Challenges for Next-Generation 3D Displays

Yasuhiro Takaki

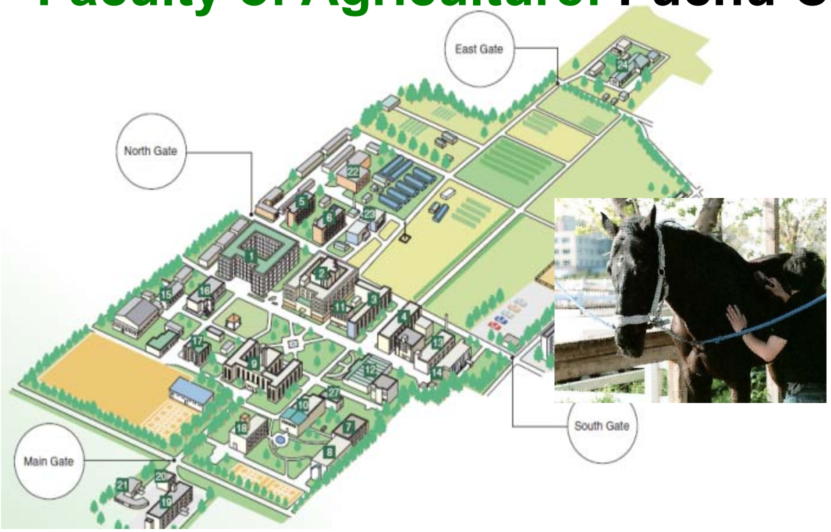
Institute of Engineering
Tokyo University of Agriculture and Technology

TUAT

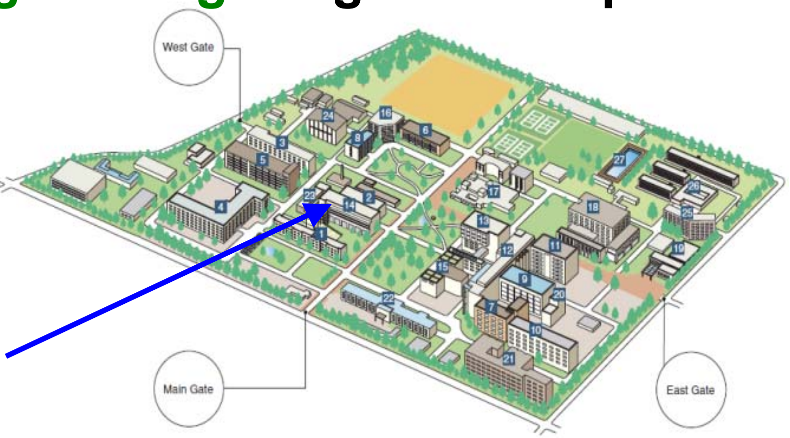
Tokyo University of Agriculture and Technology http://www.tuat.ac.jp

Established in 1877, National University in Japan

Faculty of Agriculture: Fuchu Campus



Faculty of Engineering: Koganei Campus



We are here !

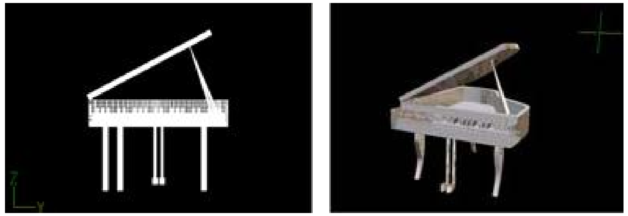
40 min. from Tokyo Station
2 hours from Narita
1.5 hours from Haneda

Undergraduates: 3,849
Postgraduates: 1,893
Faculty & Staff: 650
(2015)

Why Do We Need 3D Displays ?

1. Depth information

Structures of objects and scenes can be understood easily and precisely.



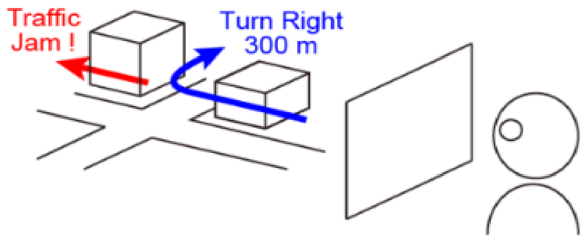
2D 3D

2. High reality & presence

We feel as if real objects existed or we were in real world.

3. Advanced man-machine interface

Digital information is provided at the same depth of real objects.



4. Object appearance reproduction

Directional light reflection on object surfaces causes gloss, transparency, softness, etc.

Effective Applications of 3D Displays

Endoscopic & robotic surgery

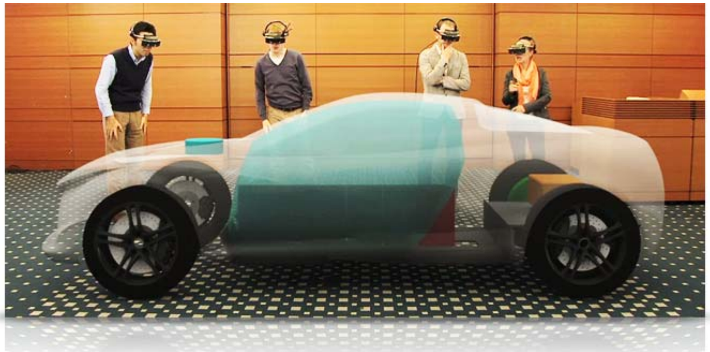
da Vinci

Robot manipulation

YANMAR

Virtual experiences

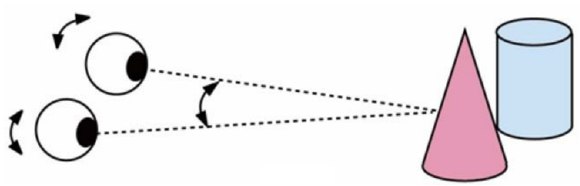
Design



CANON, MR System

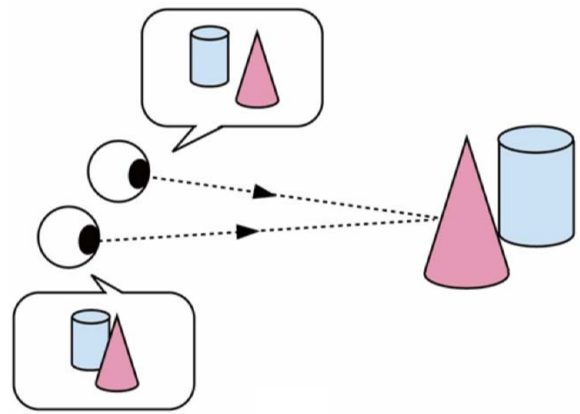
and Future TV…

3D Perception: Physiological Factors



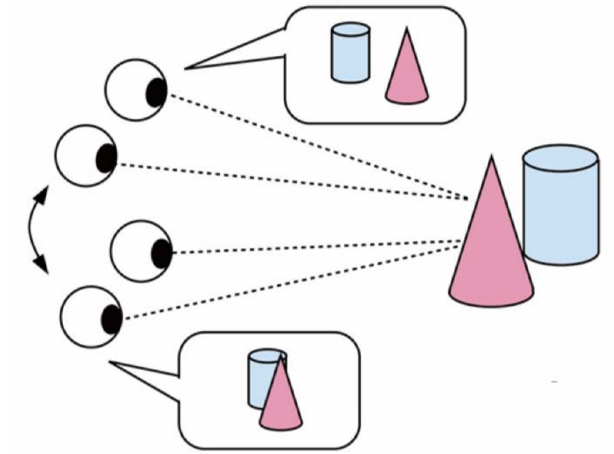
Vergence

the angle between the lines of sight when the left and the right eyes see the same point



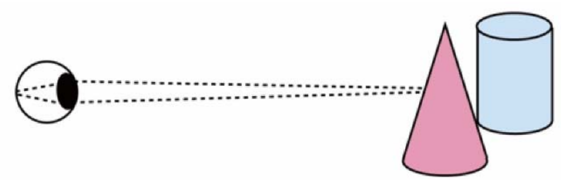
Binocular disparity

the horizontal displacement in retinal images between the left and right eyes



Motion parallax

the change in a retinal image due to the movement of eyes

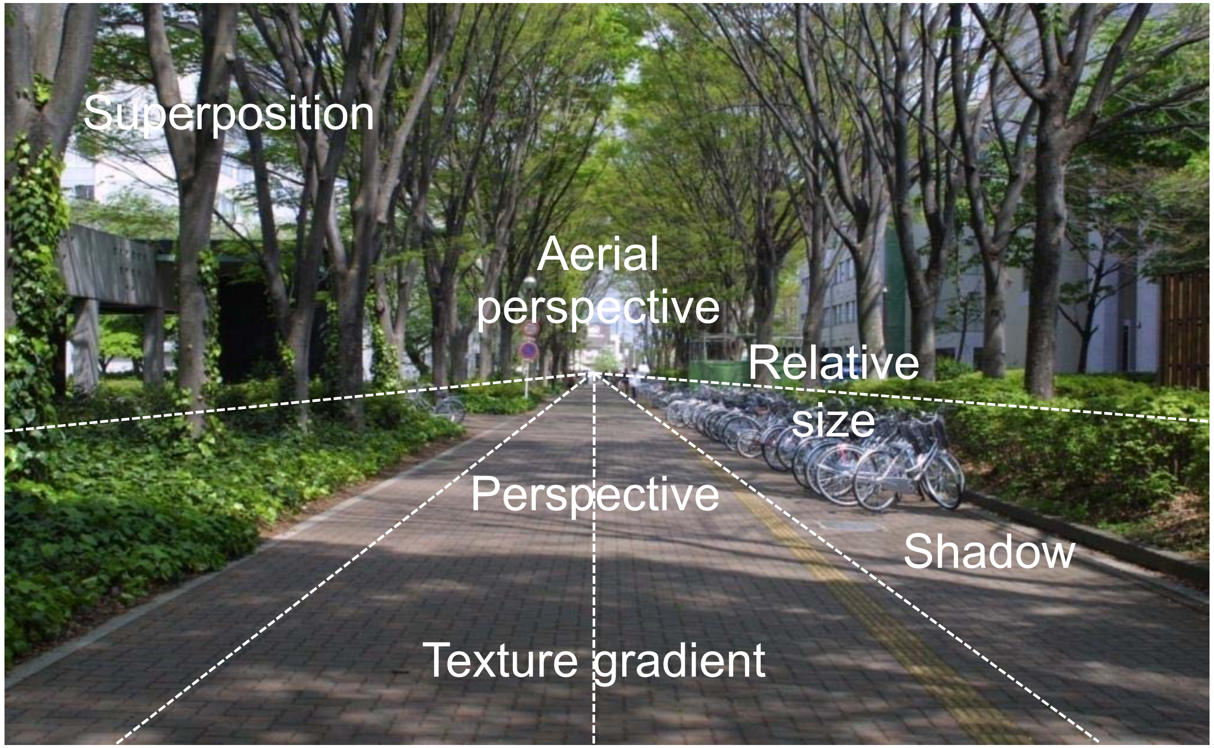


Accommodation

the change of the focal length of the lenses in the eyes when focusing on an object

Harmony among these four factors is the key to developing comfortable 3D displays.

3D Perception: Psychological Factors



Psychological factors are important in the creation of effective 3D content.

Present 3D Displays

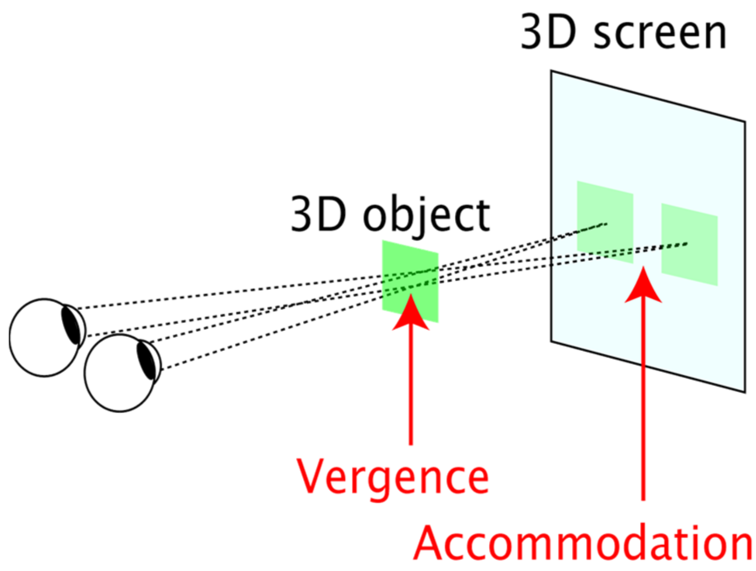
Eye-glasses based
- TV
- LC shutter glasses, polarizing glasses
- Vergence, binocular parallax

Glasses-free: two-view
- Mobile, game
- Single viewer
- Vergence, binocular parallax

Glasses-free: multi-view
- PC monitor, advertisement
- ~ 9 views, multiple viewers
- Vergence, binocular parallax, motion parallax

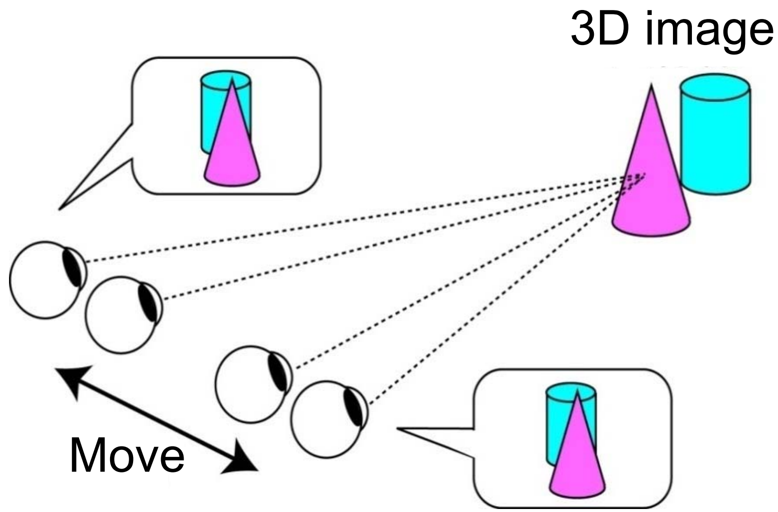
Head-mount display
- Game, VR
- Head tracking
- Vergence, binocular parallax

