Near-Eye

VR/AR Display Technologies

Kaan Akşit

Dec 2018

SIGGRAPH ASIA 2018 TOKYO

NVIDIA

Today


HTC Vive (2016)


Daqri (2017)


Google Cardboard (2016)


Microsoft Hololens (2017)

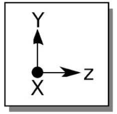
Real Max (2018)

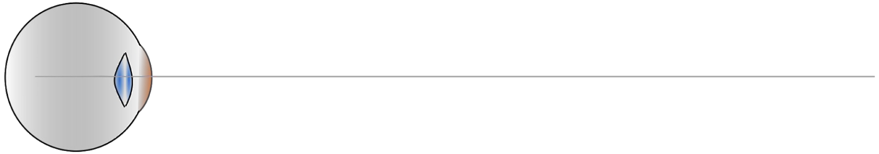
Kopin (2018)


Intel (2018)

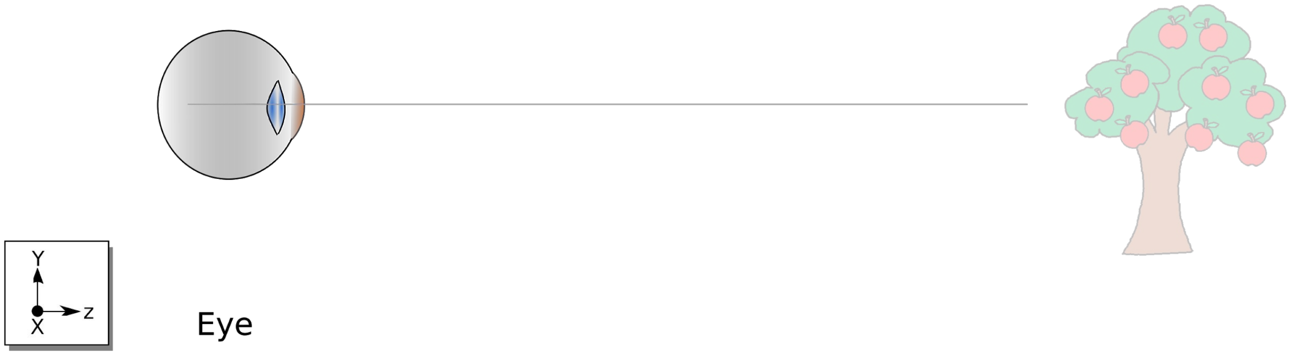
Magic Leap (2018)

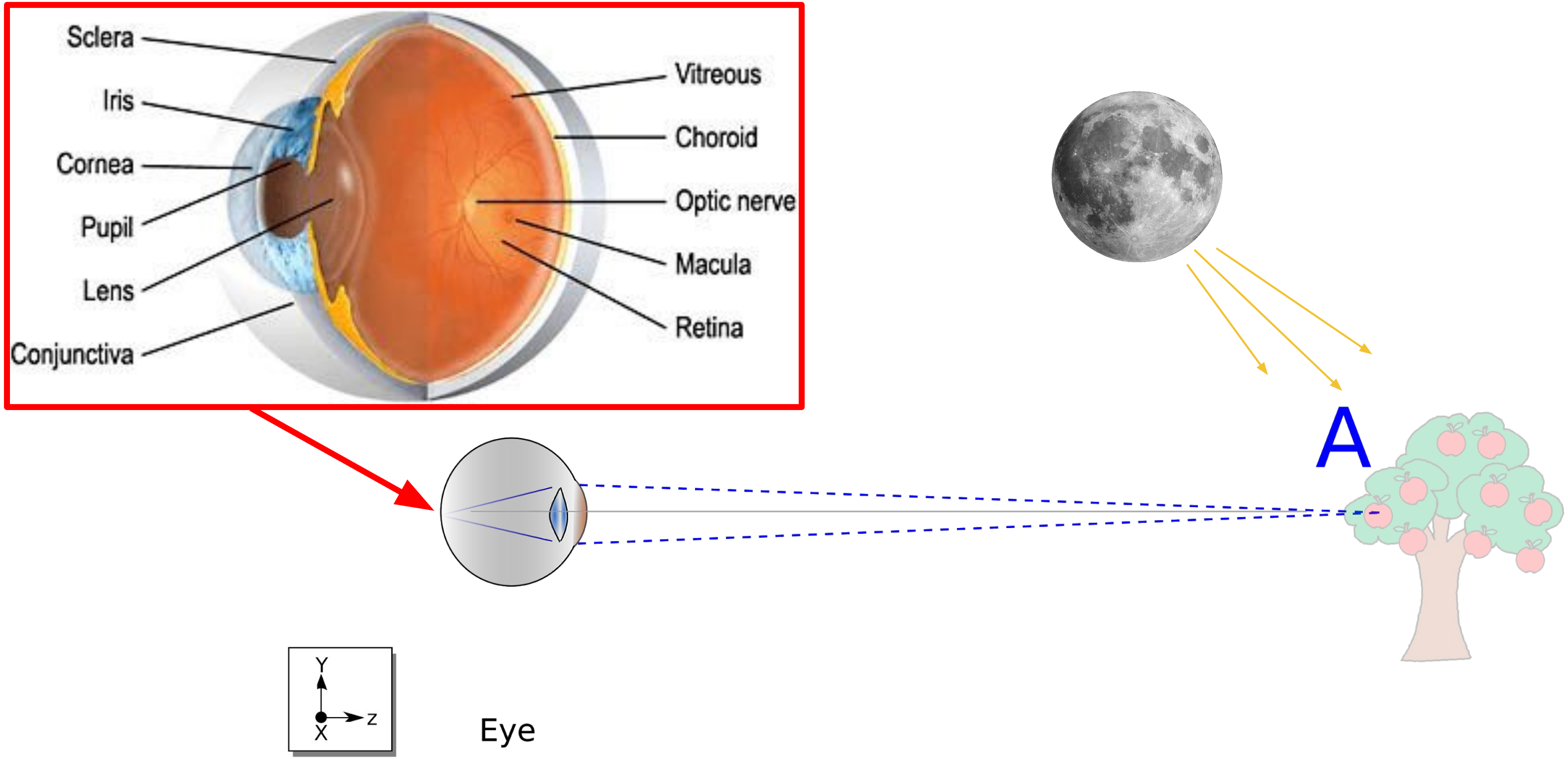
How do they work?





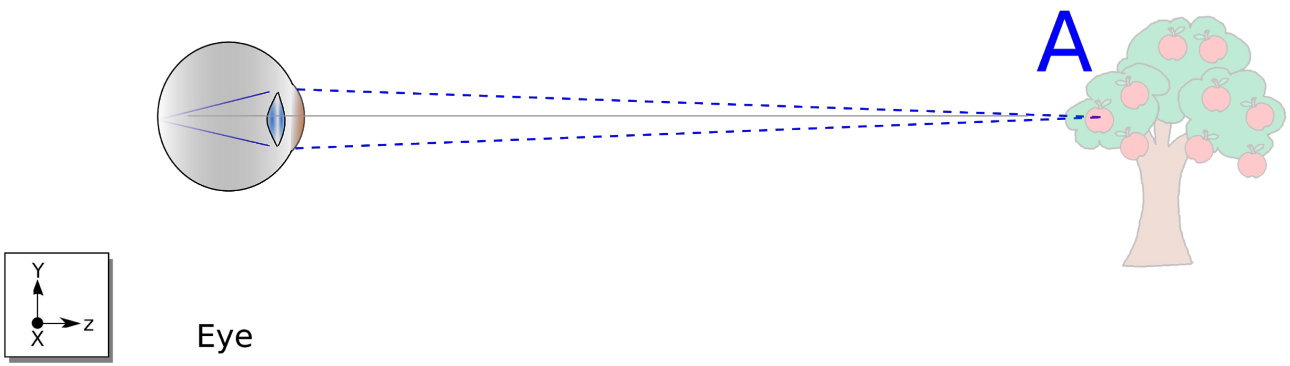
Eye


Y
Z
X
Eye

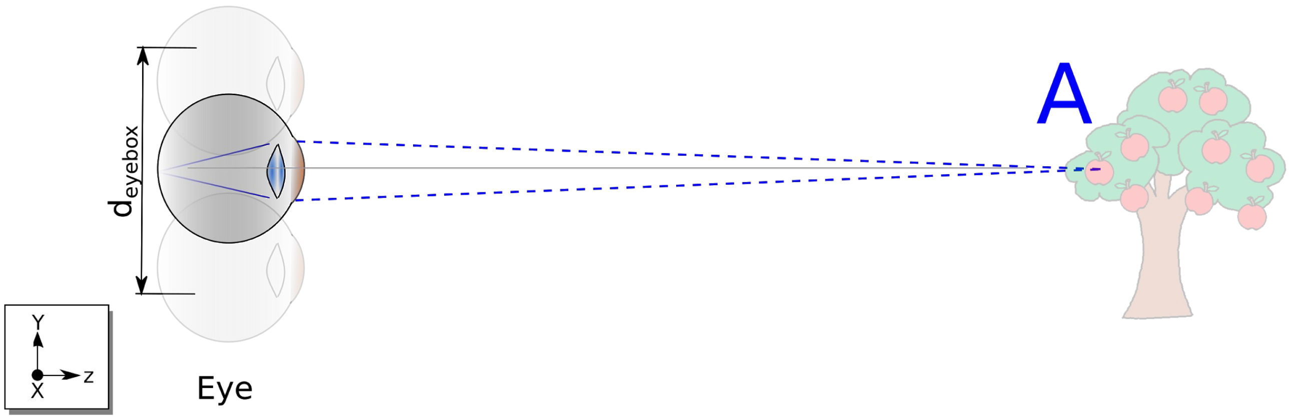


Real life is high dynamic range!

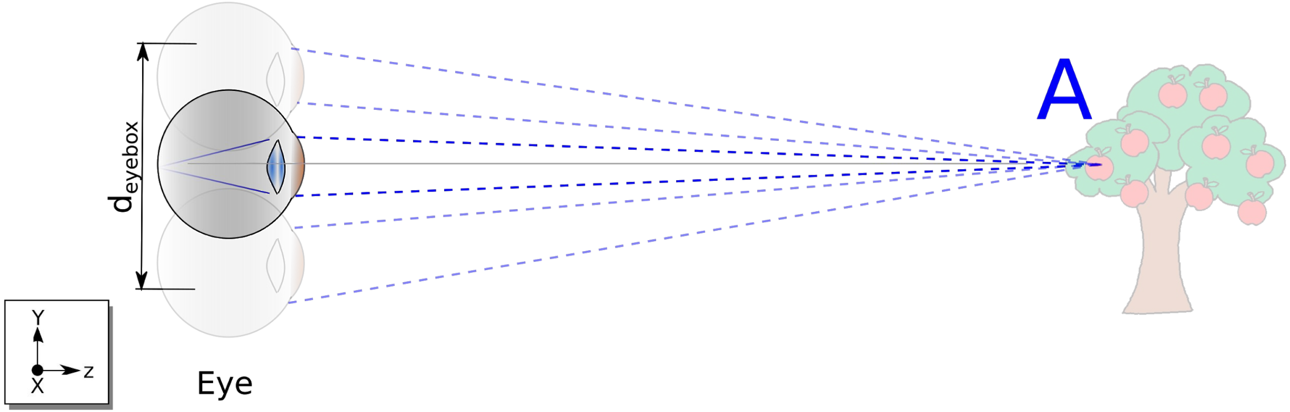
Reinhard, Erik, et al. *High dynamic range imaging: acquisition, display, and image-based lighting*. Morgan Kaufmann, 2010.


A
Y
Z
X
Eye

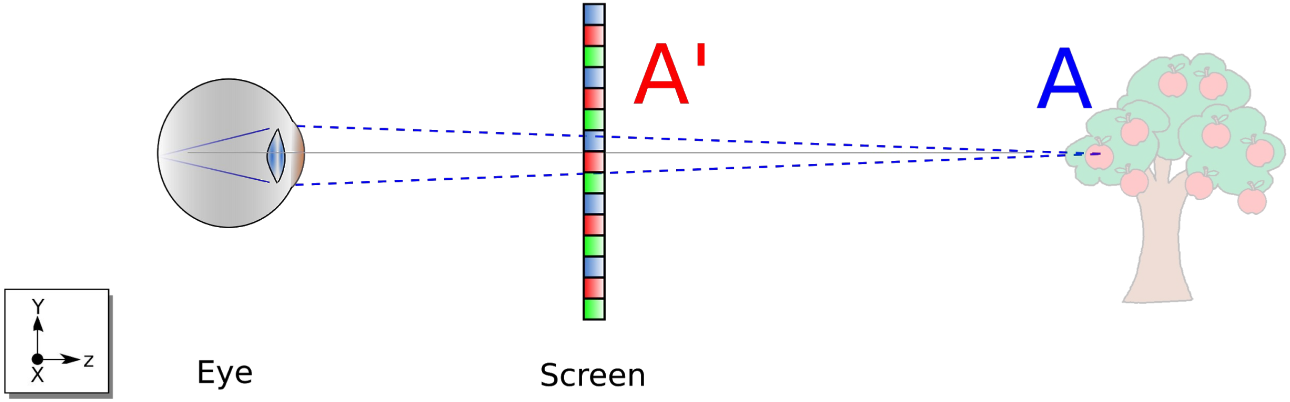
Real life has infinite eyebox/viewing zone!

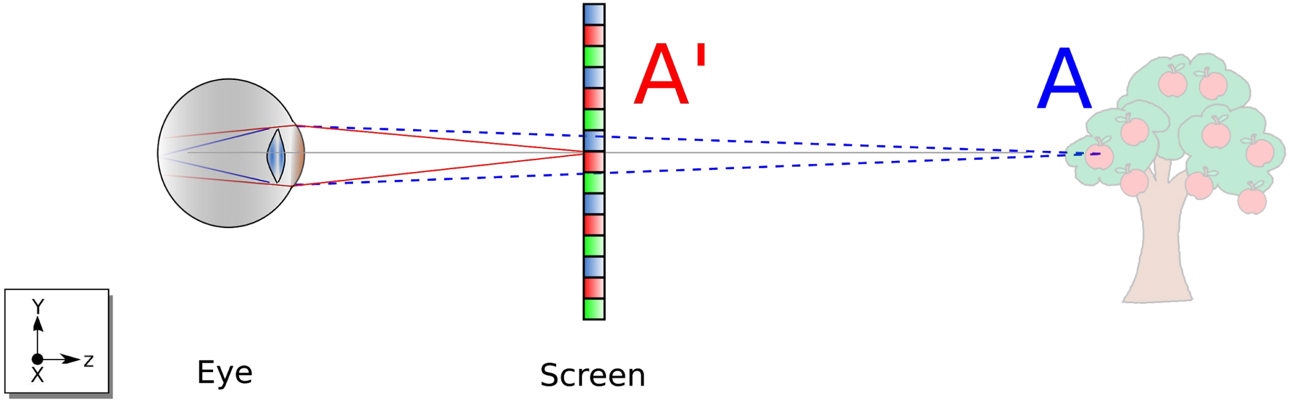


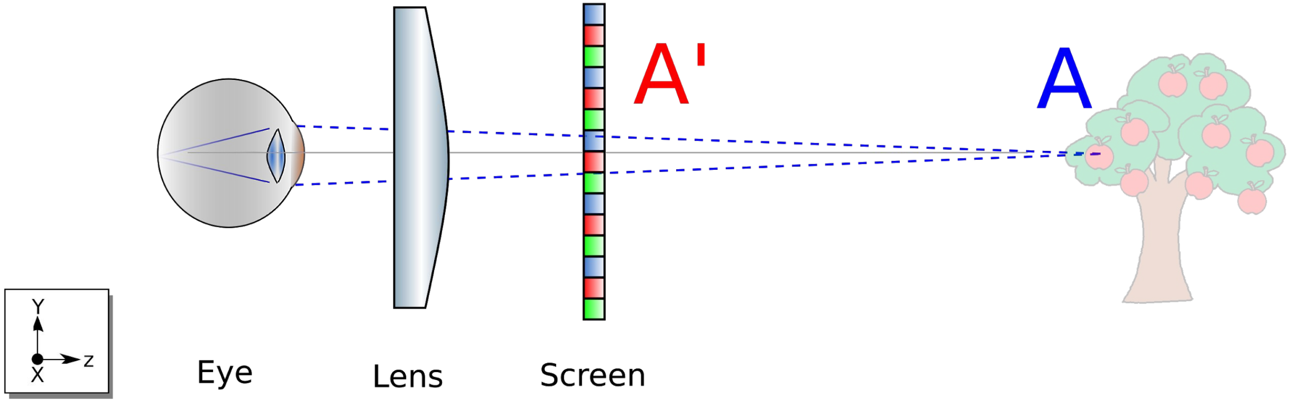
Real life is 4D Light Fields

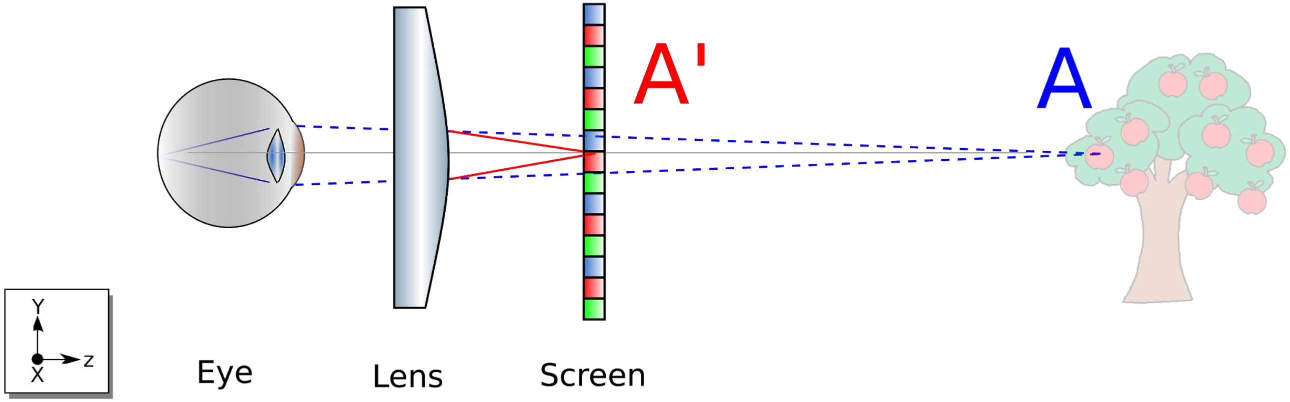


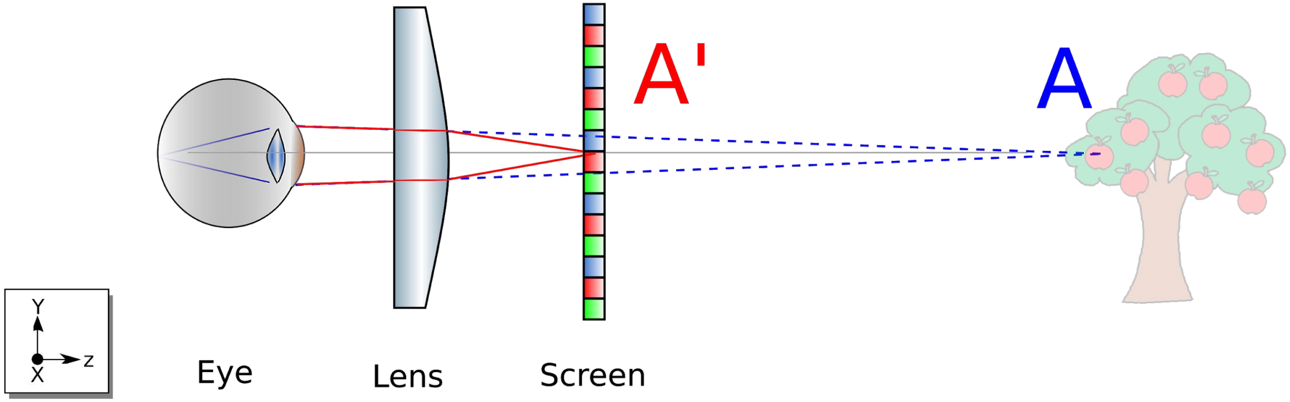
Levoy, Marc, and Pat Hanrahan. "Light field rendering." *Proceedings of the 23rd annual conference on Computer graphics and interactive techniques*. ACM, 1996.

