# Prospective Novel 3D Display Technology Development

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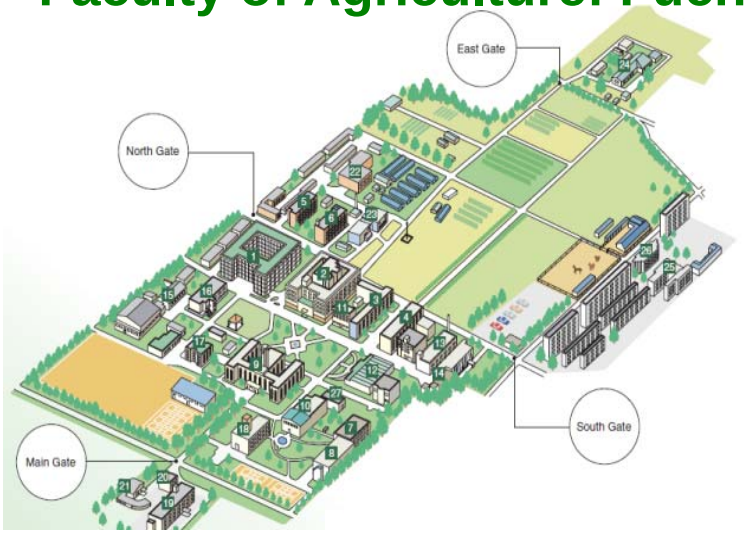
# TUAT

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

*Established in 1877, one of the national universities in Japan.*

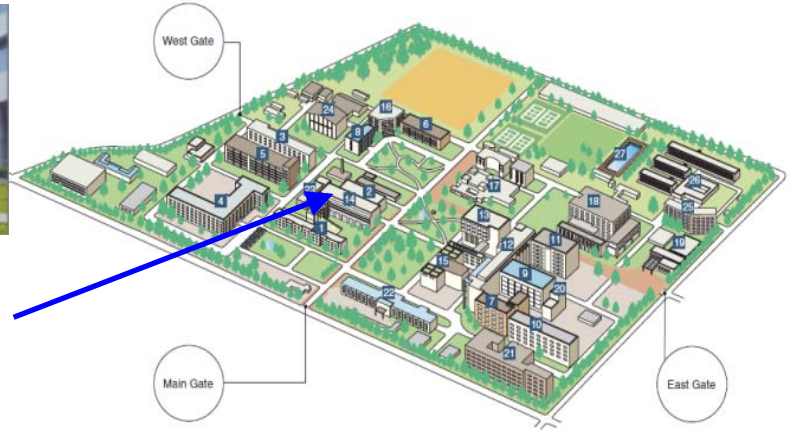
**Faculty of Agriculture: Fuchu Campus**





**40 min from Tokyo Station**

**Faculty of Engineering: Koganei Campus**




***We are here !***

Undergraduates: 3,998
Postgraduates: 1,954
Faculty & Staff: 641
(2010)

# Outline

***1. Avoidance of conflict in human***

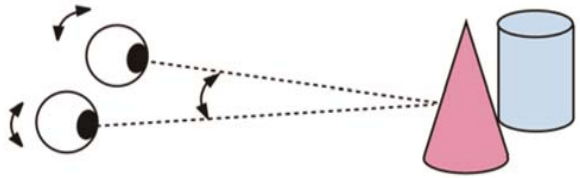
*a. Human 3D perception*

*b. Super multi-view display*

*c. Electronic holographic display*

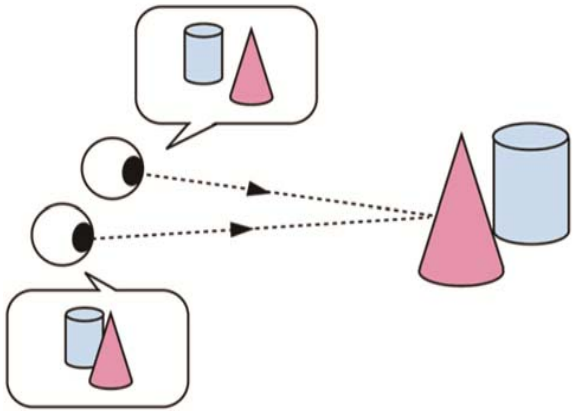
***2. Creation of new values using 3D displays***

# 3D Perception: Physiological Factors



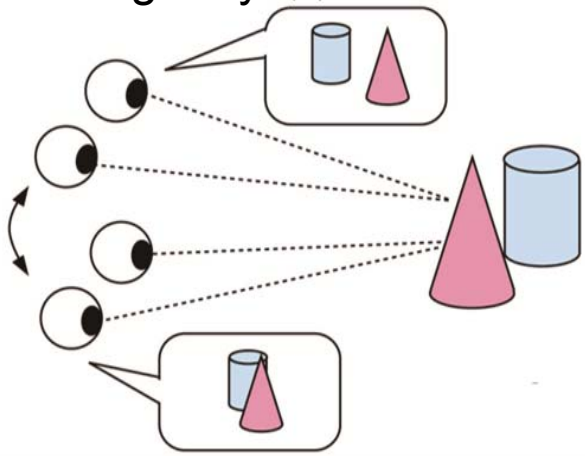
## Vergence

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

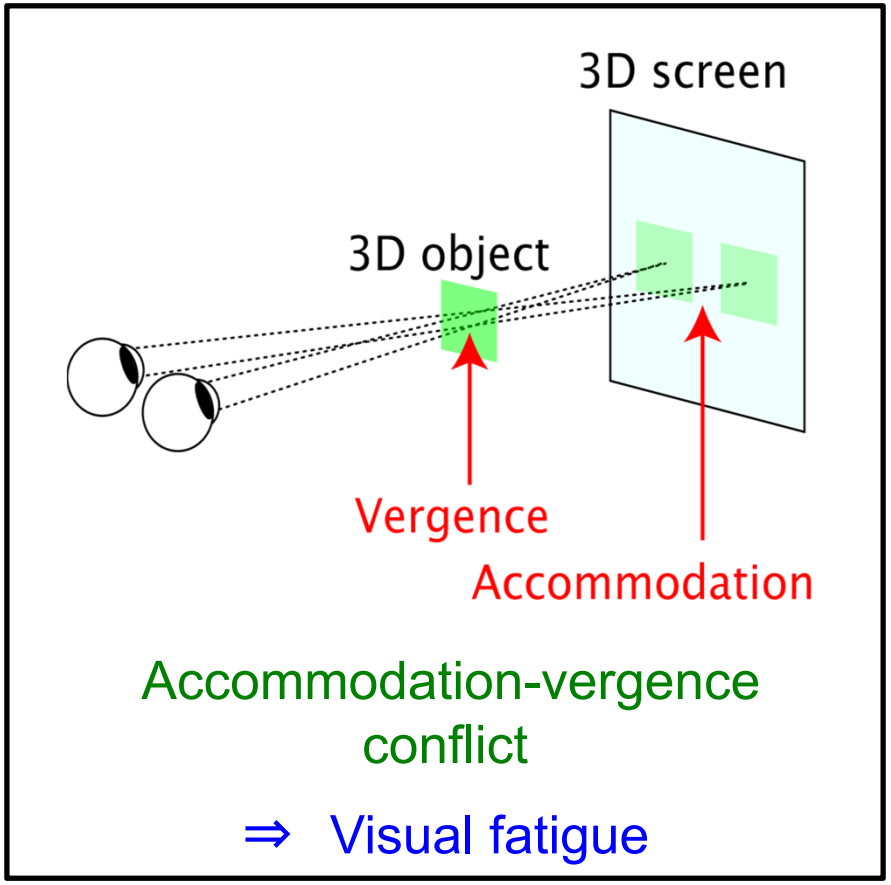
the change in a retinal image due to the movement of eyes

## Accommodation

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

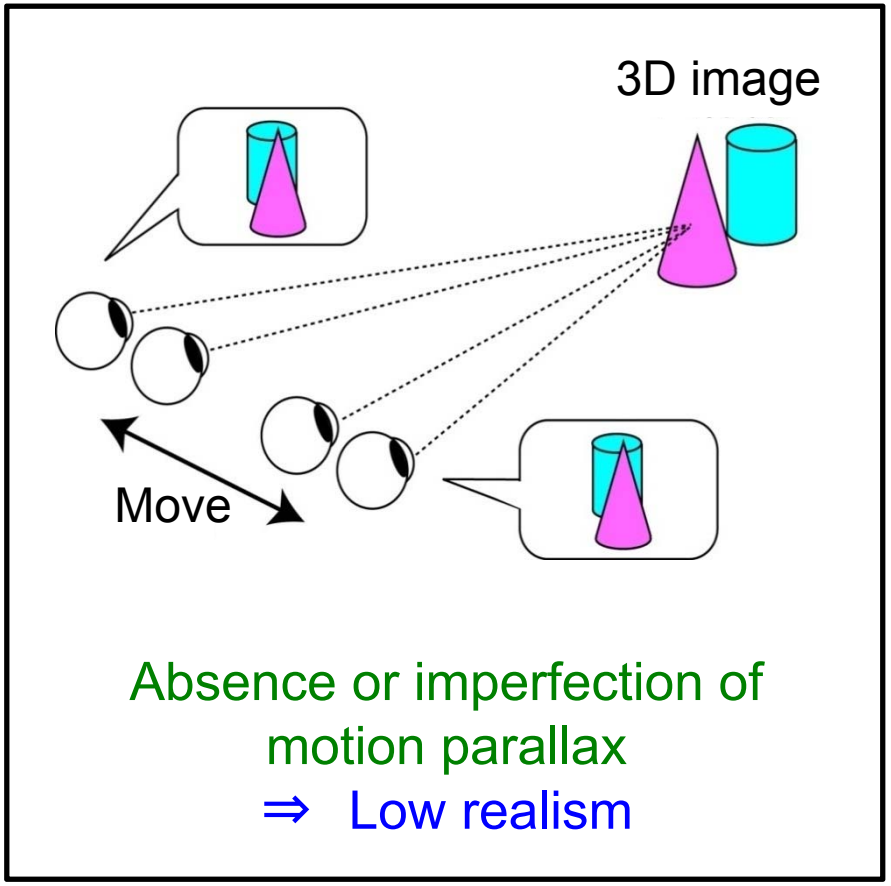
*Harmony among these four factors is the key to developing comfortable 3D displays.*

# Problems of Conventional 3D Displays




Accommodation-vergence conflict

⇒ Visual fatigue



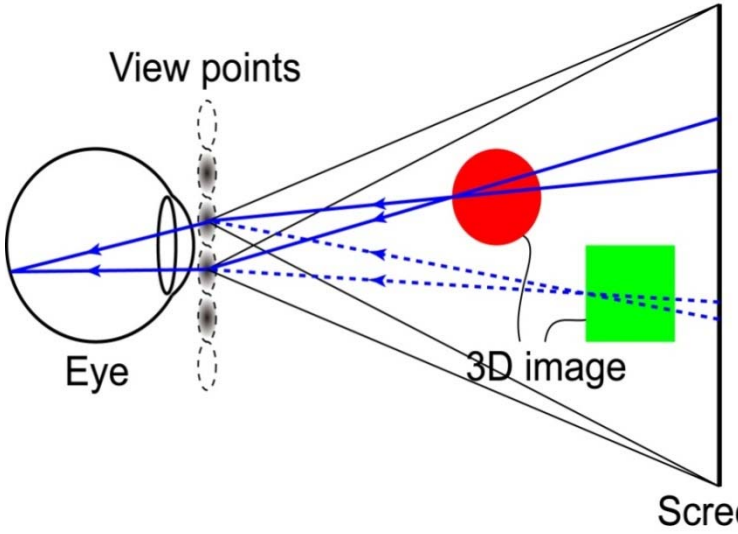

Absence or imperfection of motion parallax

⇒ Low realism

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

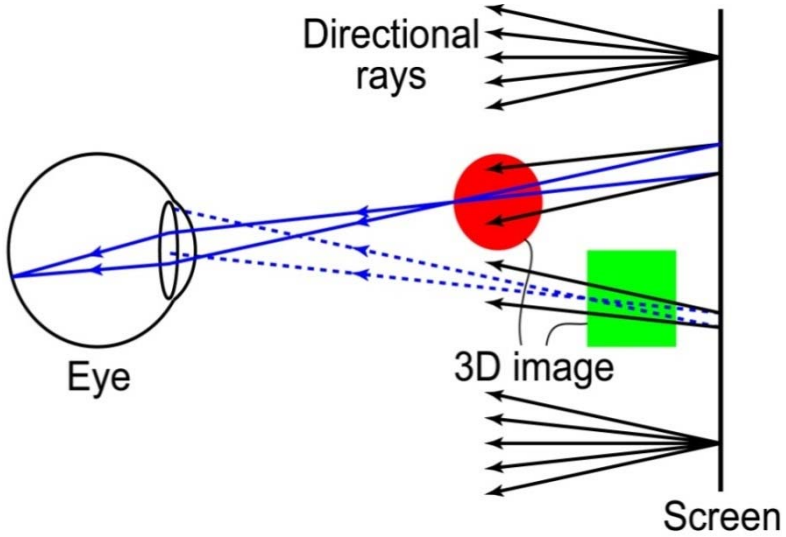
# Super Multi-View Display

## SMV (Super Multi-View) Display




The interval of viewing points is made smaller than the pupil diameter, i.e. < 5 mm.
A large number of parallax images (perspective projections) are displayed to corresponding viewing points.

## HDD (High-Density Directional) Display




The sampling pitch of the ray proceeding direction is made small, i.e. < 0.4°.
A large number of directional images (orthographic projections) are displayed with nearly parallel rays.