Problems of Present 3D Displays



Accommodation-vergence conflict

⇒ Visual fatigue



Absence or imperfection of motion parallax

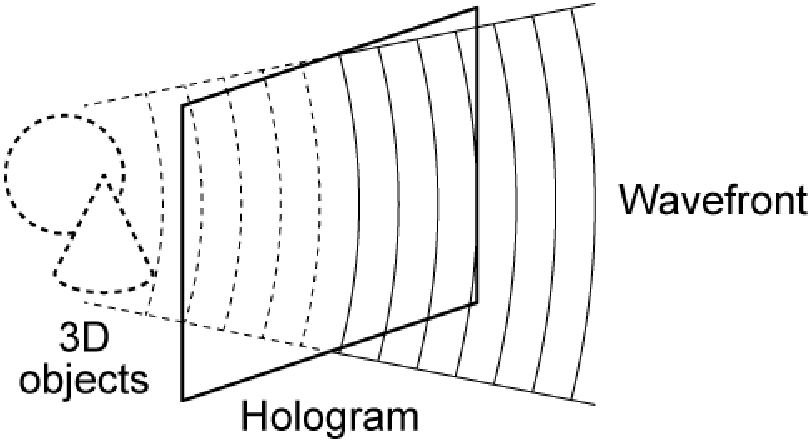
⇒ Low reality and presence

***A natural 3D display**, which is free from these two problems, needs to be developed as a next-generation 3D display.*

Classification of 3D Display Techniques

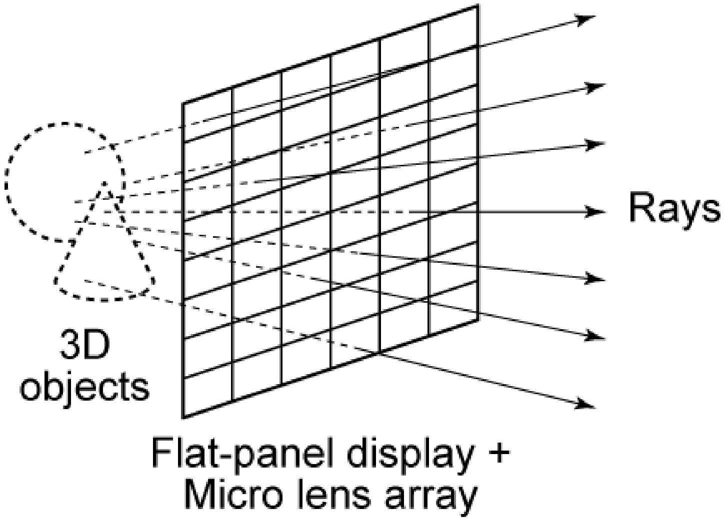
Wavefront reconstruction

Holography



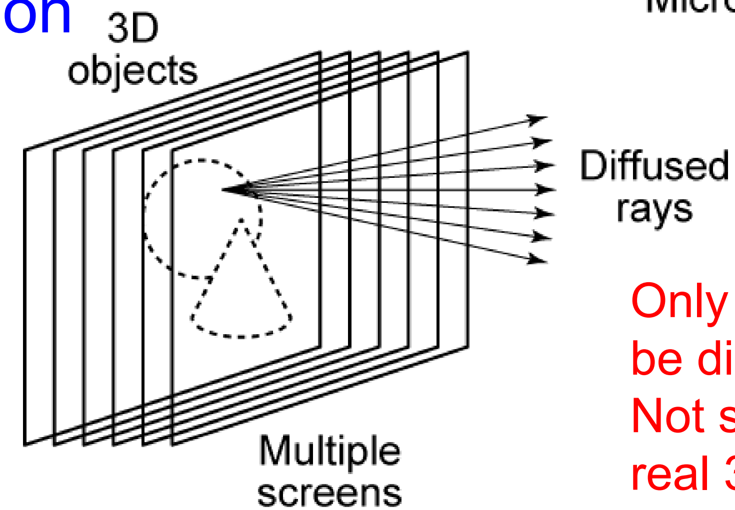
Ray reconstruction

Multi-view, integral imaging



Volume reconstruction

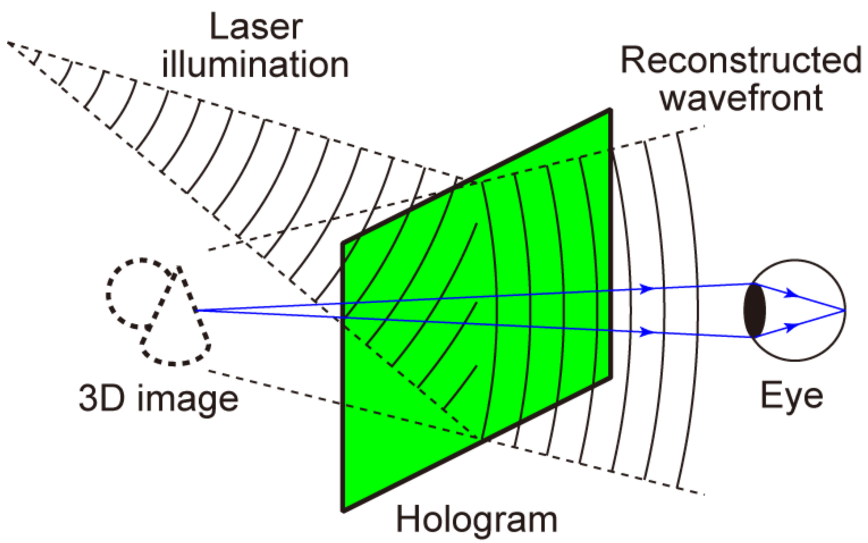
Stack of 2D images

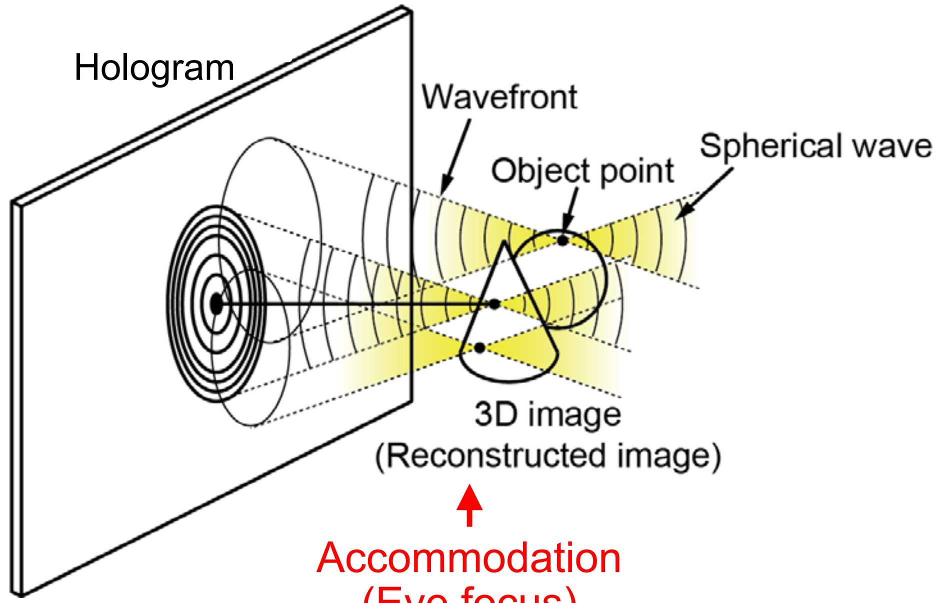


Only diffusive objects can be displayed.
Not suitable for displaying real 3D images.

Holography

Holography was invented by D. Gabor, who was awarded the Nobel Prize in 1971.





Wavefront emitted from 3D objects are reconstructed.

Vergence	○
Binocular disparity	○
Accommodation	○
Motion parallax	○

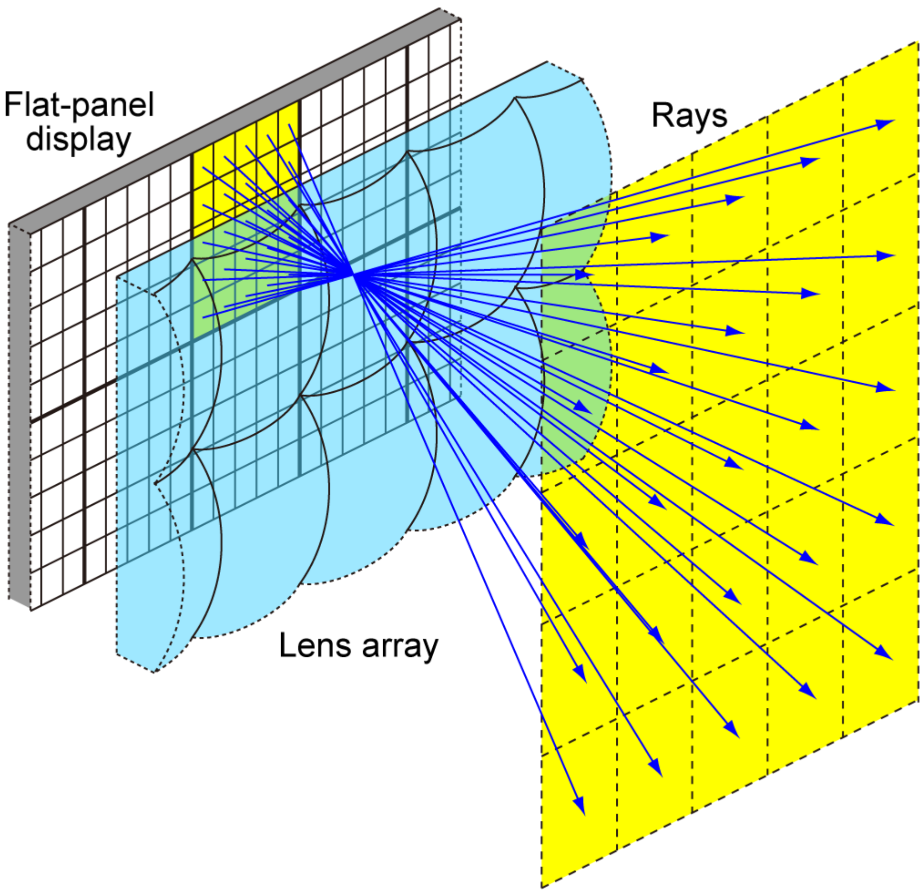
Spherical waves produce sharp points which constitute 3D images.

→ Eyes can focus on 3D images.

The vergence-accommodation conflict does not occur.

Integral Imaging

Integral imaging was invented by G. Lippmann, who was awarded the Nobel Prize in 1908. Originally, it is called "integral photography."



Rays from each lens can be controlled in horizontal and vertical directions.

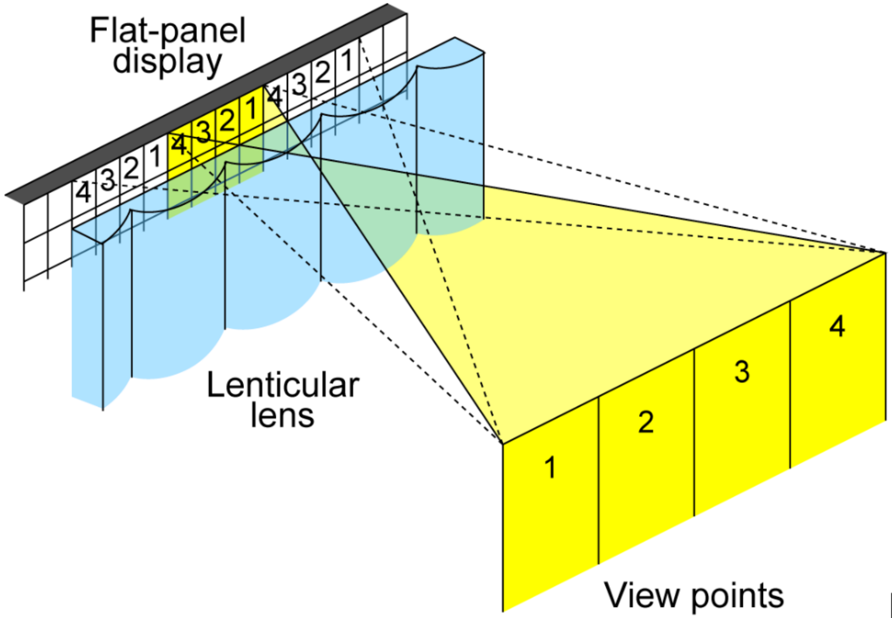
Rays emitted from 3D objects are reconstructed.

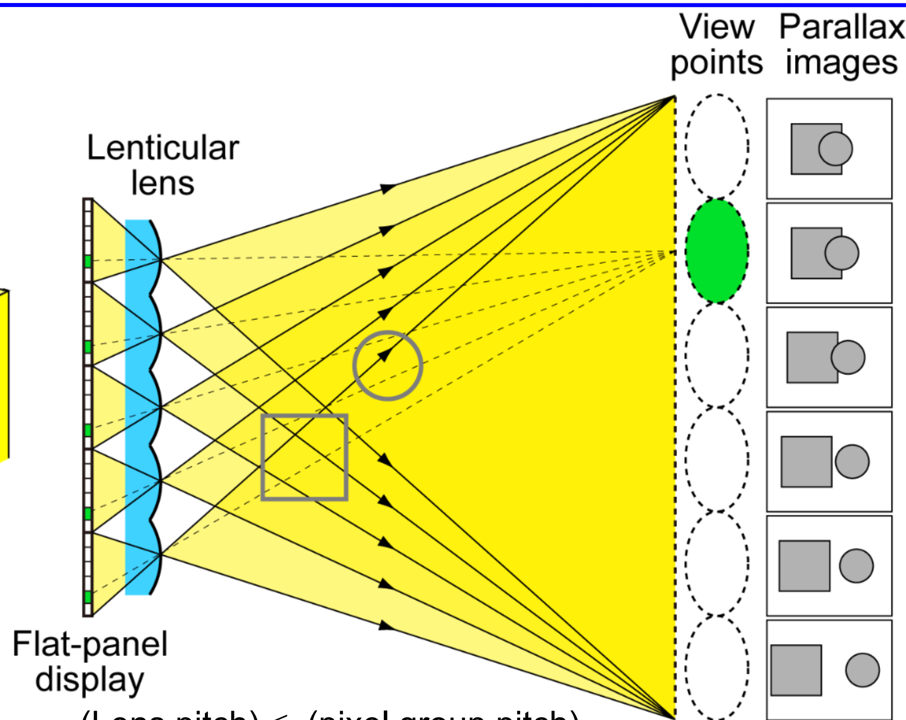
It provides 3D images with full parallax (horizontal + vertical parallaxes).