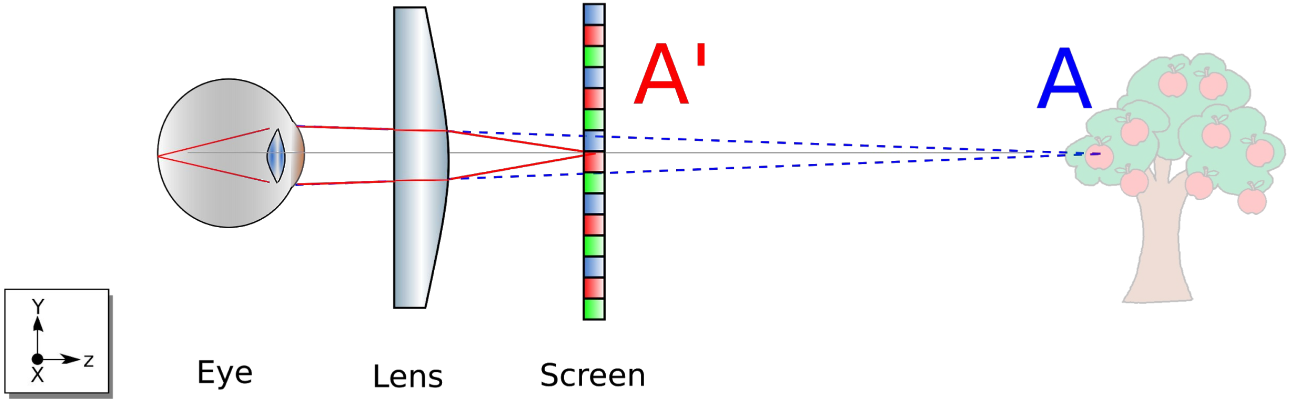

A'
A
Y
Z
X
Eye
Screen


A'
A
Y
Z
X
Eye
Screen

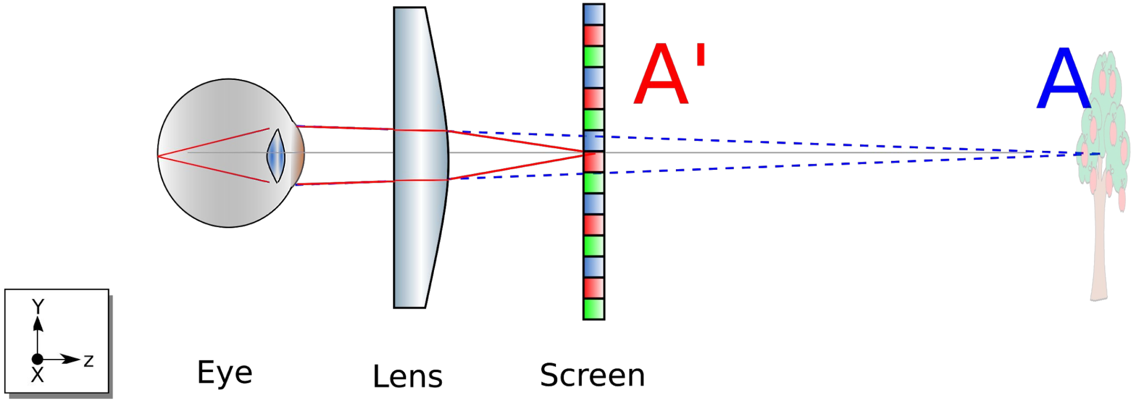

A'
A
Y
Z
X
Eye
Lens
Screen

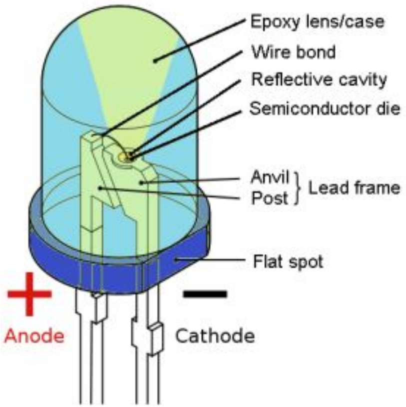

A'
A
Y
Z
X
Eye
Lens
Screen

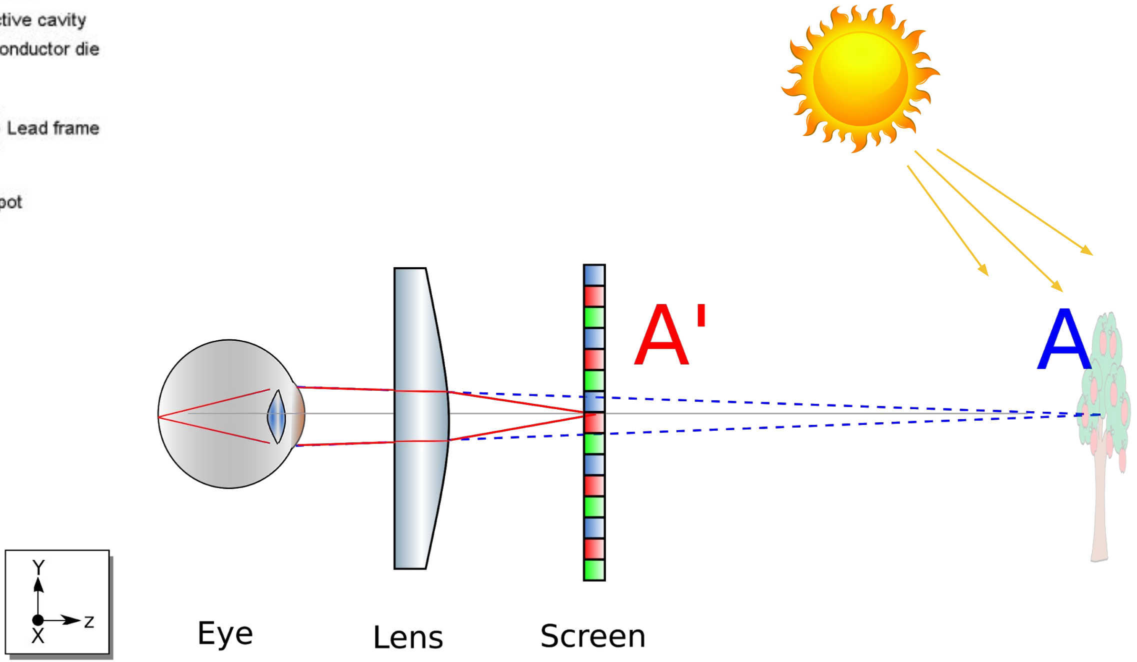

A'
A
Y
Z
X
Eye
Lens
Screen


A'
A
Y
Z
X
Eye
Lens
Screen

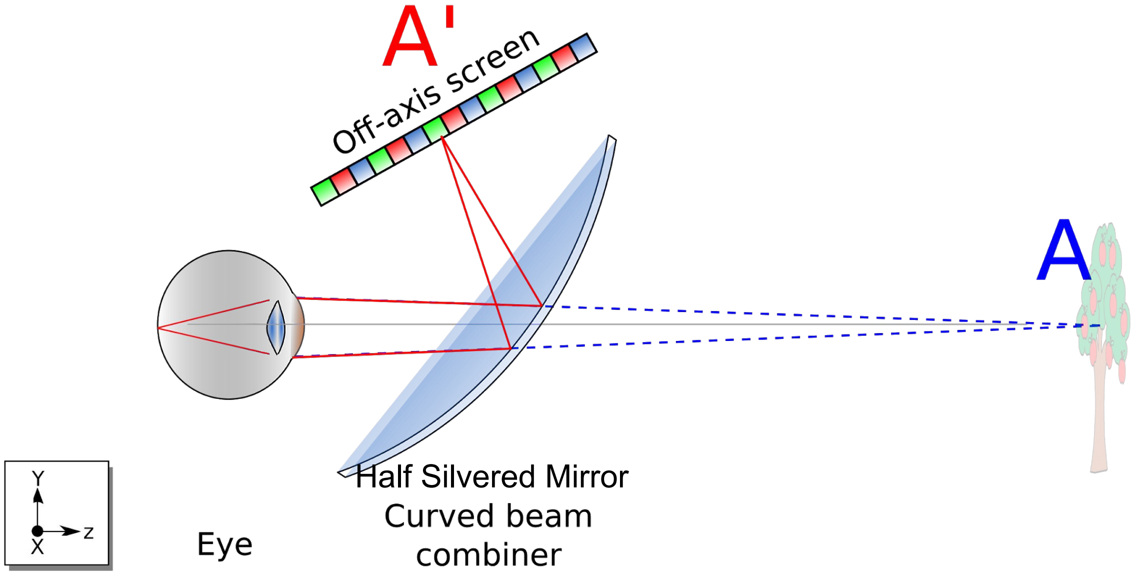
Current virtual reality near eye displays does not support different optical depth levels!





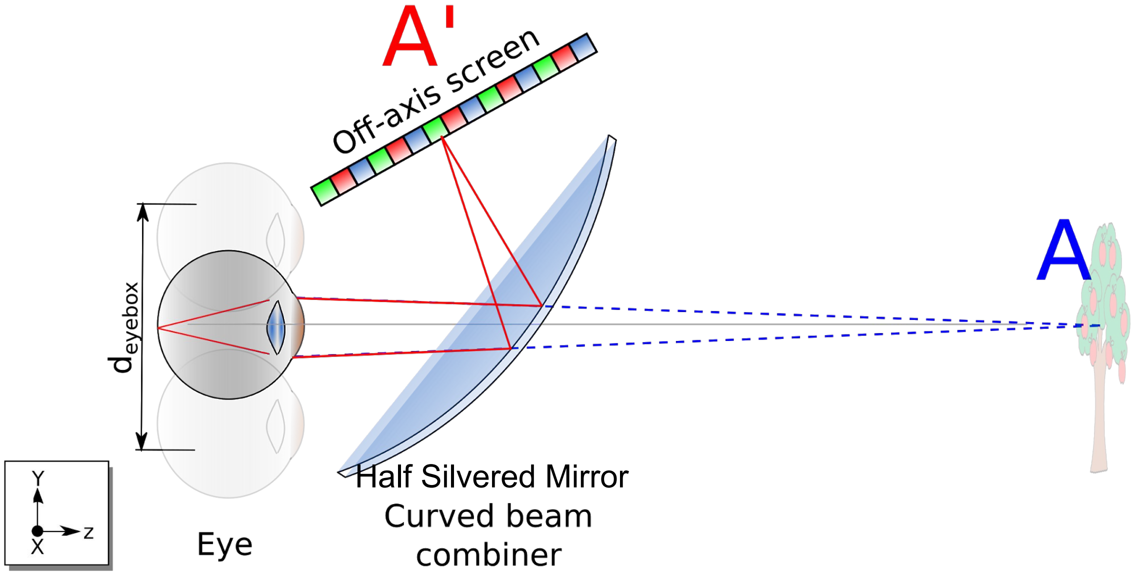


Current virtual reality near eye displays can not generate all the colors and can not support all brightness levels.



Pinhas Gilboa. 1991. Designing the right visor. In Medical Imaging. International Society for Optics and Photonics.

Current generation of augmented reality near eye displays can not generate wide eyebox as in the case of virtual reality near eye displays.



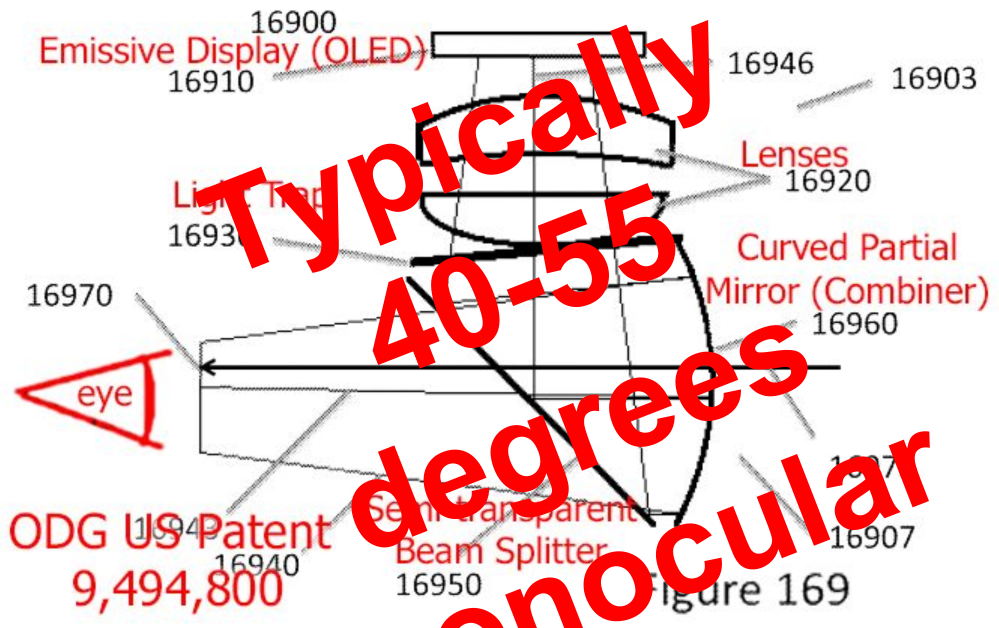
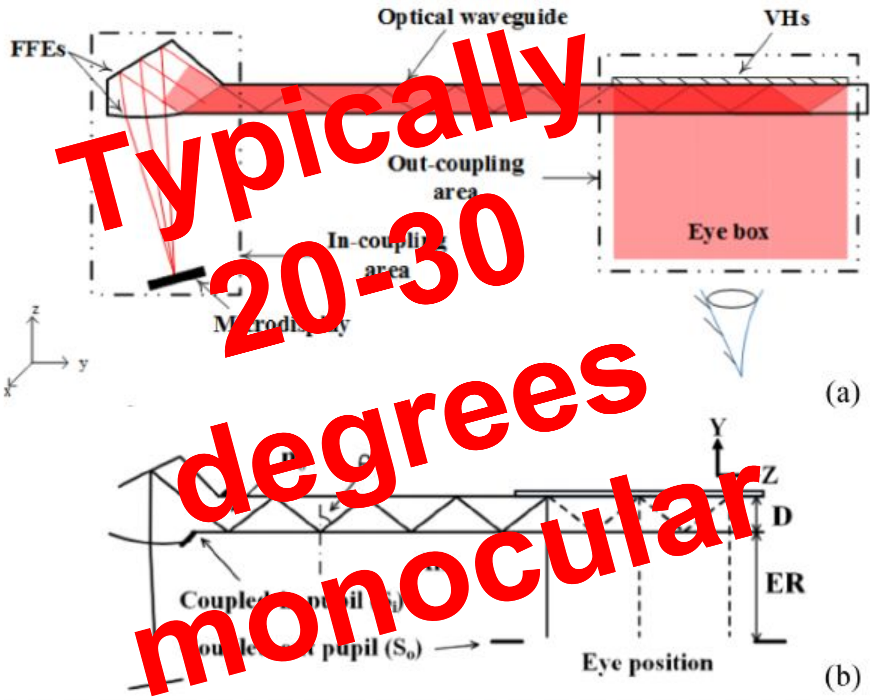


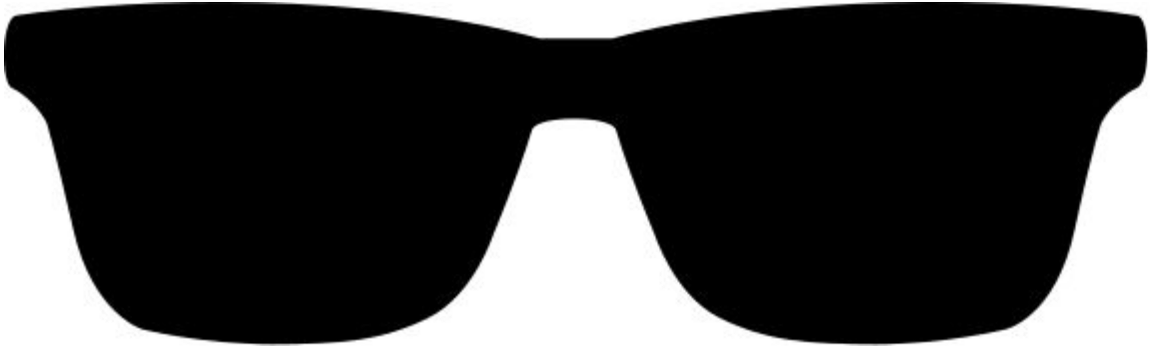
Image from
http://www.kguttag.com/2017/03/03/near-eye-bird-bath-optics-pros-and-cons-and-immys-different-approach/



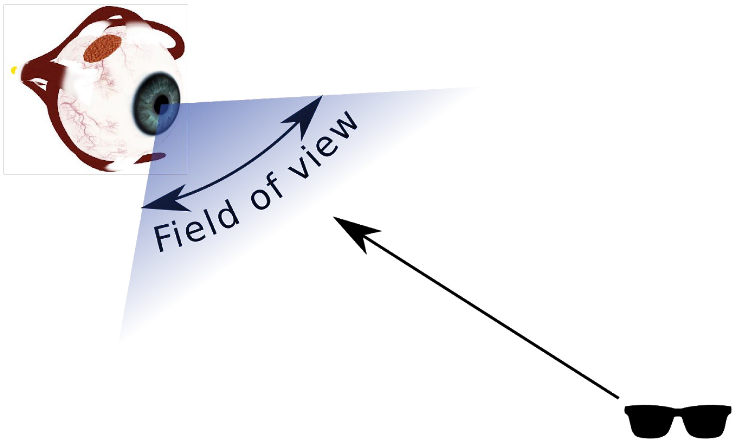
Han, Jian, et al. Optics express 23.3 (2015).

Current augmented reality near eye displays can not generate wide field of view.

Challenges?

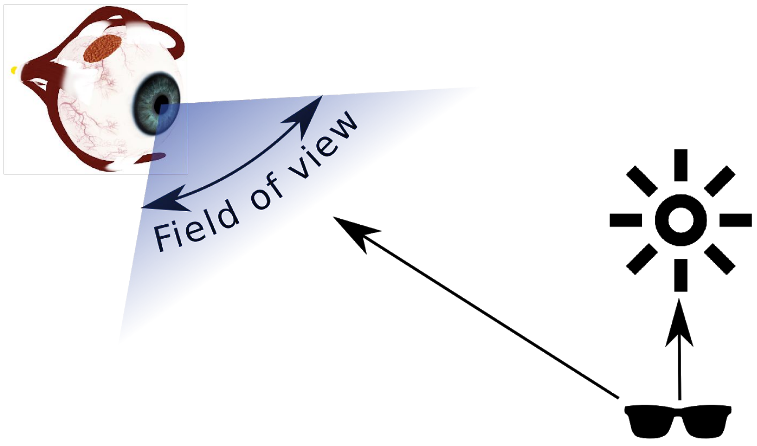


[Kramida, Gregory. IEEE transactions on visualization and computer graphics (2016),
Hua, Hong. Proceedings of the IEEE (2017)]

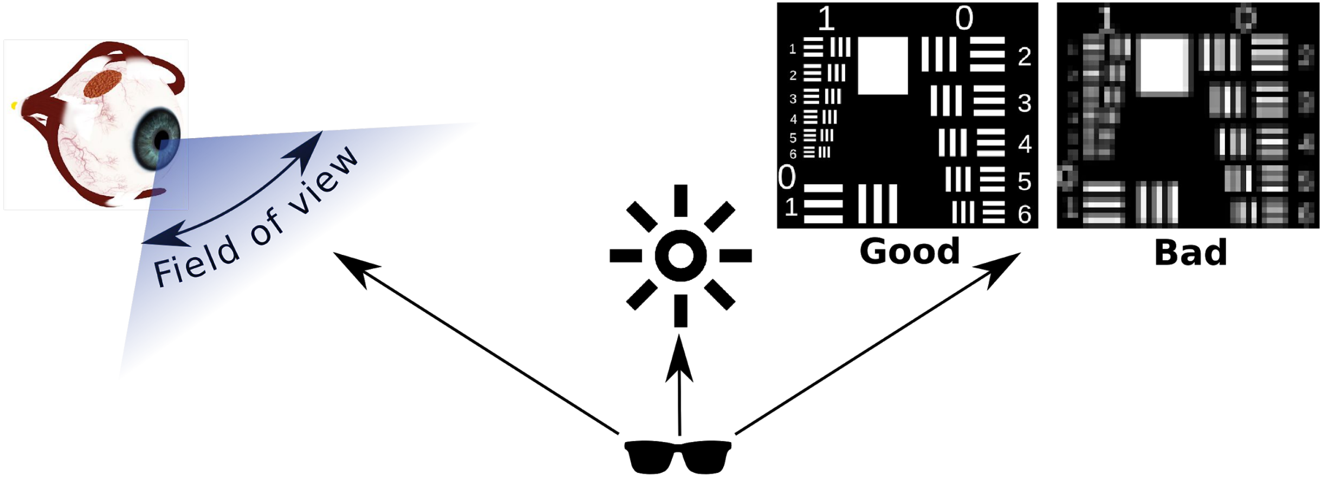


190 degrees of binocular field of view

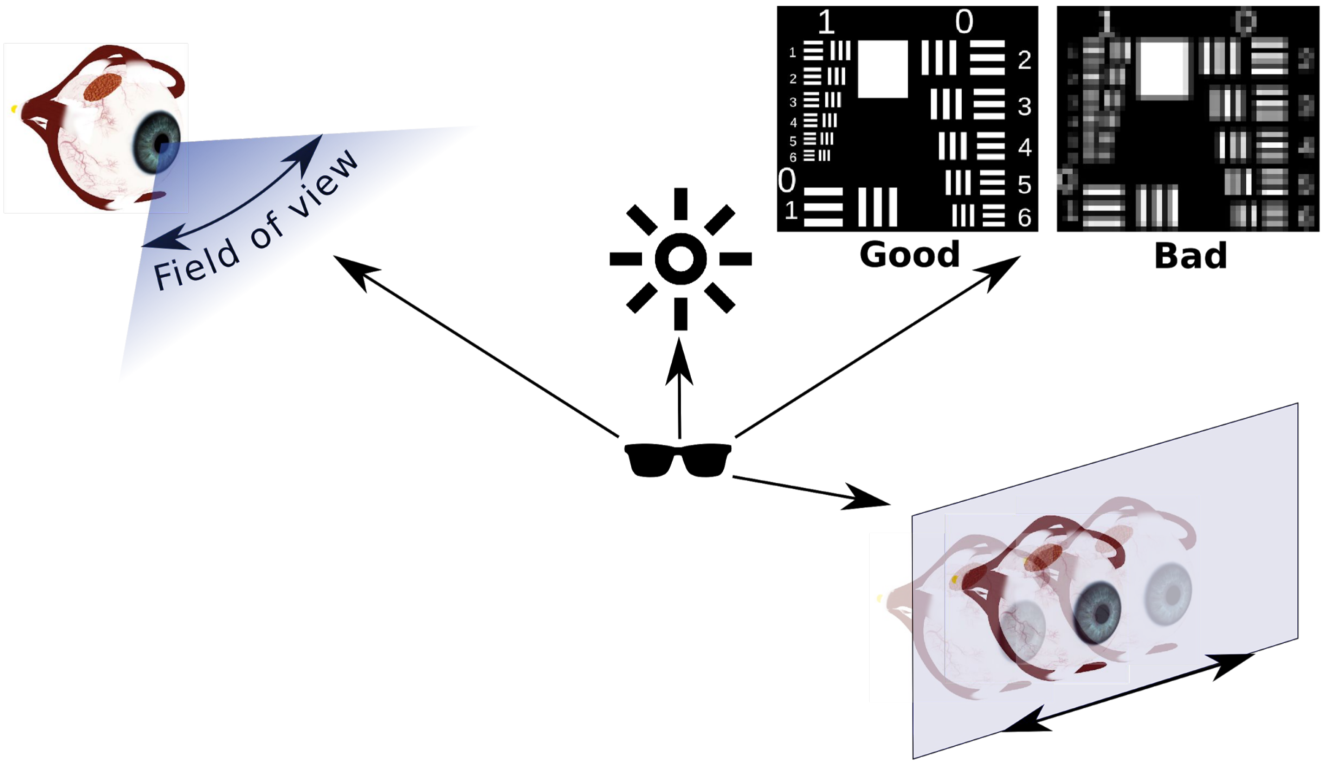
Paul Webb. 1964. Bioastronautics data book. (1964).



