy on the Eyes," *Opt. Photonics News Febr. 2015*, vol. 26, no. 2, pp. 26–33, 2015.
 - [41] "Microsoft Hololens," *Microsoft*. [Online]. Available: <https://www.microsoft.com/en-us/hololens>.
 - [42] K.-W. Zhao and J.-W. Pan, "Optical design for a see-through head-mounted display with high visibility," *Opt. Express*, vol. 24, no. 5, p. 4749, 2016.
 - [43] J. Wang, X. Xiao, H. Hua, and B. Javidi, "Augmented Reality 3D Displays With Micro Integral Imaging," *J. Disp. Technol.*, vol. 11, no. 11, pp. 889–893, 2015.
 - [44] K. Hong, J. Yeom, C. Jang, J. Hong, and B. Lee, "Full-color lens-array holographic optical element for three-dimensional optical see-through augmented reality," *Opt. Lett.*, vol. 39, no. 1, pp. 127–30, 2014.
 - [45] K. Saito and T. Tatsuma, "A transparent projection screen based on plasmonic Ag nanocubes," *Nanoscale*, vol. 7, no. 48, pp. 20365–20368, 2015.
 - [46] T. Yoshida *et al.*, "RePro3D: Full-parallax 3D display with haptic feedback using retro-reflective projection technology," *ISVRI 2011 - IEEE Int. Symp. Virtual*

- Real. Innov. 2011, Proc.*, pp. 49–54, 2011.
- [47] D. M. Krum, E. A. Suma, and M. Bolas, “Augmented reality using personal projection and retroreflection,” *Pers. Ubiquitous Comput.*, vol. 16, no. 1, pp. 17–26, 2012.
 - [48] S. R. Soomro and H. Urey, “Retro-reflective Characteristics of Transparent Screen for Head Mounted Projection Displays,” in *Frontiers in Optics 2016*, 2016, p. FTu5A.2.
 - [49] R. Zhang and H. Hua, “Imaging quality of a retroreflective screen in head-mounted projection displays,” *J. Opt. Soc. Am. A*, vol. 26, no. 5, pp. 1240–1249, 2009.
 - [50] D. G. Gallagher and R. J. Manley, “Diver’s Full Face Mask Head-Up Display System Using Waveguide Optical Display Technology,” in *OCEANS - St. John’s*, 2014, pp. 1–7.
 - [51] H. Peng *et al.*, “Design and fabrication of a holographic head-up display with asymmetric field of view,” *Appl. Opt.*, vol. 53, no. 29, p. H177, 2014.
 - [52] Y. Takaki, Y. Urano, S. Kashiwada, H. Ando, and K. Nakamura, “Super multi-view windshield display for long-distance image information presentation,” *Opt. Express*, vol. 19, no. 2, pp. 704–716, 2011.
 - [53] P. Coni, J. L. Bardon, A. Gueguen, and M. Grossetête, “Development of a 3D HUD using a tunable bandpass filter for wavelength multiplexing,” *J. Soc. Inf. Disp.*, vol. 25, no. 3, pp. 158–166, 2017.
 - [54] S. Höckh, A. Frederiksen, S. Renault, K. Hopf, M. Gilowski, and M. Schell, “Exploring crosstalk perception for stereoscopic 3D head-up displays in a crosstalk simulator,” *J. Soc. Inf. Disp.*, vol. 23, no. 9, pp. 417–428, 2015.
 - [55] D. U. J. H. Kim, and M. W. Pyeon, “Collimation Using Transparent Projection Screen for Augmented Environment HUDs,” in *CollabTech*, 2012, pp. 94–99.
 - [56] D. M. Hoffman, A. R. Girshick, K. Akeley, and M. S. Banks, “Vergence-accommodation conflicts hinder visual performance and cause visual fatigue,” *J. Vis.*, vol. 8, no. 3, pp. 1–30, 2008.
 - [57] T. Shibata, J. Kim, D. M. Hoffman, and M. S. Banks, “Visual discomfort with stereo displays: effects of viewing distance and direction of vergence-accommodation conflict,” in *Proc. SPIE 7863*, 2011, p. 78630P.
 - [58] G. Koulouris, U. Côte, B. E. E. Bui, M. S. Banks, G. Drettakis, and U. Côte, “Accommodation and Comfort in Head-Mounted Displays,” *ACM Trans. Graph.*, vol. 36, no. 4, p. 87:1-11, 2017.
 - [59] M. Lambooi, W. IJsselstein, M. Fortuin, and I. Heynderickx, “Visual Discomfort and Visual Fatigue of Stereoscopic Displays: A Review,” *J. Imaging Sci. Technol.*, vol. 53, no. 3, p. 30201, 2009.