The 3D resolution is quite low.

Vergence	○
Binocular disparity	○
Accommodation	×
Motion parallax	○

Multi-view Display





(Lens pitch) ≤ (pixel group pitch)

Each lens images multiple pixels behind it to generate multiple viewpoints.

Images generated by all lens are superimposed at a certain distance.

Through viewpoints, corresponding parallax images can be viewed.

3D images with horizontal parallax are provided.

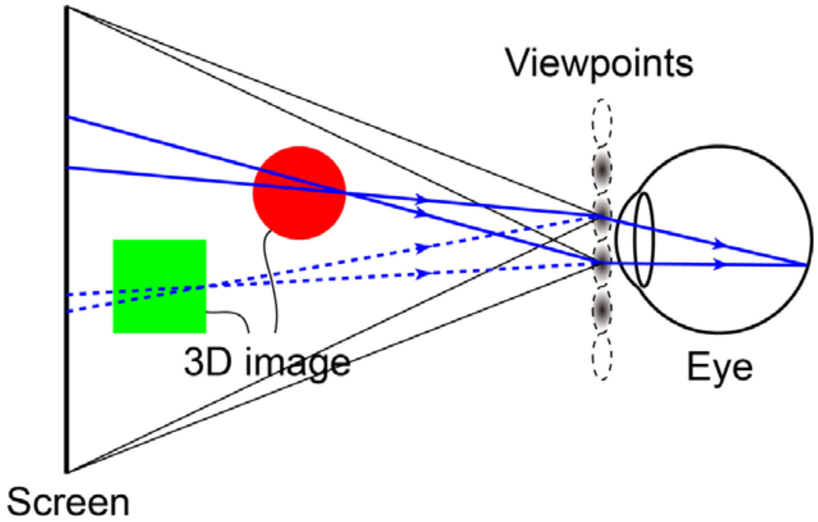
(3D resolution) =
(Flat-panel resolution) / (Number of views)

Vergence	○
Binocular disparity	○
Accommodation	×
Motion parallax	○

Super Multi-view Display Technique

The interval of viewpoints is made smaller than the pupil diameter of eyes.

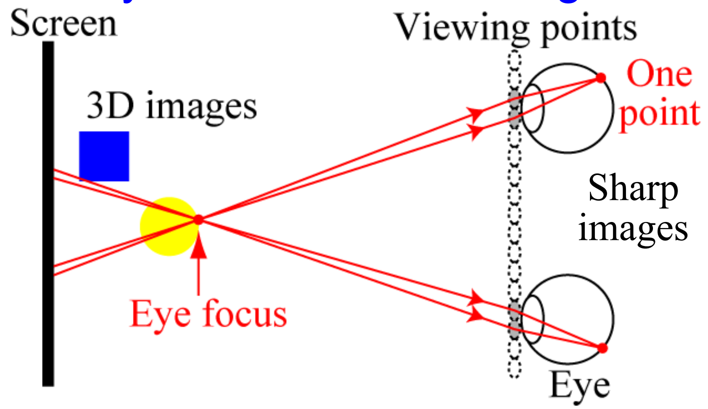
→ Two or more rays passing through an identical point in the space enter the pupil simultaneously.



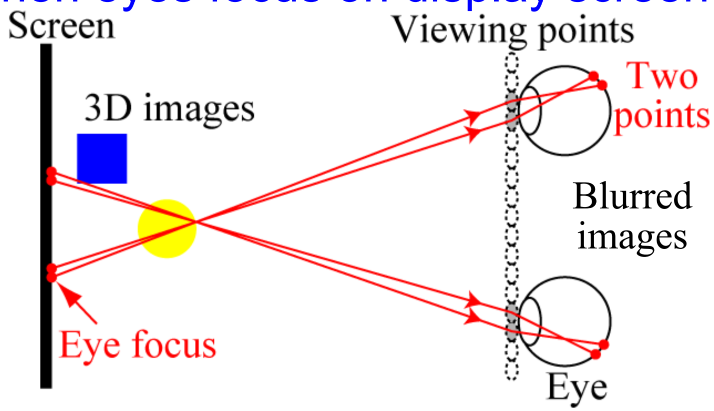
Pupil diameter: 2 ~ 8 mm (average 5 mm)
→ Interval of viewpoints: < 5 mm
Number of viewpoints: 30 ~ 100 (horizontal)

Vergence	○
Binocular disparity	○
Accommodation	○
Motion parallax	○

When eyes focus on 3D images

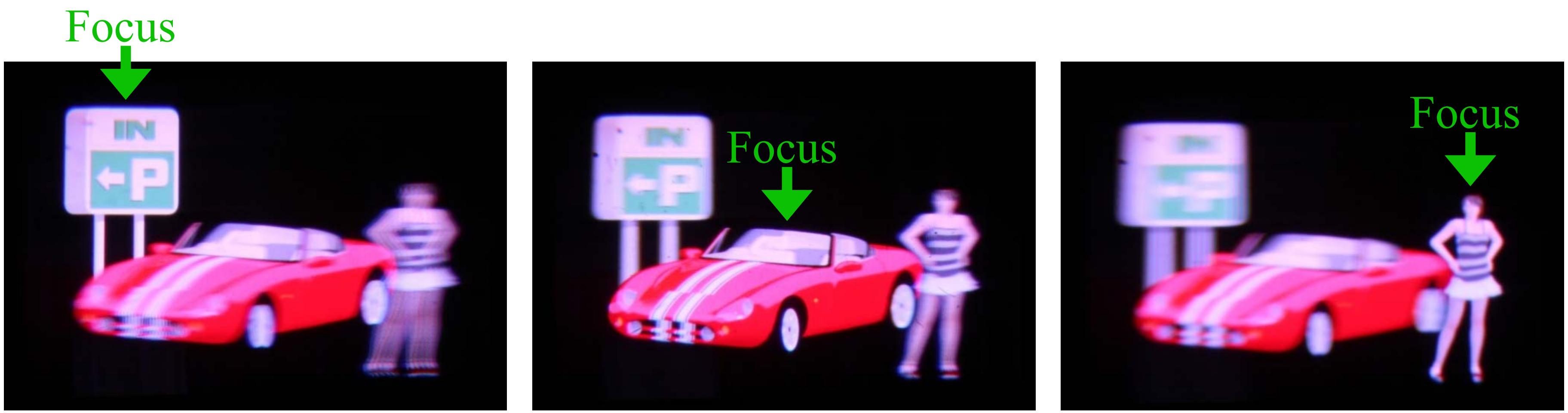


When eyes focus on display screen



Eyes can focus on 3D images.
→ The vergence-accommodation conflict does not occur.

Video of Super Multi-view Image

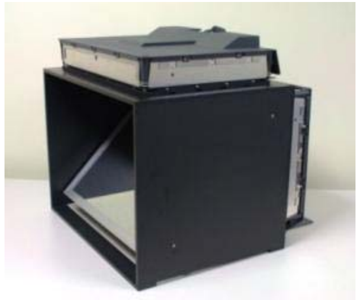


Generated by scanning type SMV display
T. Ueda, Y. Toda, and Y. Takaki, IDW2012

Number of viewpoints	55
Resolution	1,024 × 768
Width of viewing zone	182 mm
Interval of viewpoints	3.3 mm
Screen size	40 × 30 mm^2 (2.0 in.)
Refresh rate	48.5 Hz

Flat-panel Type Super Multi-view Displays

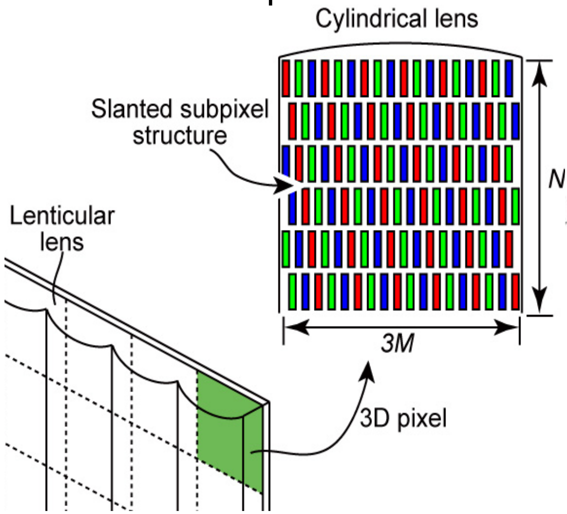
Number of views: 72
Resolution: 320 × 400
Screen size: 22.2 in.
4K panels is used.

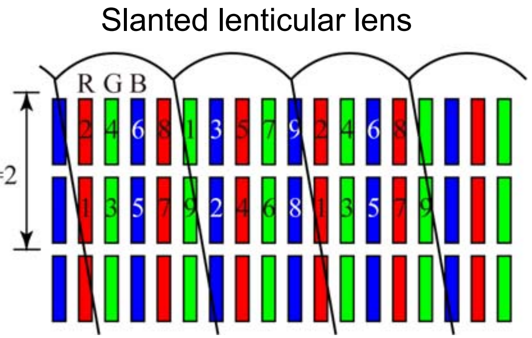


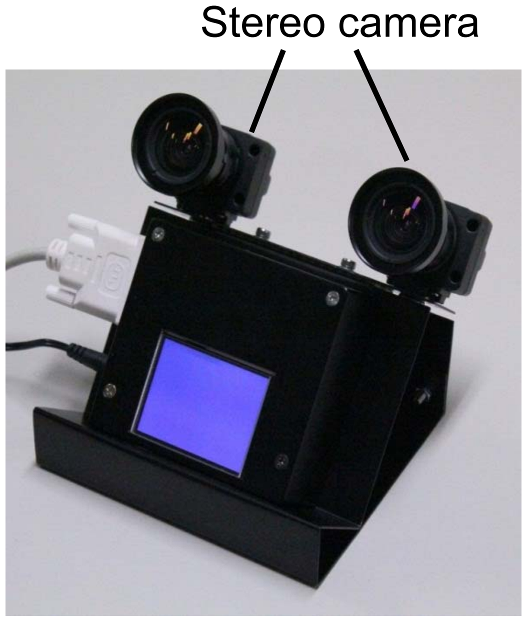
Number of views: 72
Resolution: 640 × 400
Screen size: 22.2 in.
Two 4K panels are used.

Number of views: 30
Resolution: 256 × 128
Screen size: 7.2 in.
Mobile use
Developed with NTT Docomo

Flat-panel displays with slanted subpixel structure and the slanted lenticular technique are used to increase the number of views.







Eye tracking is introduced to reduce the required number of views.

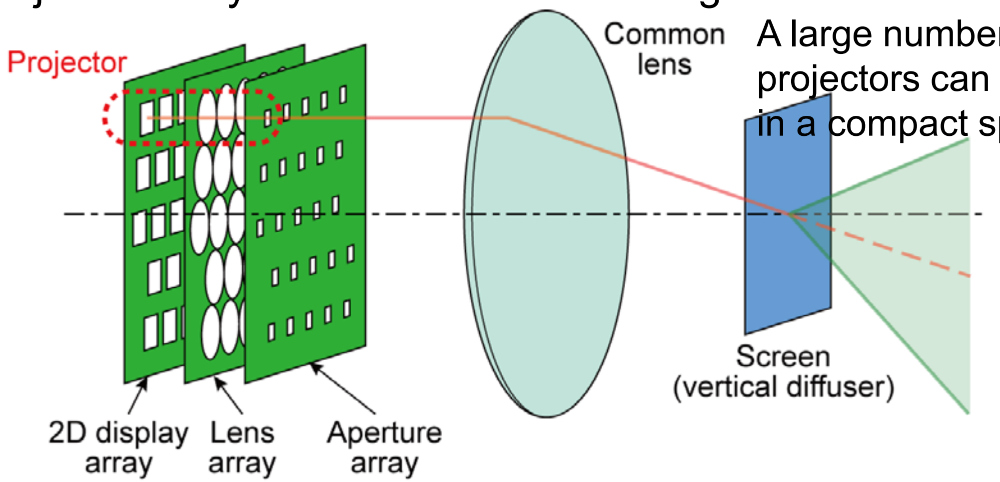
Interval of views	2.6 mm
Number of views	R 8 + L 8
Resolution	256 × 192
Screen size	2.57 in.
Observation distance	350 mm

Developed with Seiko Epson

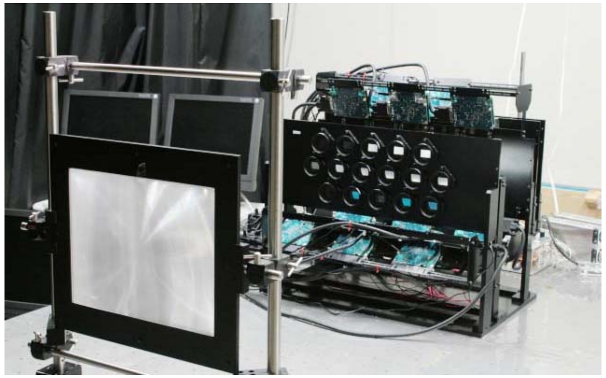
Y. Takaki et al., Opt. Express **19**, 4129 (2011)

Multi-projector Type Super Multi-view Displays

Projector array with a slanted 2D arrangement



A large number of projectors can be aligned in a compact space.