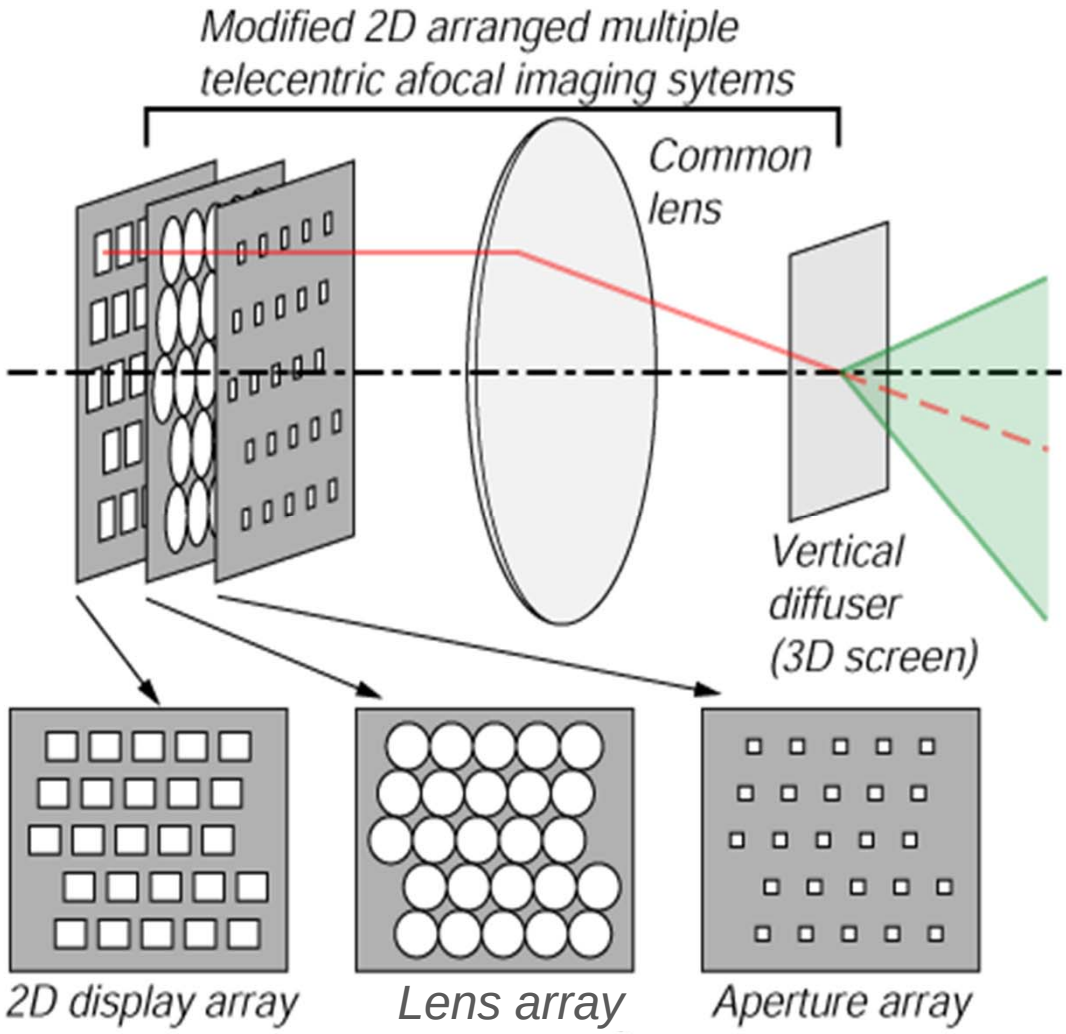
Required number of images: approximately 50 ~ 100（horizontally）

*The fundamental idea: "When two or more rays passing through the same point in space enter the pupil simultaneously, the eye can focus on that point."*
*Extreme smooth motion parallax is also obtained.*

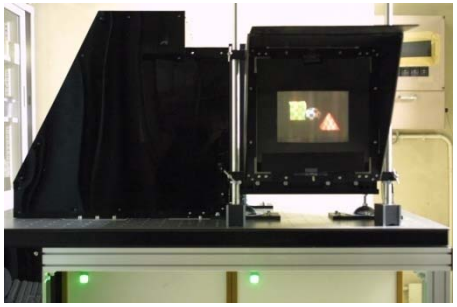
# Systems for SMV/HDD Displays

1. Multi-projection system
2. Flat-panel system
3. Time multiplexing system
4. Hybrid system
5. Reduced-view system

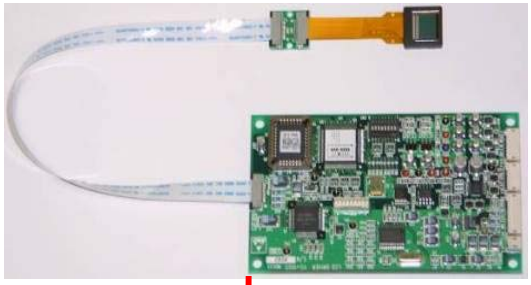
# Multi-Projection System



# Prototype Multi-Projection HDD Displays

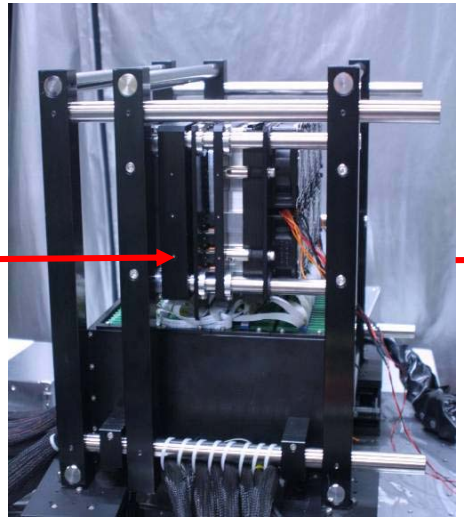
| | | | |
|---|---|---|---|
| Number of ray directions | 64 | 128 | 128 |
| Horizontal ray angle pitch | 0.34º | 0.23º | 0.28º |
| Horizontal viewing angel | 21.6º | 29.6º | 35.7º |
| 3D resolution | ~QVGA | ~QVGA | SVGA |
| Screen size | 9.25” | 13.2” | 12.8” |
| Photo |  |  |  |

# 128-direction QVGA Display



0.44” color LCD
Resolution: ~QVGA
（SONY　LCX033AK）

16×8 LCD panels with modified 2D arrangement



Optical engine

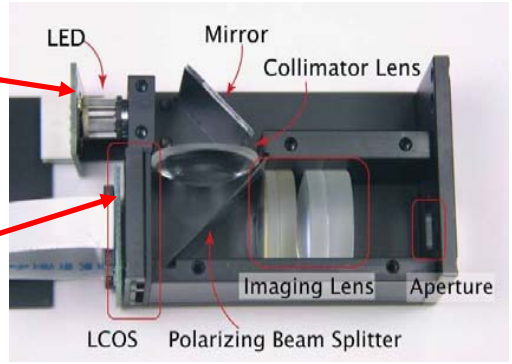
Display system

H. Nakanuma, H. Kamei, Y. Takaki, Proc. SPIE **5664**, 28 (2005)

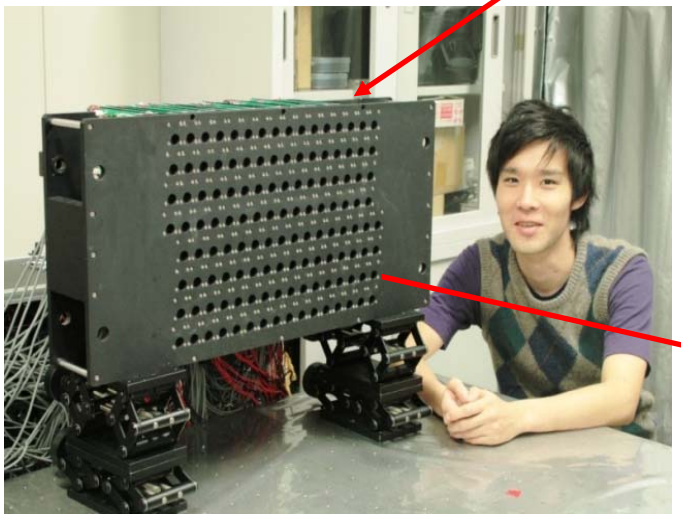
# 128-direction SVGA Display

RGB LED

0.49” LCOS
(MicroDisplay Tec.)
Resolution : 800 × 600
Frame rate: 180 Hz
(Field Sequential Color)




Small projector unit
$26 \times 38 \times 63$ mm$^3$

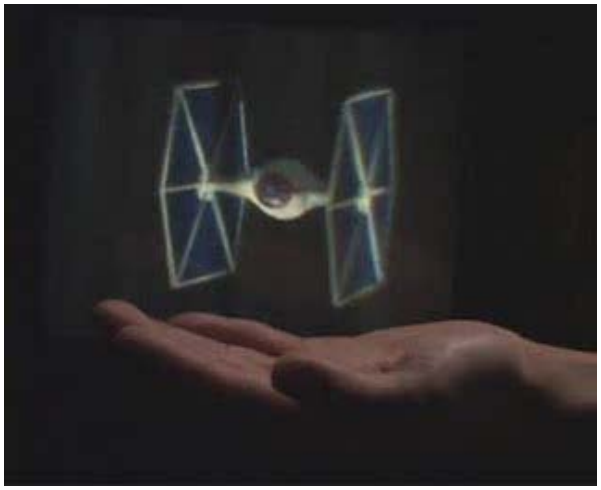


16×8 projector units
with modified 2D arrangement

Display system

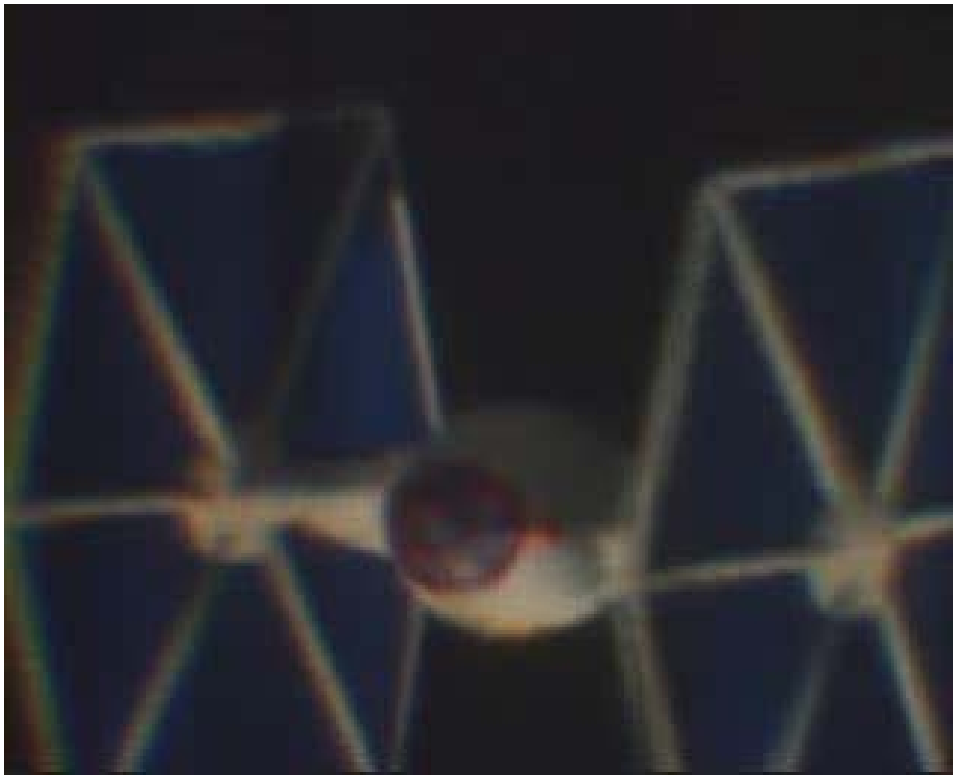
K. Kikuta and Y. Takaki, Proc. SPIE **6490**, 64900U (2007)

# 3D images by 64-direction QVGA Display



3D image with absolute depth position

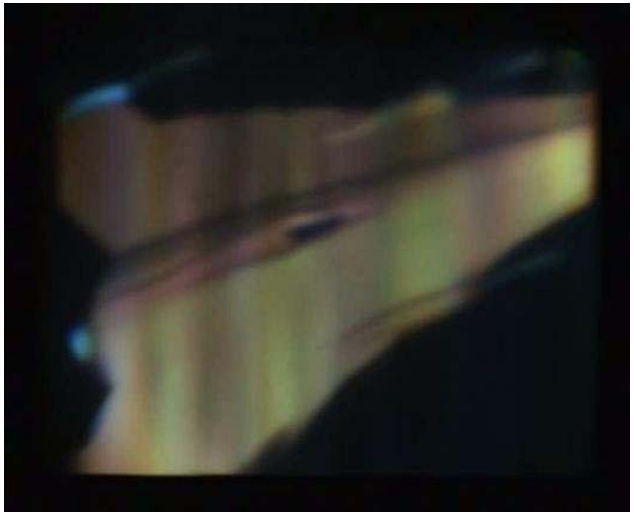
Wide observation depth range

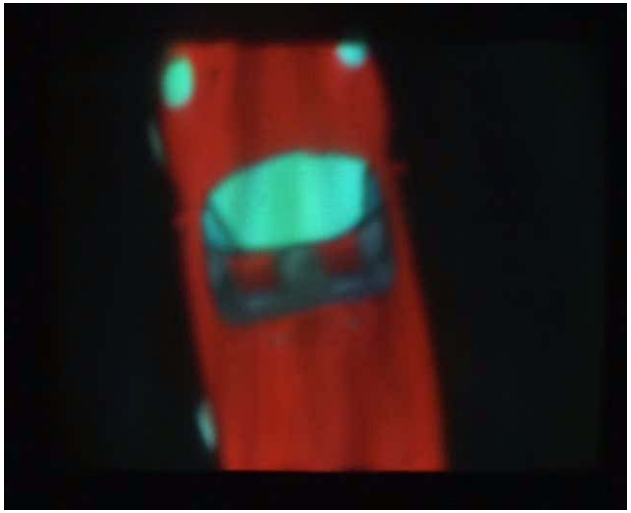


Focus changes between body and wing

Y. Takaki, Proc. IEEE **94**, 654 (2006)

# 3D images by 128-direction QVGA Display





Interactive Manipulation of 3D images

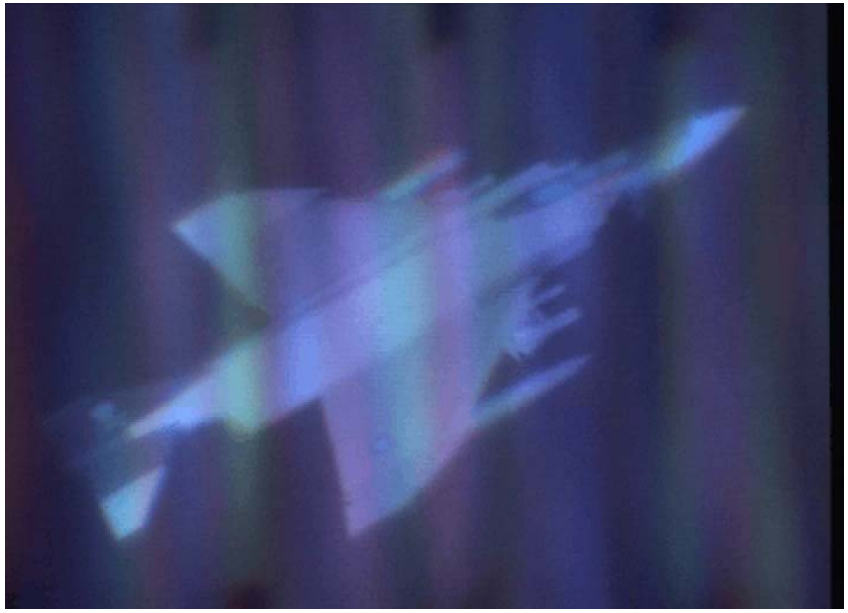
PC Cluster for Real-Time
3D Image Generation