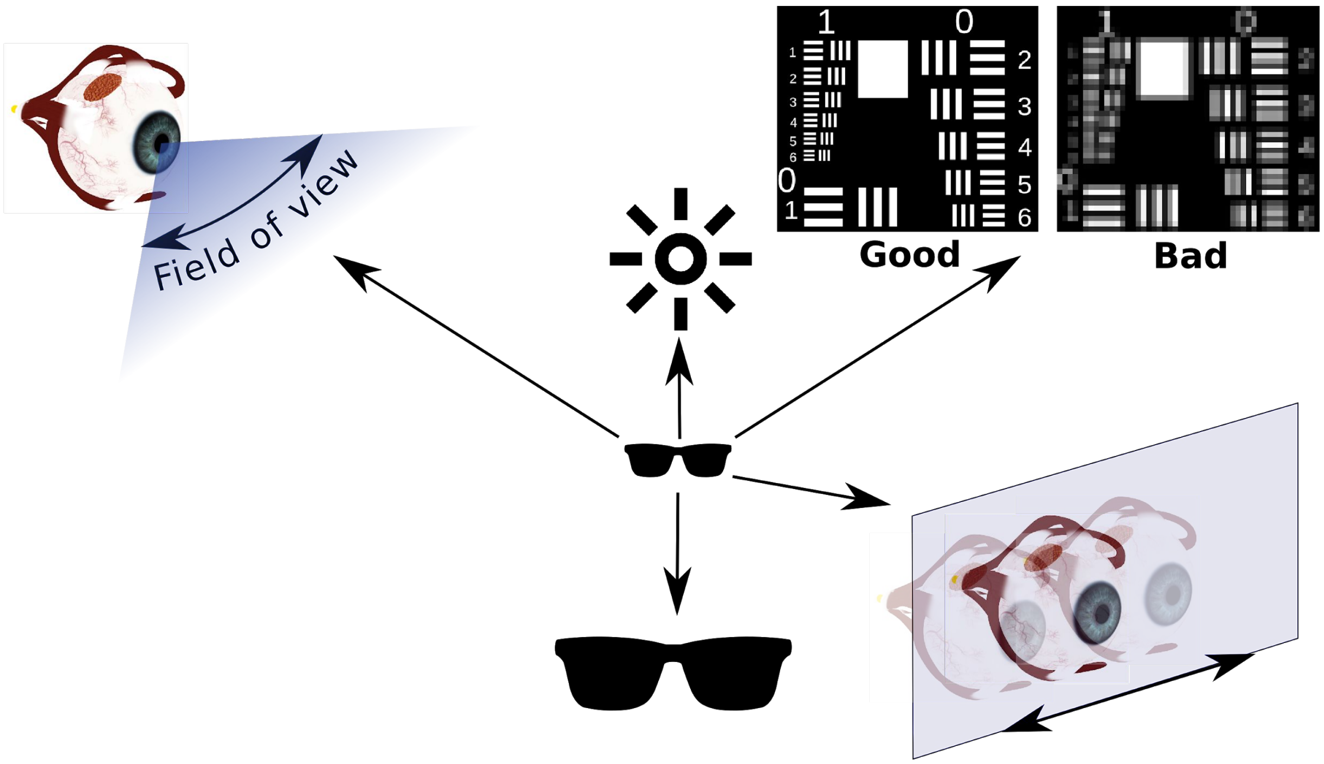
The human visual system can adapt from ~10^-6 cd/m^2 to ~10^6 cd/m^2. It has an unique color perception.



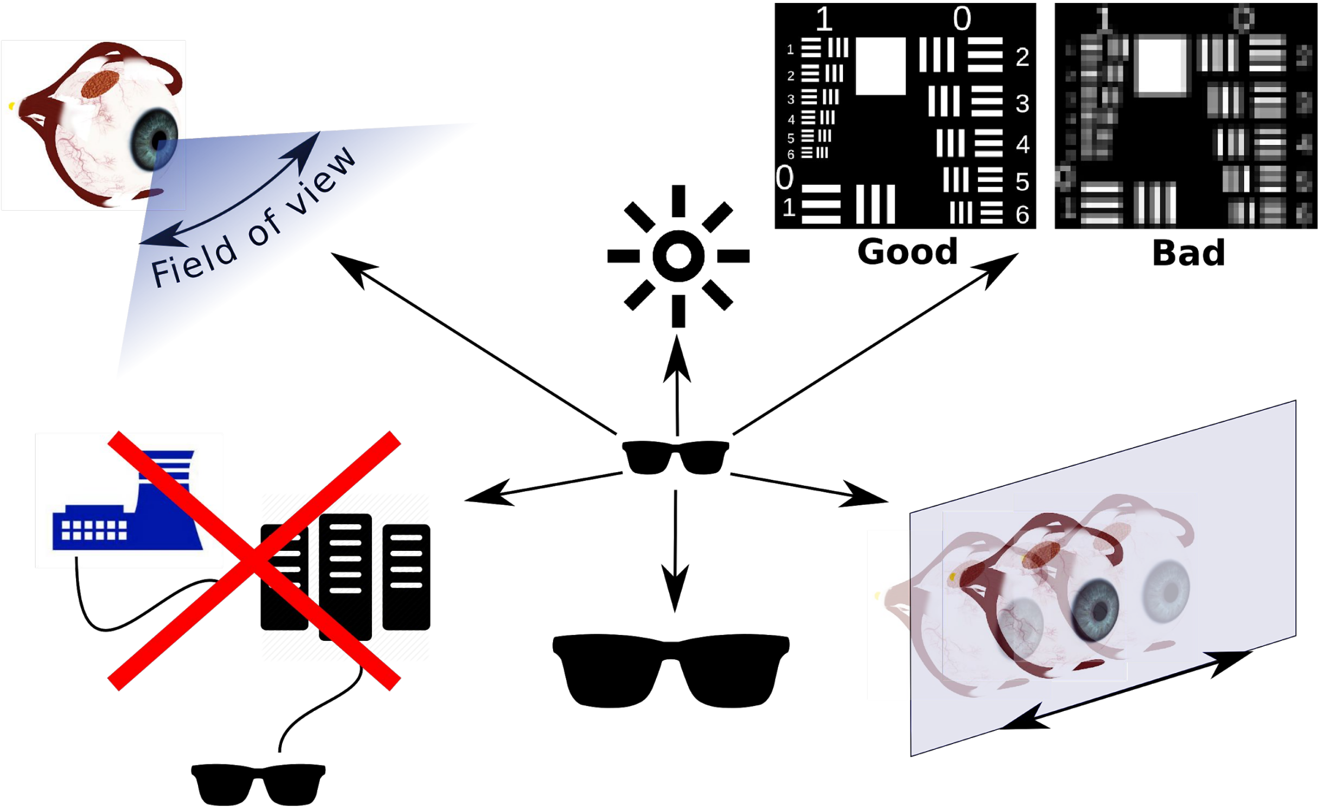
The human visual system has 20/20 visual acuity, 1 arcmin of resolution.



A large eyebox is needed in front of an eye, typically 20 mm x 20 mm.

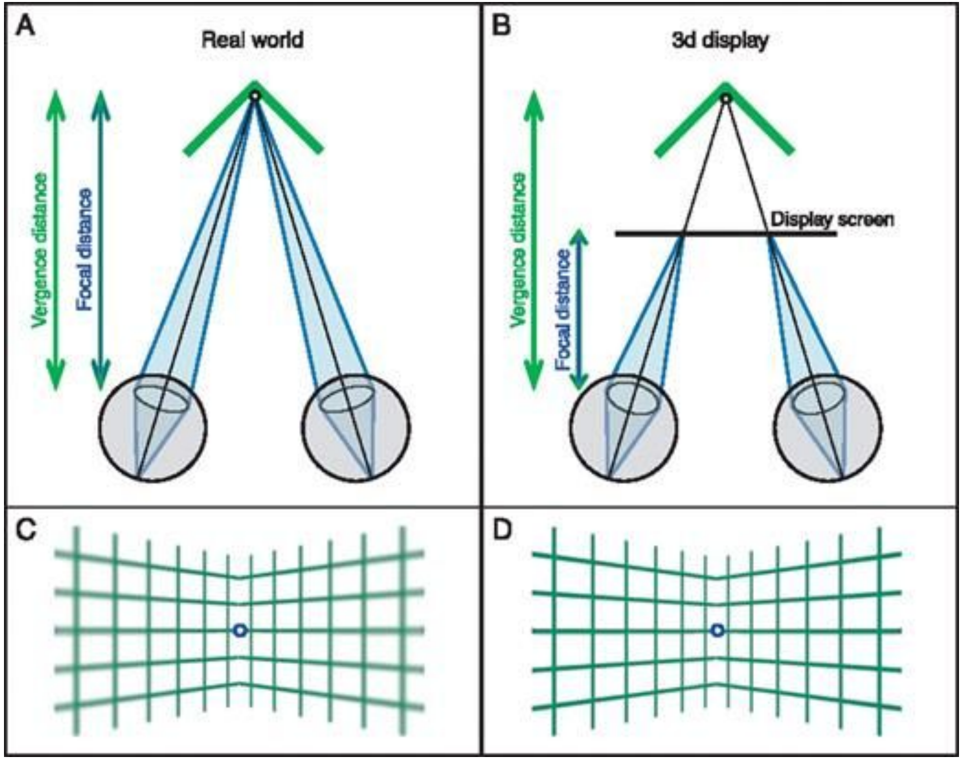


Slim form factor



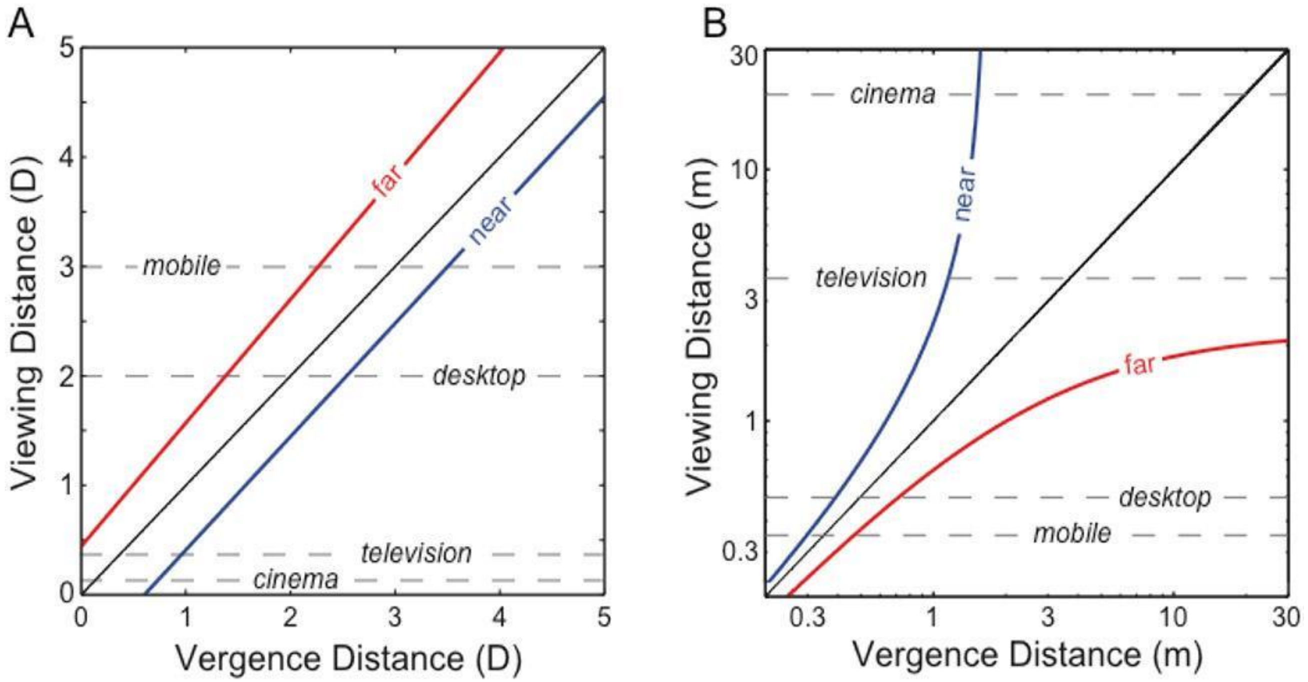
A typical smartphone has 5.45 Wh energy with an 1.7Ghz Quad-Core ARM Cortex-A53 CPU.

Accommodation - Vergence Conflict



[Hoffman, David M., et al. Journal of vision 8.3 (2008): 33-33.]

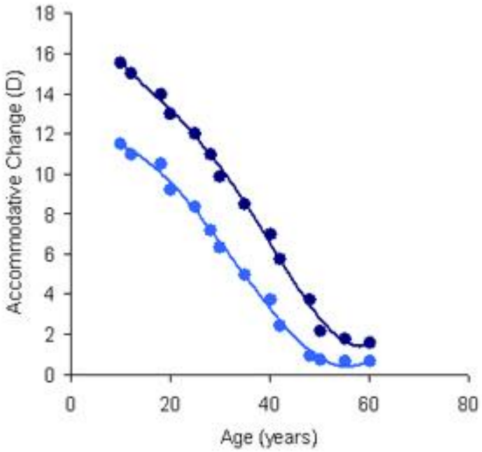
Zone of Comfort



[T. Shibata, et al *Journal of vision* (2011)]

Presbyopia

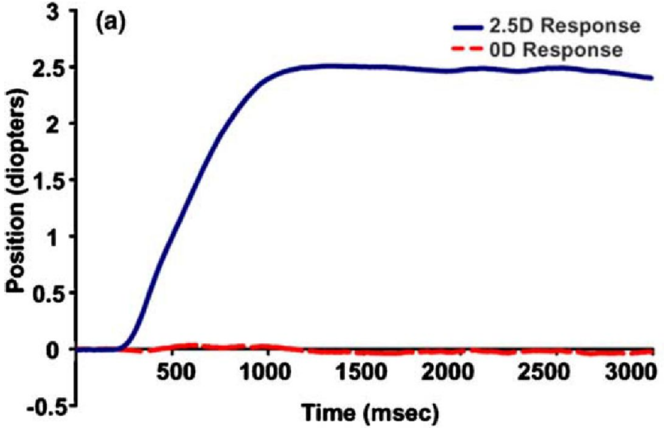
- As we age, our focal adaptation weakens
- For those advanced in age, having fixed focus in VR can be good if it is the right focus
- Not so for optical see-through AR: when the real world needs to be corrected



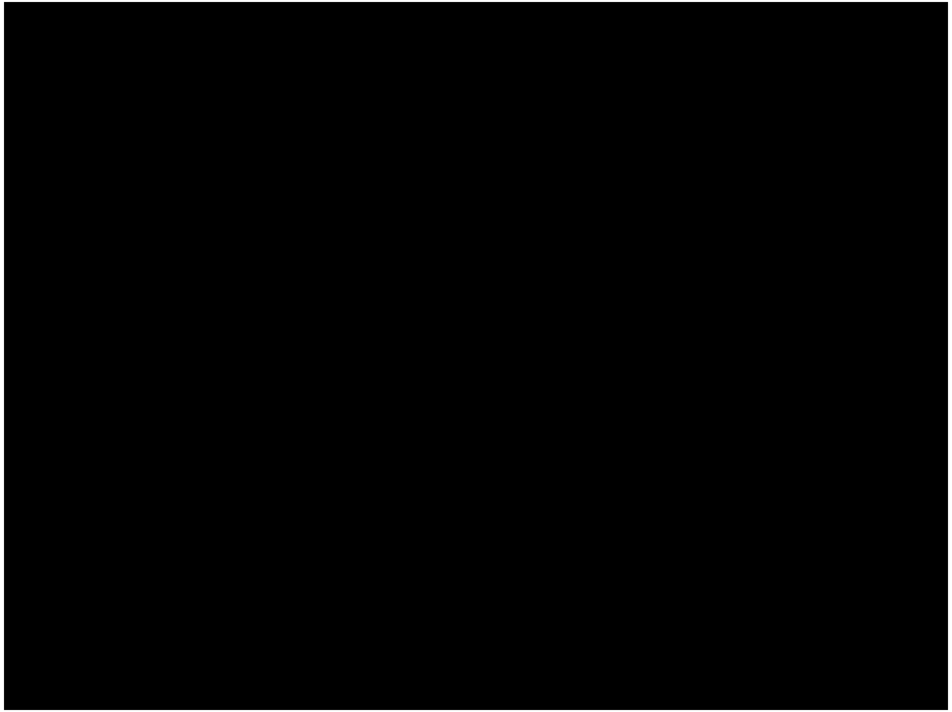
http://www.cvs.rochester.edu/yoonlab/research/pa.html
http://eyeglasses-asheville.com

Accommodation response

- Step change of fixated object depth
  - Smooth and steady accommodation increase
    - up to 1 second to achieve the full accommodation state
    - ~300 ms latency



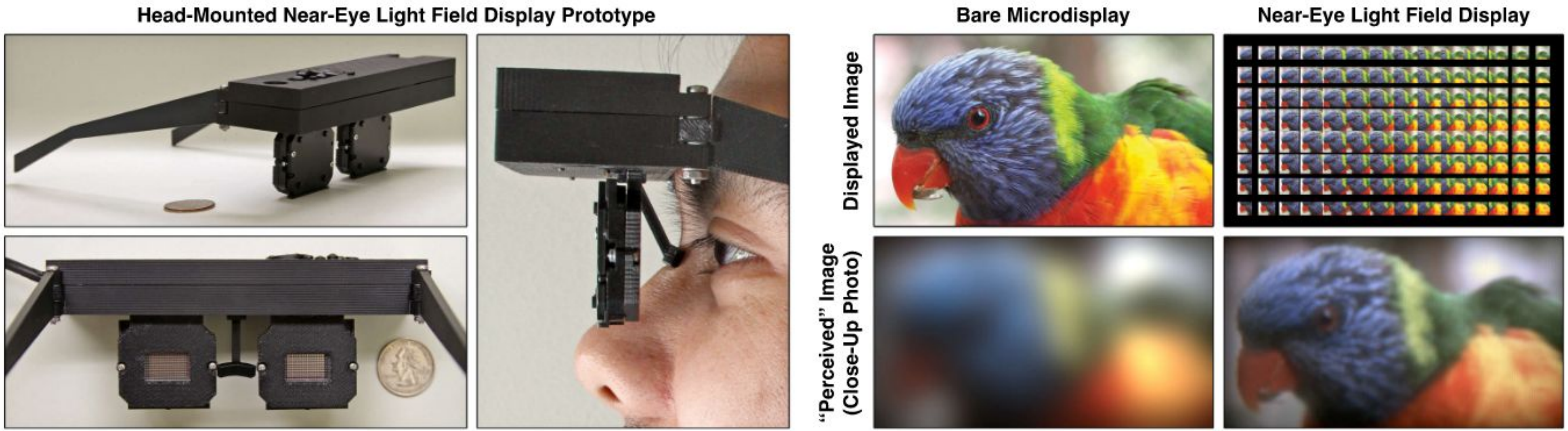
[Bharadwaj and Schor, Vision Research 2004]

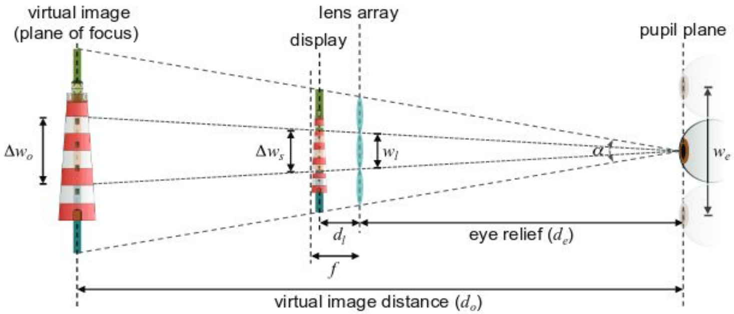


Video from Edmund Optics

Investment : >1-5 Million USD + Permanent technical personnel + Long processing times (6-8 weeks)

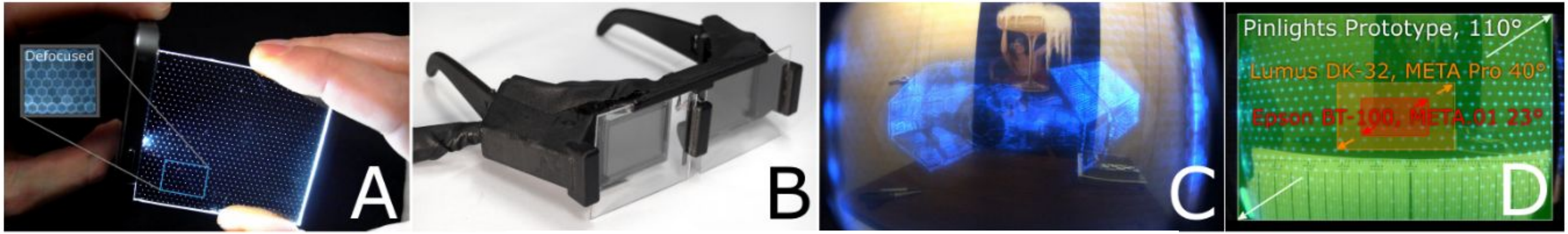
Nvidia’s near eye displays

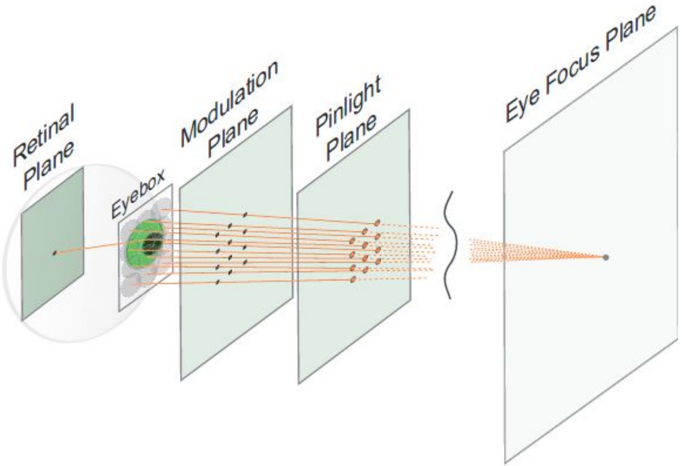




Microlens displays

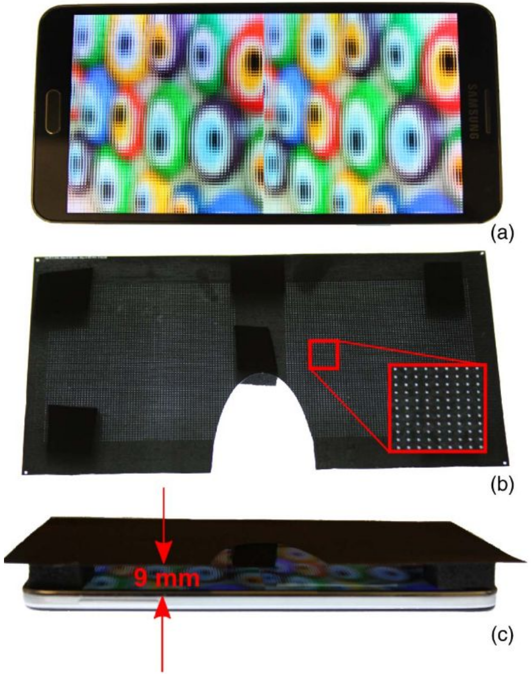
[Lanman and Luebke *ACM SIGGRAPH ASIA* 2013]