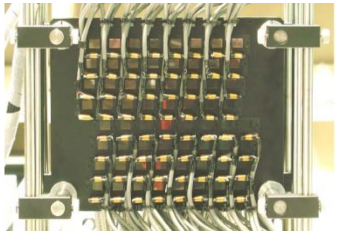


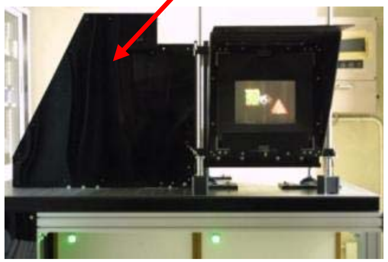
SMV256

Number of views: 256

Sixteen sets of 16-view displays are combined by multi-projection system.

8 × 8 LCD panels

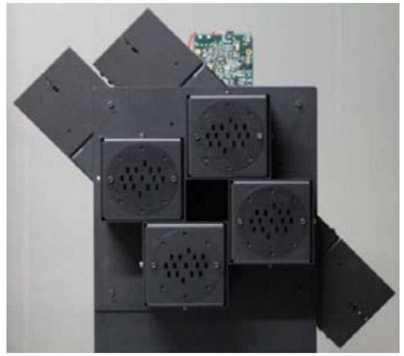




Number of views: 64
Resolution: ~QVGA
Screen size: 9.25 in.

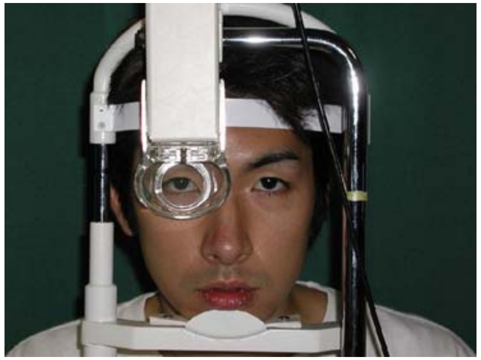
Number of views: 128
Resolution: ~QVGA
Screen size: 13.2 in.

Number of views: 128
Resolution: SVGA
Screen size: 12.8 in.

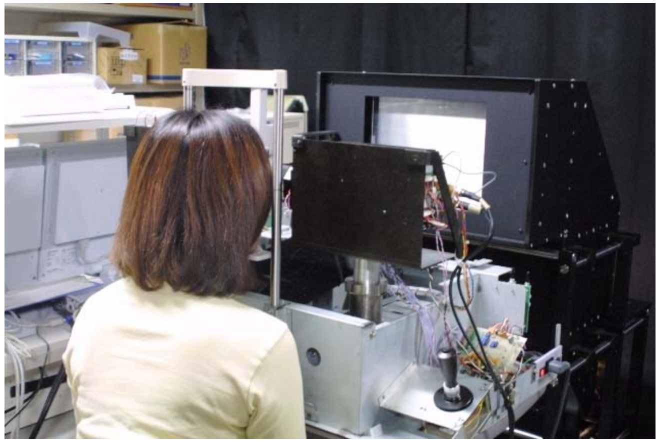


Number of views: 64
Time multiplexing technique is used.

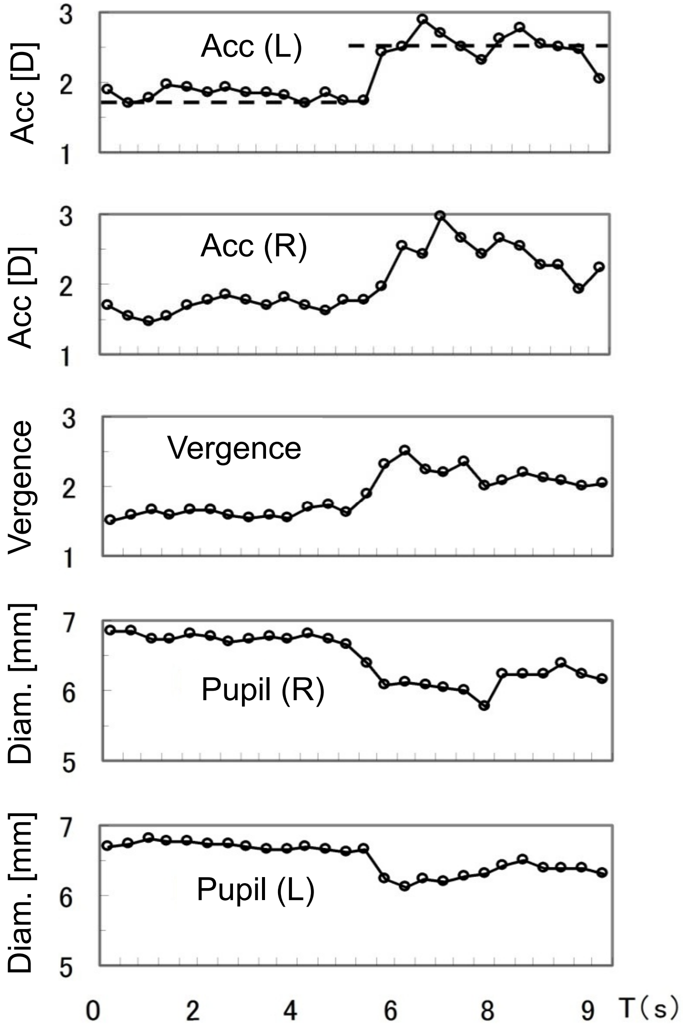
Accommodation Measurement



Auto refractometer
FR-5000S
(Grand Seiko Corp.)

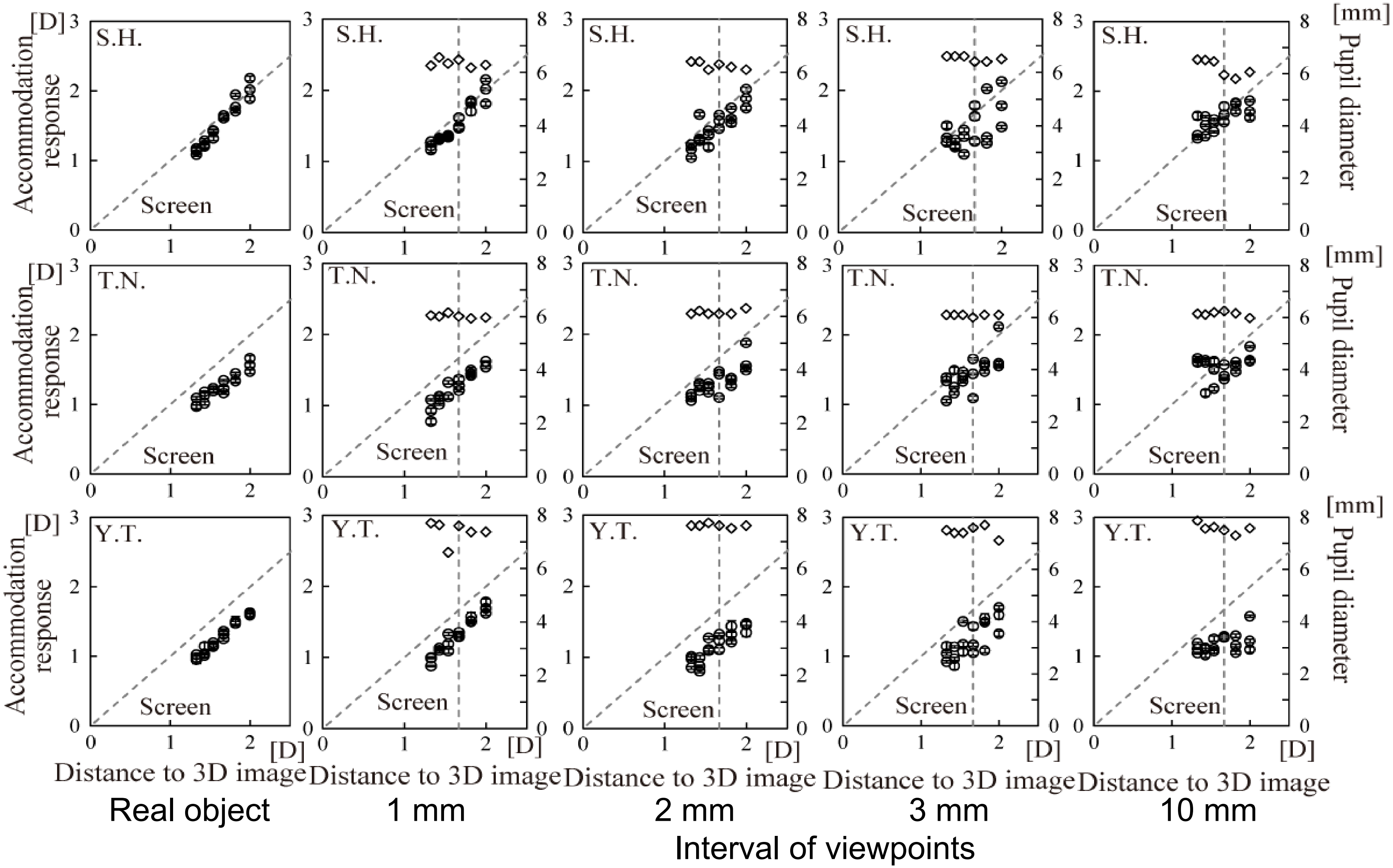


Visual function measurement equipment specialized for 3D displays
Jointly developed with TOPCON Corp. under the SCOPE project
R & L Accommodation + Vergence
+ R & L Pupil diameters



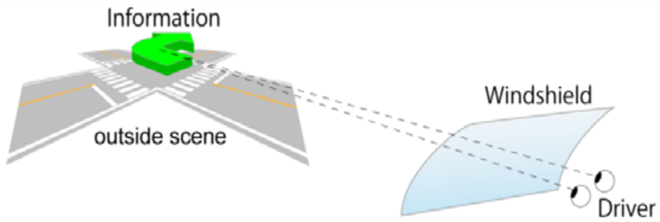
Results of Accommodation Measurement

Diopter [D]: reciprocal of Length [m]



Other Super Multi-view Displays

【Windshield SMV display】

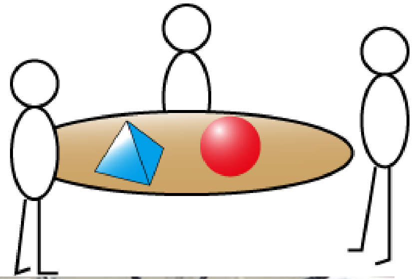


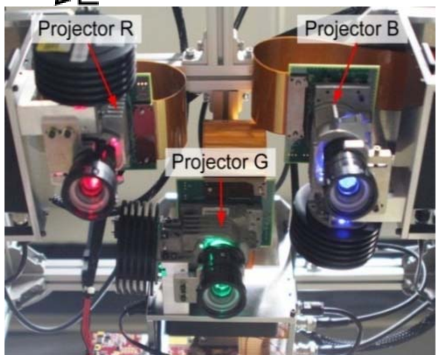
Developed with DENSO

36-view SMV-WSD

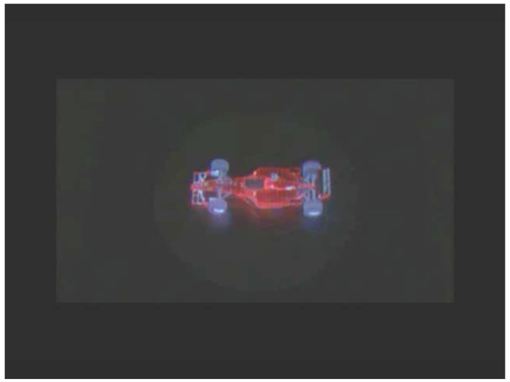
Opt. Express **19**, 704 (2011)

【360-degree SMV display】



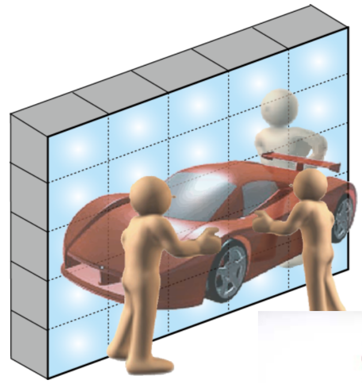


High-speed RGB projector



Opt. Express **20**, 8848 (2012)

【Large-screen SMV display】



Frameless modules are tiled.

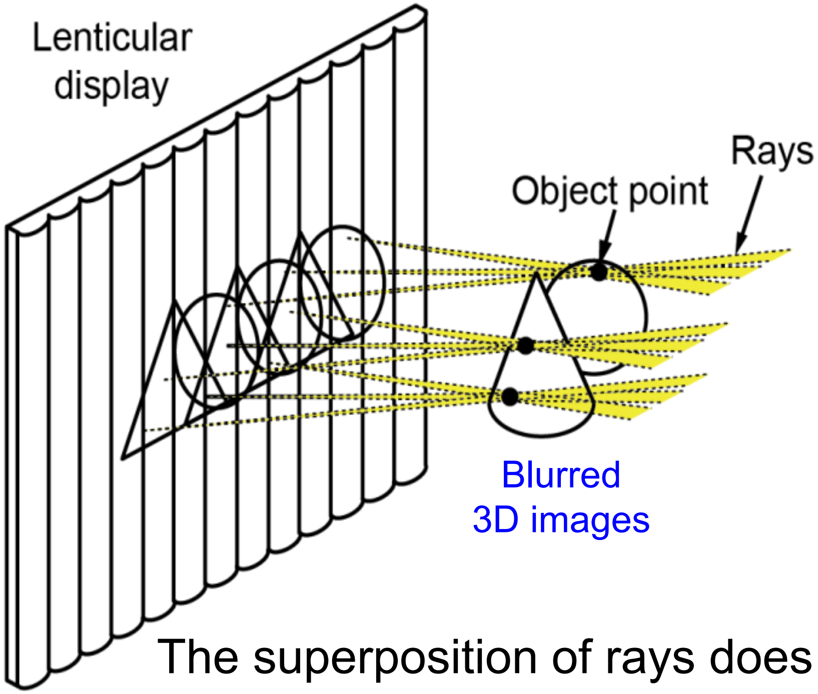
Four modules are aligned vertically.