 - [60] R. Yamamoto, Y. Uema, M. Sugimoto, and M. Inami, “Study on Visual Display for Stereoscopic Vision Based on Binocular Parallax Using Retro-reflective Projection Technology,” 2014.

-
- [61] S. Peterson and E. Pinska, "Human Performance with Simulated Collimation in Transparent Projection Screens," in *Second International Conference on Research in Air Transportation (ICRAT)*, 2006, pp. 231–237.
 - [62] P. Coni, S. Hourlier, A. Gueguen, X. Servantie, and L. Laluque, "50-3: A Full Windshield Head-Up Display using Simulated Collimation," in *SID Symposium Digest of Technical Papers*, 2016, pp. 684–687.
 - [63] S. Kim and A. K. Dey, "Simulated augmented reality windshield display as a cognitive mapping aid for elder driver navigation," *Proc. 27th Int. Conf. Hum. factors Comput. Syst. - CHI 09*, p. 133, 2009.
 - [64] M. D. Stoudt and K. Vedam, "Retroreflection from spherical glass beads in highway pavement markings. 1: Specular reflection.," *Appl. Opt.*, vol. 17, no. 12, pp. 1855–8, 1978.
 - [65] H. Snellen, *Probebuchstaben zur bestimmung der sehschärfe*. H. Peters, 1873.
 - [66] A. Colenbrander, "The Historical Evolution of Visual Acuity Measurement," *Vis. Impair. Res.*, vol. 10, no. 2–3, pp. 57–66, 2008.
 - [67] G. Lippmann, "Epreuves reversibles, photographies integrales," *CR Acad. Sci.*, vol. 146, pp. 446–451, 1908.
 - [68] B. Javidi *et al.*, "Multidimensional Optical Sensing and Imaging System (MOSIS): From Macroscales to Microscales," *Proc. IEEE*, vol. 105, no. 5, pp. 850–875, 2017.
 - [69] M. Levoy and P. Hanrahan, "Light Field Rendering," in *Siggraph*, 1996, pp. 31–42.
 - [70] Edmund Y. Lam, "Computational photography with plenoptic camera and light field capture : tutorial," *J. Opt. Soc. Am. A*, vol. 32, no. 11, pp. 2021–2032, 2015.
 - [71] M. Martinez-Corral, A. Dorado, J. C. Barreiro, G. Saavedra, and B. Javidi, "Recent Advances in the Capture and Display of Macroscopic and Microscopic 3-D Scenes by Integral Imaging," *Proc. IEEE*, vol. 105, no. 5, pp. 825–836, 2017.
 - [72] E. H. Adelson and J. R. Bergen, "The plenoptic function and the elements of early vision," *Comput. Model. Vis. Process.*, pp. 3–20, 1991.
 - [73] T. N. Taguchi, Yuichi, Keita Takahashi, "Design and Implementation of a Real-Time Video-Based Rendering System Using a Network Camera Array Design and Implementation of a Real-Time Video-Based Rendering System Using a Network Camera Array," *IEICE Trans. Inf. Syst.*, vol. 92, no. 7, pp. 1442–1452, 2009.
 - [74] M. Zhang, Y. Piao, N. Kim, and E. Kim, "Distortion-free wide-angle 3D imaging and visualization using off-axially distributed image sensing," *Opt. Lett.*, vol. 39, no. 14, pp. 4212–4214, 2014.
 - [75] R. Schulein, M. Daneshpanah, and B. Javidi, "3D imaging with axially distributed sensing," *Opt. Lett.*, vol. 34, no. 13, pp. 2012–2014, 2012.
 - [76] H. Navarro, J. C. Barreiro, G. Saavedra, and B. Javidi, "High-resolution far-field integral-imaging camera by double snapshot," *Opt. Express*, vol. 20, no. 2, pp. 890–895, 2012.

-
- [77] Y. Taguchi, A. Agrawal, A. Veeraraghavan, S. Ramalingam, and R. Raskar, "Axial-cones: modeling spherical catadioptric cameras for wide-angle light field rendering," *ACM Trans. Graph. (Proceedings SIGGRAPH Asia 2010)*, vol. 29, no. 6, p. 172:1–172:8, 2010.
 - [78] M. Fuchs, M. Kächele, and S. Rusinkiewicz, "Design and fabrication of faceted mirror arrays for light field capture," *Comput. Graph. Forum*, vol. 32, no. 8, pp. 246–257, 2013.