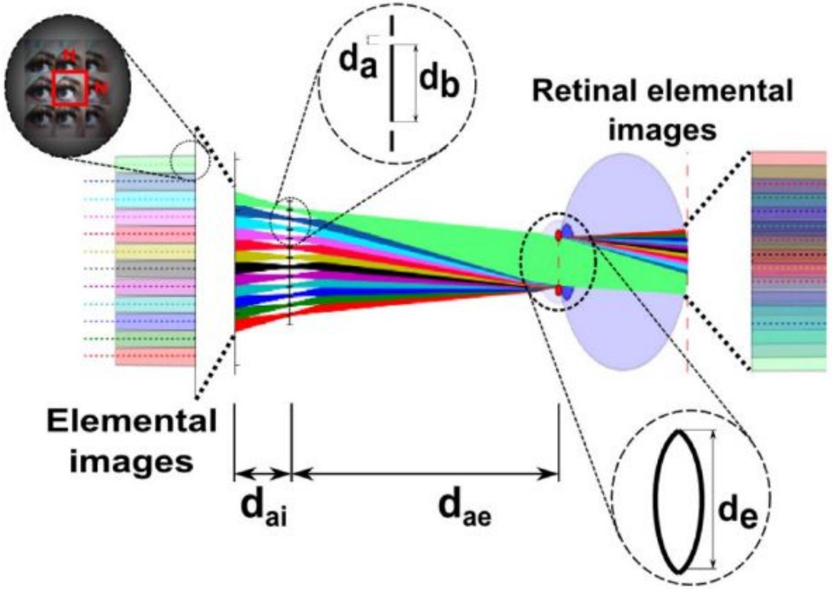




Pinlight displays

[Maimone et al. *ACM SIGGRAPH 2014]*

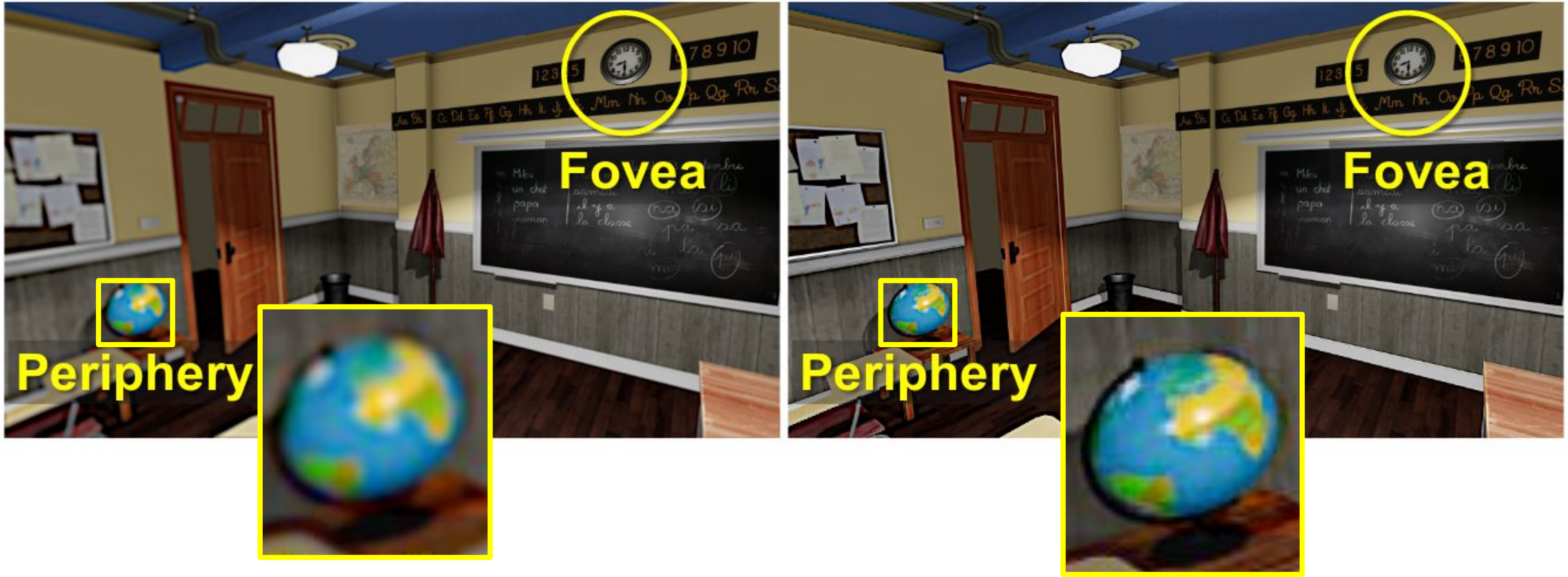




Pinhole displays

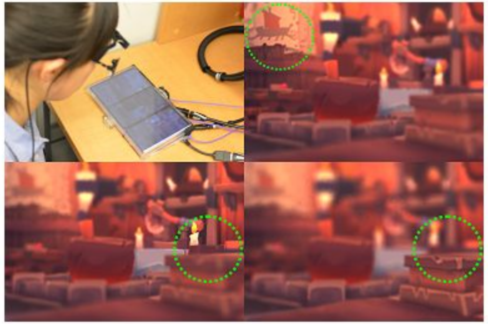
[Kaan Akşit et al. *Applied optics, 2015*]

NEED GAZE AWARE RENDERING



Patney et al."Perceptually-based foveated virtual reality." In *ACM SIGGRAPH 2016 Emerging Technologies*, p. 17. ACM, 2016.

Perceptually-Guided Foveation for Light Field Displays



A variety of applications such as virtual reality and immersive cinema require high image quality, low rendering latency, and consistent depth cues. 4D light field displays support focus accommodation, but are more costly to render than 2D images, resulting in higher latency. The human visual system can resolve higher spatial frequencies in the fovea than in the periphery. This property has been harnessed by recent 2D foveated rendering methods to reduce computation cost while maintaining perceptual quality. Inspired by this, we present foveated 4D light fields by investigating their effects on 3D depth perception. Based on our psychophysical experiments and theoretical analysis on visual and display bandwidths, we formulate a content-adaptive importance model in the 4D ray space. We verify our method by building a prototype light field display that can render only 16%-30% rays without compromising perceptual quality.

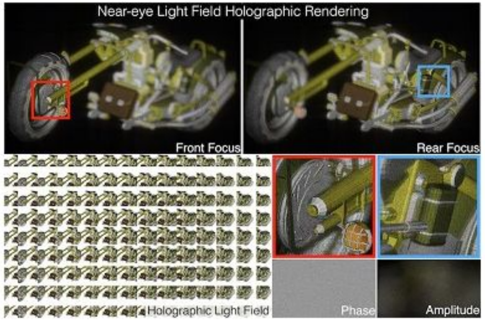
Authors: Qi Sun (Stony Brook University & NVIDIA)
Fu-Chung Huang
Joohwan Kim
Li-Yi Wei (University of Hong Kong)
David Luebke
Arie Kaufman (Stony Brook University)

Publication Date: Monday, November 27, 2017

Published in: ACM SIGGRAPH ASIA 2017

[Qi et al., *ACM SIGGRAPH 2017]*

Near-eye Light Field Holographic Rendering with Spherical Waves for Wide Field of View Interactive 3D Computer Graphics



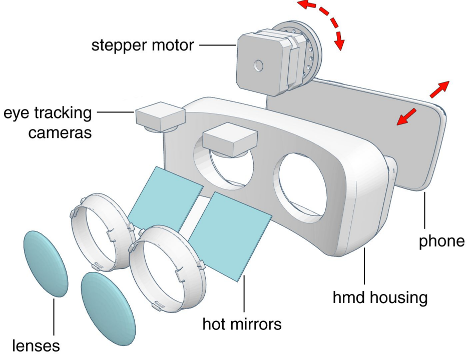
Holograms have high resolution and great depth of field allowing the eye to view a scene much like seeing through a virtual window. Unfortunately, computer generated holography (CGH) does not deliver the same promise due to hardware limitations under plane wave illumination and large computational cost. Light field displays have been popular due to their capability to provide continuous focus cue. However, light field displays suffer from the trade offs between spatial and angular resolution, and do not model diffraction. We present a light field based CGH rendering pipeline allowing for reproduction of high-definition 3D scenes with continuous depth and support of intra-pupil view dependent occlusion. Our rendering accurately accounts for diffraction and supports various types of reference illumination for holograms. We prevent under- and over-sampling and geometric clipping suffered in previous work. We also implement point-based methods with Fresnel integration that are orders of magnitude faster than the state of art, achieving interactive volumetric 3D graphics. To verify our computational results, we build a see-through near-eye color display prototype with CGH that enables co-modulation of both amplitude and phase. We show that our rendering accurately models the spherical illumination introduced by the eye piece and produces the desired 3D imaginary at designated depth. We also derive aliasing, theoretical resolution limits, depth of field, and other design trade-off space for near-eye CGH.

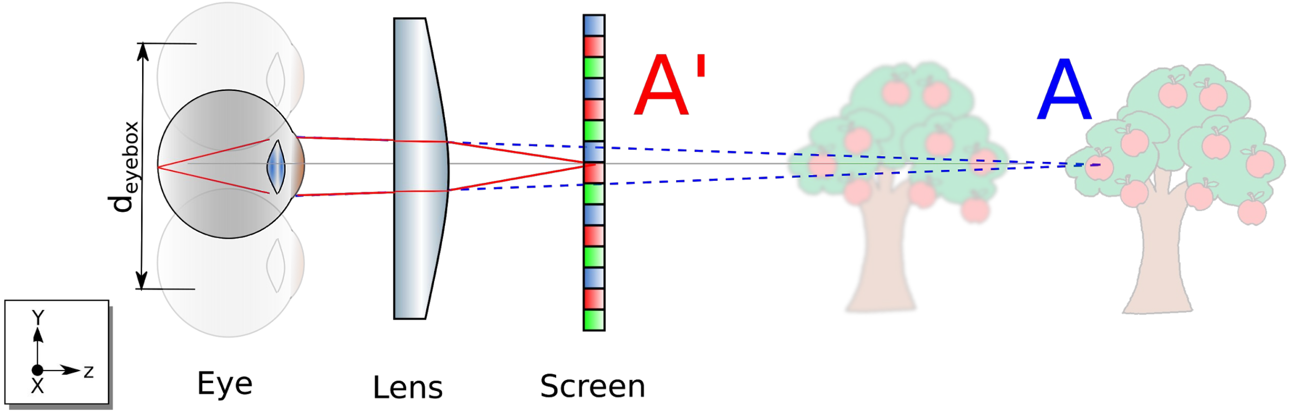
Authors: Liang Shi (NVIDIA & MIT CSAIL)
Fu-Chung Huang
Ward Lopes
Wojciech Matusik (MIT CSAIL)
David Luebke

[Liang et al. *Siggraph Asia, 2017*]

Varifocal display proposal I

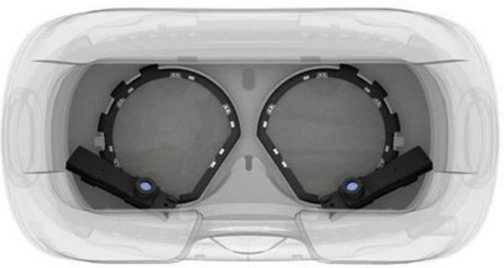
Kaan Akşit, Ward Lopes, Jonghyun Kim, Peter Shirley, and David Luebke. 2017. Near-eye varifocal augmented reality display using see-through screens. *ACM Trans. Graph.* 36, 6, Article 189 (November 2017)



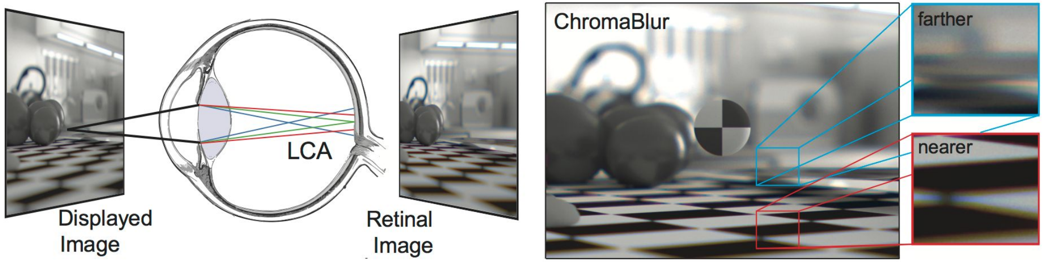


Our understanding of varifocal is aligned with

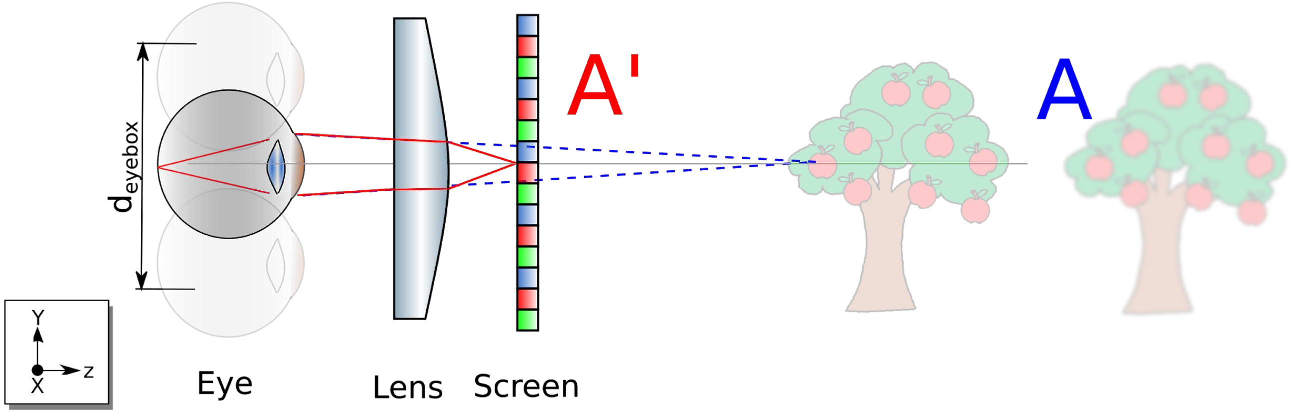
Padmanaban, Nitish, et al. "Optimizing virtual reality for all users through gaze-contingent and adaptive focus displays." Proceedings of the National Academy of Sciences (2017): 201617251.



Pupillabs eye tracker for HTC Vive



Cholewiak, Steven A., et al. "ChromaBlur: Rendering chromatic eye aberration improves accommodation and realism." Siggraph Asia (2017).



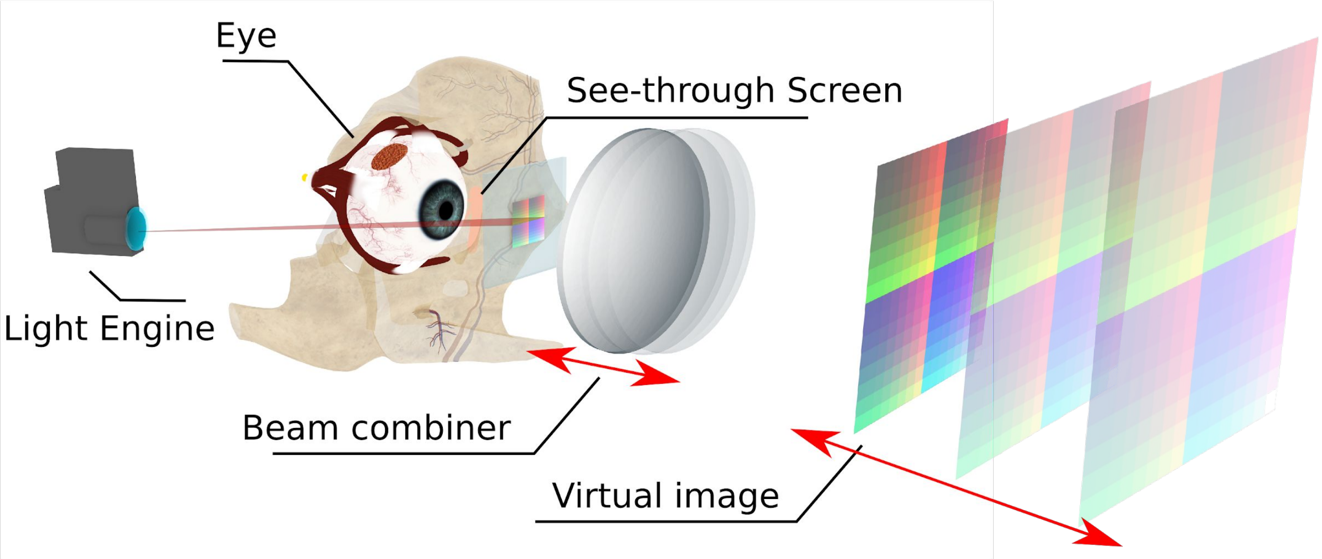
Moving depth plane in synchronism with an eye tracker, and applying a computational blur for mimicking optical blur.

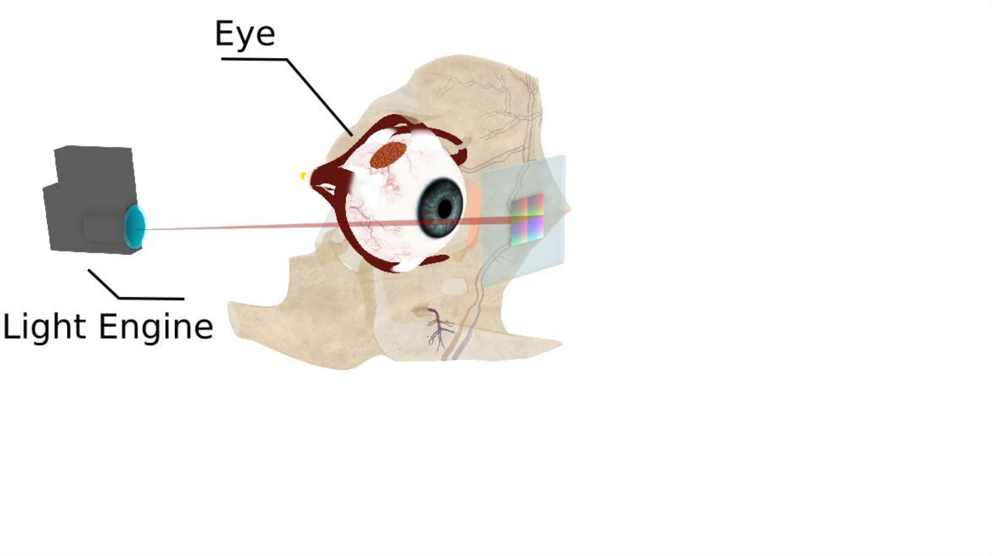
“Studies show evidence that supporting accommodative cues through a varifocal mechanism improves visual comfort and user performance while being simpler than other methods, but most current approaches sacrifice FoV and bulk.”

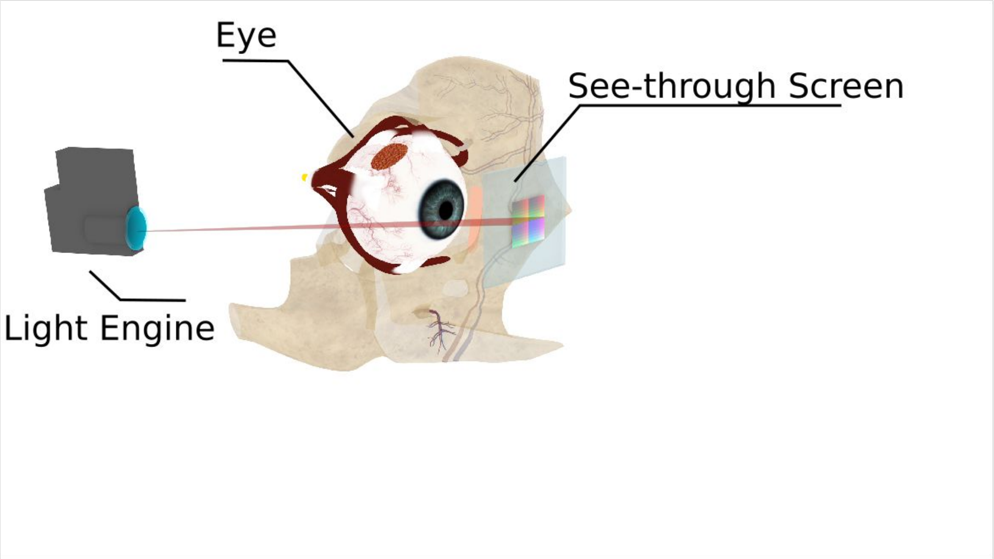
[Johnson et al. Optics Express 2016, Konrad et al. Human Factors in Computing 2016]

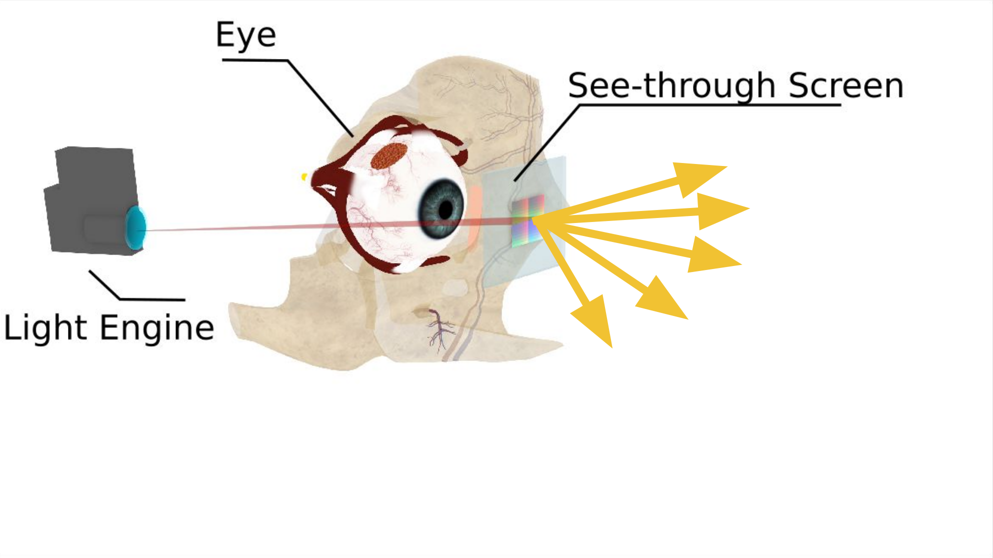
“The duration of actual lens accommodation of 500−800 ms has been reported, which means that the complete accommodation cycle, including the latency, typically requires around 1 second.”