Opt. Express **19**, 704 (2011)

Ray Reconstruction v.s. Wavefront Reconstruction

Ray reconstruction

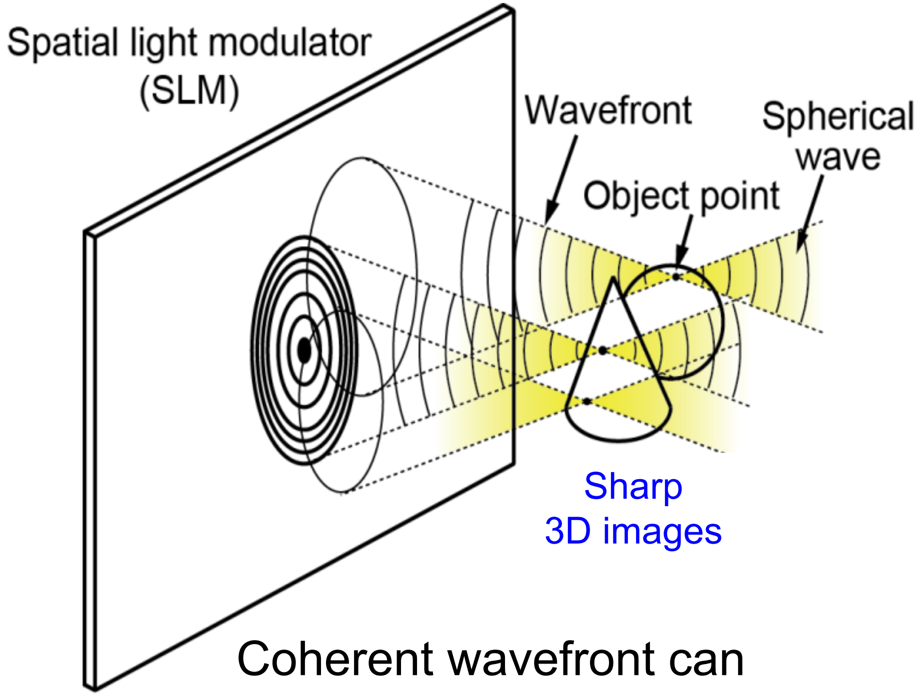
Super multi-view display



The superposition of rays does not reduce the beam width.

Wavefront reconstruction

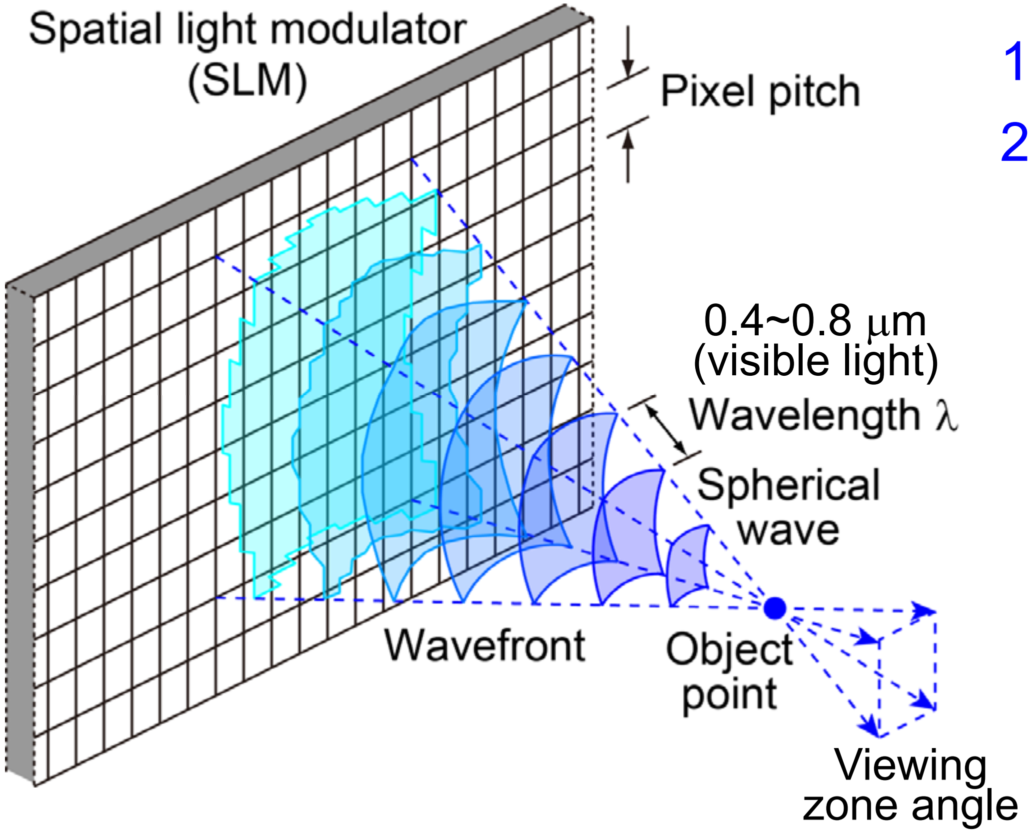
Holography



Coherent wavefront can generate sharp 3D images.

Holographic displays can produce sharper 3D images than super multi-view displays.

Problems of Electronic Holographic Display



Requirements for SLM:

1) Pixel pitch needs to be ~1 μm.
2) To increase the screen size, the number of pixels must be proportionally increased.

Viewing zone angle:

$$\Phi = 2\sin^{-1}(\lambda / 2p)$$

Screen size:

$$Np \times Mp$$

Pixel pitch of SLM: p
Resolution of SLM: $N \times M$
Wavelength of light: λ

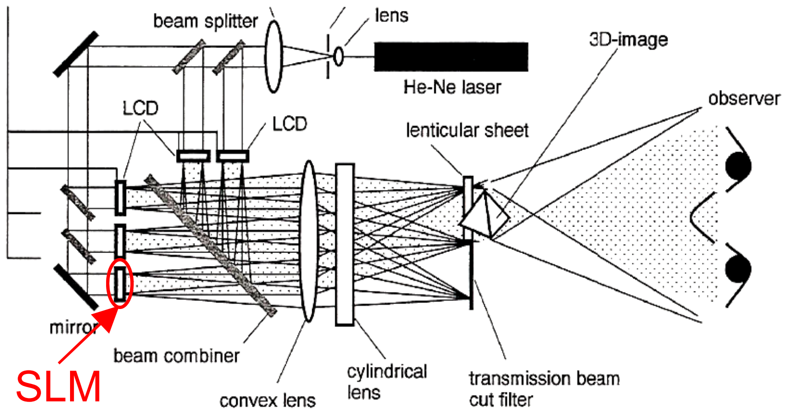
Screen 40 in., viewing zone angle 30° (λ = 0.6 μm)
Pixel pitch: p = 0.97 μm
Resolution: $N \times M$ = 764,000 × 430,000

Super Hi-Vision (Ultra HD)
Resolution: 7,680 × 4,320

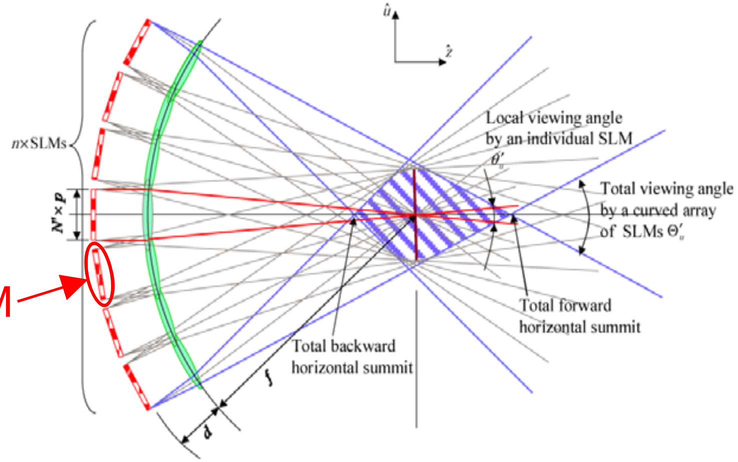
Previously Proposed Holographic Displays

【Multiple SLMs】

TAO (Japan), 5 SLMs
SPIE **2652**, 1519 (1996)

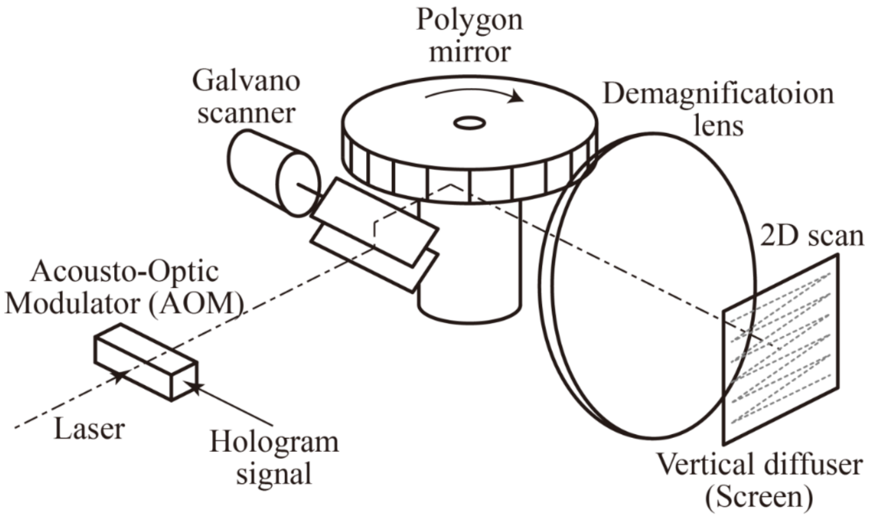


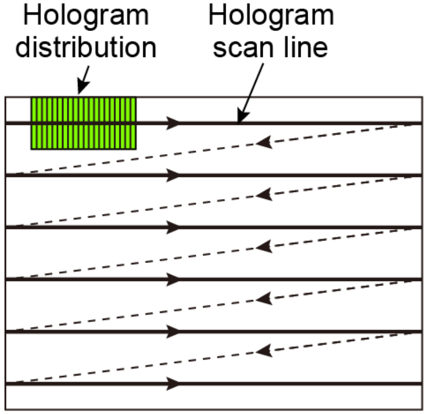
Seoul National University (Korea), 12 SLMs
Opt. Express **16**, 12372 (2008)



【AOM + 2D scanning】

MIT (U.S.A.) SPIE **1212**, 174 (1990)
J.Opt.Soc.Am. **9**, 1969 (1992)

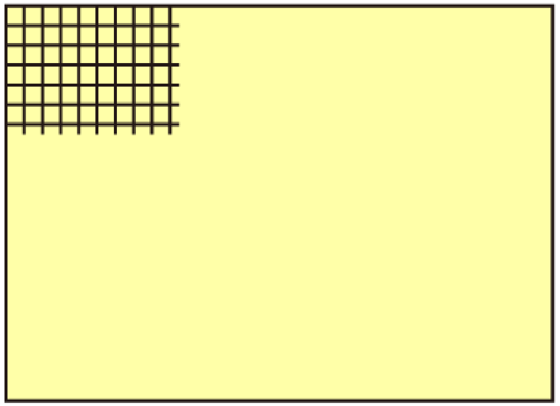




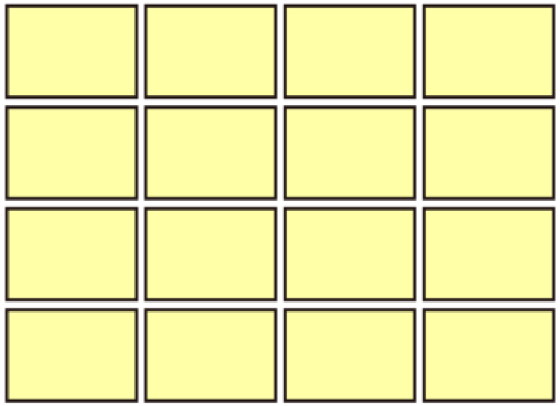
Horizontal-Parallax-Only (HPO) hologram

Comparisons of Holographic Displays

Ultra-high resolution SLM

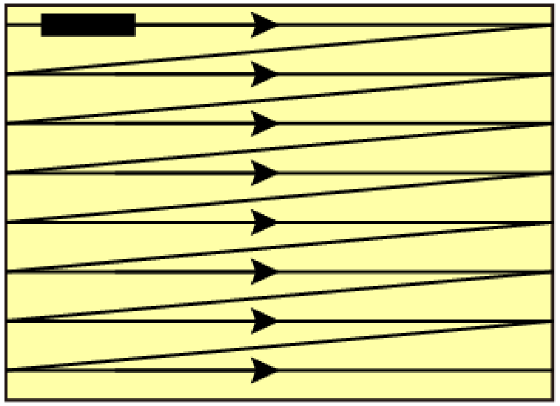


Multiple SLMs



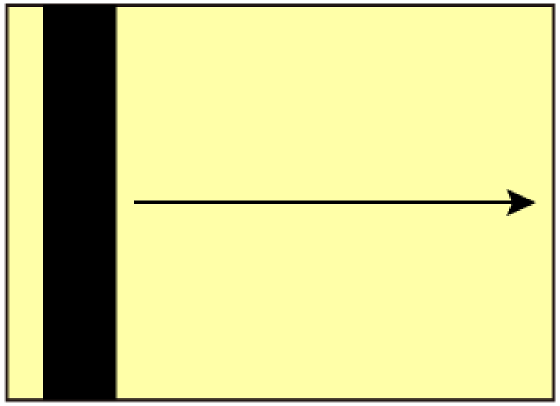
TAO, NICT
SNU
Bilkent Univ.