Fingertip Manipulation

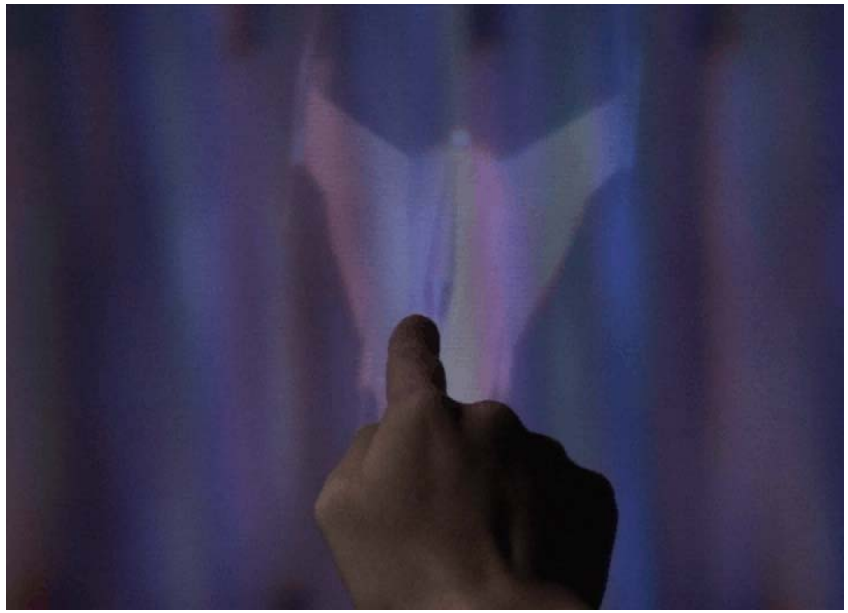
3D Drawing by Fingertip


Fingertip Detection System

# 3D Images by 128-direction SVGA Display

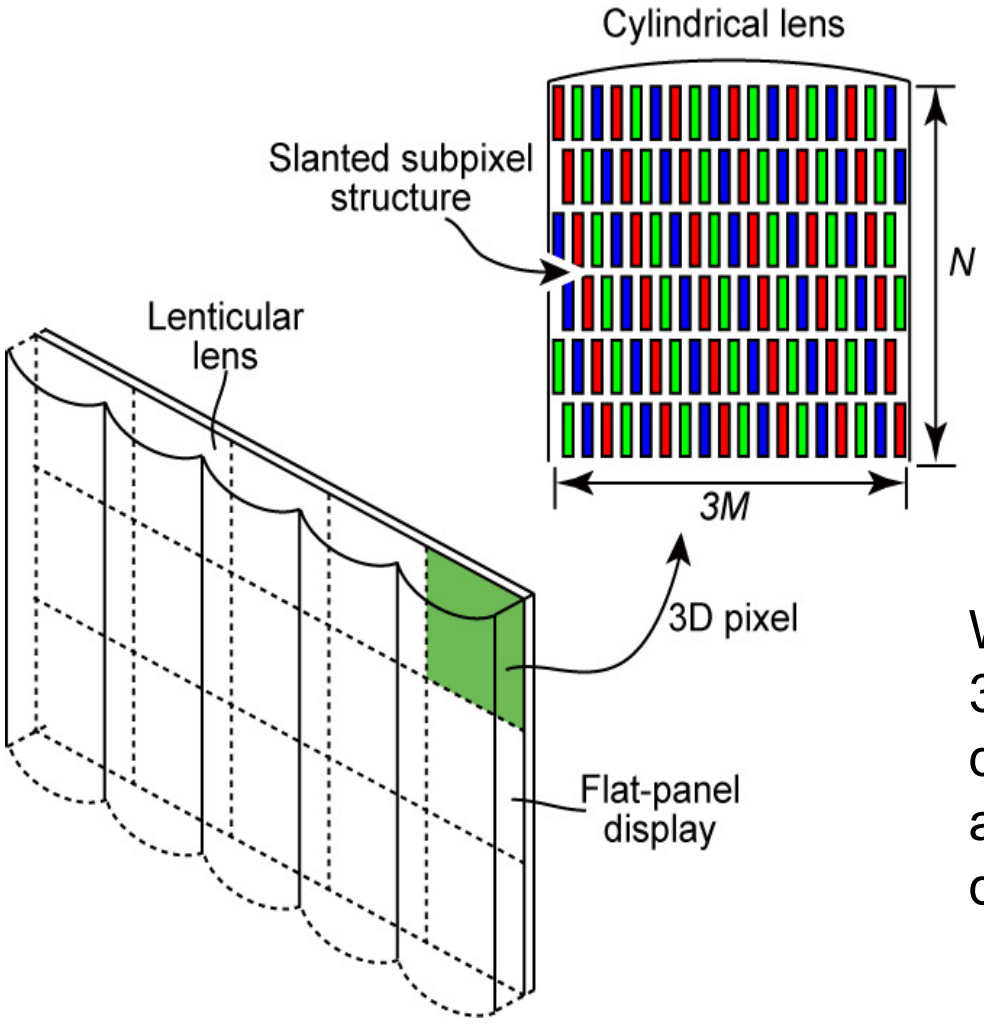


3D input device: 3D mouse
3D data format: VRML
Frame rate: 15-20 fps



3D input device: fingertip detection system
3D data format: VRML
Frame rate: 15-20 fps

# Flat-panel System




## Slanted subpixel arrangement:

The horizontal positions of all subpixels are different for each color.

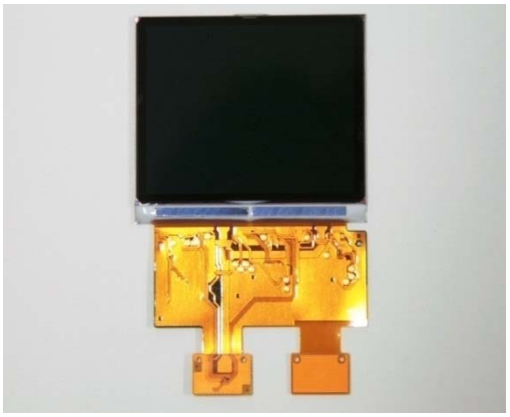
The light-emitting area of the subpixels is continuous in the horizontal direction in each color.

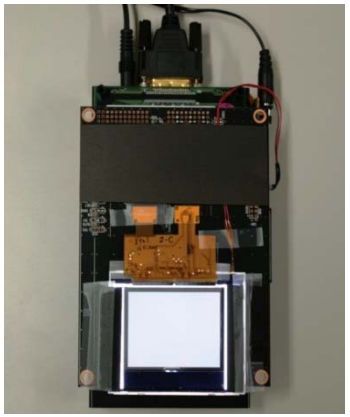
When each 3D pixel consists of $3M \times N$ subpixels, rays are emitted in different $M \times N$ horizontal directions, and $M \times N$ images are displayed in different horizontal directions.

Y. Takaki, J. Soc. Inf. Display **18**, 476 (2010)

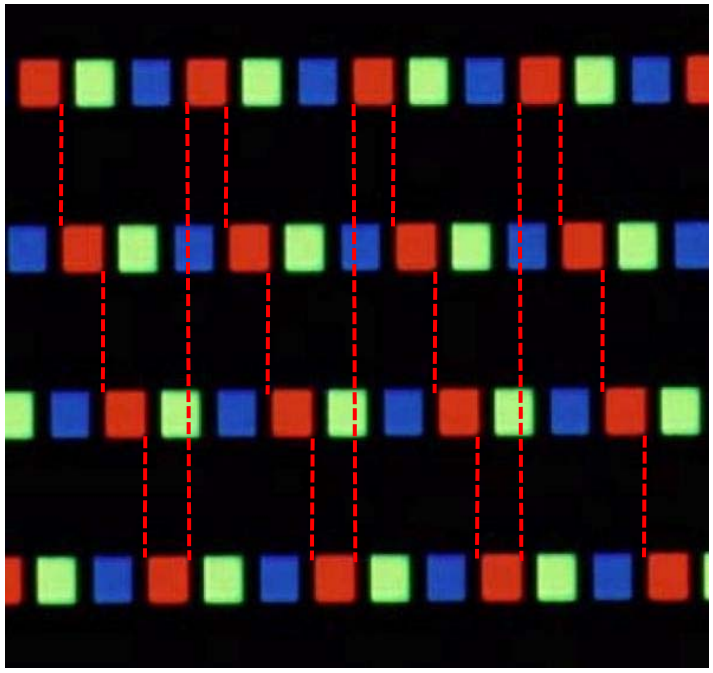
# Slanted Subpixel Arrangement

| | |
|---|---|
| Screen size | 2.57” |
| Number of views | 16 |
| 3D resolution | 256 × 192 |
| Pixel density | 500 ppi |
| Width of subpixel | 12.75 μm |
| Width of black matrix region | 4.25 μm |



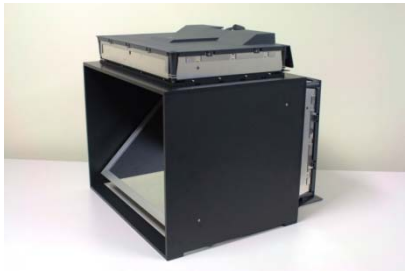


Joint development with Seiko EPSON



Photograph of subpixel structure of LCD panel for 16-view display

# Prototype Flat-panel HDD displays

| | | | |
|---|---|---|---|
| Number of ray directions | 72 | 72 | 30* |
| Horizontal ray angle pitch | 0.38º | 0.38º | 0.71º |
| Horizontal viewing angel | 27.6º | 27.6º | 21.2º |
| 3D resolution | 320 × 400<br>~half VGA | 640 × 400<br>~VGA | 256 × 128 |
| Screen size | 22.2” | 22.2” | 7.2” |
| Photo |  |  |  |

*Joint development with NTT DoCoMo

# 72-direction Display

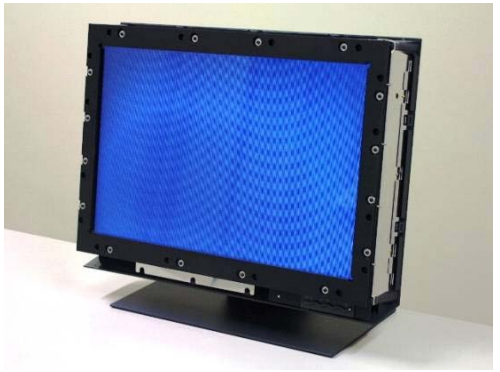
High-resolution LCD

| | |
|---|---|
| Resolution | 3, 840 × 2,400 (WQUXGA) |
| Pixel pitch | 0.1245 mm |
| Subpixel pitch | 0.0315 mm |
| Screen size | 22.2” |

Slanted lenticular sheet

| | |
|---|---|
| Number of cylindrical lenses | 320 |
| Lens pitch | 1.494 mm |
| Lens surface | aspherical |
| Slant angle | 9.46º |

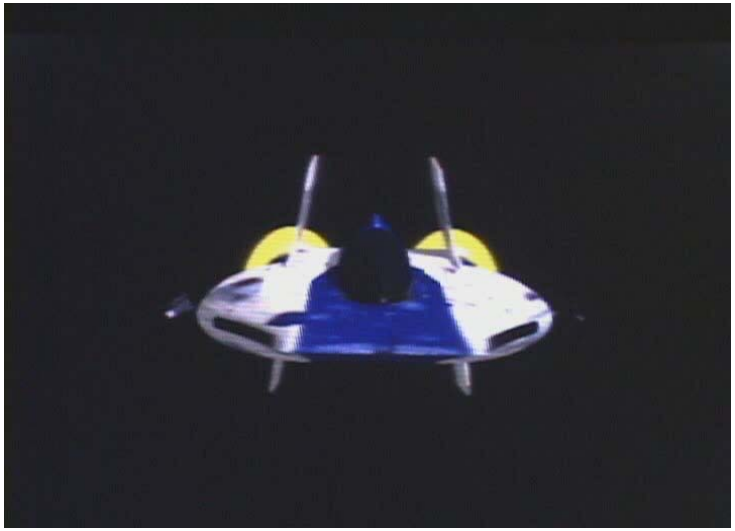
72-directional HDD display

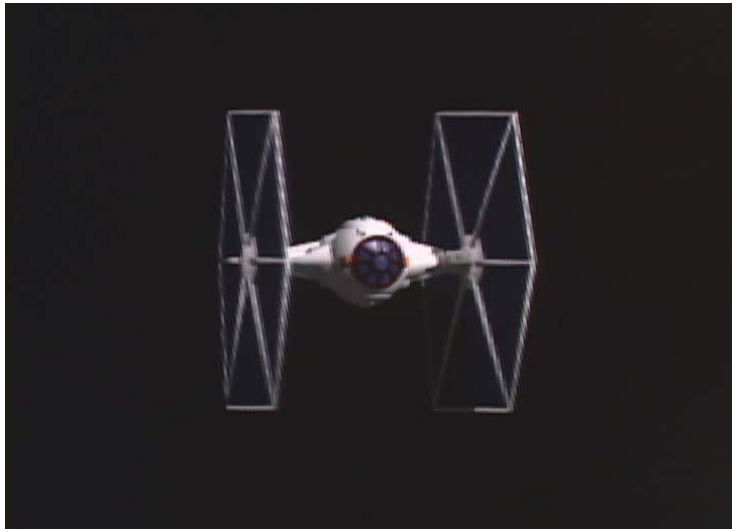


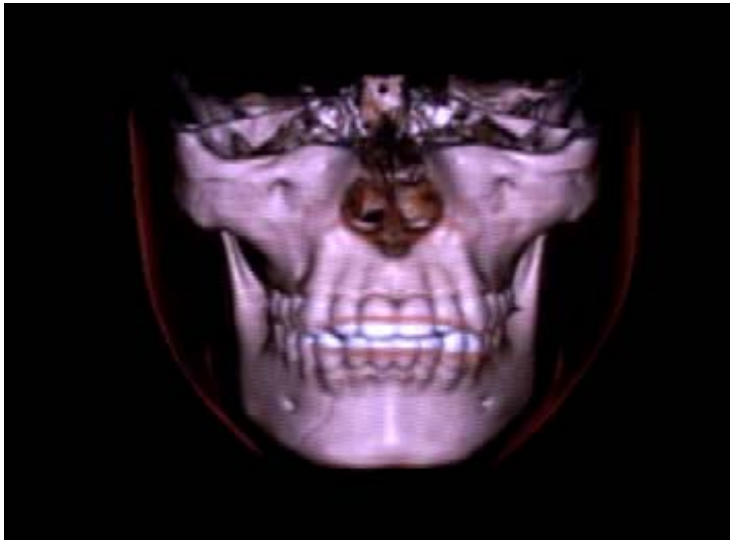
| | |
|---|---|
| *M* | 12 |
| *N* | 6 |
| Number of ray directions | 72 |
| Number of 3D pixels | 320 × 400 |
| Horizontal ray angle pitch | 0.38º |
| Horizontal viewing angle | 27.6º |
| Screen size | 22.2” |

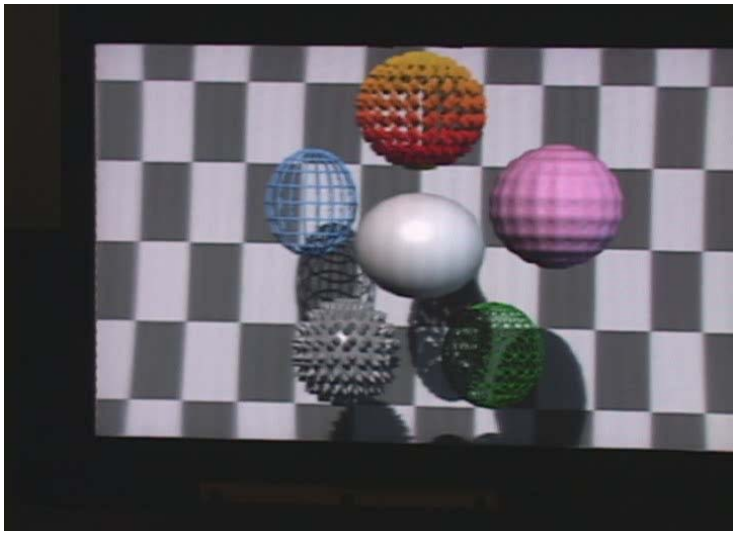
Y. Takaki, Proc. SPIE **5664**, 56 (2005)