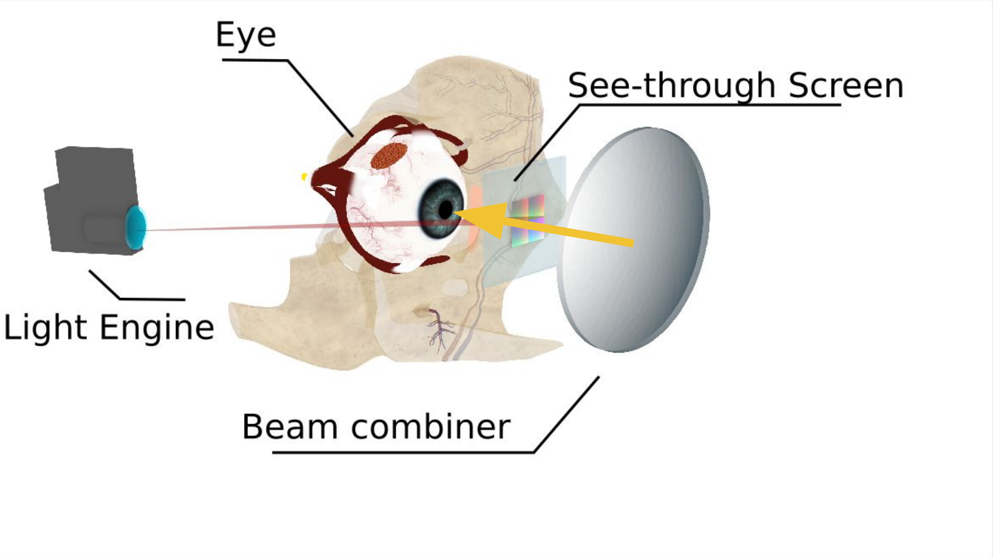
[S. R. Bharadwaj and C. M. Schor. Vision Research, (2005), F. Campbell and G. Westheimer. J. Physiol., (1960), G. Heron, W. Charman, and C. Schor. Vision Research, (2001), P. S., D. Shirachi, and S. L. American Journal of Optometry & Archives of American Academy of Optometry, (1972)]

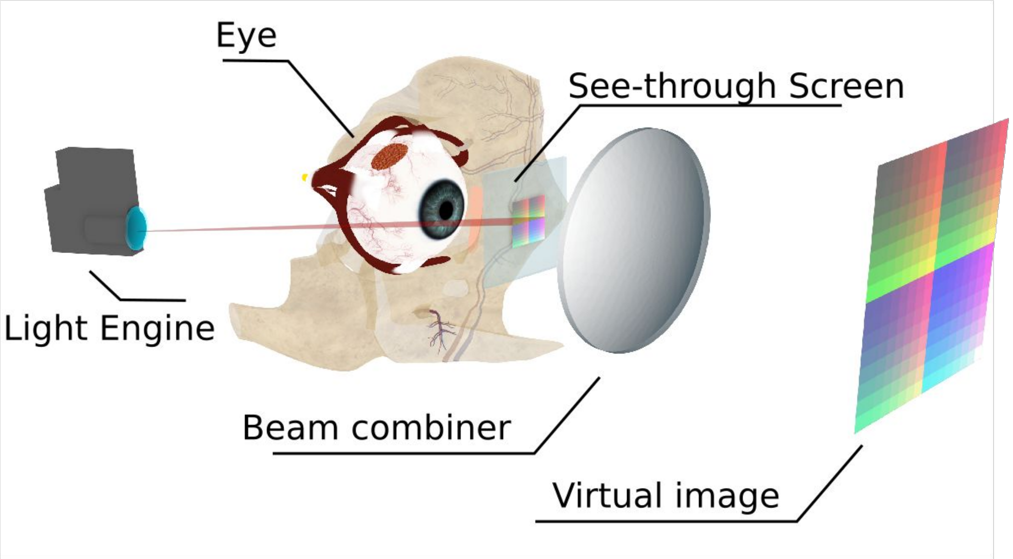

Eye
See-through Screen
Light Engine
Beam combiner
Virtual image

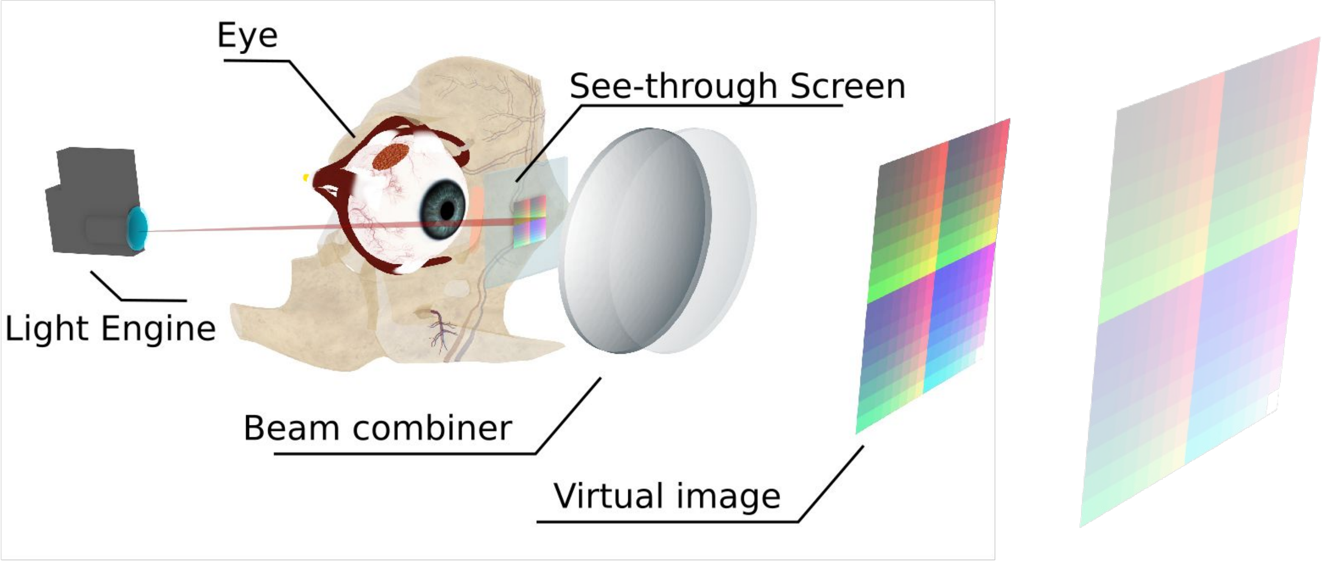

Eye
Light Engine

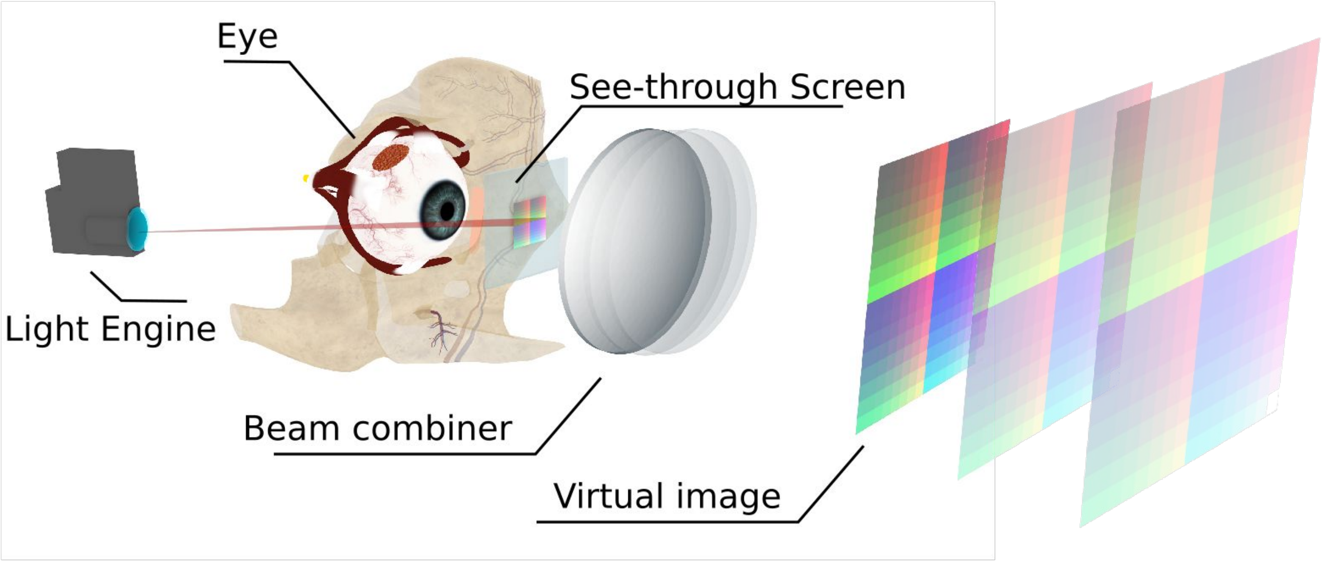

Eye
See-through Screen
Light Engine


Eye
See-through Screen
Light Engine


Eye
See-through Screen
Light Engine
Beam combiner


Eye
See-through Screen
Light Engine
Beam combiner
Virtual image

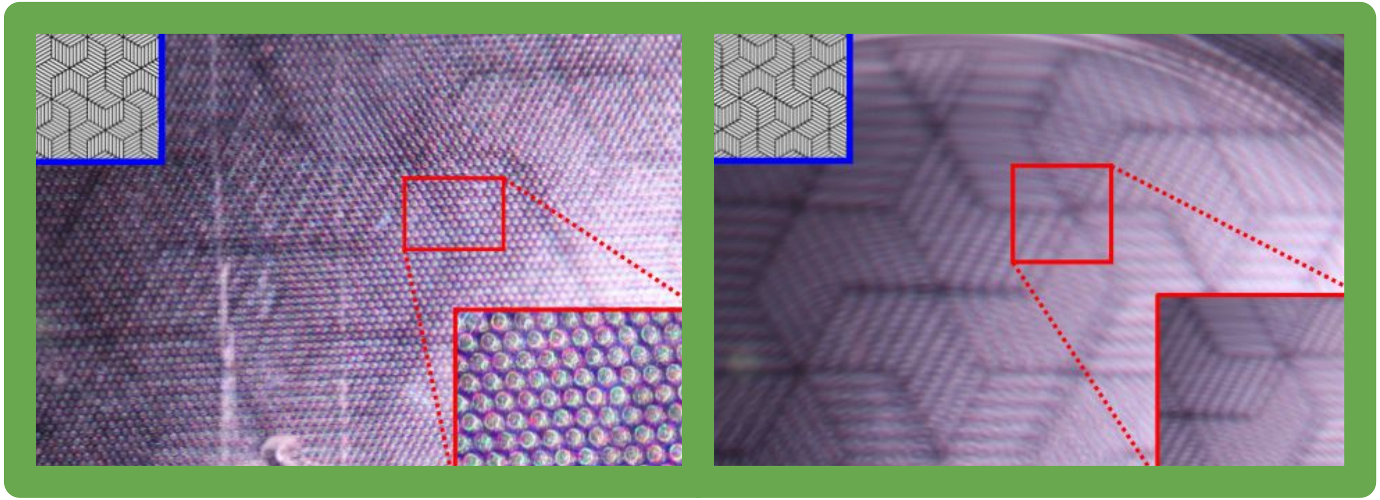

Eye
See-through Screen
Light Engine
Beam combiner
Virtual image


Eye
See-through Screen
Light Engine
Beam combiner
Virtual image

How to build it?

See-through Screens

Rotating diffusers



Cheap and dirty!

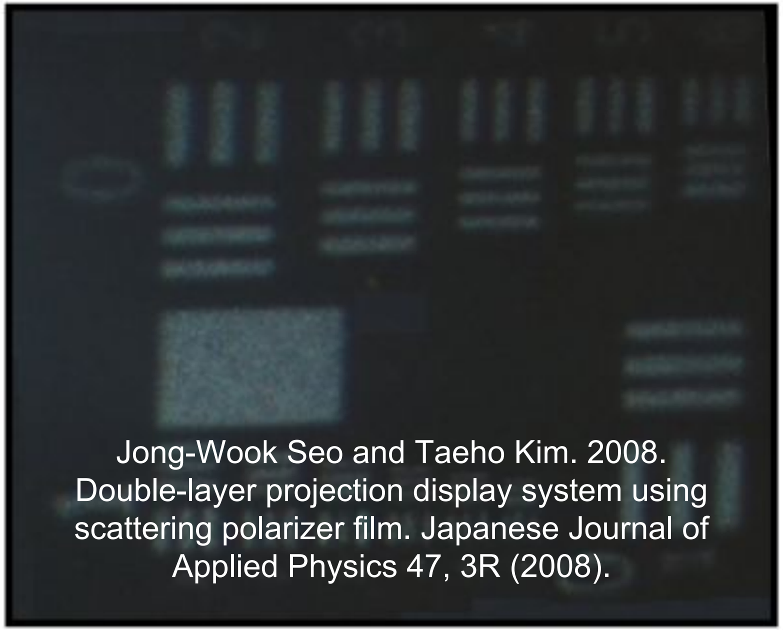
See-through Screens

Rotating diffusers

Polarization
Selective Diffusers

Polarization Selective Diffuser

Limited screen size!



See-through Screens

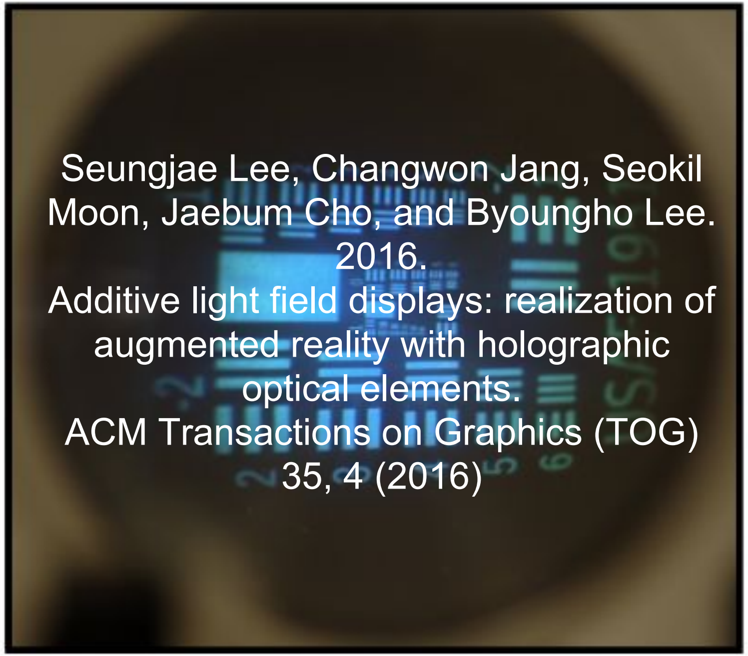
Rotating diffusers

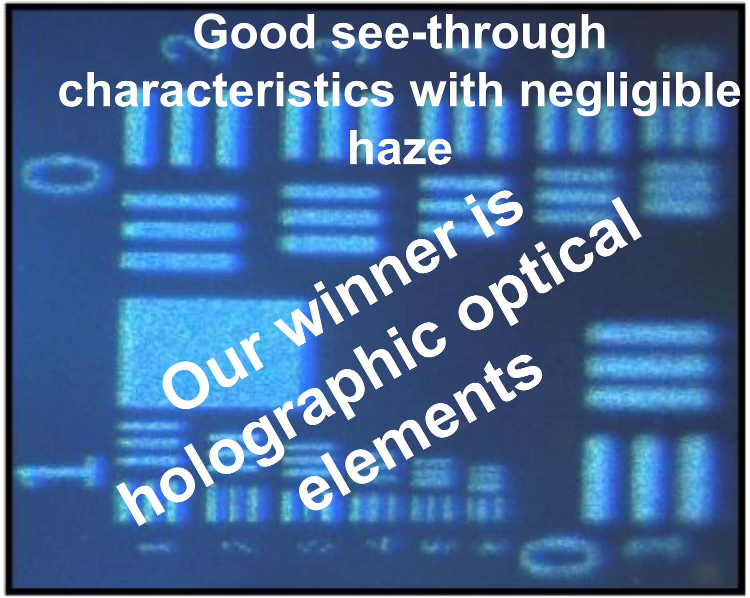
Polarization Selective Diffusers

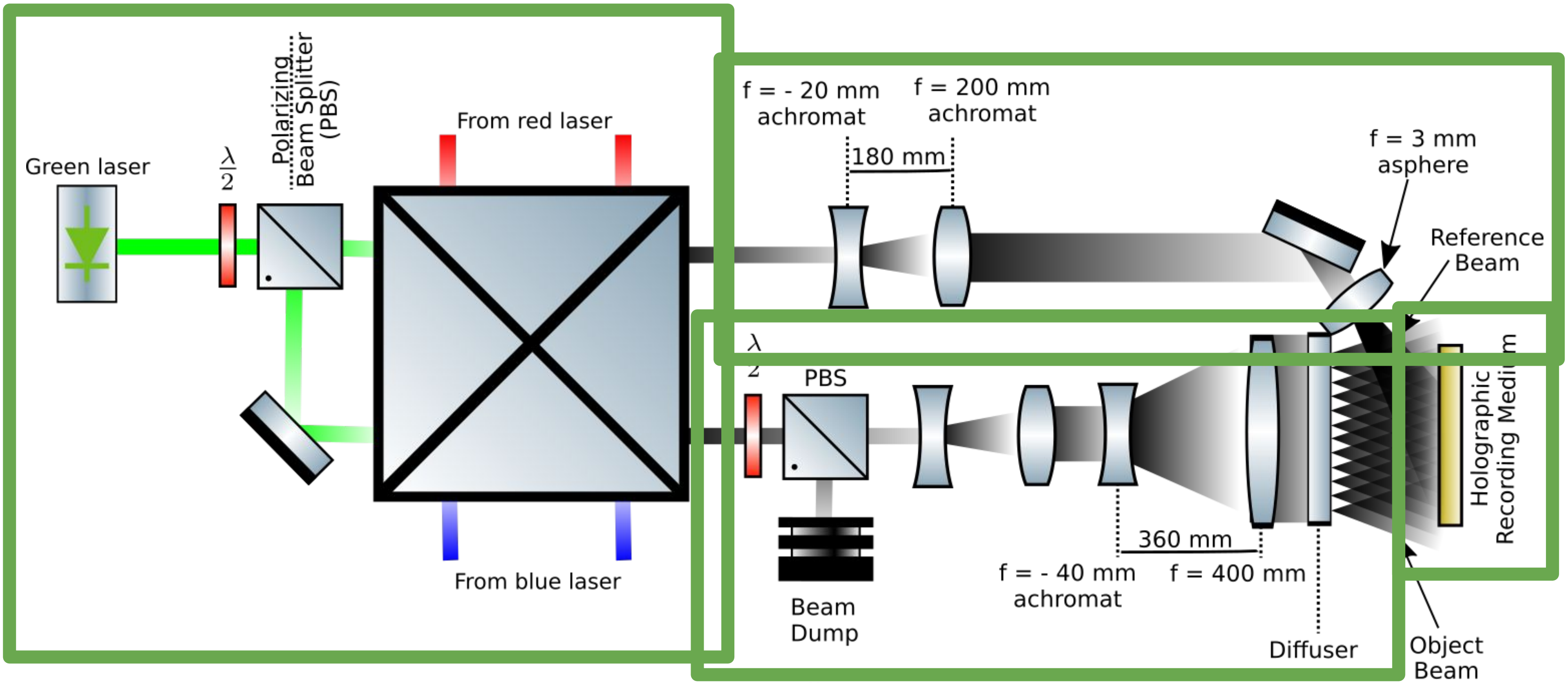
Holographic Optical Elements

In-house made

Holographic Optical Element

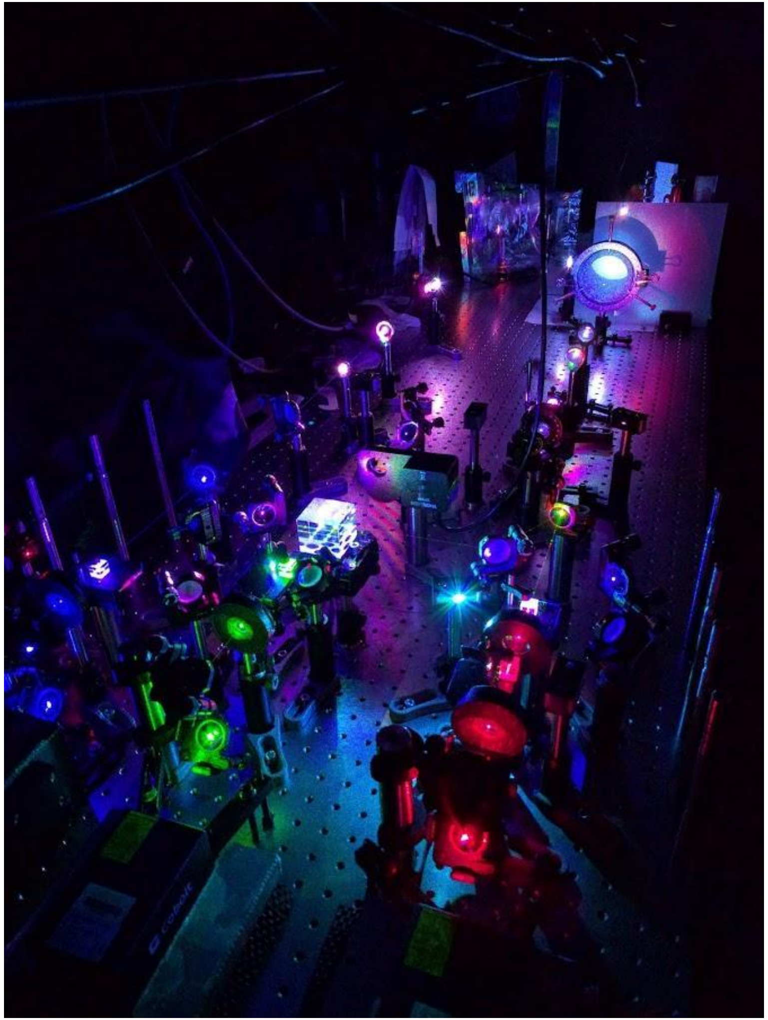






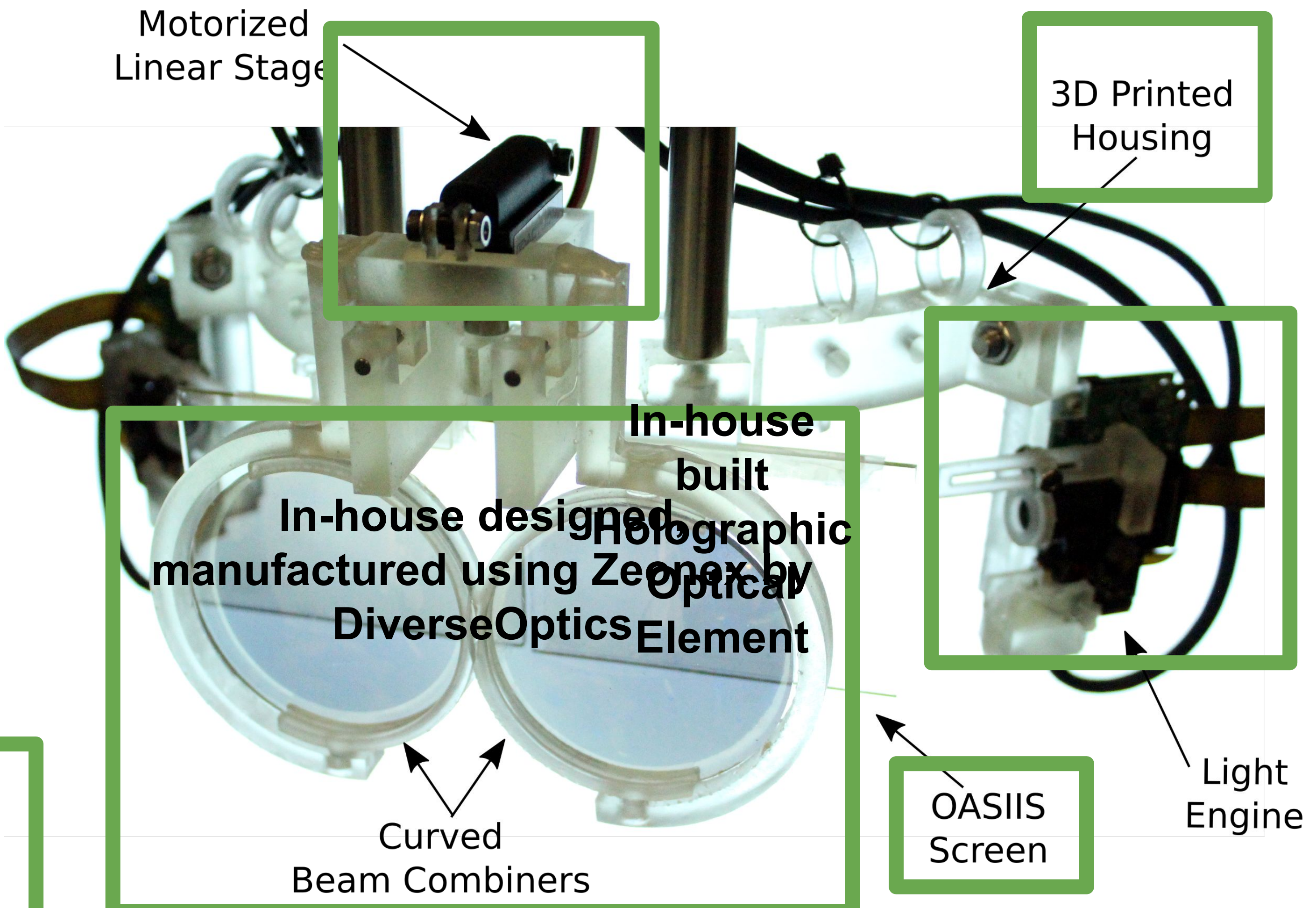
Recording Process

Note that this is an one time recording process, see-through screen are recorded to display dynamic content.