 - [79] T. Georgiev, K. C. Zheng, B. Curless, D. Salesin, S. Nayar, and C. Intwala, "Spatio-angular resolution tradeoffs in integral photography," in *Eurographics Symposium on Rendering (EGSR)*, 2006, pp. 263–272.
 - [80] R. Munoz-Salinas, "ARUCO: a minimal library for Augmented Reality applications based on OpenCv," *Univ. Crdoba*, 2012.
 - [81] H. Hua, A. Girardot, C. Gao, and J. P. Rolland, "Engineering of head-mounted projective displays," *Appl. Opt.*, vol. 39, no. 22, pp. 3814–3824, 2000.
 - [82] H. Hua and B. Javidi, "A 3D integral imaging optical see-through head-mounted display," *Opt. Express*, vol. 22, no. 11, p. 13484, 2014.
 - [83] M. Guillaumée *et al.*, "Curved transfective holographic screens for head-mounted display," in *Proc. SPIE*, 2013, vol. 8643, pp. 864306–864306–7.
 - [84] K.-H. L. Son, Jung-Young, Hyoung Lee, Beom-Ryeol Lee, "Holographic and Light-Field Imaging as Future 3-D Displays," *Proc. IEEE*, vol. 105, no. 5, pp. 789–804, 2017.
 - [85] D. Lanman and D. Luebke, "Near-eye light field displays," *ACM SIGGRAPH 2013 Emerg. Technol. - SIGGRAPH '13*, vol. 32, no. 6, pp. 1–1, 2013.
 - [86] D. Dunn *et al.*, "Wide Field of View Varifocal Near-Eye Display Using See-Through Deformable Membrane Mirrors," *IEEE Trans. Vis. Comput. Graph.*, vol. 23, no. 4, pp. 1275–1284, 2017.
 - [87] A. Maimone, A. Georgiou, and J. S. Kollin, "Holographic near-eye displays for virtual and augmented reality," *ACM Trans. Graph.*, vol. 36, no. 4, pp. 1–16, 2017.
 - [88] S. R. Soomro and H. Urey, "Augmented reality 3D display using head-mounted projectors and transparent retro-reflective screen," in *Proc. SPIE*, 2017, vol. 10126, p. 101260E.
 - [89] D. Kade, K. Akşit, H. Ürey, and O. Özcan, "Head-mounted mixed reality projection display for games production and entertainment," *Pers. Ubiquitous Comput.*, vol. 19, no. 3, pp. 509–521, 2015.
 - [90] S. Tachi, "Telexistence and Retro-reflective Projection Technology (RPT)," in *Proceedings of Virtual Reality International Conference (VRIC)*, 2003, p. 69/1--69/9.
 - [91] J. Yang, M. Everett, C. Buehler, and L. McMillan, "A real-time distributed light field camera," *Eurographics Assoc.*, pp. 1–10, 2002.
 - [92] J. Kim, J.-H. Jung, C. Jang, and B. Lee, "Real-time capturing and 3D visualization

- method based on integral imaging,” *Opt. Express*, vol. 21, no. 16, pp. 18742–18753, 2013.
- [93] A. Stern and B. Javidi, “3-D computational synthetic aperture integral imaging (COMPSAII),” *Opt. Express*, vol. 11, no. 19, pp. 2446–2451, 2003.
- [94] W. Matusik and H. Pfister, “3D TV: A Scalable System for Real-Time Acquisition, Transmission, and Autostereoscopic Display of Dynamic Scenes,” *ACM SIGGRAPH 2004 Pap. - SIGGRAPH '04*, vol. 23, no. 3, p. 814, 2004.
- [95] A. Maimone, J. Bidwell, K. Peng, and H. Fuchs, “Enhanced personal autostereoscopic telepresence system using commodity depth cameras,” *Comput. Graph.*, vol. 36, no. 7, pp. 791–807, 2012.
- [96] M. Dou, Y. Shi, J. M. Frahm, H. Fuchs, B. Mauchly, and M. Marathe, “Room-sized informal telepresence system,” in *Proceedings - IEEE Virtual Reality*, 2012, pp. 15–18.
- [97] “Holoportation by Microsoft,” *Microsoft*. [Online]. Available: <https://www.microsoft.com/en-us/research/project/holoportation-3/>.
- [98] “High Contrast Linear Polarizer.” [Online]. Available: <http://www.polarization.com/polarshop/>.
- [99] S. R. Soomro, E. Ulusoy, and H. Urey, “Decoupling of Real and Digital Content in Projection-based Augmented Reality Systems Using Time Multiplexed Image Capture,” *J. Imaging Sci. Technol.*, vol. 61, no. 1, pp. 104061–104066, 2017.