# 3D Images by 72-direction Display



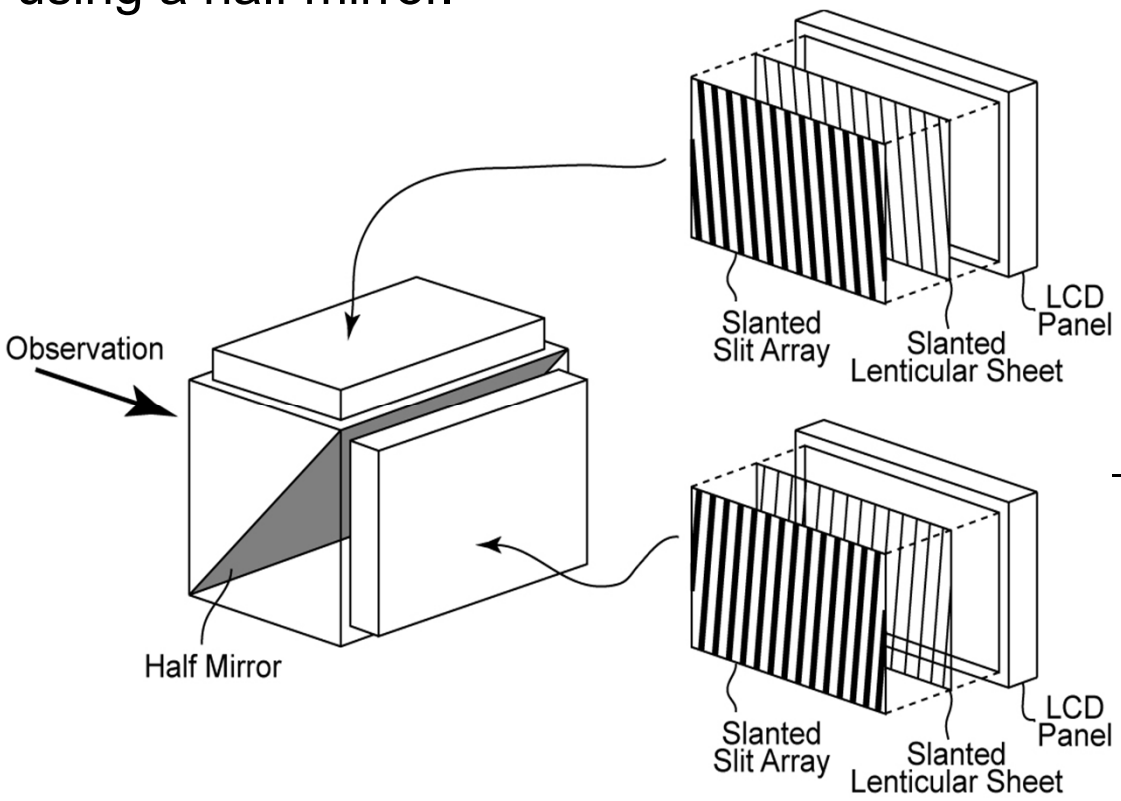




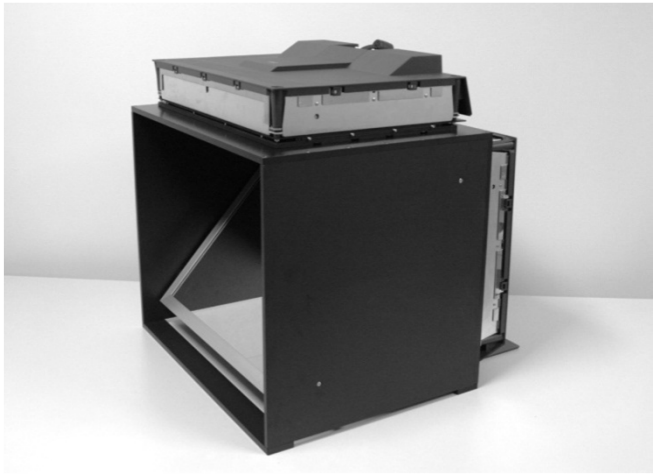


# 72-direction VGA Display

Two 72-direction displays are combined using a half mirror.



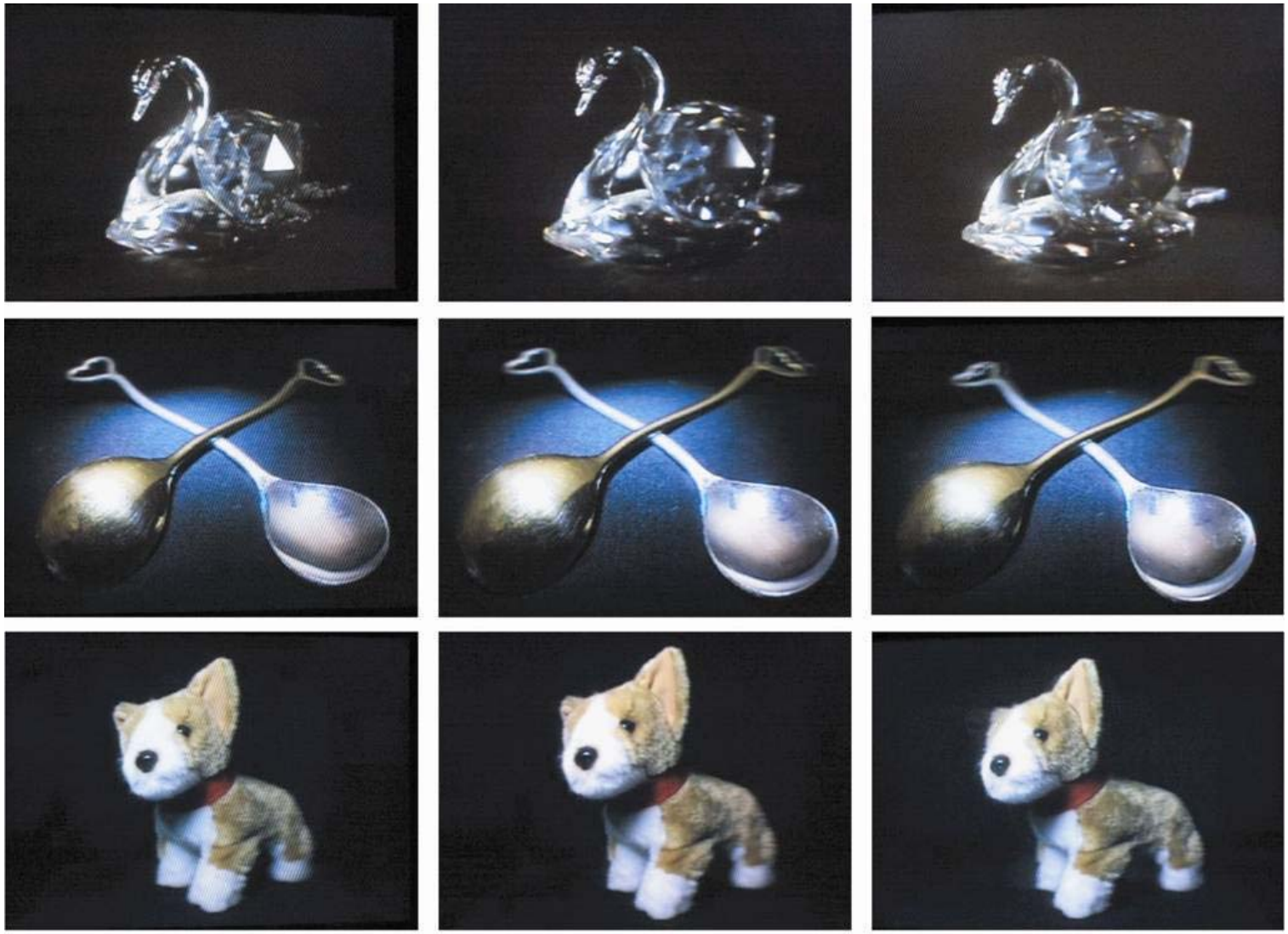

| Specifications | |
|---|---|
| 3D resolution | 640 × 400 |
| Number of ray directions | 72 |
| Horizontal ray angle pitch | 0.38° |
| Horizontal viewing angle | 27.6° |
| Screen size | 22.2” |



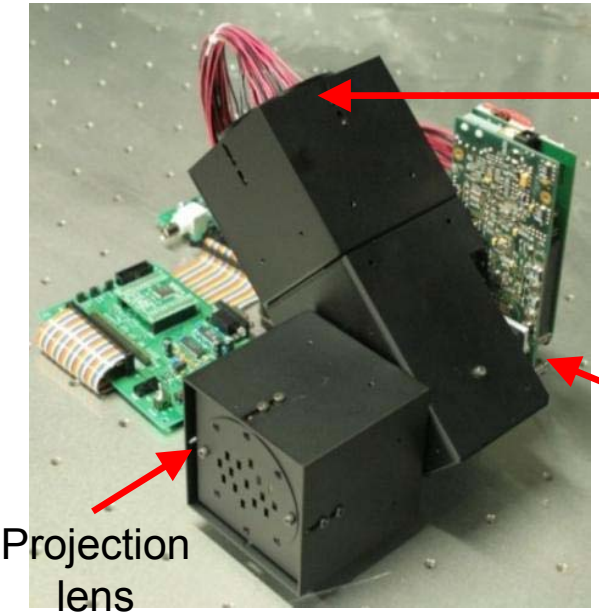
Slit arrays are located on the focal planes of the lenticular lenses to reduce crosstalk among 3D pixels.

Y.Takaki and T.Dairiki, Proc. SPIE **6055**, 60550X (2006)

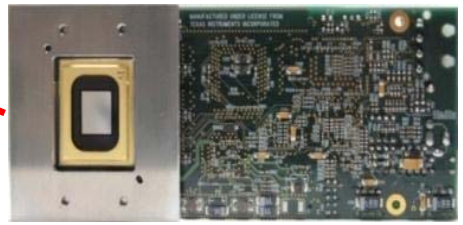
# 3D Images by 72-direction VGA Display



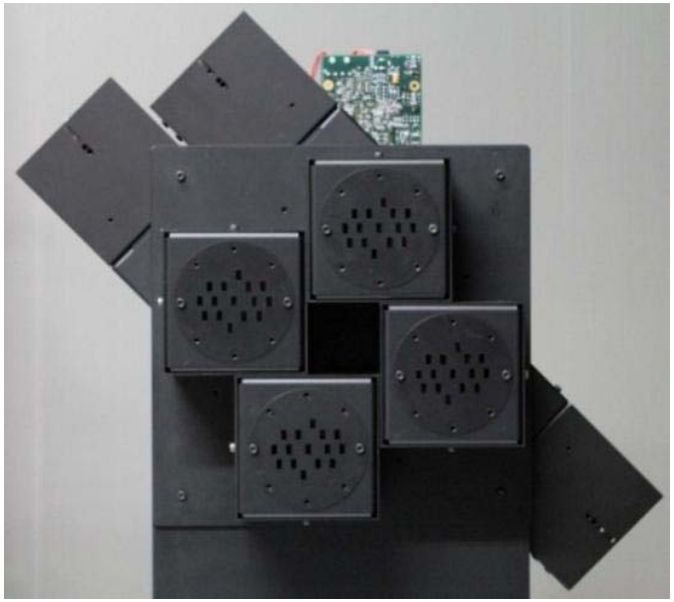
# Time Multiplexing System




15 LEDs



High frame rate DMD
Discovery™1100



## Time-multiplexed Display Module

| | |
|---|---|
| Number of images | 15 |
| Resolution | XGA |
| Frame rate | 60 fps |
| Number of gray levels | 5 bits |
| Frame rate of DMD | 900 fps |
| Number of LEDs | 15 |

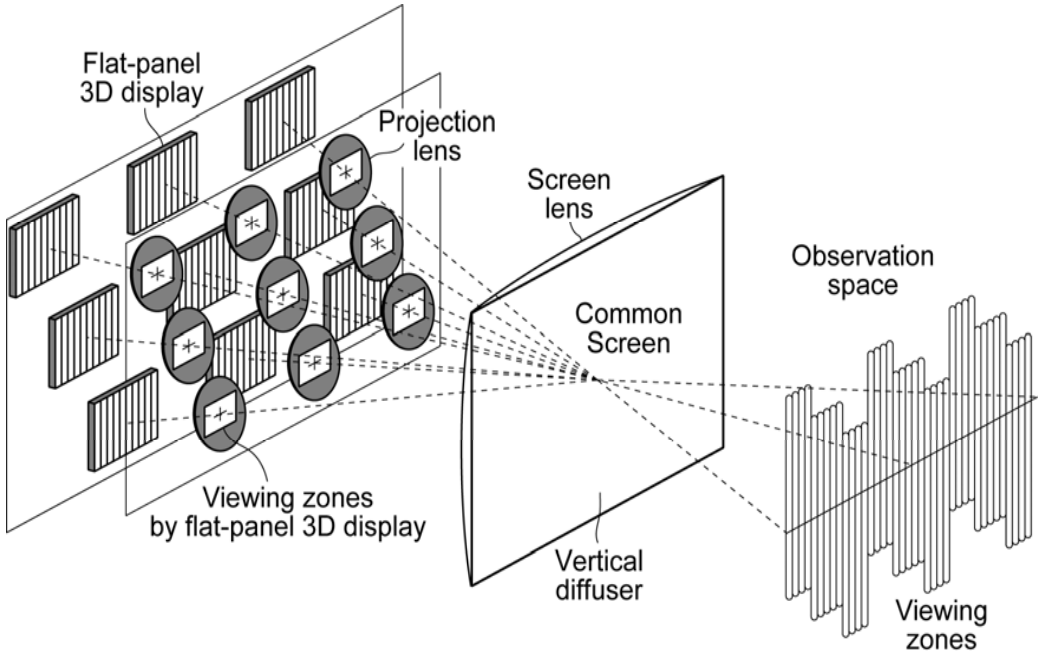
## Optical Engine

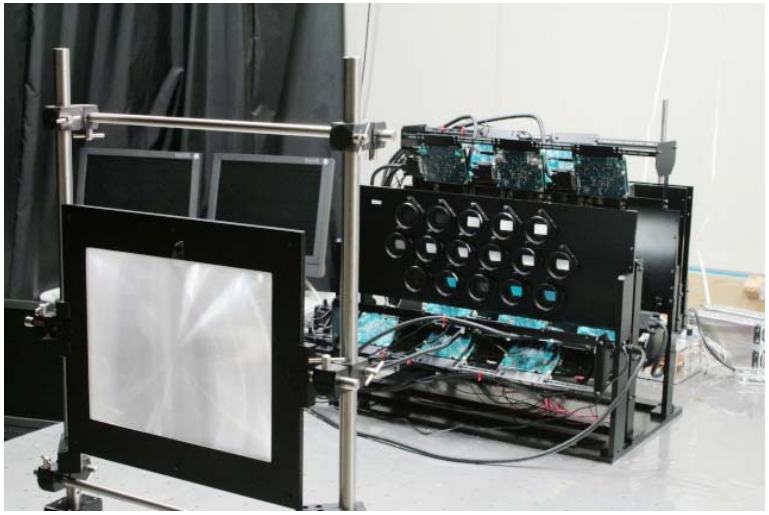
| | |
|---|---|
| Number of images | 60 |
| Horizontal display angle pitch | 0.31˚ |
| Horizontal viewing angle | 18.3˚ |
| Resolution | XGA |
| Frame rate | 60 fps |
| Number of modules | 4 |