In-house analog holography setup

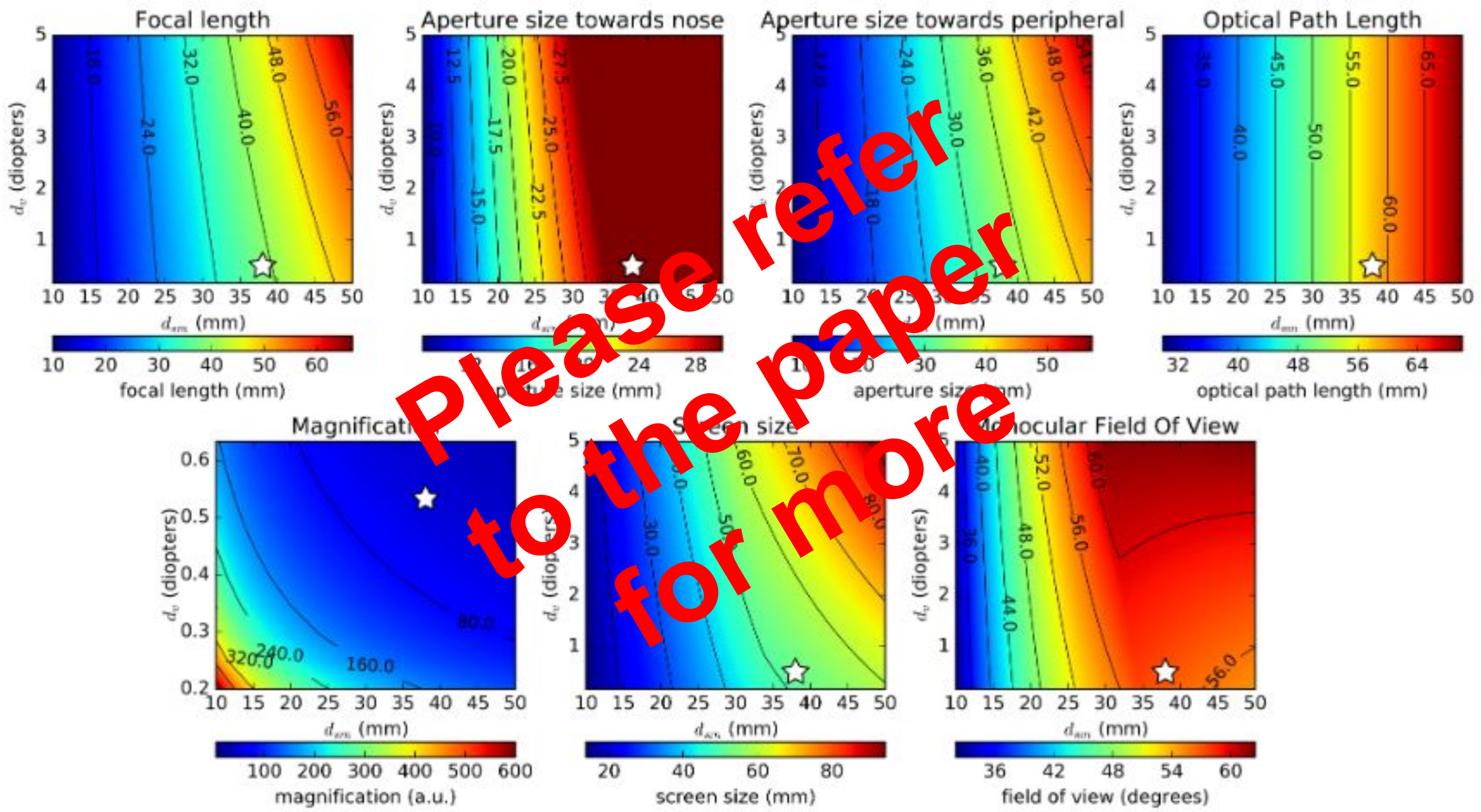
- Coherence length larger than 15 m, and 660-532-460 nm wavelengths for red, green, blue
- 120 grit ground glass diffuser from Edmund Optics
- Holographic recording medium from LitiHolo (16 um)



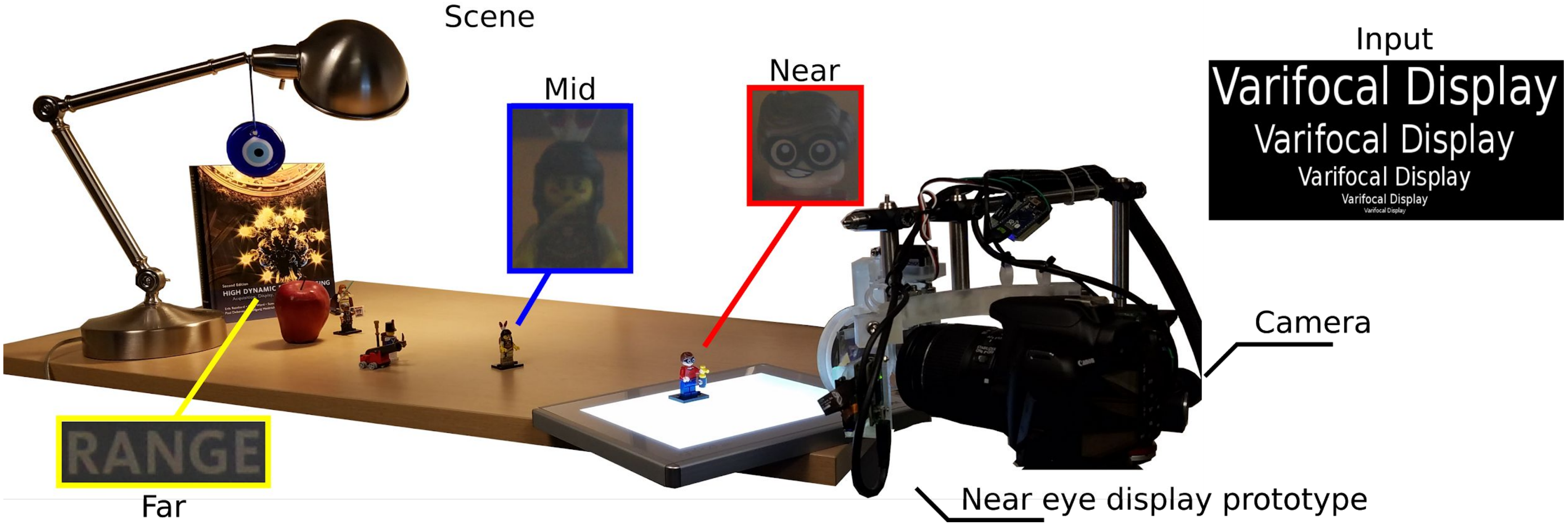
720p, 60 Hz, Liquid Crystal On Silicon (LCoS) from Imagine Optix

In-house OpenGL Based Renderer

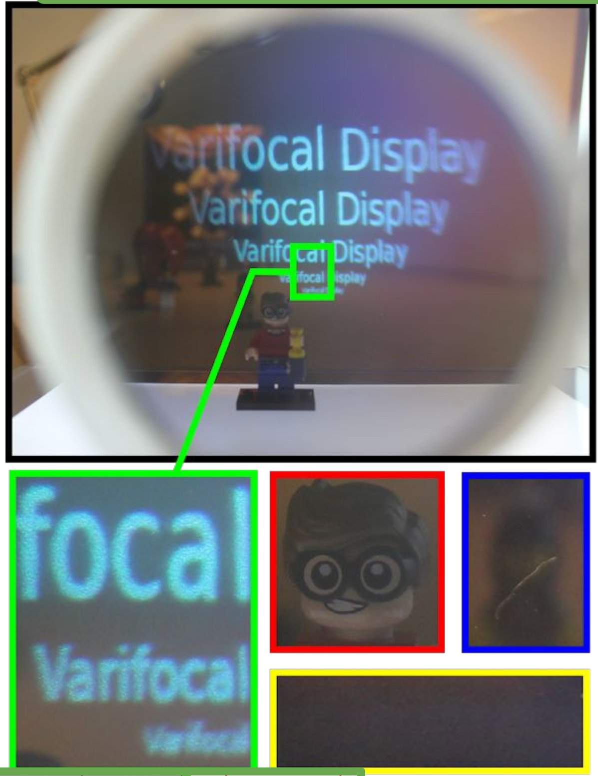
Wearable Varifocal Prototype

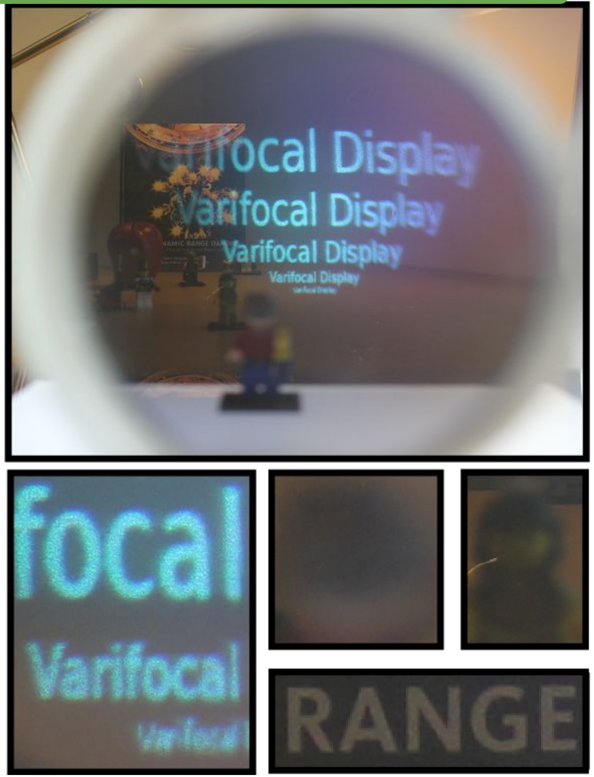

Focal length
focal length (mm)
Aperture size towards nose
Aperture size towards peripheral
Optical Path Length
optical path length (mm)
Magnification
magnification (a.u.)
Screen size
screen size (mm)
Monocular Field Of View
field of view (degrees)
Please refer to the paper for more

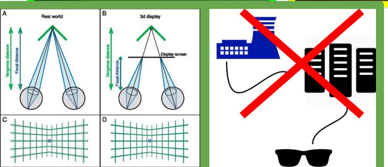
Results


Scene
Mid
Near
RANGE
Far
Input
Varifocal Display
Varifocal Display
Varifocal Display
Varifocal Display
Camera
Near eye display prototype

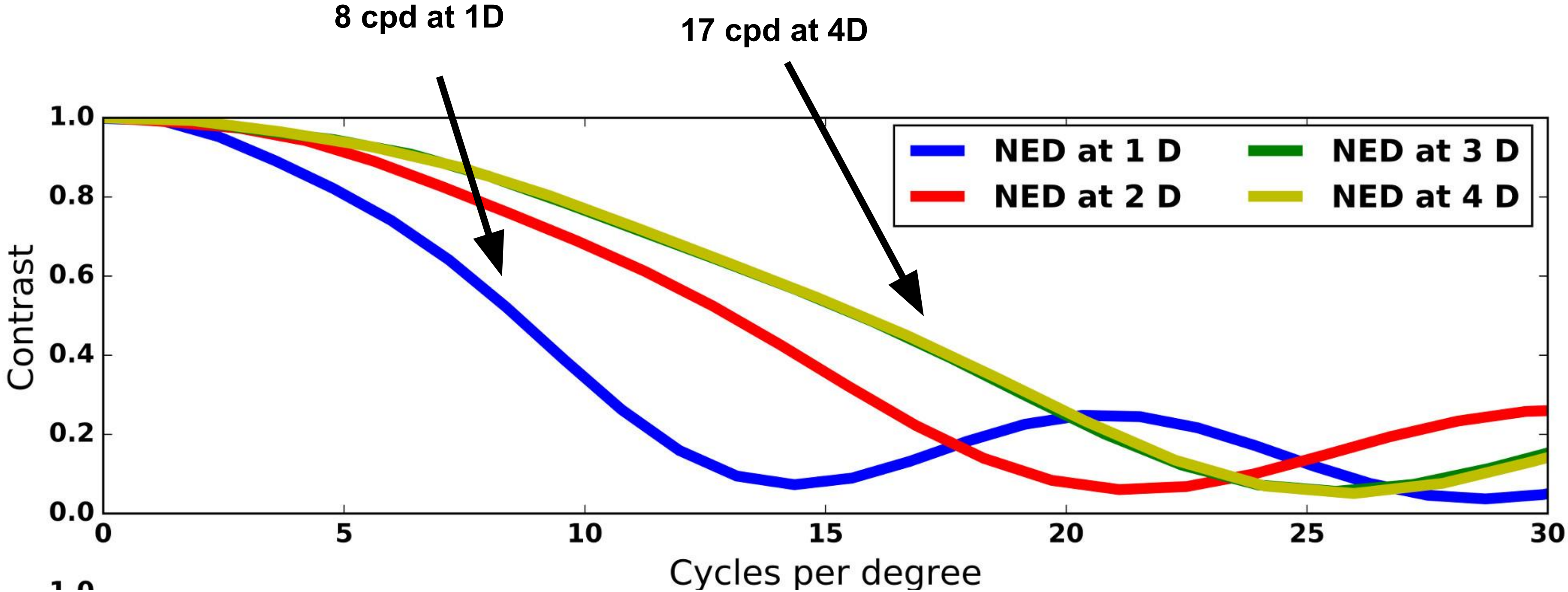
Near	**Mid**	**Far**
25 cm	50 cm	100 cm



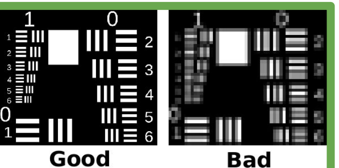


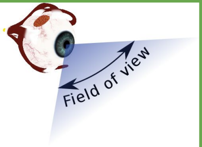


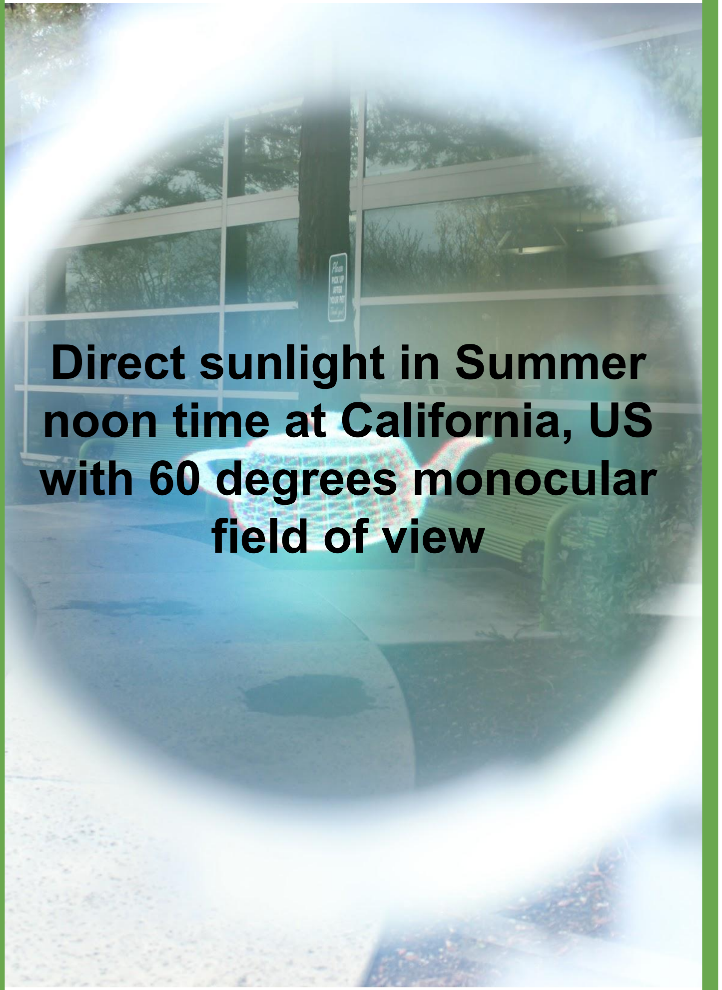
25 cm to infinity (6 m) with maximum 410 ms latency

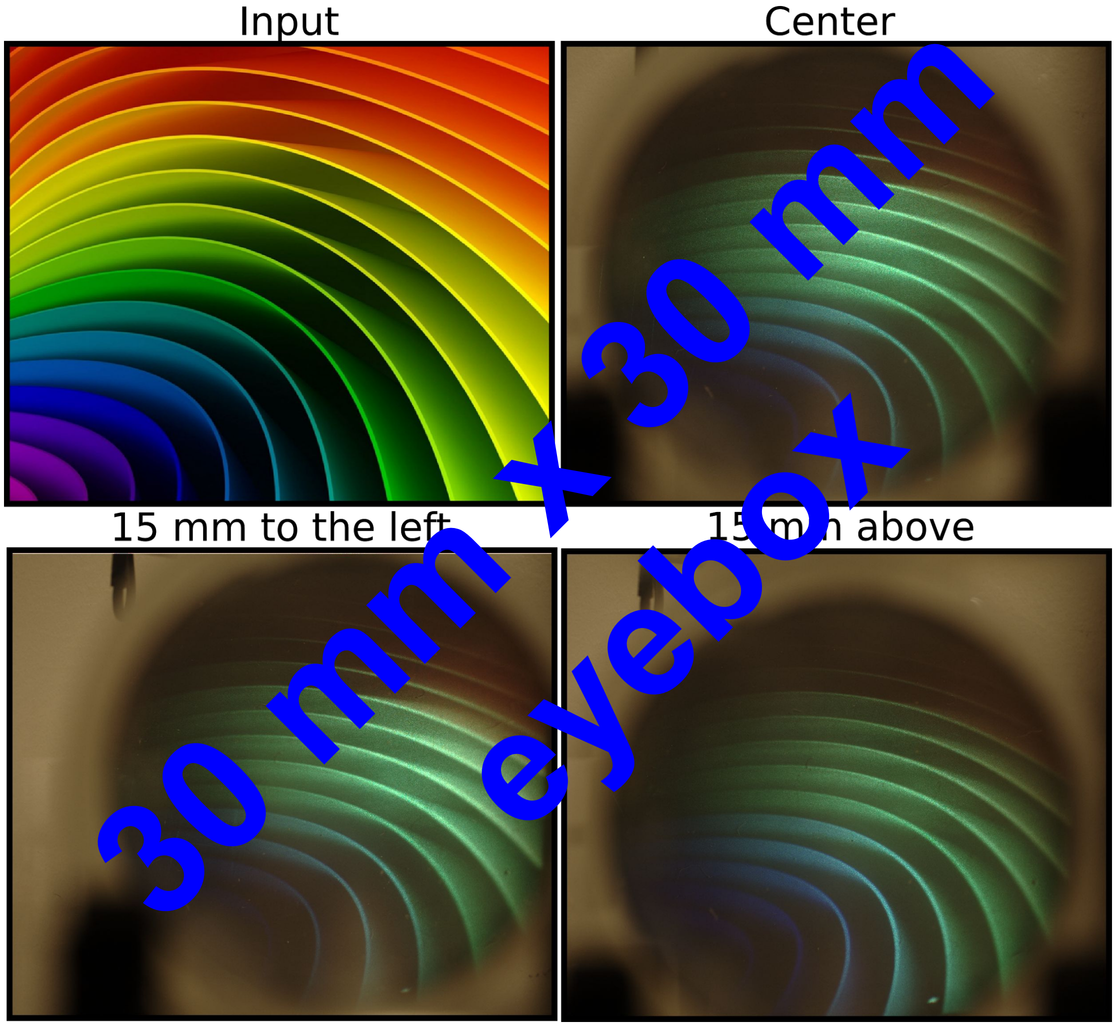


Peter D Burns. 2000. Slanted-edge MTF for digital camera and scanner analysis. Conference of Society for imaging science and technology, 135–138

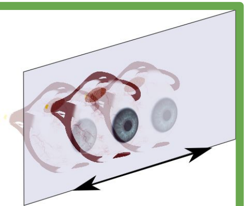


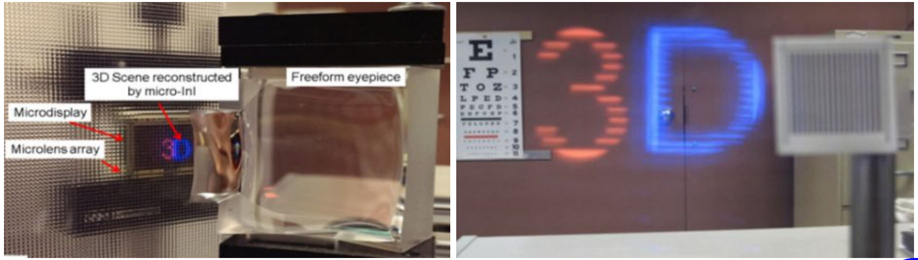

Field of view


Direct sunlight in Summer
noon time at California, US
with 60 degrees monocular
field of view

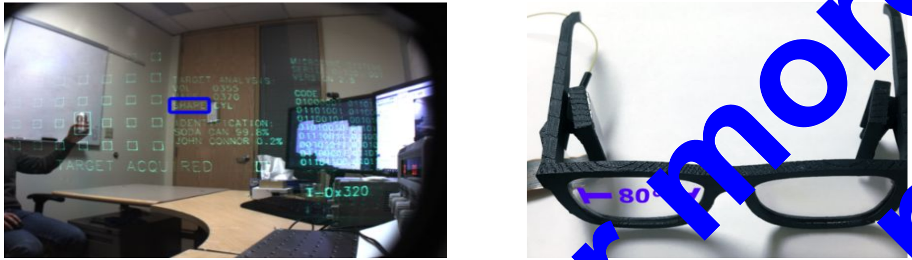


Input
Center
15 mm to the left
15 mm above
30 mm x 30 mm eyebox

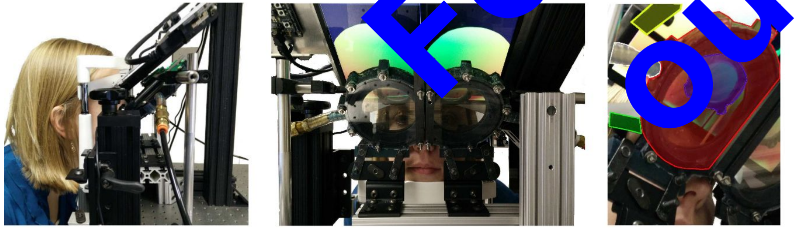




Hong Hua and Bahram Javidi. 2014. A 3D integral imaging optical see-through head-mounted display. Optics express 22, 11 (2014).