1-D modulation (AOM)
+ 2-D scanning



MIT

2-D modulation (MEMS)
+ 1-D scanning



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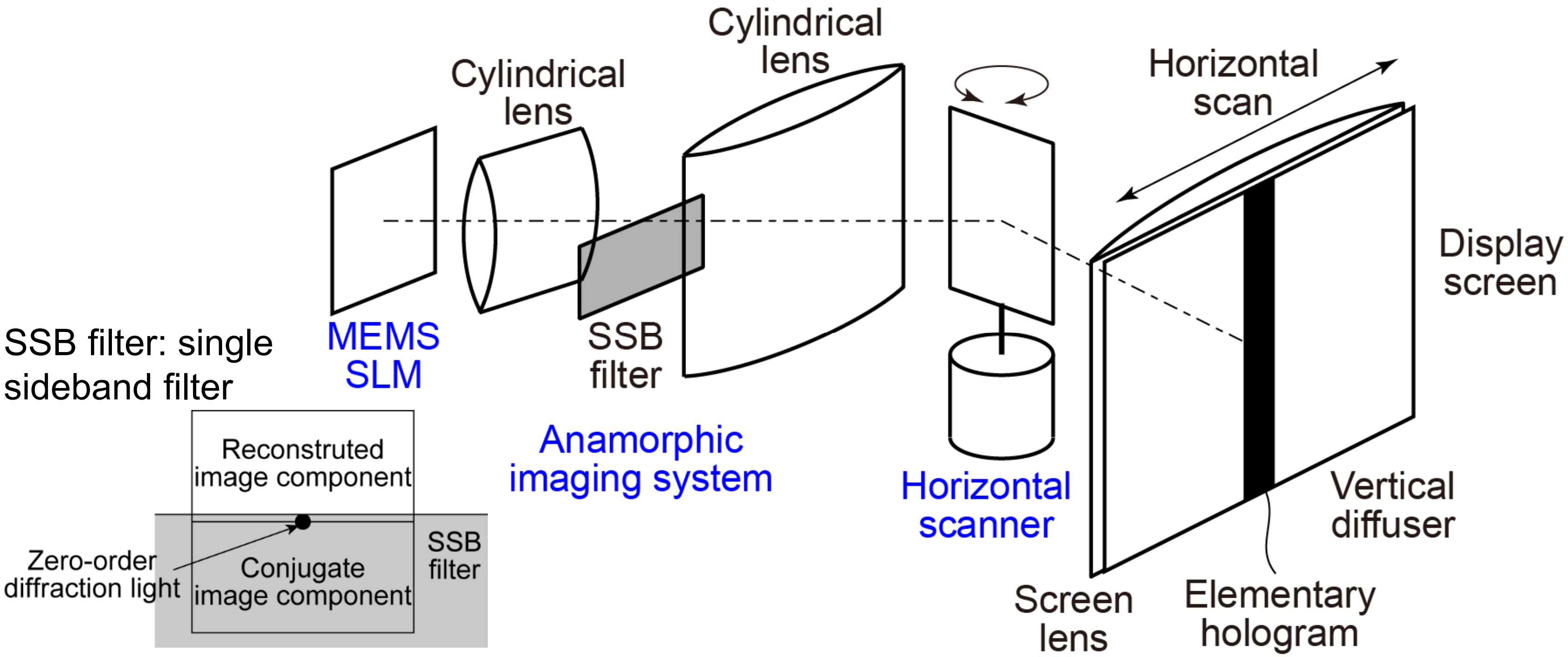
Horizontally scanning holography using MEMS SLM

Horizontally Scanning Holography Using MEMS-SLM

Screen scanning system

Y. Takaki et al., Appl. Opt. **48**, 3255 (2009)
Y. Takaki et al., Opt. Express **18**, 11327 (2010)



Anamorphic imaging system:

Horizontal: reduce pixel pitch → Viewing zone angle increases

Vertical: increase image height

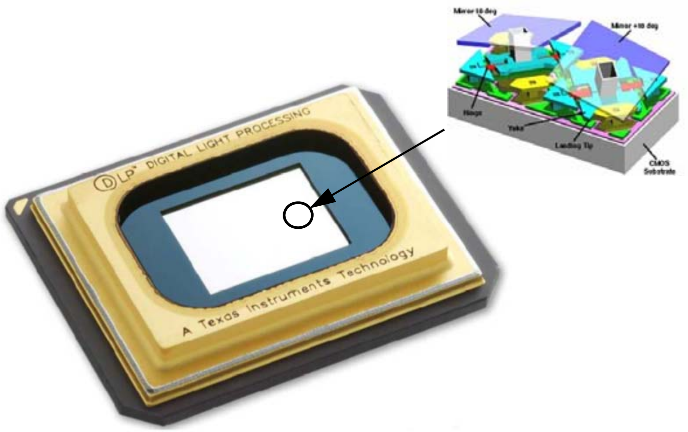
Horizontal Scanning:

Increase image width

(Vertical: increase image height; Increase image width) → Screen size increases

Screen Scanning System: Experimental System

MEMS-SLM



Digital Micromirror Device (DMD)
Discovery™3000

Frame rate: 13.333 kHz
Resolution: 1,024 × 768
Pixel pitch: 13.68 μm
Screen size: 0.7 in.
(14.0 × 10.5 mm²)

Anamorphic imaging system

M_x = 0.183

M_y = 5.00

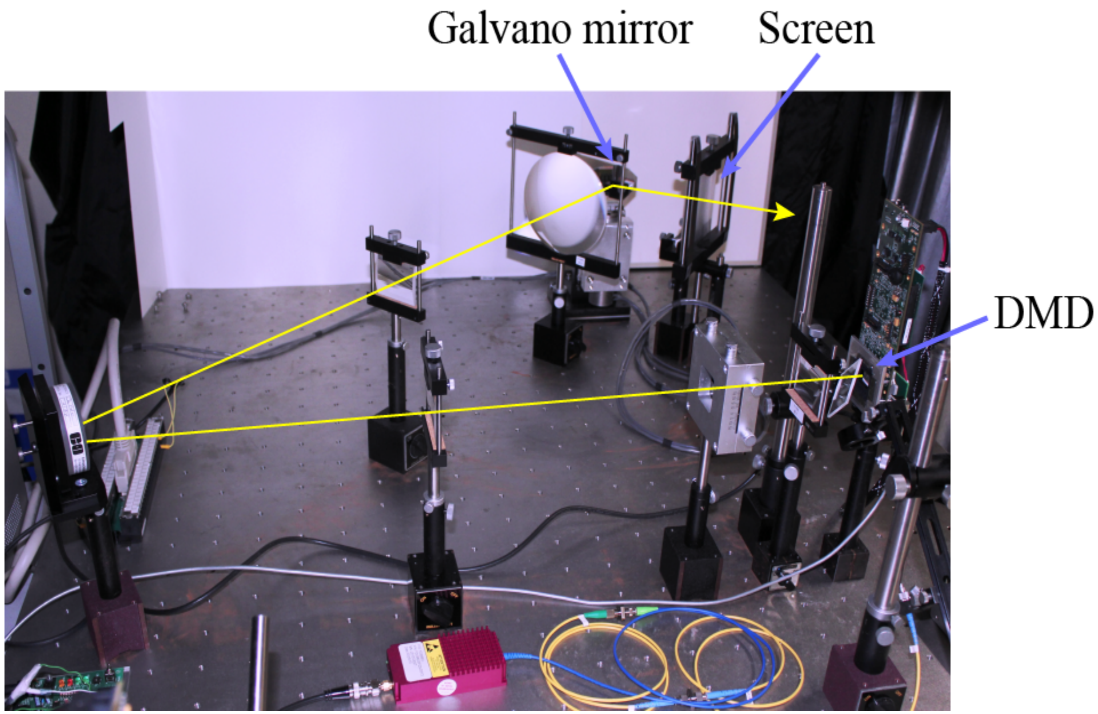
Elementary hologram
Size: 2.56 × 52.5 mm²
Horizontal pixel pitch: 2.5 μm
Horizontal viewing angle: 15 º

Horizontal scanner

Galvano mirror
MicroMax™Series671

Scanning frequency : 60 Hz
Scan angle : ±18.1º
Screen size : 3.5 in.
(73.1 × 52.5 mm²)
Number of elementary holograms : 222

Screen Scanning System: Reconstructed Image



Symbols

Viewing zone angle: 15°
Screen size: 3.5 inches
Frame rate: 60 Hz

Screen Scanning System: Color System

MEMS SLM

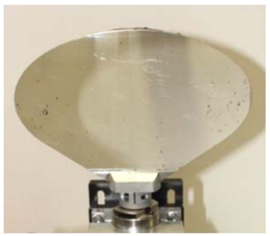
DMD Discovery 4100
(Texas Instruments Inc.)

Resolution: 1,024 × 768
Pixel pitch: 13.68 μm
Frame rate: 22.727 kHz

Horizontal scanner

Cambridge Technology
MicroMax™ Series671

Scan angle: ±6.8°
Scan frequency: 30 Hz
Mirror size: 95 × 170 mm^2

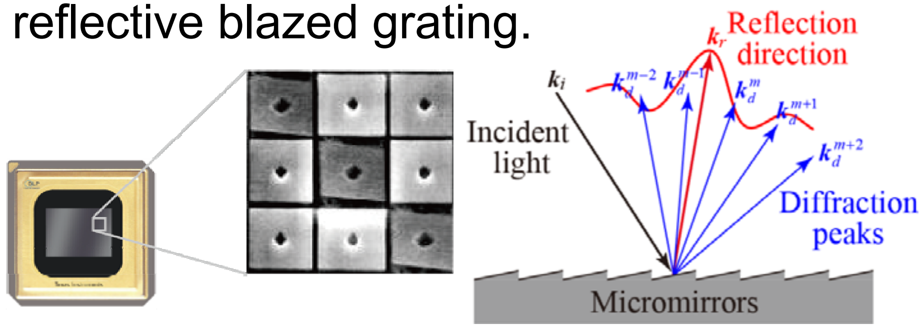


Lasers

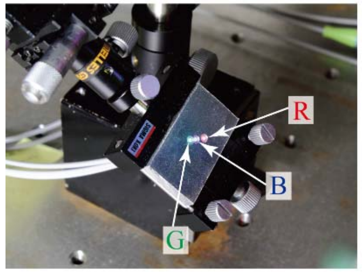
Toptica Photonics
Fiber coupled laser diodes

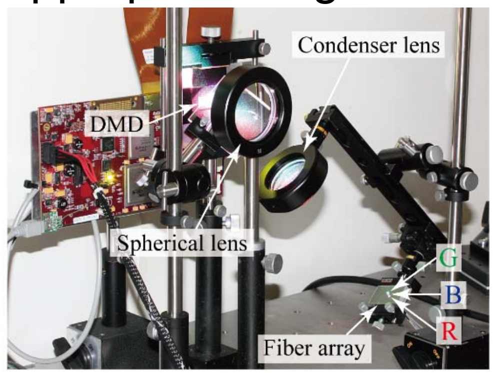
R: 640 nm, G: 515 nm, B: 445 nm

DMD screen has a structure similar to a reflective blazed grating.



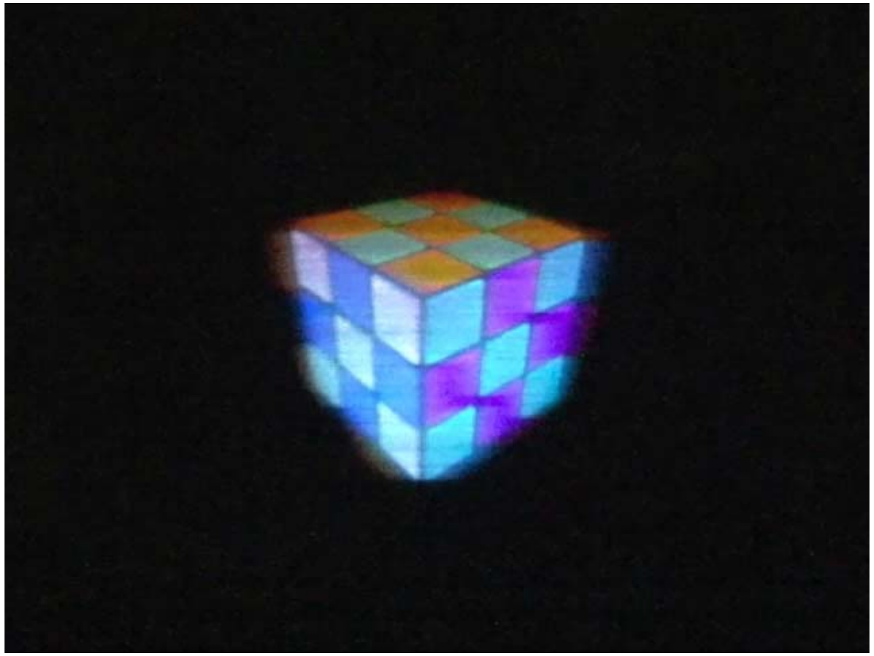
R, G, and B laser lights should illuminate DMD with different appropriate angles.





Pixel pitch: 2.5 μm (horizontal)
Viewing zone angles:
Red: 14.7°, Green: 11.8°, Blue: 10.2°
Screen size: 6.2 inches
Frame rate (hologram): 30 Hz

Screen Scanning System: Color Images



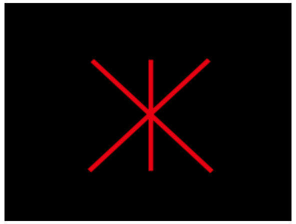
cube

snowman

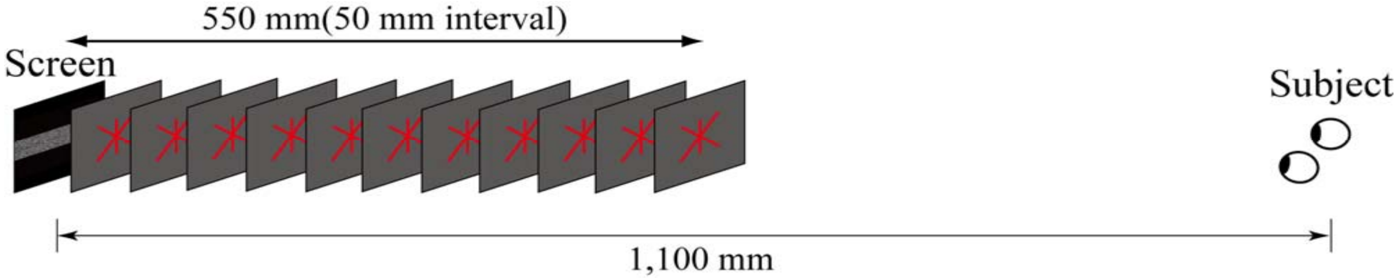
Error diffusion technique was used to binarize elementary hologram patterns.