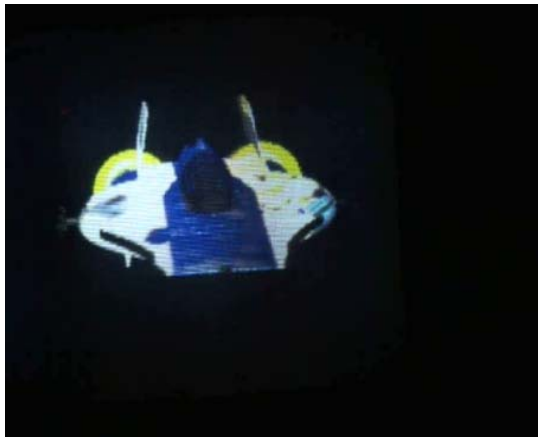
T. Kanebako and Y. Takaki, Proc. SPIE **6803**, 68030P (2008)

# Hybrid System

*Multiple flat-panel 3D displays are combined by multi-projection system.*



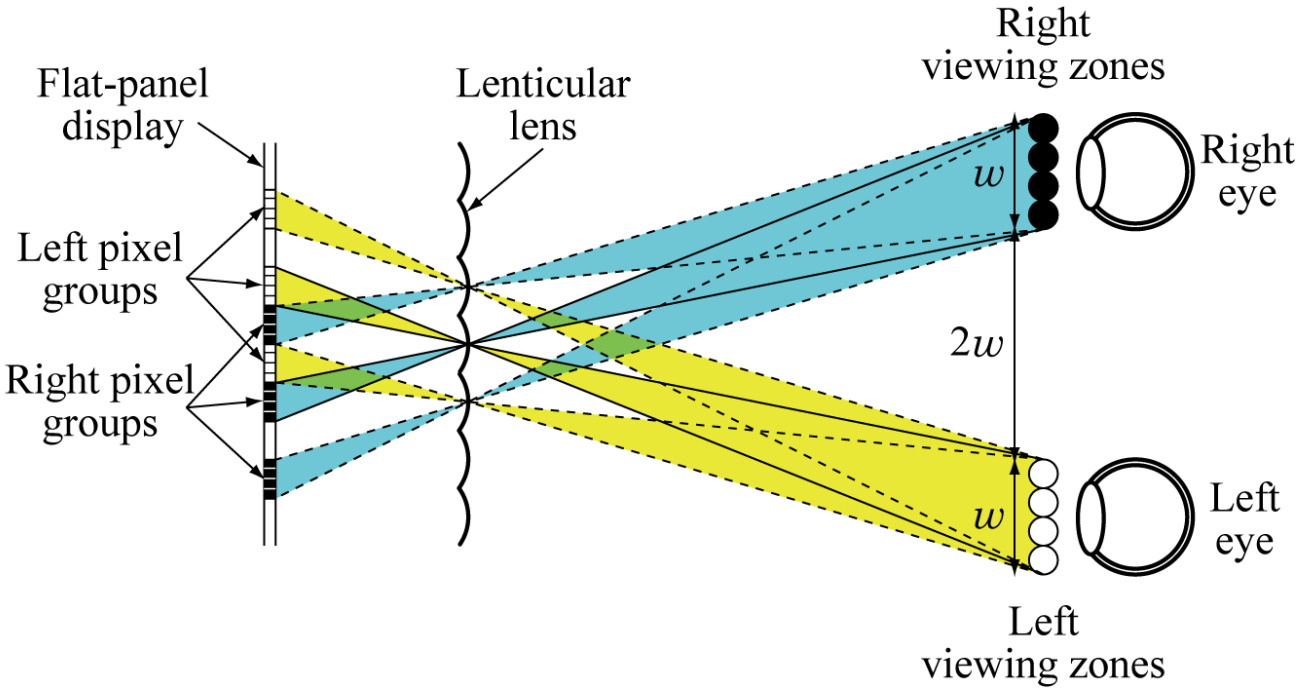





| | |
|---|---|
| Number of views | 256 |
| 3D resolution | 256 × 192 |
| Screen size | 10.3 in. |
| Interval of views | 1.31 mm |
| Number of flat-panel 3D displays | 16 |
| Number of views of flat-panel 3D displays | 16 |

Y. Takaki et al., Opt. Express **18**, 8824 (2010)

# Reduced-View SMV Display



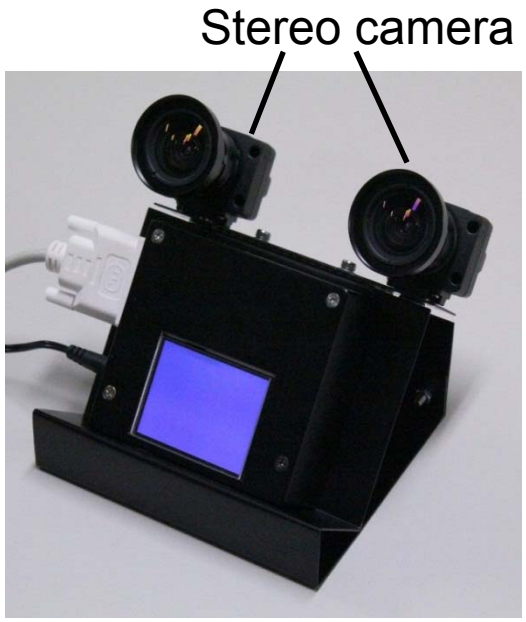

Viewing zones are generated only around left and right eyes.

The resolution required for the flat-panel display is reduced.

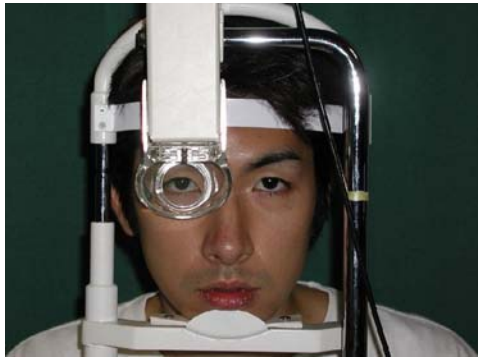
| | |
|---|---|
| Interval of viewing zones | 2.6 mm |
| Number of views (left + right) | 8 + 8 |
| 3D resolution | 256 × 192 |
| Screen size | 2.57 inch |
| Observation distance | 350 mm |

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

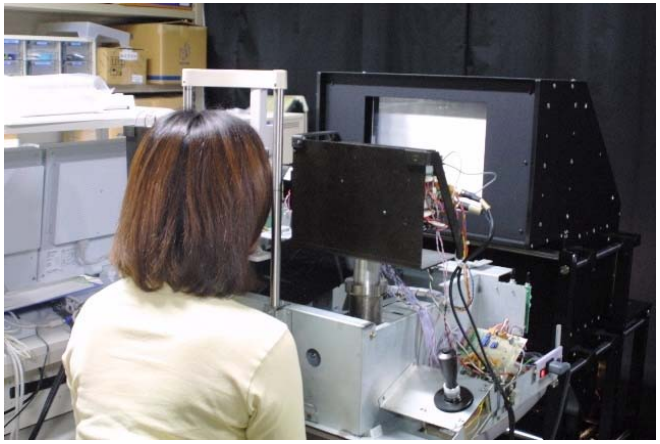
The detection of the viewer's eye positions and the movement of the pixel groups increase the freedom of the viewing position.



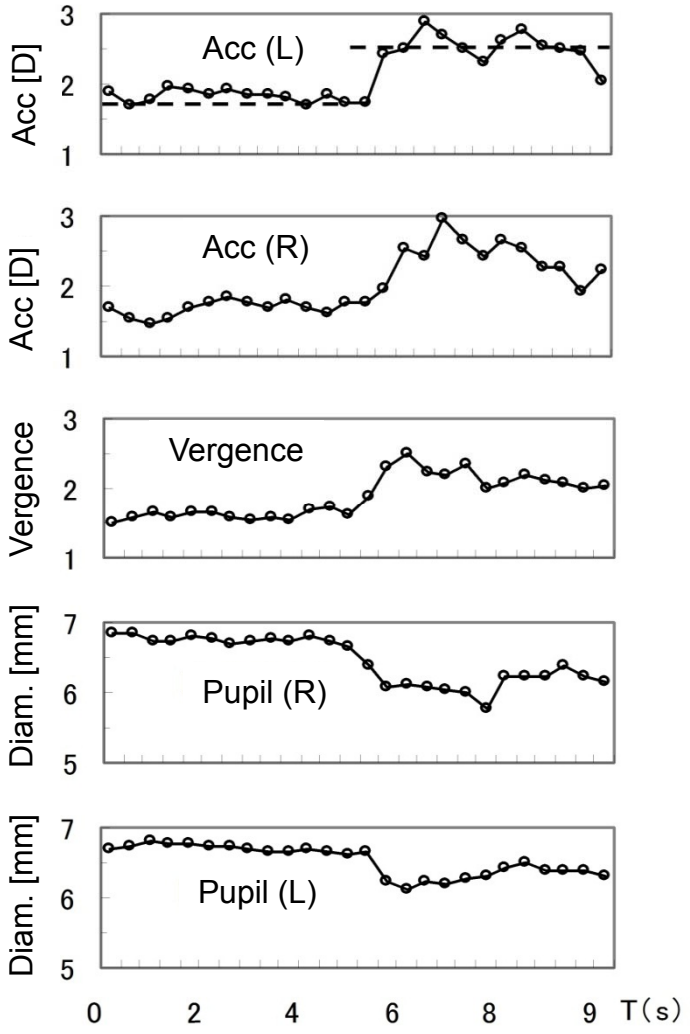
# Accommodation Measurement



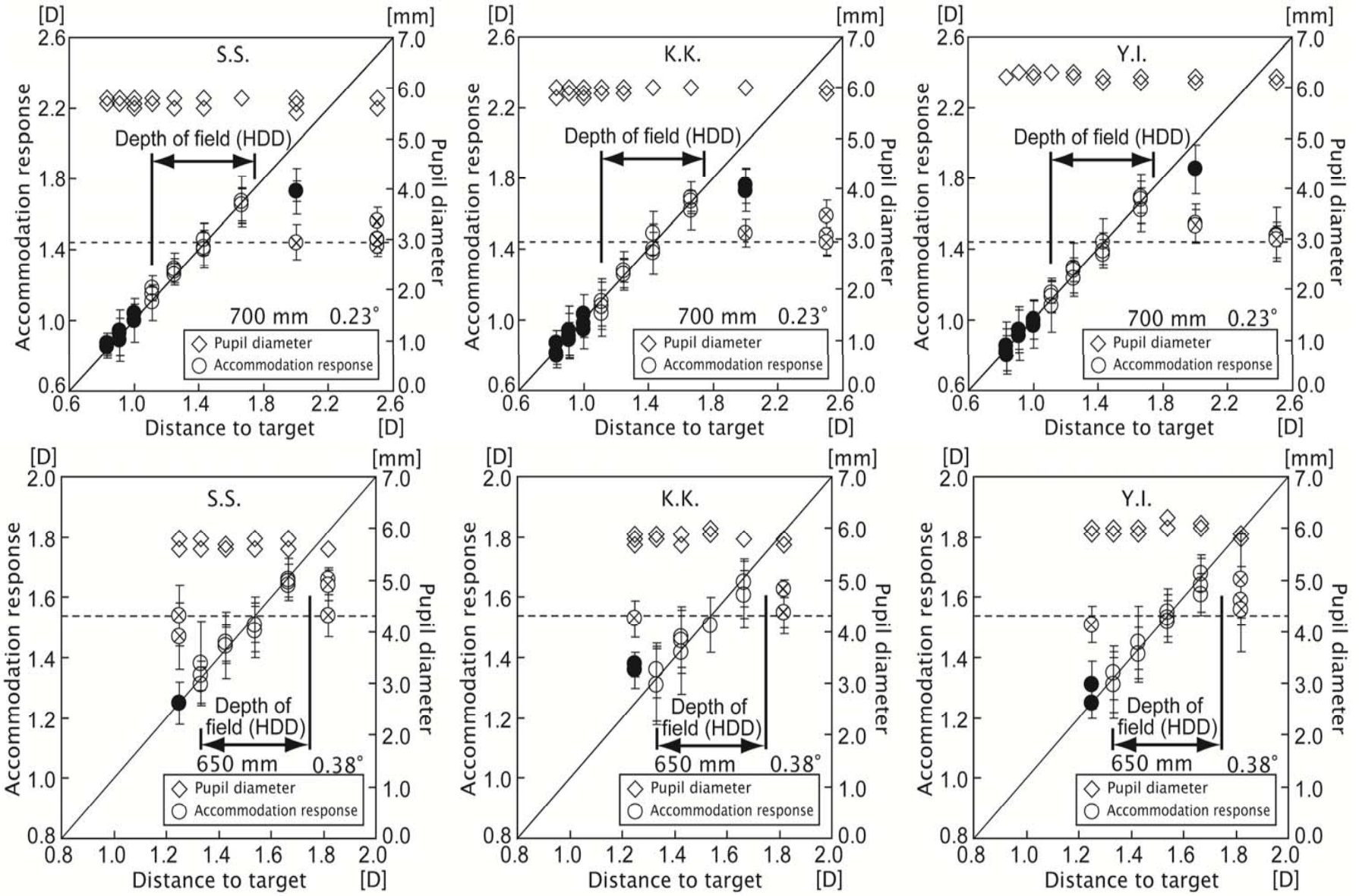
Auto refractometer
FR-5000S
(Grand Seiko Corp.)