Andrew Maimone, Andreas Georgiou, and Joel Kollin. 2017. Holographic Near-Eye Displays for Virtual and Augmented Reality. ACM Transactions on Graphics 36 (2017).



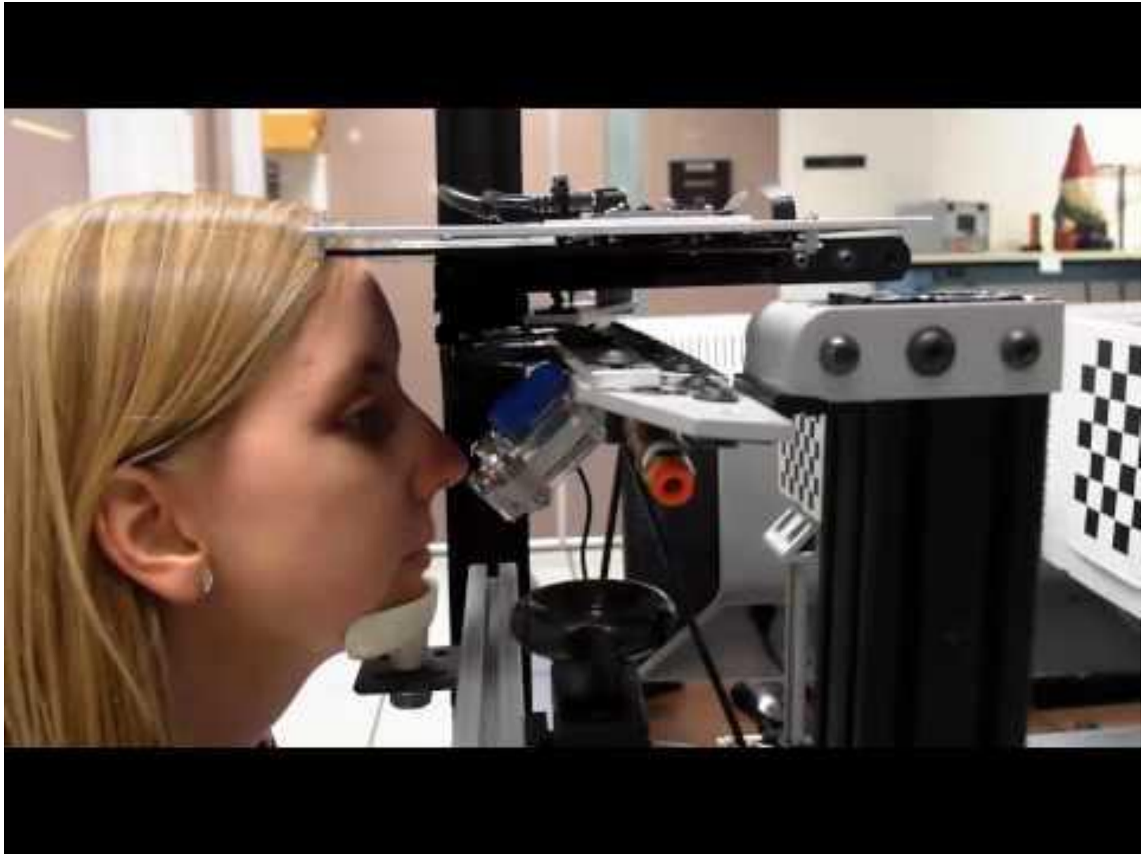
Side view Front view Bottom view

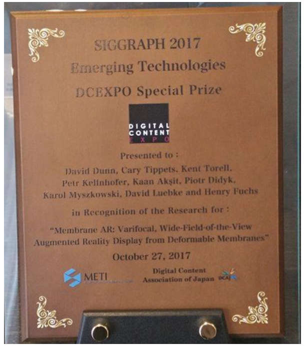
Dunn, David, et al. "Wide Field Of View Varifocal Near-Eye Display Using See-Through Deformable Membrane Mirrors." *IEEE Transactions on Visualization and Computer Graphics* 23.4 (2017): 1322-1331.

Lightfield AR No mechanically moving part or active lens, no need for a gaze tracker	Varifocal AR Less compute demand, larger eyebox, better resolution, and much wider field of view
Holography AR No mechanically moving part or active parts, better form-factor	Varifocal AR Much less compute demand, much larger eyebox,
Varifocal AR Much faster focus change	Varifocal AR Much better form factor, much larger eyebox

For more see our paper

Varifocal display proposal II



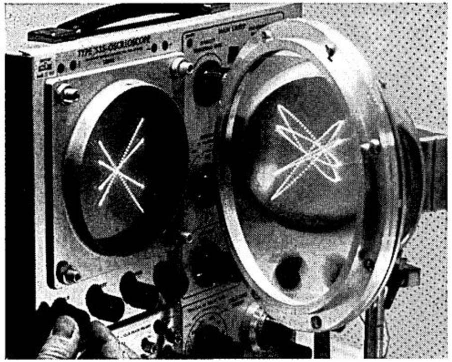


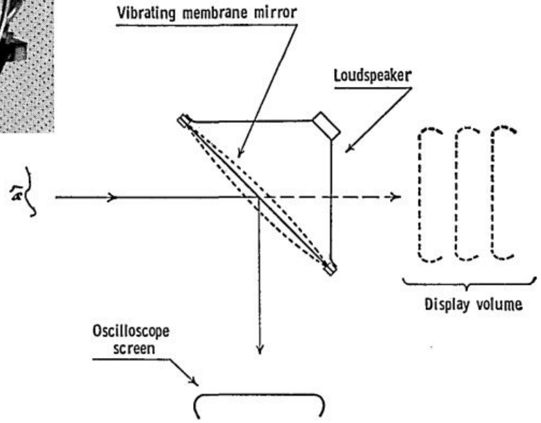
SIGGRAPH 2017
DCEXPO SPECIAL
PRIZE!

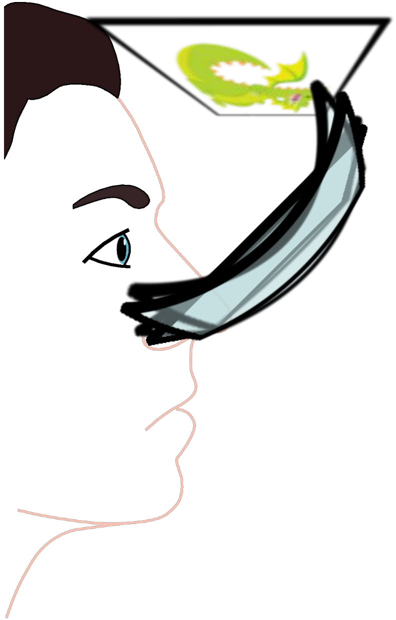
David Dunn, Cary Tippets, Kent Torell, Petr Kellnhofer, Kaan Akşit, Piotr Didyk, Karol Myszkowski, David Luebke, and Henry Fuchs. "Wide Field Of View Varifocal Near-Eye Display Using See-Through Deformable Membrane Mirrors." *IEEE Transactions on Visualization and Computer Graphics* 23, no. 4 (2017)

VOLUMETRIC DISPLAYS

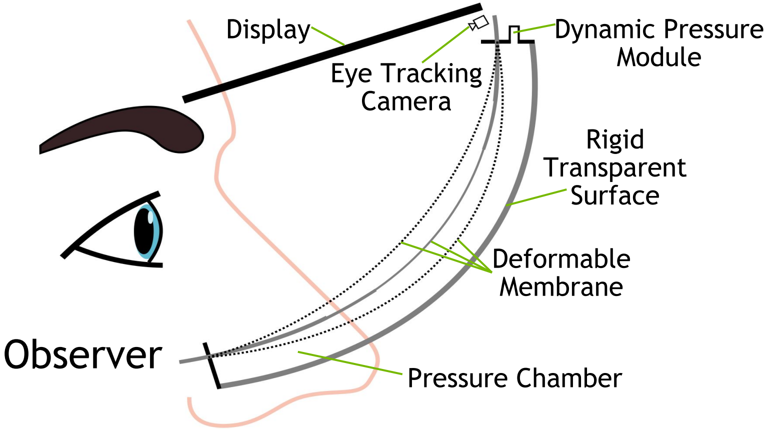
- Vibrating membrane mirror
- Refresh dictated by speed of display/depth resolution
- Defined volumetric range
- Small diagonal FOV
- Not see-through







- Dynamic focal depth
- Wide field of view
- Single element optics



Membrane

Dynamic Pressure System

Membrane Tracking System

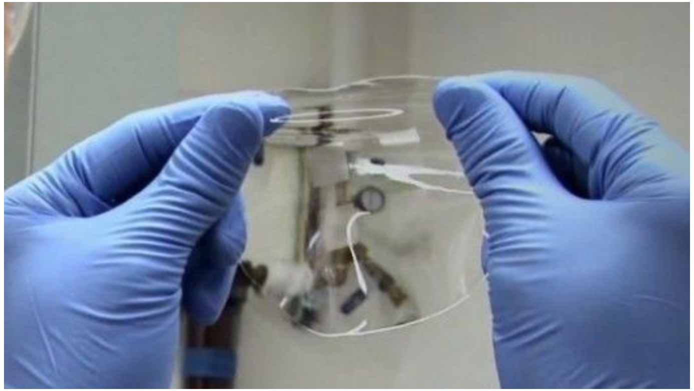
Eye Tracking System

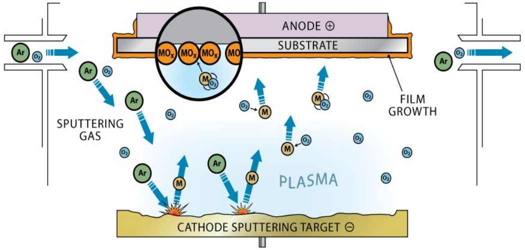
How to build it?

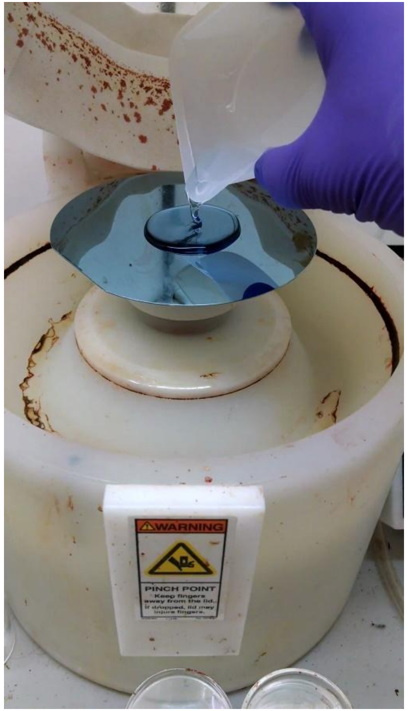
Membrane Creation: Material

Polydimethylsiloxane [PDMS]

- Silicon-based organic polymer
- Optically clear
- Viscoelastic material
- Sputter coated with silver to enhance reflection

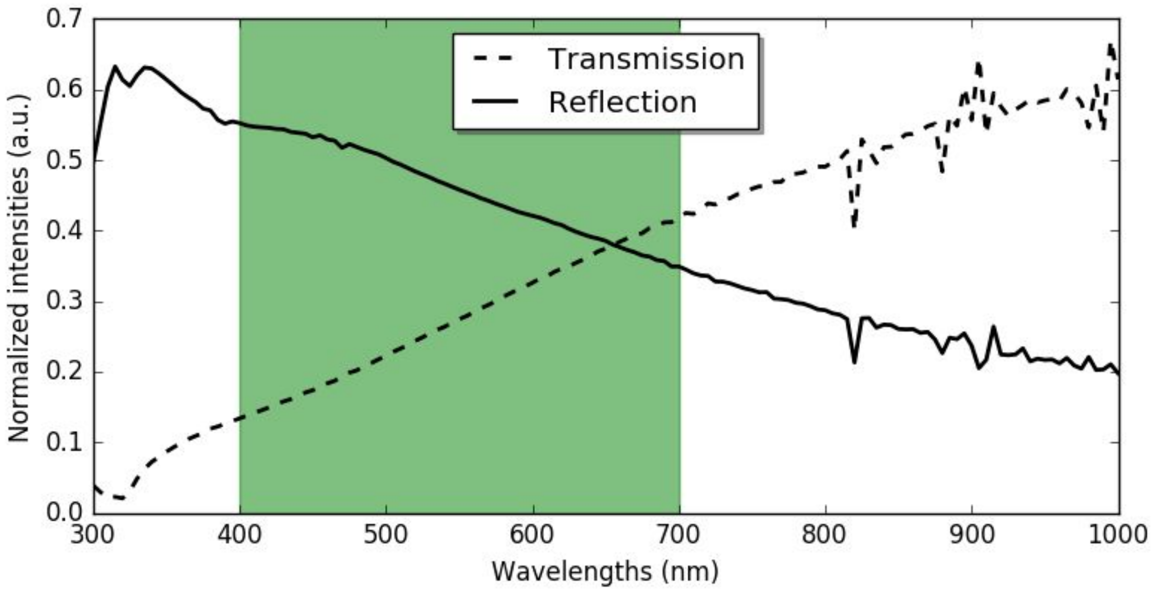




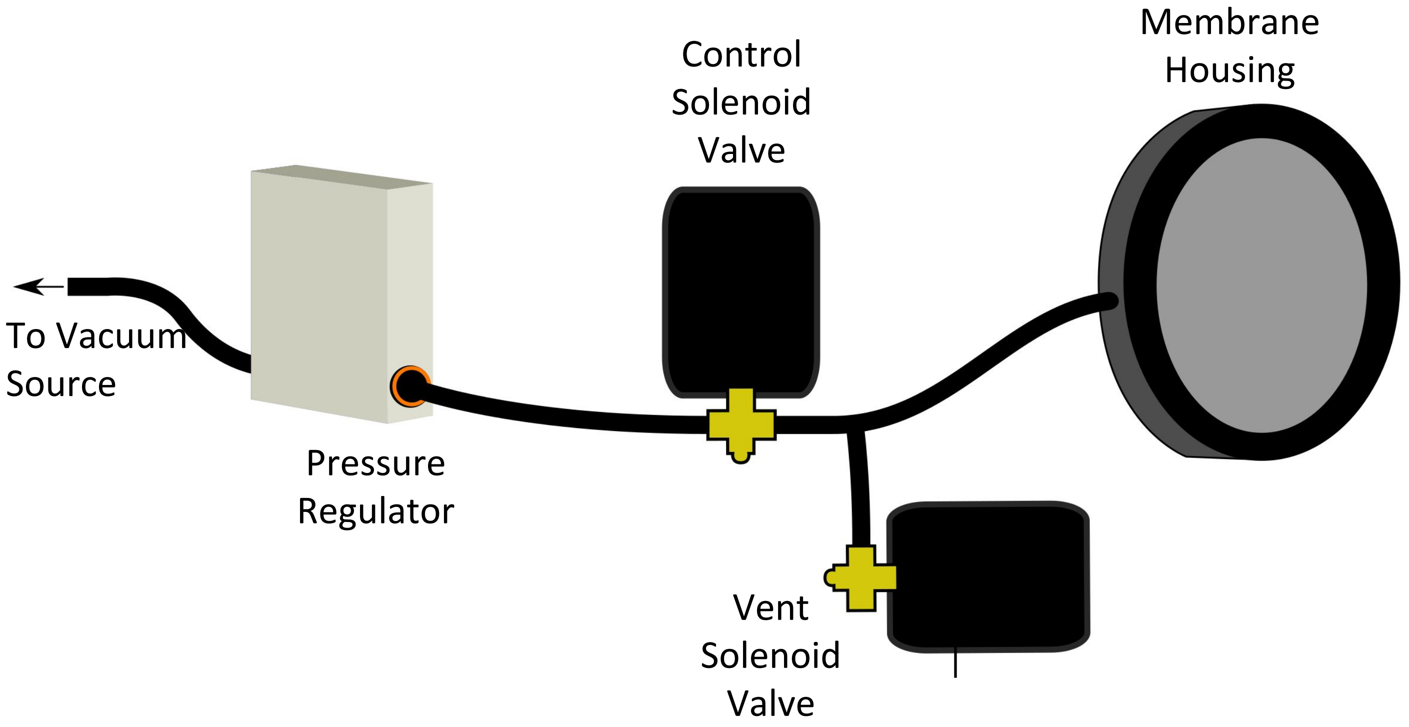


https://www.youtube.com/watch?v=5boywxr8ot4
http://clearmetalsinc.com/technology/

Reflection is Wavelength Dependent



Vacuum System

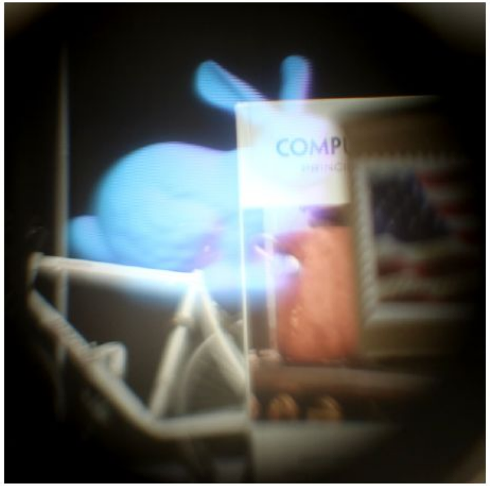


ISMAR
Munich, Germany
October 16-20

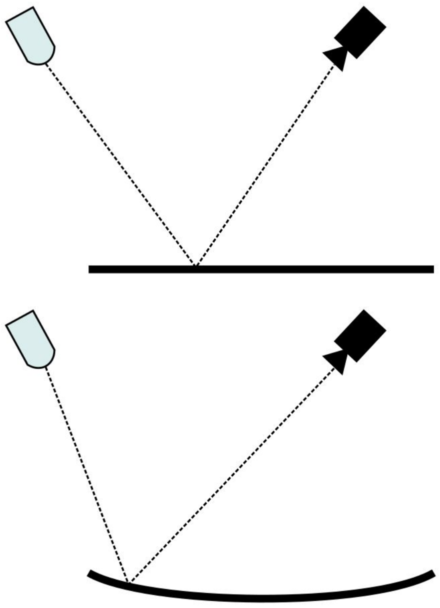
ISMAR BEST PAPER AWARD!