Viewing zone angles:
Red: 14.7˚, Green: 11.8˚, Blue: 10.2˚
Screen size: 6.2 inches
Frame rate: 30 Hz

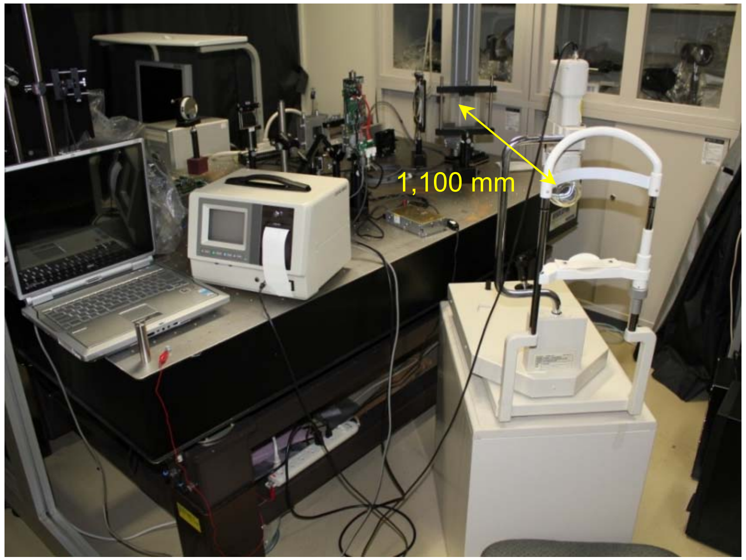
Accommodation Measurements

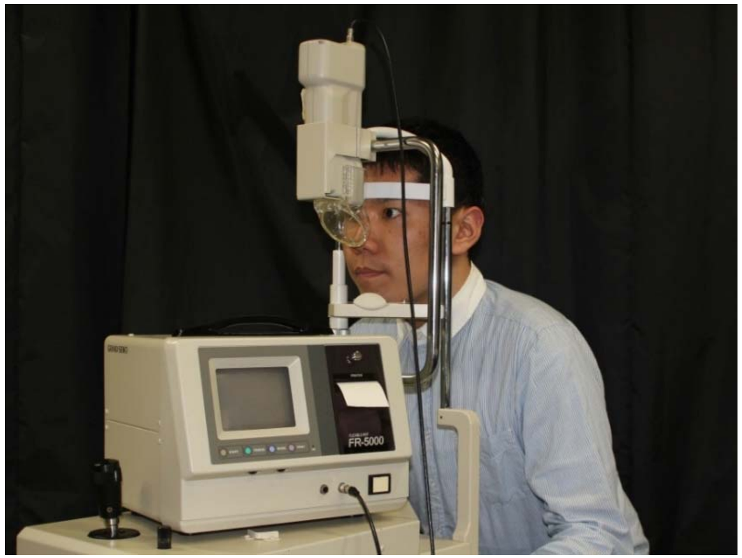


Test image
(1.1°× 1.1°)



The measurements were performed for 10 s, and the responses for 2 s without blink were averaged to obtain an experimental result.



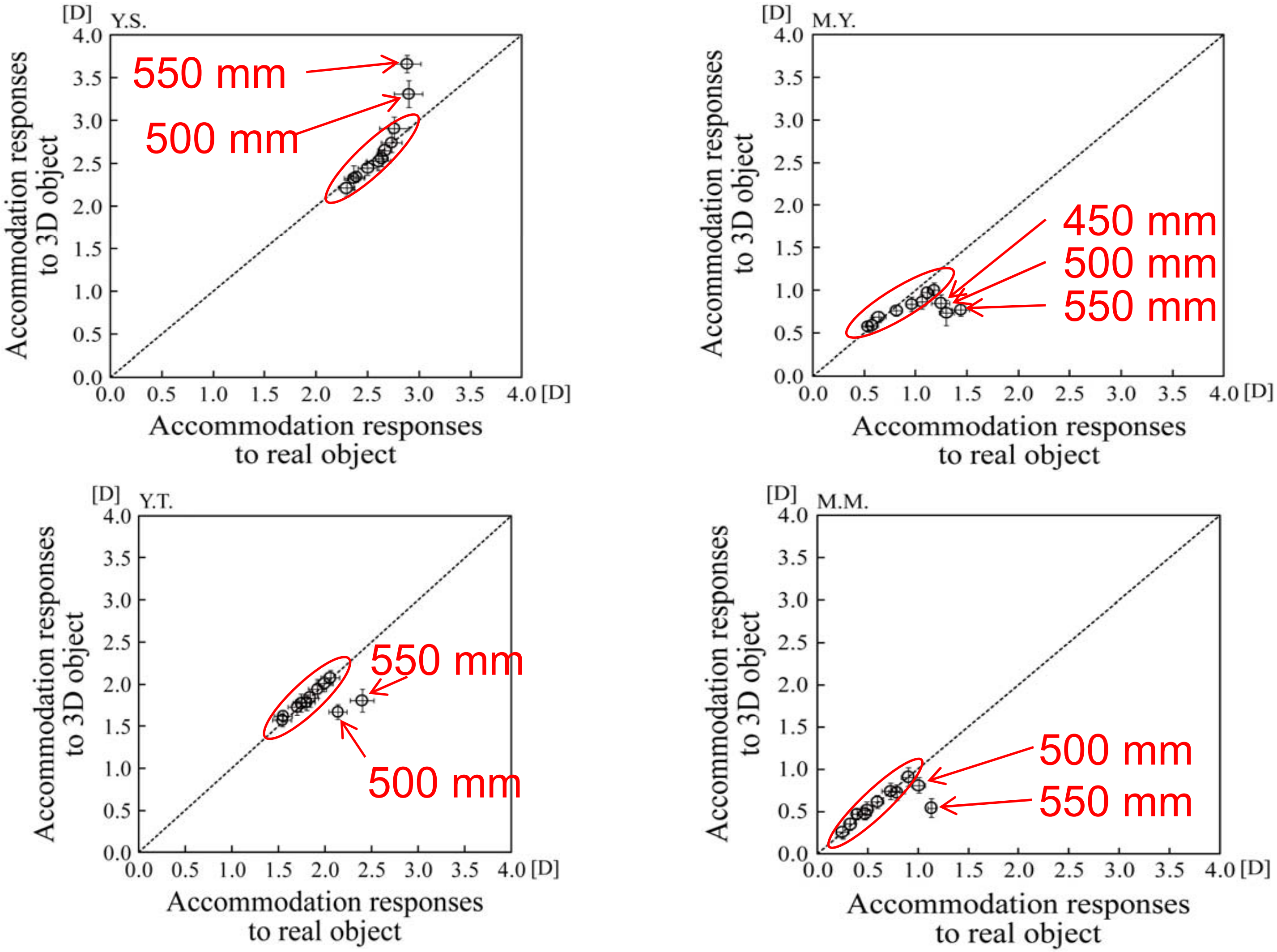


Auto refractometer: FR-5000S
(Grand Seiko Co., Ltd.)

Y. Takaki and M. Yokouchi, Opt. Express **20**, 3918-3931 (2012)

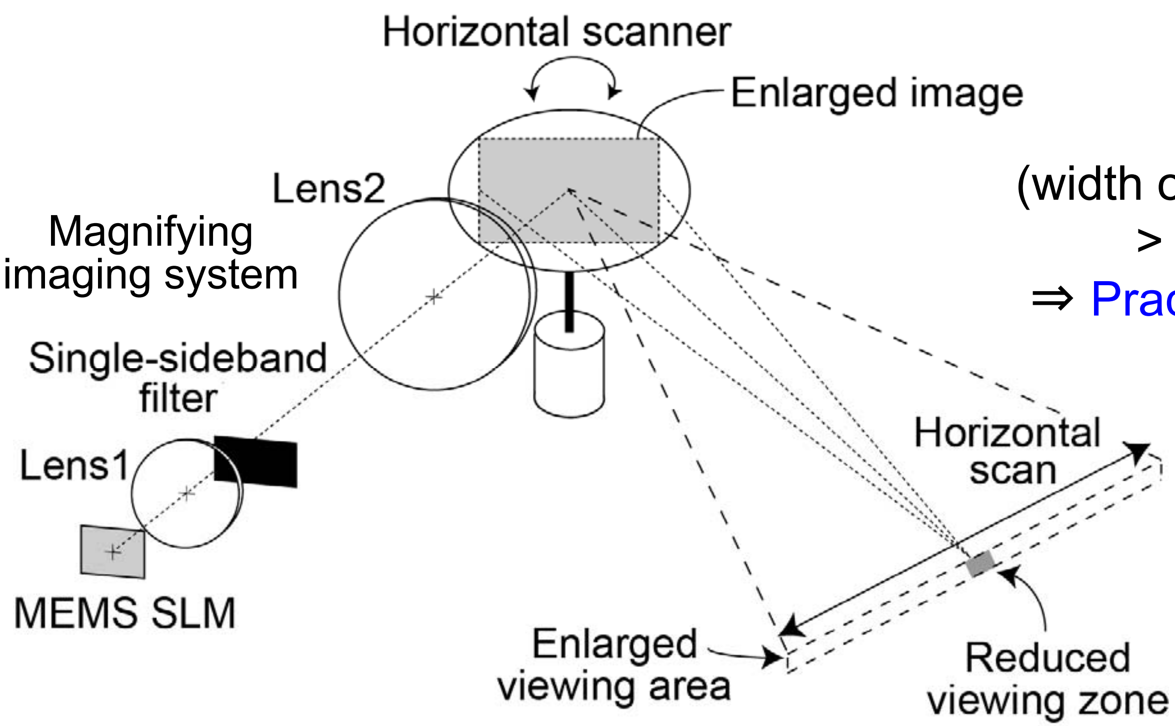
Results of Accommodation Measurements

Diopter [D] =
1/Length [m]



Viewing-zone Scanning System

Y. Takaki et al., Opt. Express **22**, 24713 (2014)

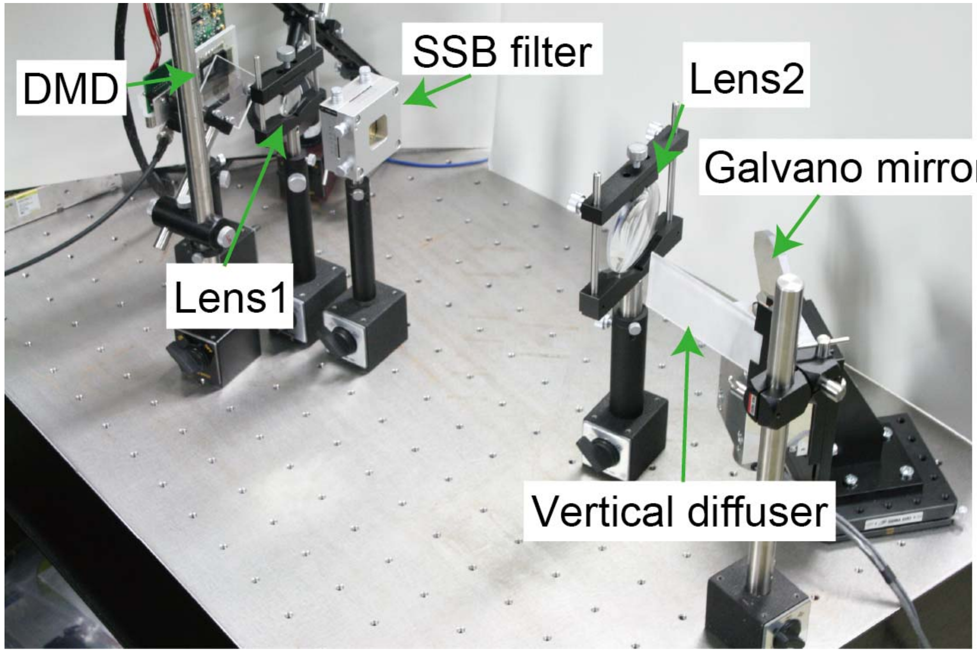


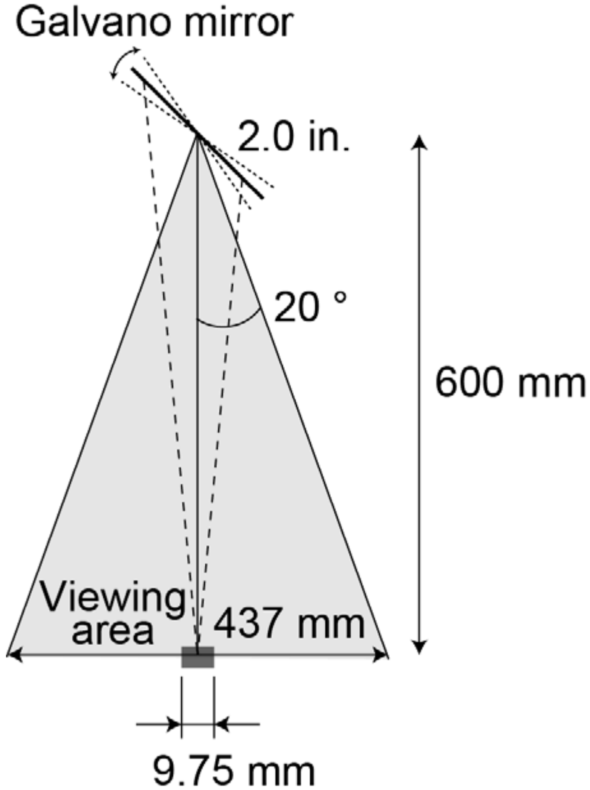
(width of localized viewing zone)
> (pupil diameter)
⇒ Practical wavefront reconstruction

Screen size is enlarged by magnifying imaging system.
⇒ Pixel pitch increases ⇒ Viewing zone reduces

Reduced viewing zone is scanned by horizontal scanner.
⇒ Viewing zone is enlarged