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

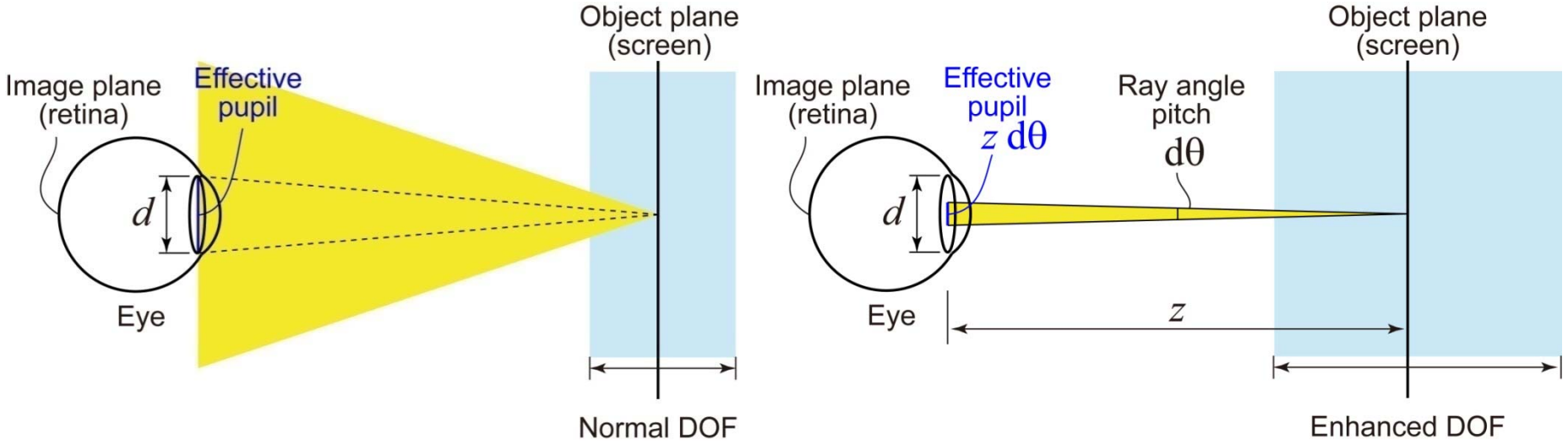


# Results of Accommodation Measurement



# Enhancement of Eye's DOF

Depth of Field (DOF) of an eye-imaging system




Conventional 3D SMV/HDD

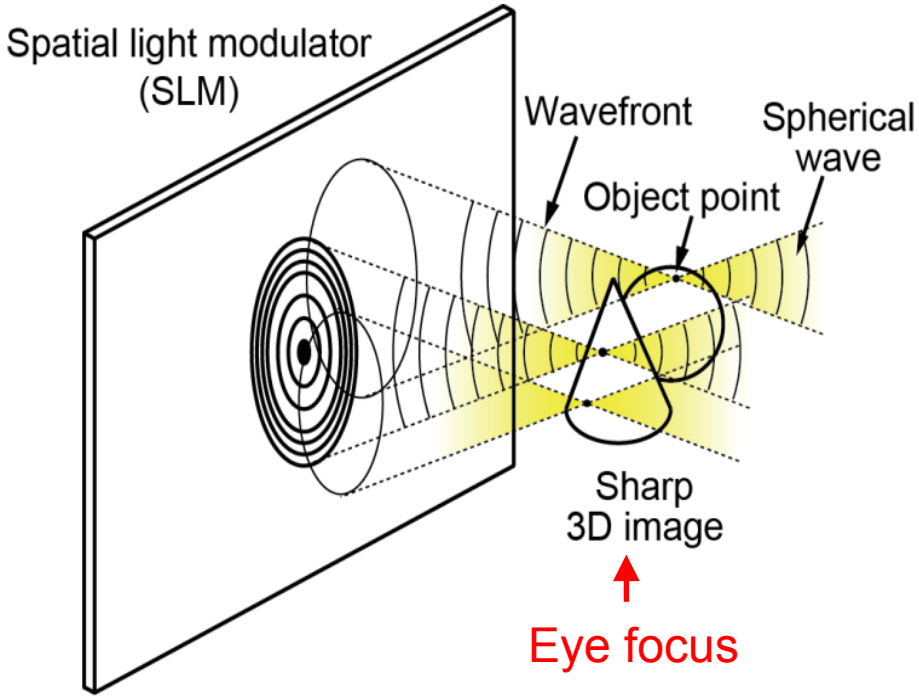
The SMV and HDD display techniques decrease the width of rays at the pupil of an eye, so that the DOF range of an eye-imaging system increases.

When a 3D image is displayed in this enhanced DOF range, the eye can focus on a 3D image and the accommodation-vergence conflict does not occur.

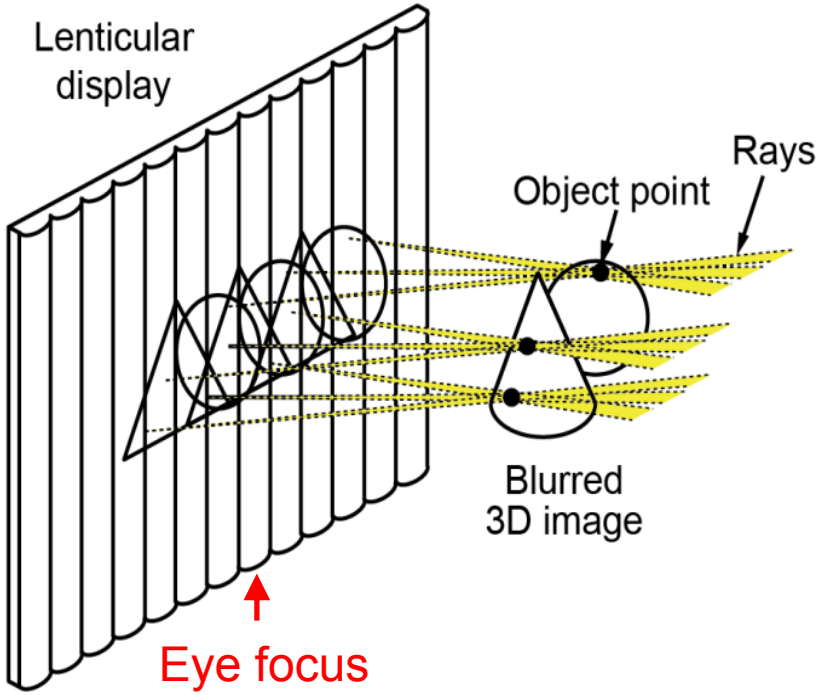
Y. Takaki and H. Kikuta, IDW2006, 1909 (2006)

# Wavefront Reconstruction v.s. Ray Reconstruction

## Wavefront reconstruction
holography

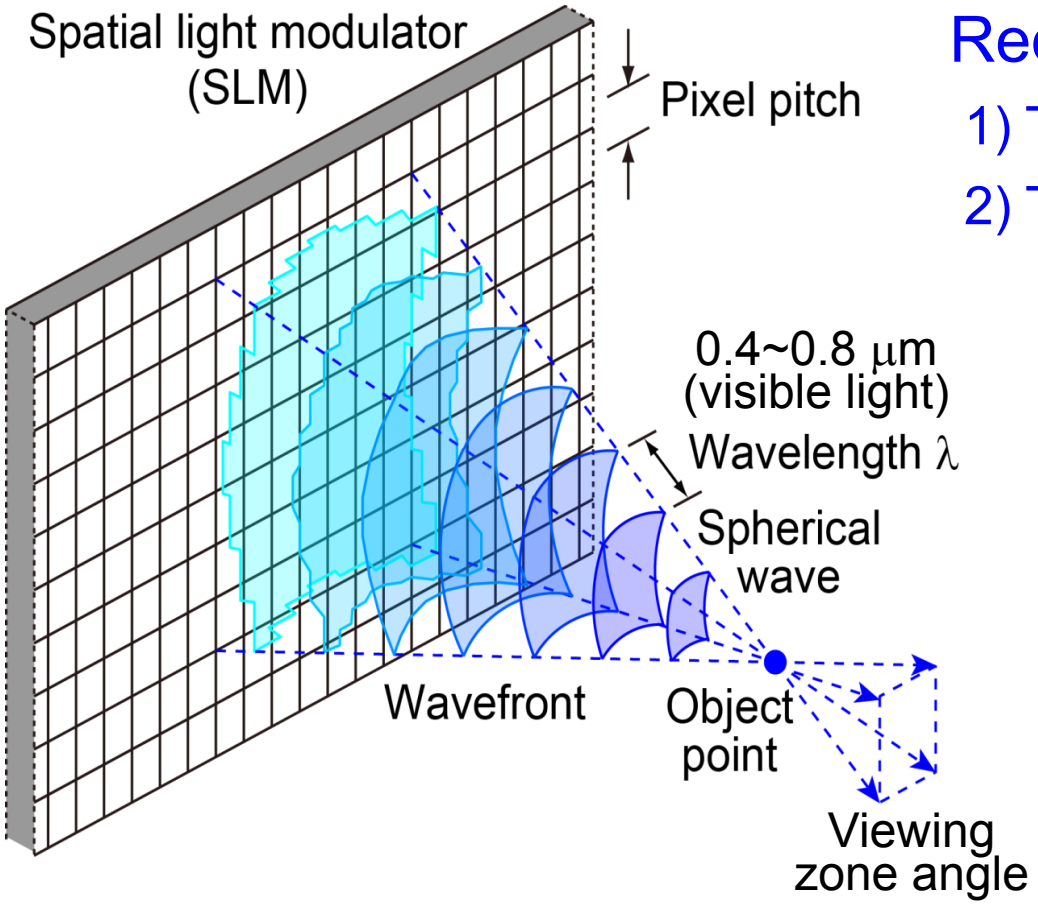



## Ray reconstruction
multi-view, integral imaging




Holographic displays can produce 3D images that are free from the vergence-accommodation conflict.

# Problems of Electronic Holographic Display




## Requirements for SLM:

1) The 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: $\lambda$

Screen 20”, viewing zone angle 30°

Pixel pitch: $p$ = 0.97 μm

Resolution: $N \times M$ = 421,000 × 316,000

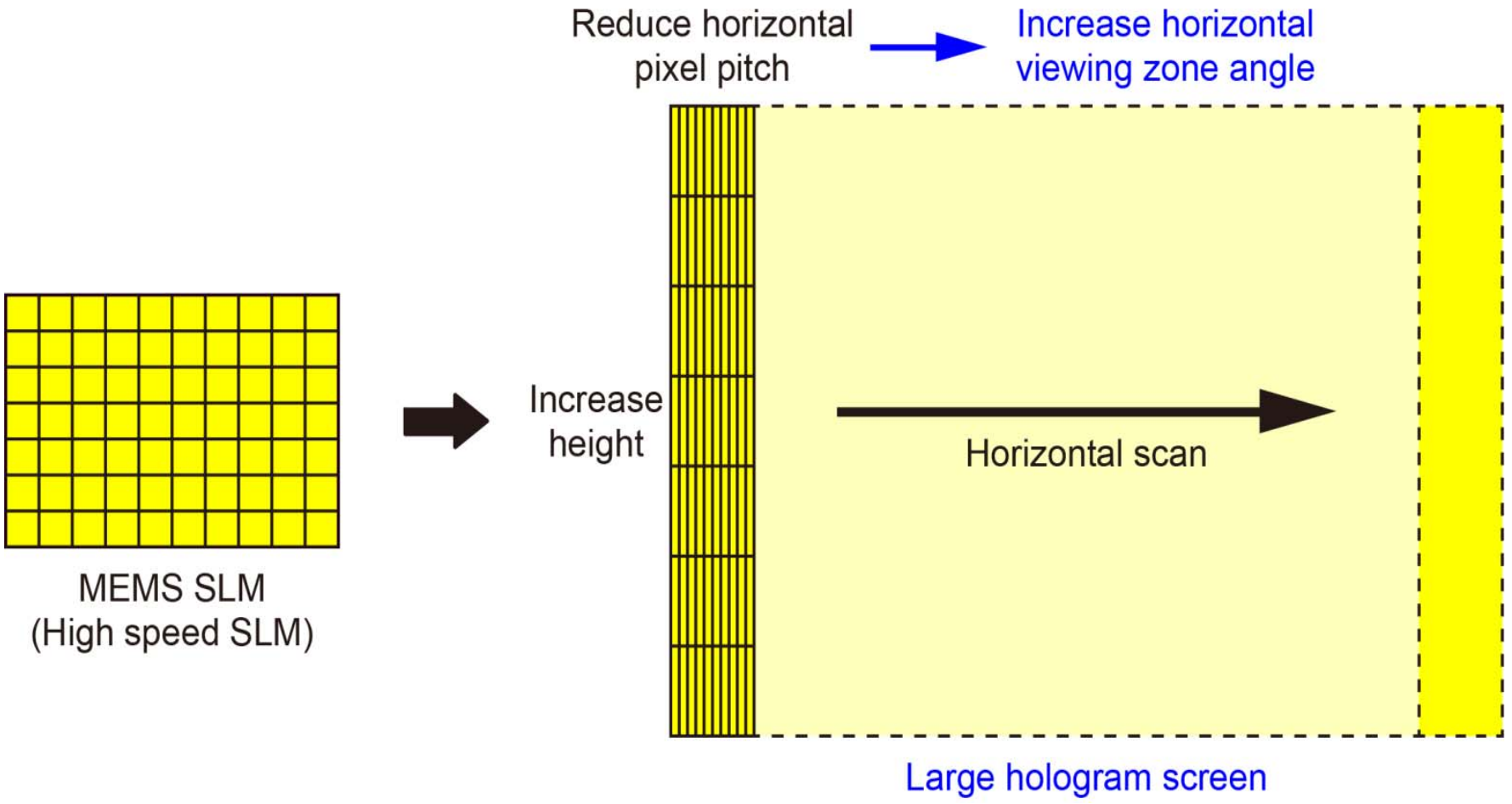
# *Electronic Holographic Display Systems*

*1. Horizontally scanning system*

*2. Resolution redistribution system*

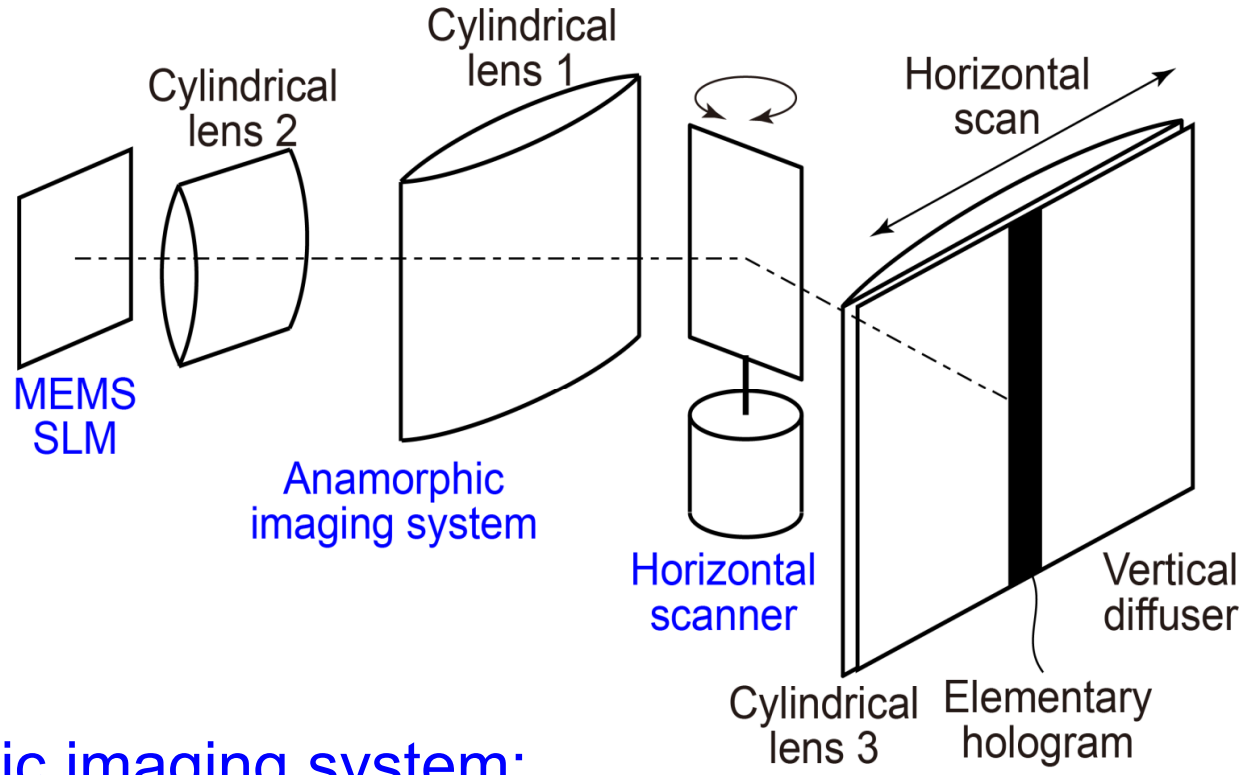
# Horizontal Scanning Holography

## MEMS SLM + 1D Scanning




Y. Takaki et al., Appl. Opt. **48**, 3255 (2009)

# Horizontally Scanning Holography Using MEMS SLM




Anamorphic imaging system:

Horizontal: reduce pixel pitch → Viewing zone angle increases

Vertical: increase image height

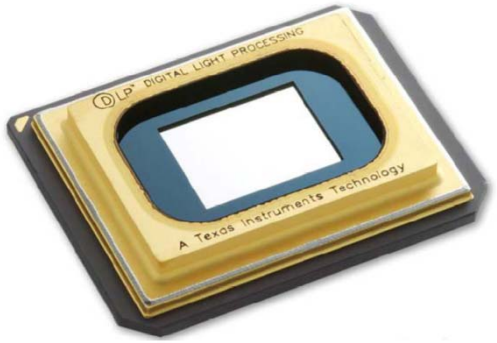
Horizontal Scanning:

Increase image width

→ Screen size increases

# 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 mm$^2$)

## Anamorphic imaging system

$M_x$ = 0.183

$M_y$ = 5.00

Elementary hologram
Size: 2.56 × 52.5 mm$^2$
Horizontal pixel pitch:
2.5 μm
Horizontal viewing angle:
15 °

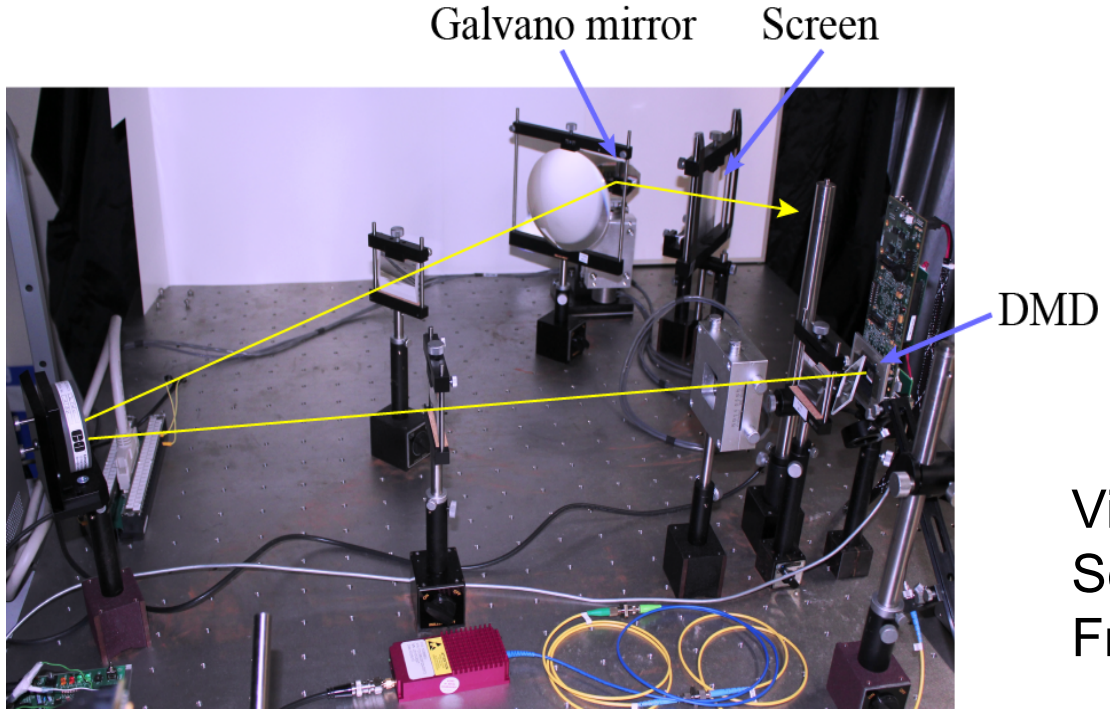
## Horizontal scanner

Galvano mirror
MicroMax™Series671

Scanning frequency: 60 Hz
Scan angle: ±18.1°
Screen size: 4.3 in
(96.9 × 52.5 mm$^2$)
Number of elementary holograms: 222

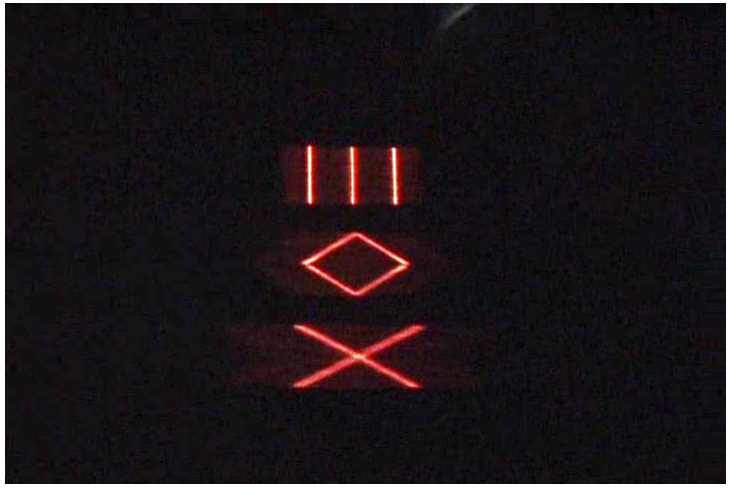
Y. Takaki et al., Opt. Express **18**, 11327-11334 (2010)

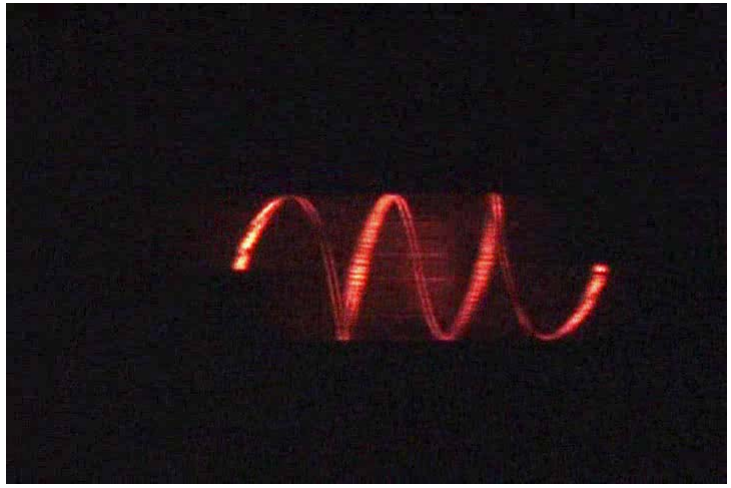
# Reconstructed Image

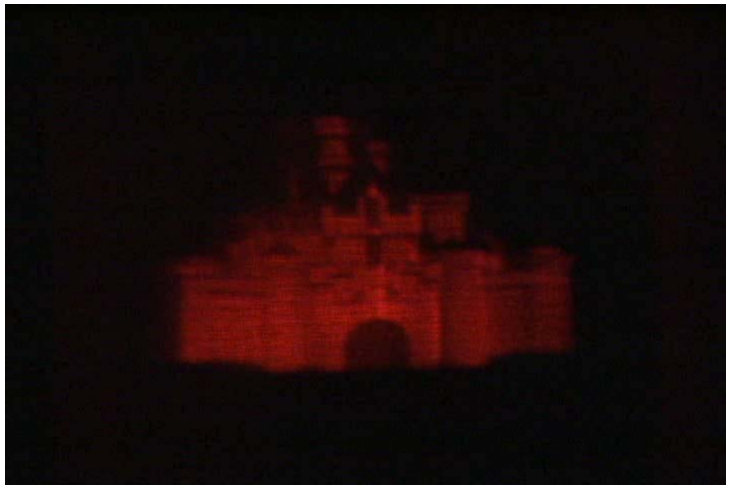



Viewing zone angle: 15°
Screen size: 4.3 in
Frame rate: 60 Hz

# Movies: Reconstructed Images





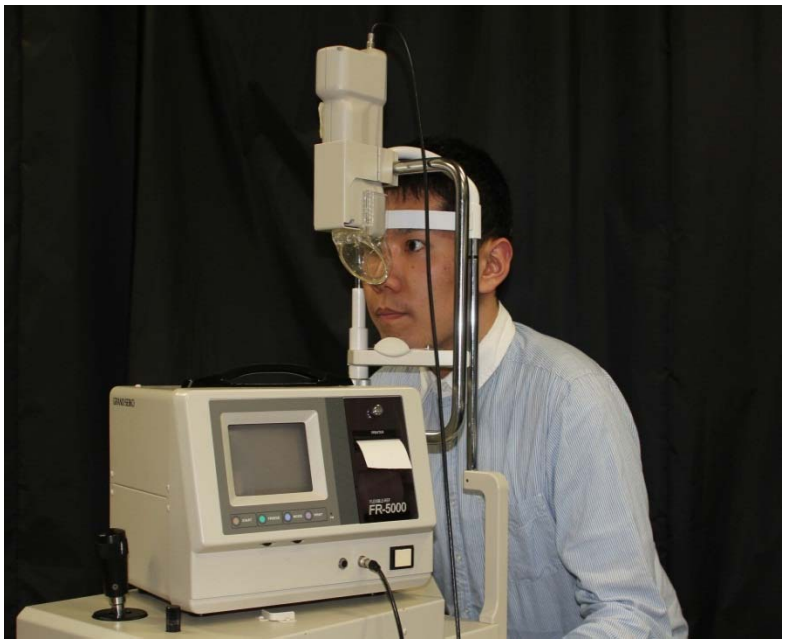


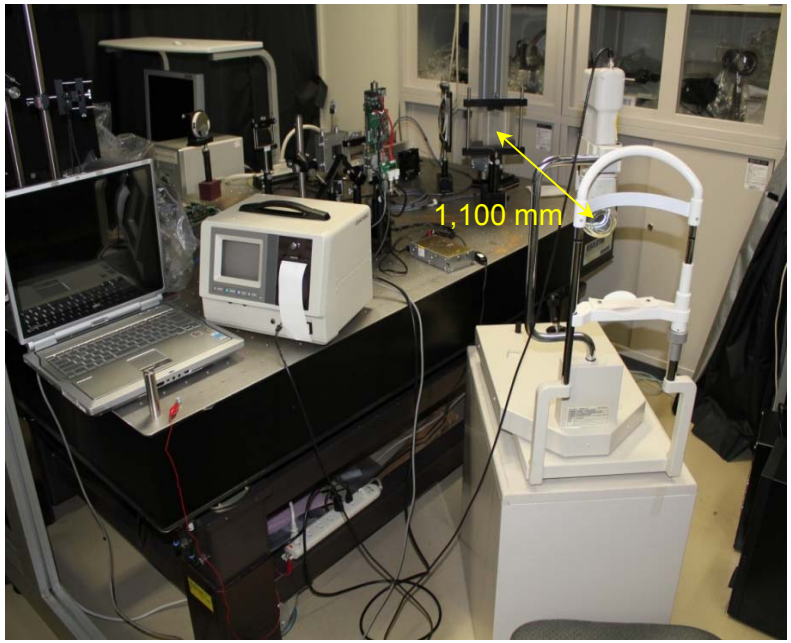
castle

truck

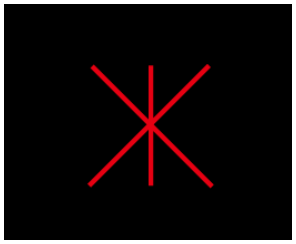
Y. Takaki, et al., Opt. Express **18**, 24926 (2010)

# Accommodation Measurements

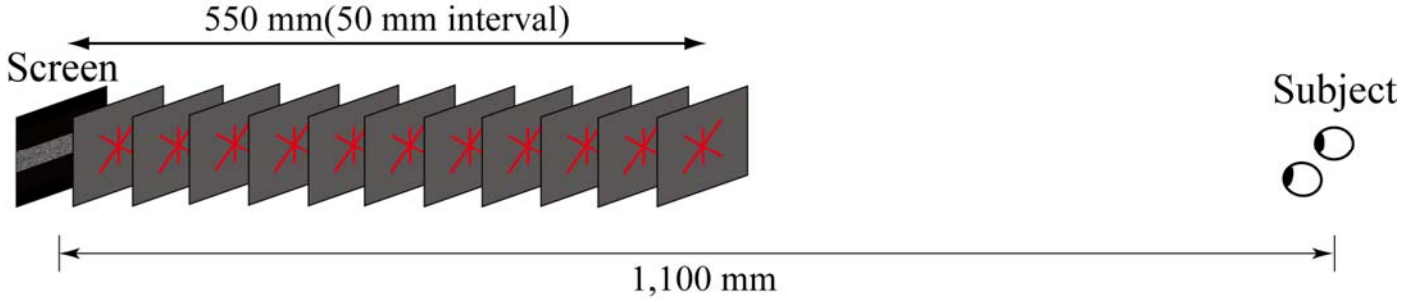



Auto refractometer : FR-5000S (Grand Seiko Co., Ltd.)



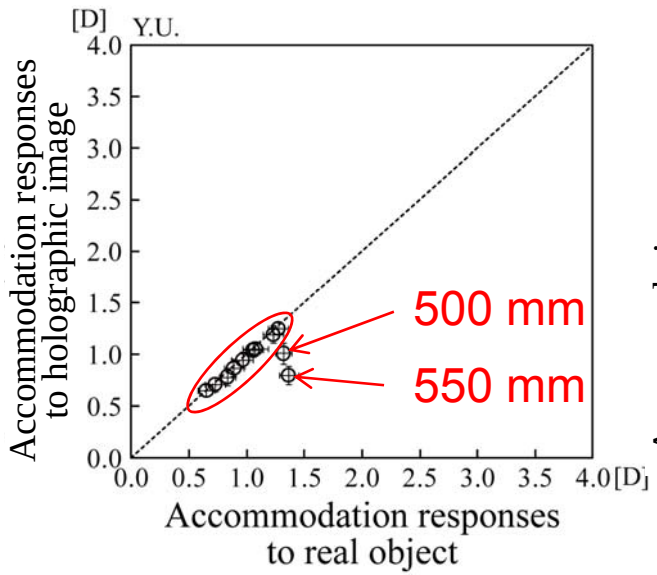
Test image
(1.1°× 1.1°)

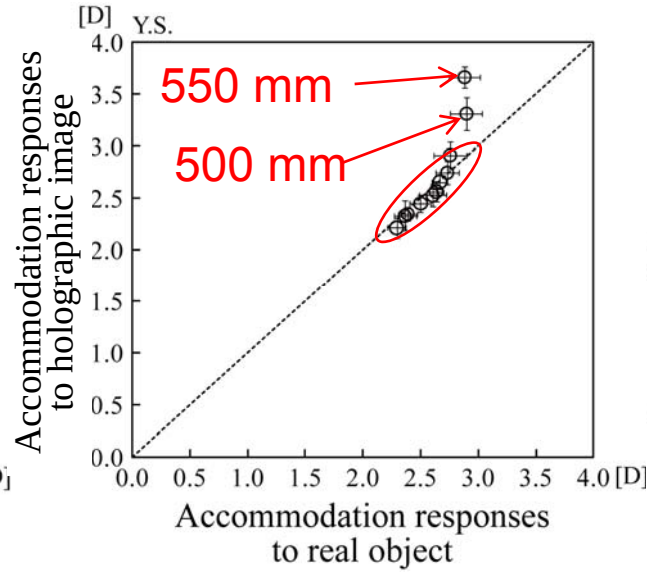


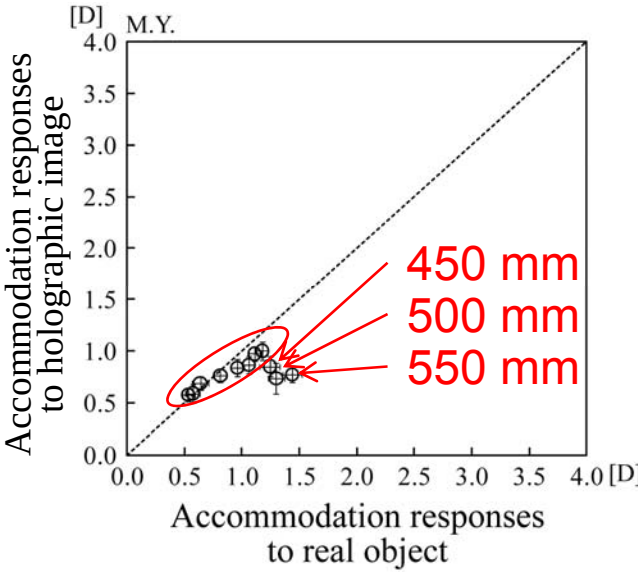

The measurements were performed for 10 s, and the responses for 2 s without blink were averaged to obtain an experimental result.