FocusAR: Auto-focus Augmented Reality Eyeglasses for both Real World and Virtual Imagery

Praneeth Chakravarthula, David Dunn, Kaan Akşit* and Henry Fuchs
UNC Chapel Hill *NVIDIA Research



LED Camera System



Feedback to know the shape of the membrane

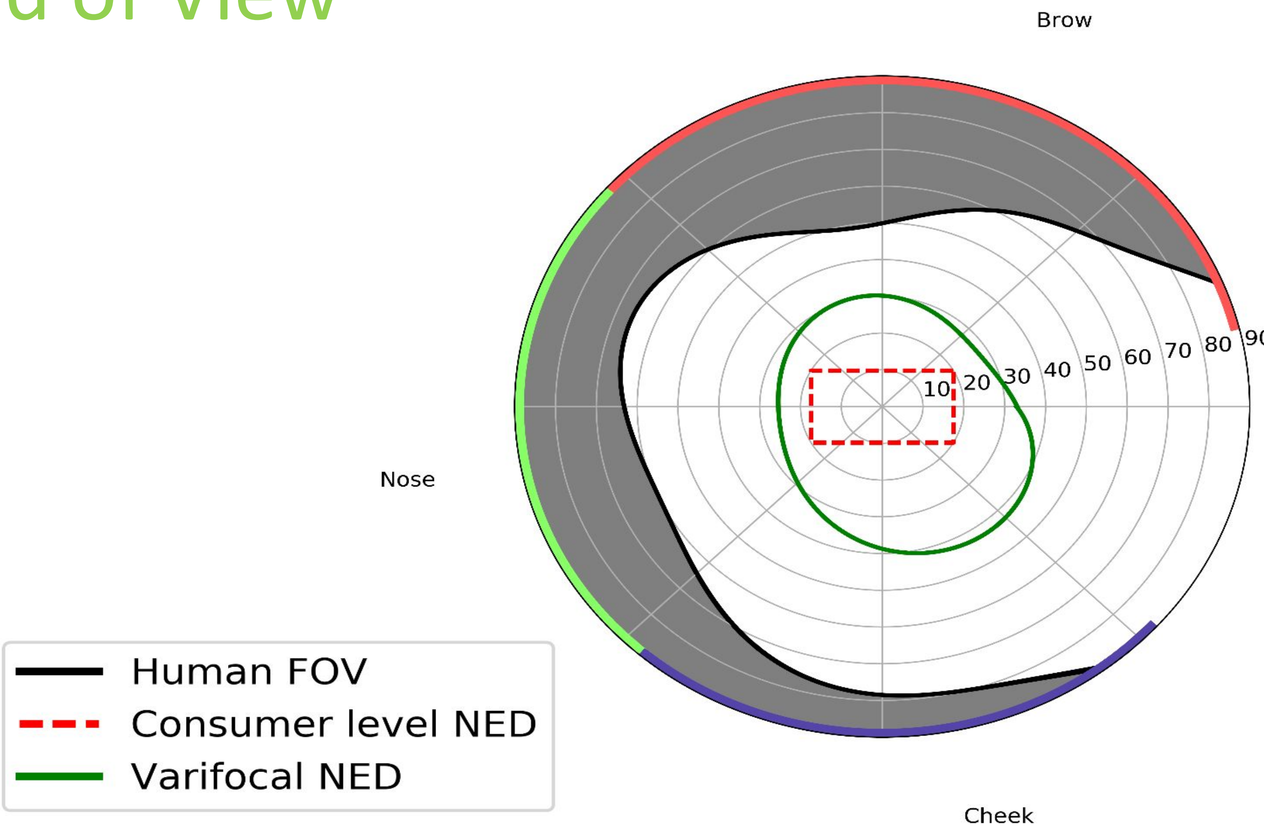
As the membrane deforms the LED’s reflection moves

Blob detection is used to locate and track the motion

Uses infrared light to not distract the user

Results

Field of View



Monocular FOV:

75° diagonal

55° horizontal

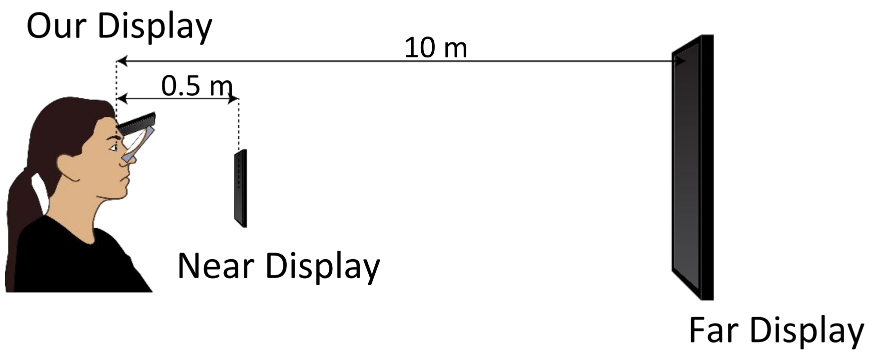
65° vertical

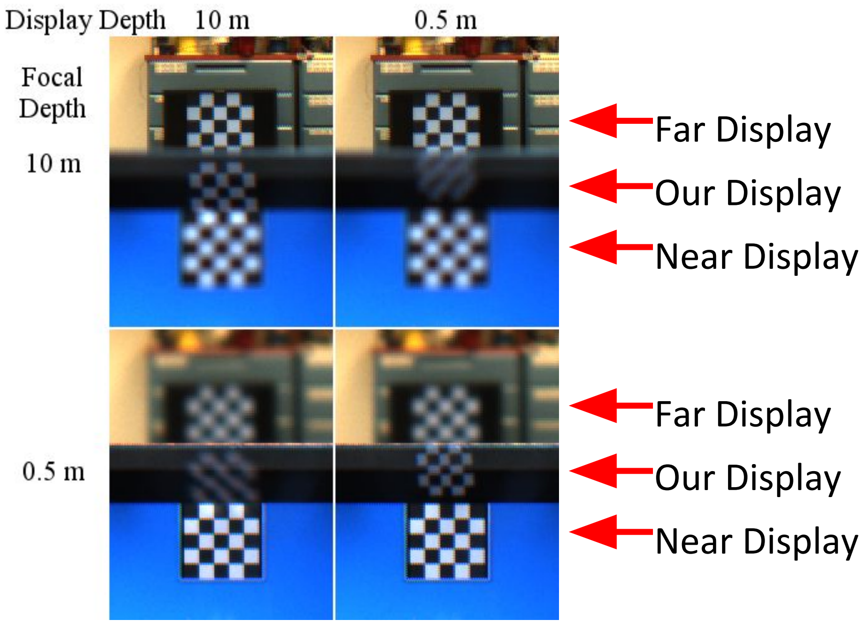
Focal Depth

7 diopter range (15cm - infinity)

Under 300ms from far to near

Under 300ms from near to far





Focus Consistency

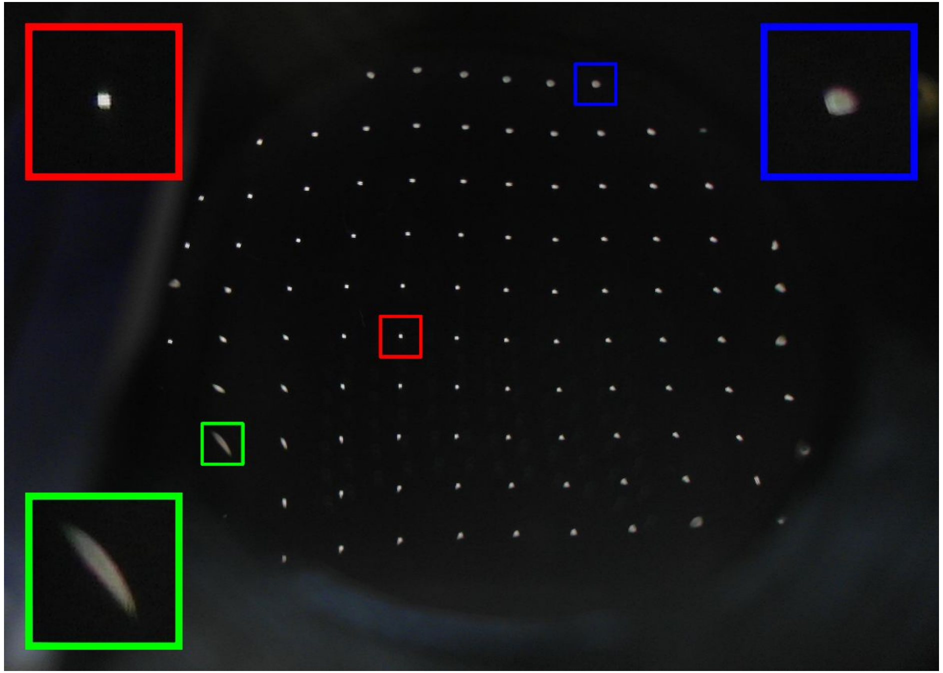
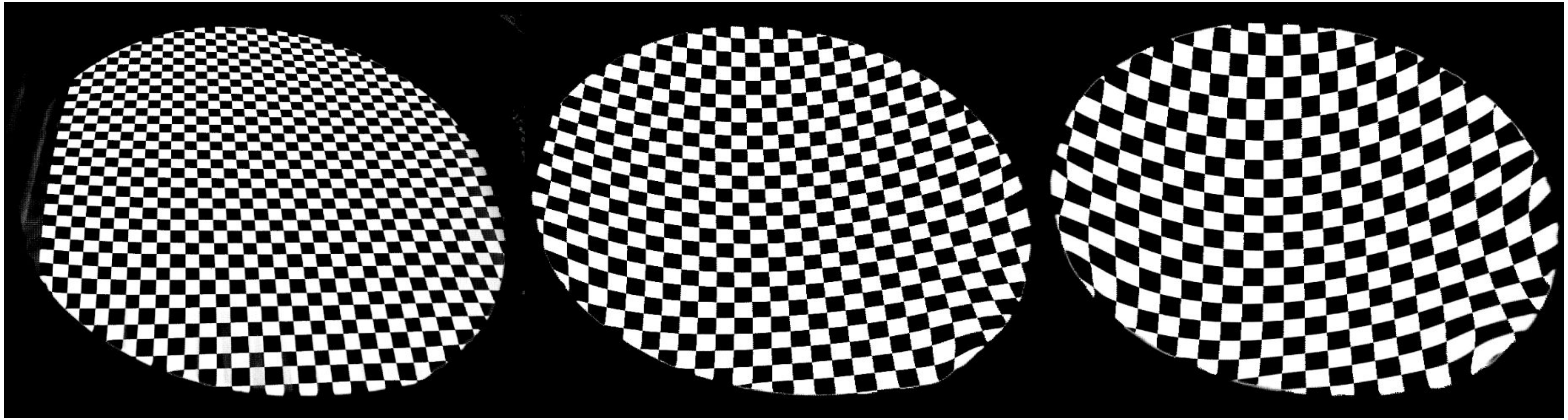
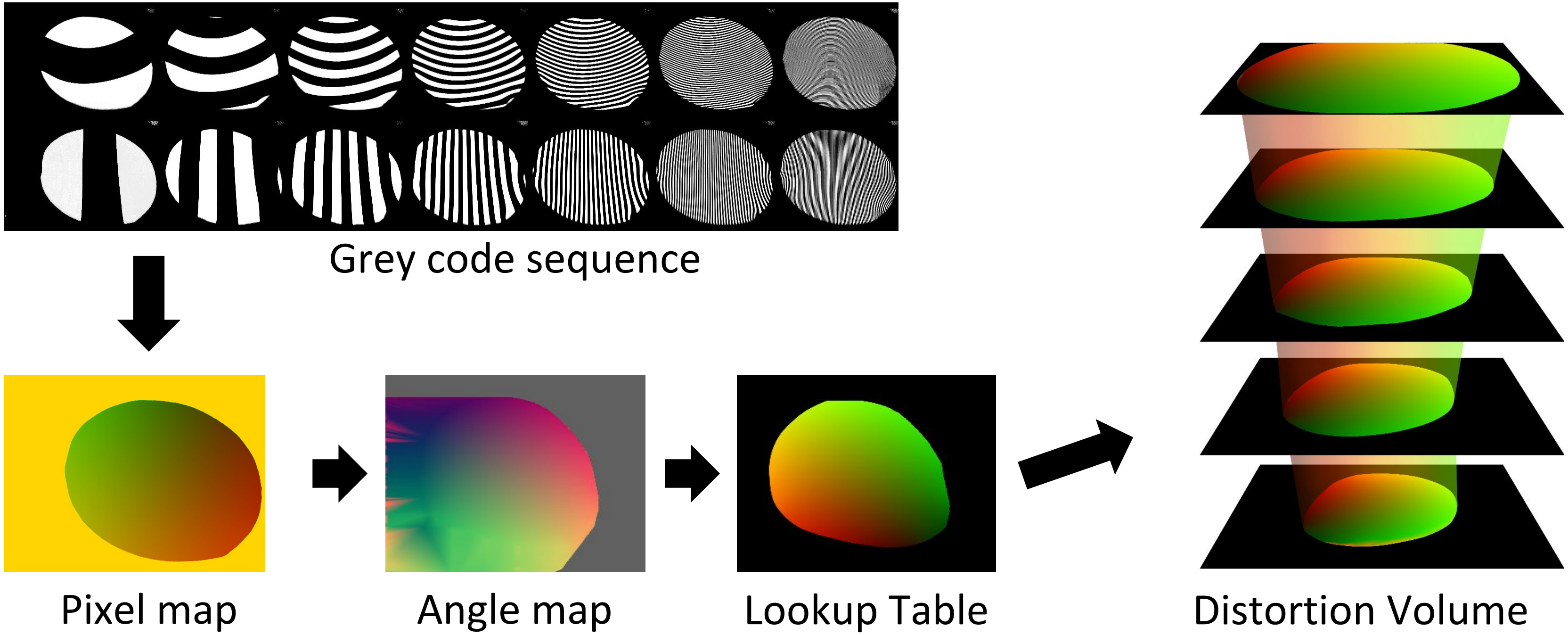


Image Distortion

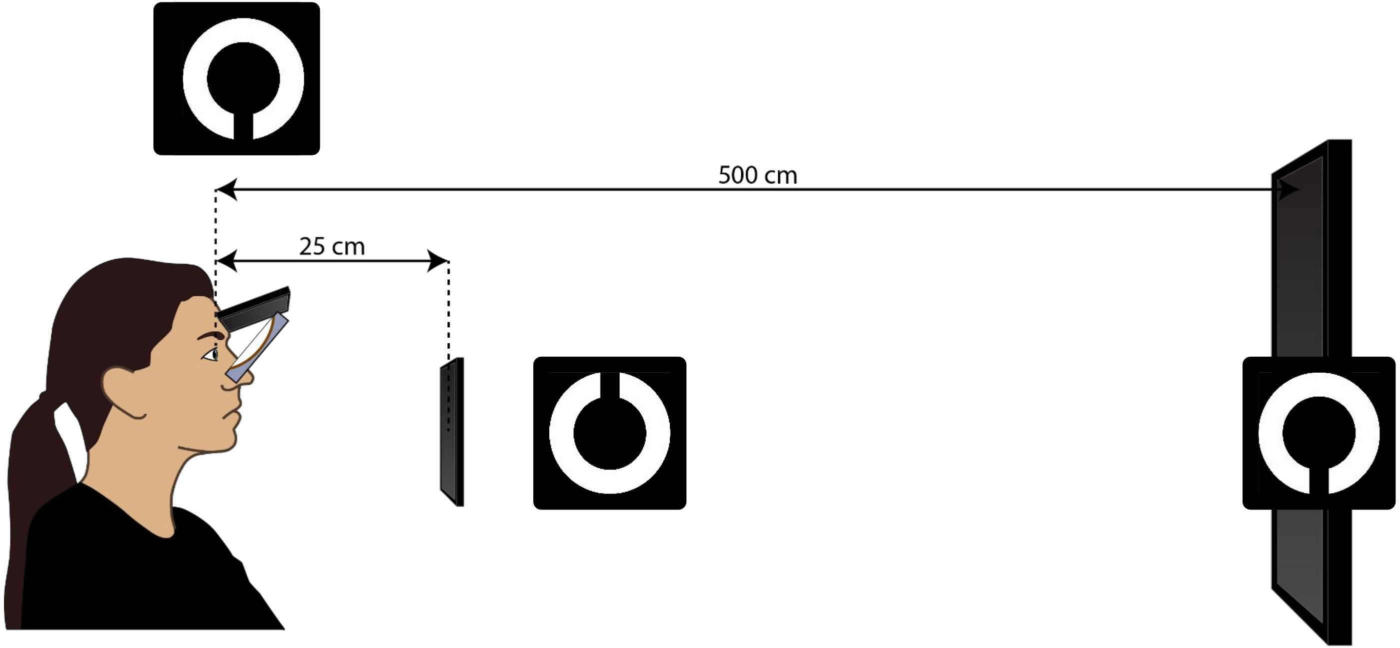


Near Mid Far

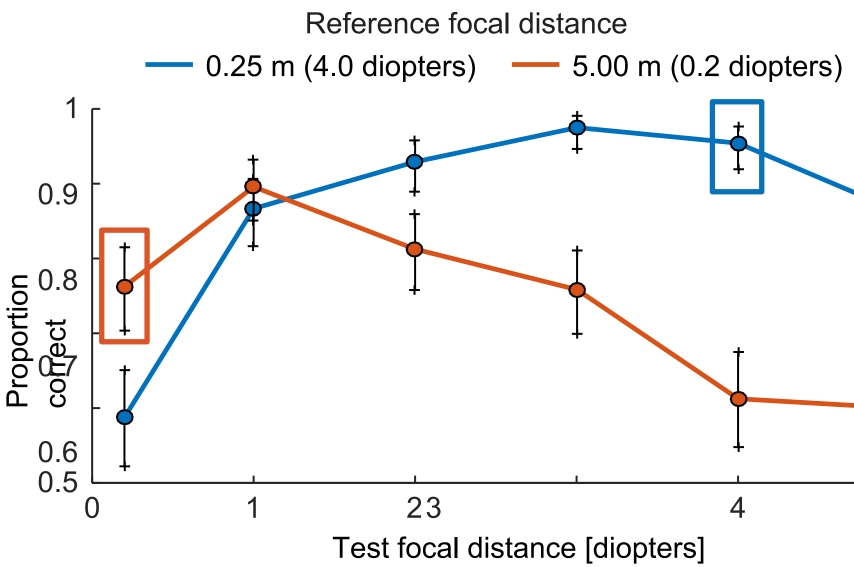
Distortion Correction



Perceptual Experiment



Perceptual Experiment



3D printed optics

Formlabs 2

Price: 4999 USD

Formmech 508DT

Price: 7413 USD

Norland
Optical Adhesive

Price: 30 USD

Clear Acrylic

Price: 10 USD

Investment : ~15-20k USD + you + short processing times (1 day)

---> Good for fast prototyping <---

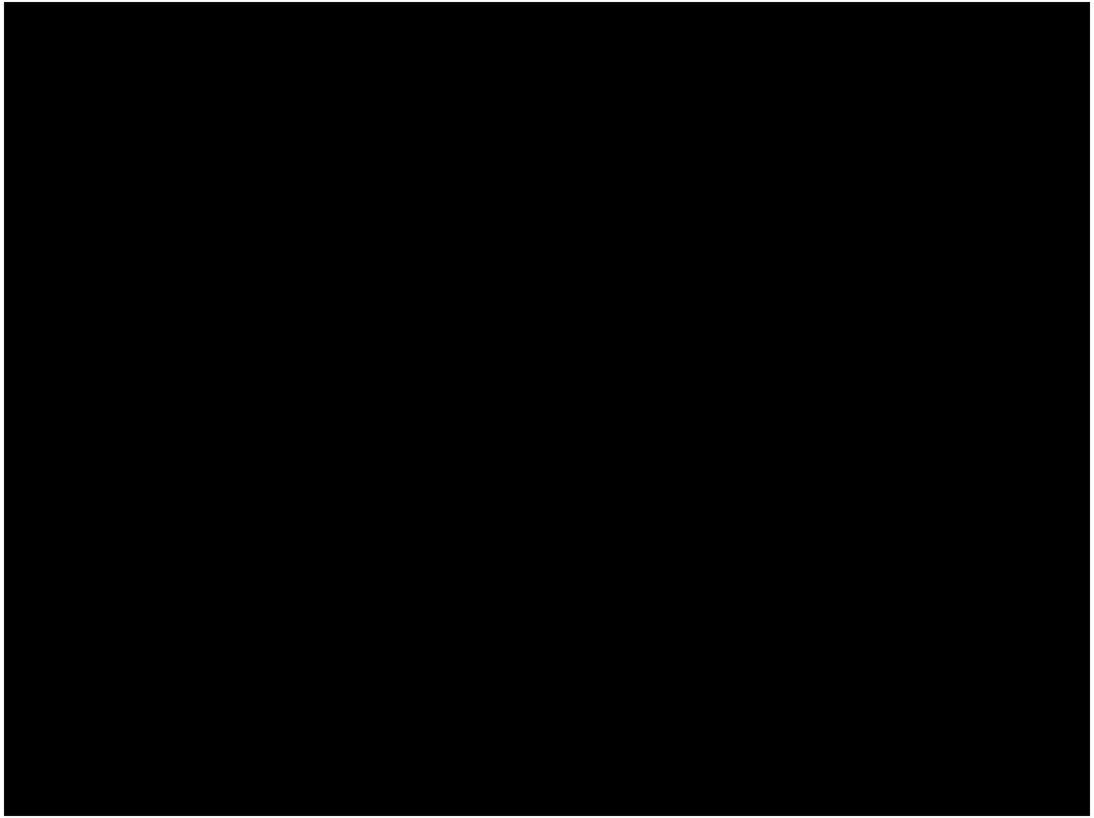
BA2M

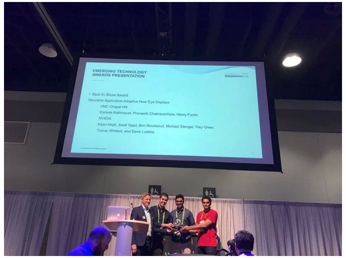
Manufacturing Application-Driv
Near-Eye Displays
NVIDIA.
Manufacturing freeform optical components is a slow, expensive, and labor-intensive task that restricts computation
optical designers to only existing components which may be sub-optimal, and limits their ability to iterate and explore new
typical required investment
in the orders of 1-5 Million USD
trained personnel is required, labor
intesive task, and slow
Optical adhesive
Cost: < 200 USD
A series of photographs showing optical components built using our manufacturing technique based on 3D printing, optical bonding, and vacuum forming
Two photographs showing a view of a mobile phone display magnified by (Left) an off-the-shelf lens (Thorlabs LA1401), and (right) a clone of the same lens manufactured using our technique, to provide a visual comparison of optical quality
choose the optically challenging scenario of near-eye displays to evaluate both our manufacturing
and our computational methodology for calculating interchangeable freeform surfaces for a given
display optical layout. We design and manufacture a completely untethered near-eye display prototype.

Lens Cleaning Tissue

Op
Gl ed
ba
Le

Printed Near-Eye Displays





SIGGRAPH 2018
BEST IN SHOW
AWARD!

Kaan Akşit, Praneeth Chakravarthula, Kishore Rathinavel, Youngmo Jeong, Rachel Albert, Henry Fuchs and David Luebke. “Manufacturing Application-Driven Foveated Near-eye Displays”, Conditionally Accepted to IEEEVR 2019.

What is next?

“The Last Slide”

New layouts based on novel see-through screens enables on-axis/off-axis paths: better resolution, field of view and eyebox!

New manufacturing techniques for faster iterations!

More resolutions, more field of view, slimmer form factor?

Merging with others?

Prime time proof for varifocal?

DEMO SESSION AT THE END OF THE COURSE!

Thank you for listening

Nvidia Research
http://research.nvidia.com

Kaan Akşit,
kaksit@nvidia.com
https://kaanaksit.com