Viewing-zone Scanning System: Experimental System

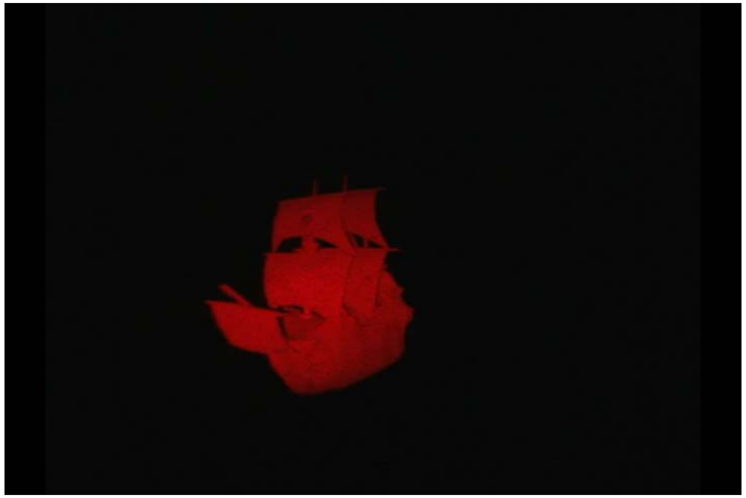


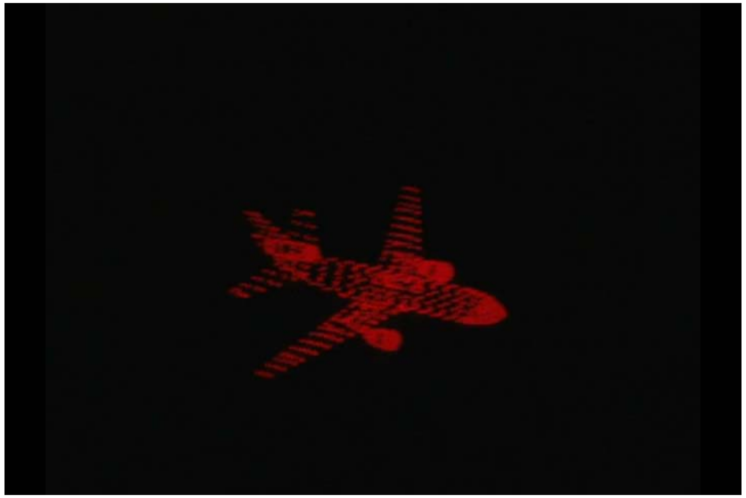


Magnification of imaging system: 2.86
Screen size: 40.0 × 30.0 mm^2 (2.0 in.)
Reduced viewing zone width: 9.75 mm
Viewing zone width: 437 mm (at 600 mm)
Viewing zone angle: 40°
Frame rate: 60 Hz

Number of hologram patterns: 222

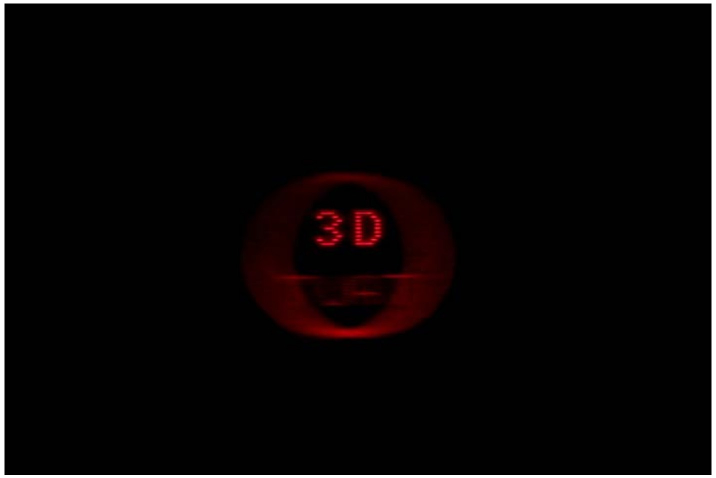
Viewing-zone Scanning System: Reconstructed Images





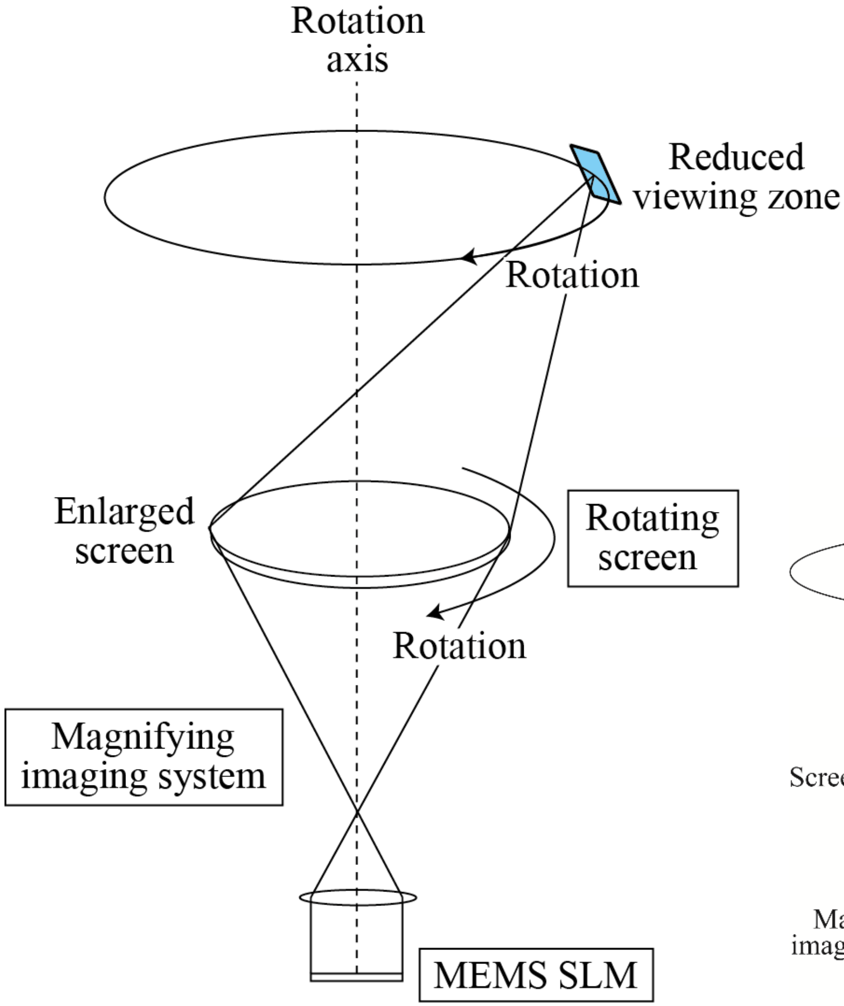
Focus of camera was changed.

3D: +100 mm
TUAT: +30 mm
Circle: −100 mm



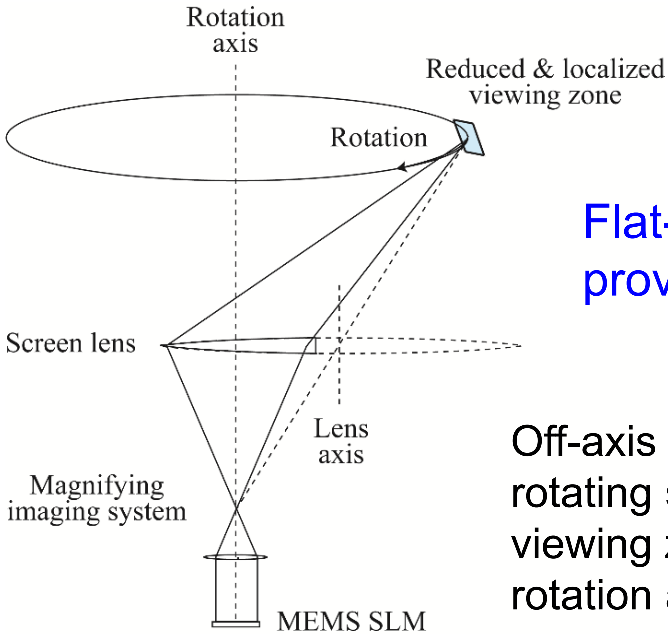
Screen size: 2.0 in.
Viewing zone width: 437 mm (at 600 mm)
Refresh rate: 60 Hz

360-degree Scanning System



Screen size is enlarged by magnifying imaging system.
Pixel pitch increases.
→ Viewing zone reduces.

Reduced viewing zone is scanned circularly by rotating lens screen.
→ Viewing zone is enlarged to 360 degrees.



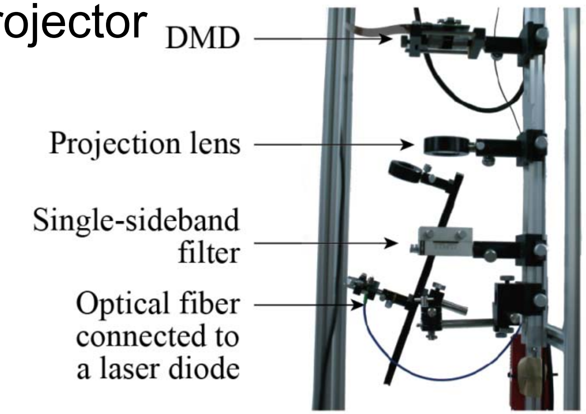
Flat-table screen is provided.

Off-axis lens is used as rotating screen to generate viewing zone outside rotation axis.

T. Inoue and Y. Takaki, Opt. Express **23**, 6533 (2015)

360-degree Scanning System: Experimental System

Projector



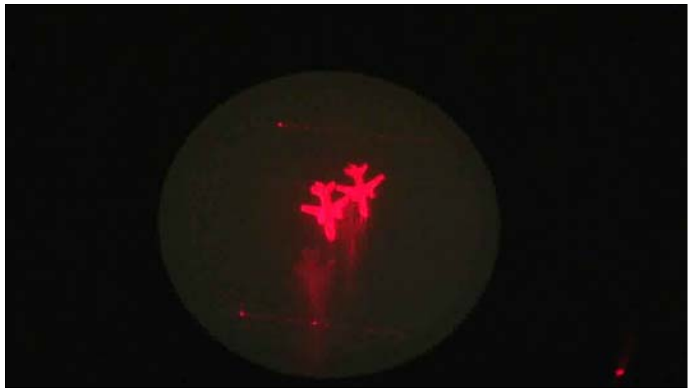
Rotating screen

DMD: Discovery 4100
Frame rate: 22.727 kHz
Resolution: 1,024 × 768
Pixel pitch: 13.68 μm
Laser: 635 nm, 23 mW

Magnification: 5.71
Screen size: 80 x 60 mm^2
(Diameter 100 mm)
Pixel pitch: 78.1 μm
Reduced viewing zone: 5.81 mm x 2.91 mm

Rotation speed: 1,700 rpm
Number of hologram / rotation: 800
Frame rate (3D): 28.4 Hz

3D: 110 mm, TUAT: 90 mm, circle: 70 mm



plane1: 90 mm, plane2: 110 mm

Requirement for Display Devices

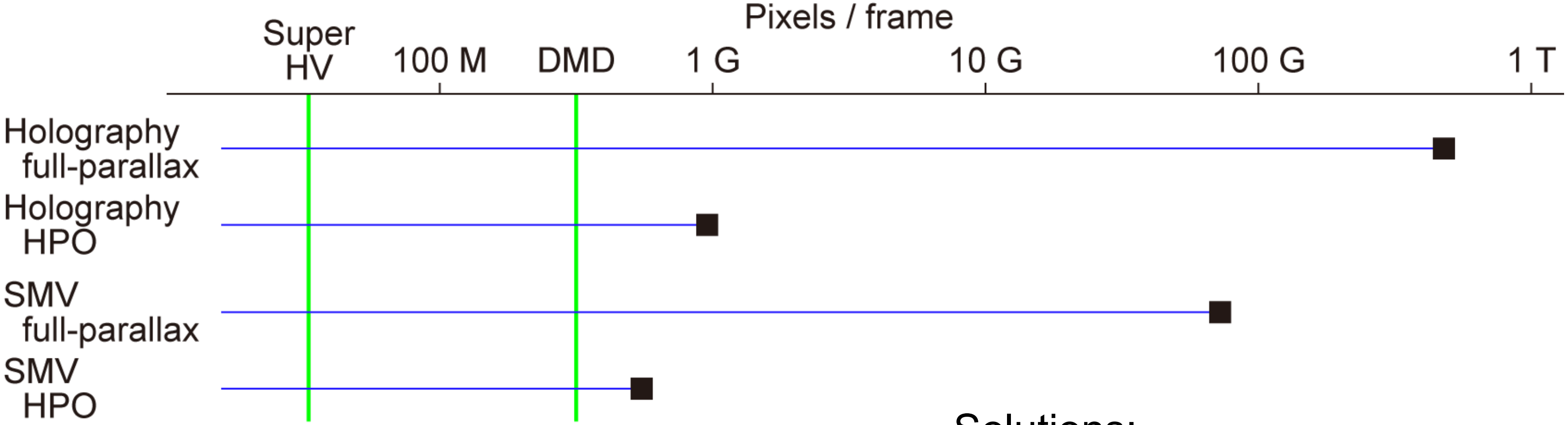
Screen size: 40 in. (886 mm × 498 mm)
Frame rate: 60 Hz

Display technology:

- Holography (pixel pitch: 1 μm)
  - full-parallax: 441 Gpixels
  - HPO: 956 Mpixels
- SMV (resolution: 1920 × 1080)
  - full-parallax: 256 × 128 views: 70 Gpixels
  - HPO: 256 views: 531 Mpixels

Device technology:

- Full HD: 2 Mpixels
- 4K: 8 Mpixels
- Super HV: 33 Mpixels
- DMD: 300 Mpixels (binary)



Solutions:

- Use of multiple devices
- Eye tracking / Face tracking

Summary

The next-generation 3D displays should be free from visual fatigue caused by the vergence-accommodation conflict, and also provide smooth motion parallax.

Holography and SMV displays are candidates for the next-generation 3D displays.

Several types of the SMV displays, the scanning holography using MEMS SLM, and the accommodation responses were shown.

The requirement for display devices to realize these displays was discussed.

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