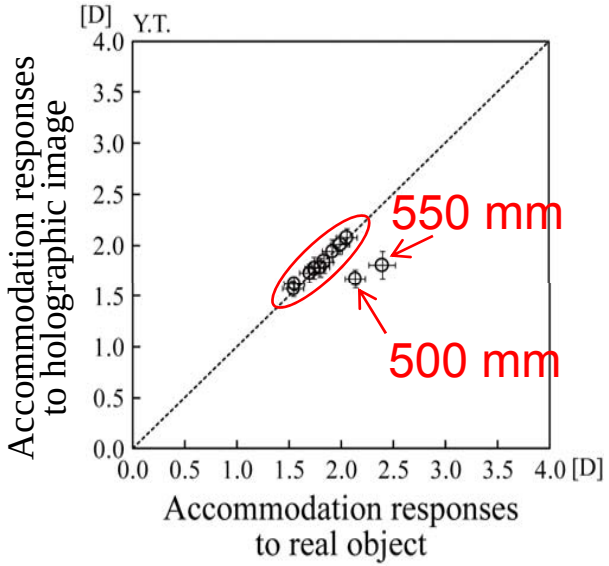
Y. Takaki and M. Yokouchi, Opt. Express **20**, 3918 (2012)

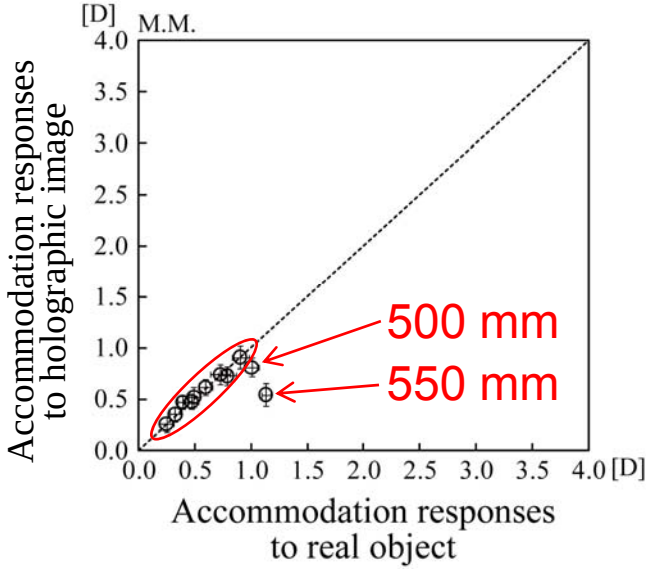
# Measured Accommodation Responses



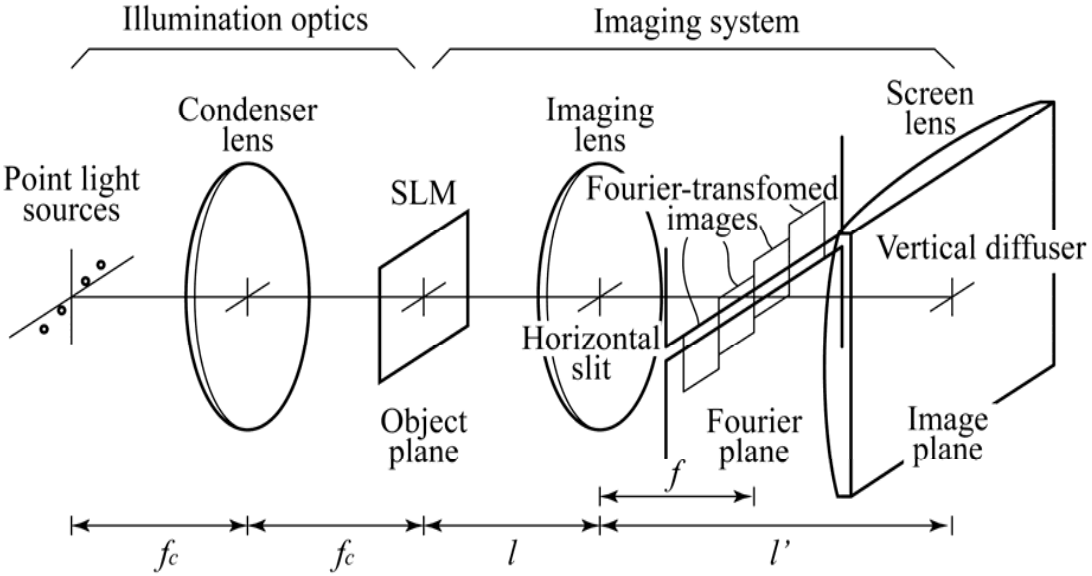



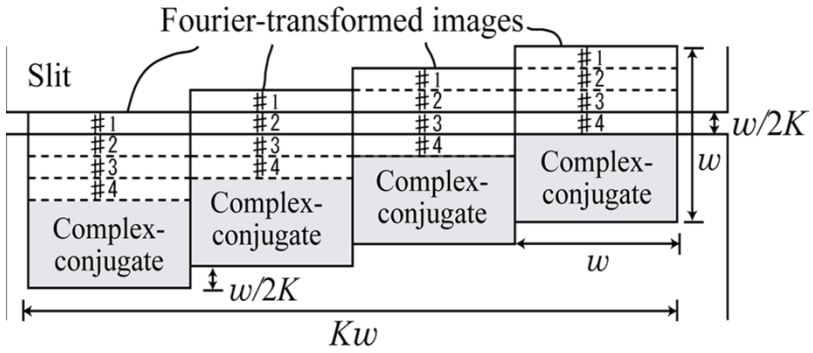



# Resolution Redistribution Technique




Optical system




Fourier plane

| | Pixel pitch | Viewing zone angle | Screen size |
|---|---|---|---|
| Horizontal | $Mp / K$ | $2\sin^{-1}(K\lambda/2Mp)$ | $\times M$ |
| Vertical | $2K\,Mp$ | Diffuse | |

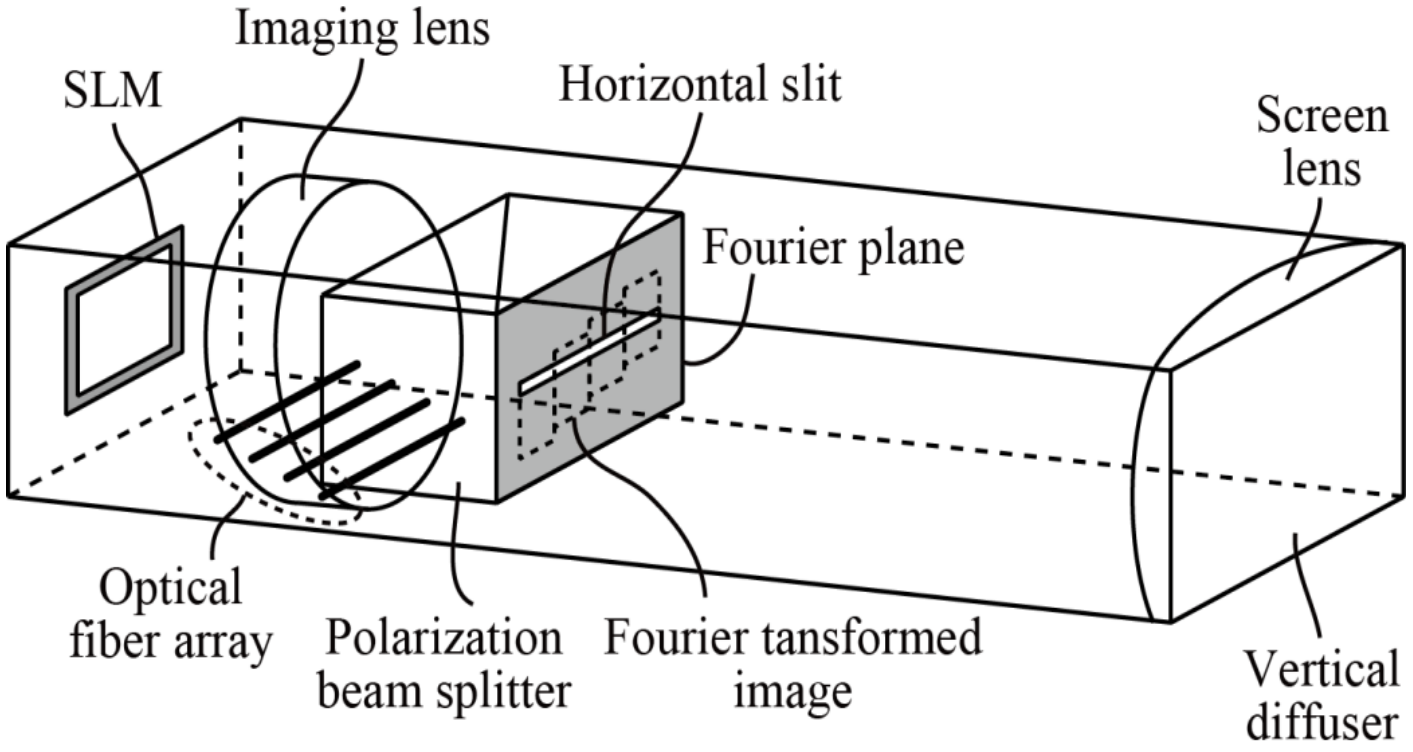
$K$: number of point light sources
$M$: magnification of imaging system
$p$: pixel pitch of SLM

Both the screen size and the viewing zone angle can be enlarged.

The screen lens can be made larger than the imaging lens.

Y. Takaki et al., Appl. Opt. **47**, D6 (2008)
Y. Takaki et al., Appl. Opt. **47**, 4302 (2008)

# Holographic Display Module

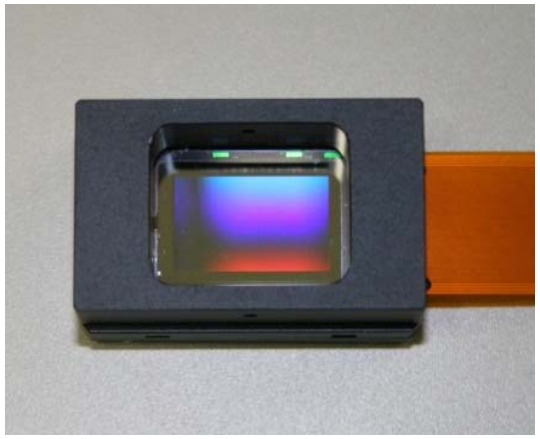



Because a reflection-type SLM is used, the imaging lens also works as a condenser lens.

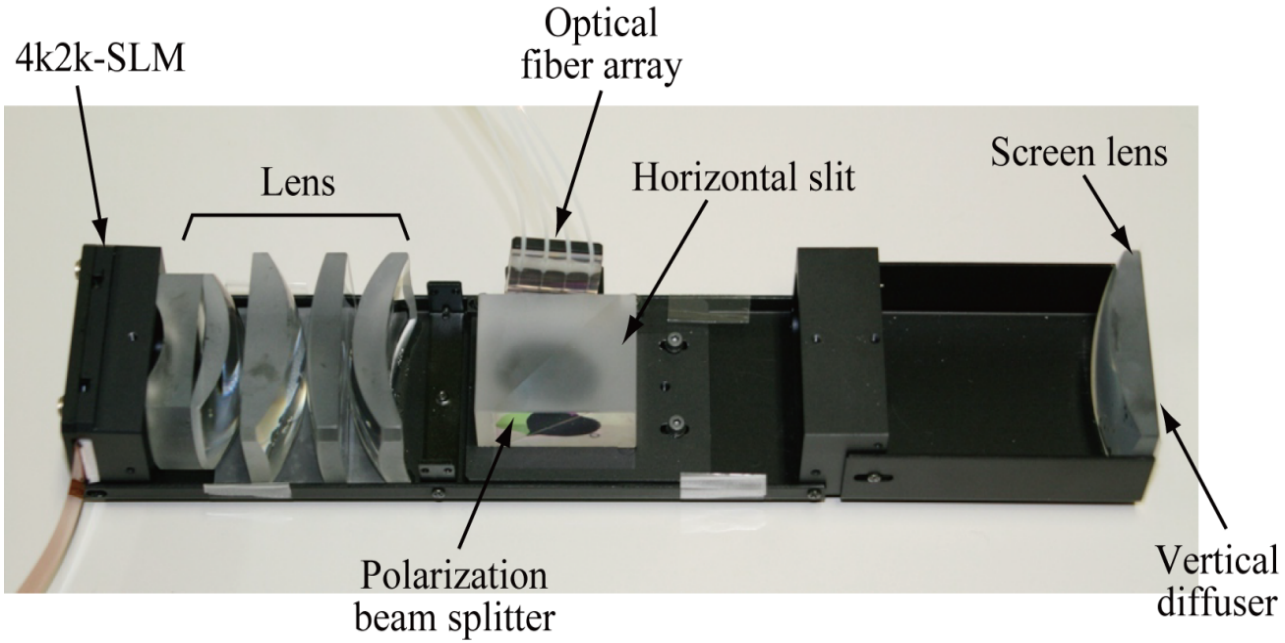
A frameless screen is obtained.

Y. Takaki et al., Opt. Express **18**, 10294 (2010)

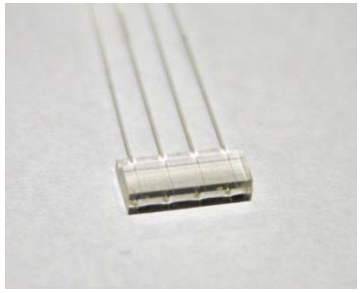
# Holographic Display Module Using 4k2k-SLM



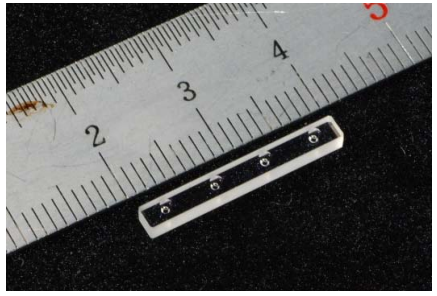
4k2k-SLM (JVC Kenwood)
Resolution: 3,840 × 2,400
Pixel pitch: 4.8 μm
Central 3,200 × 1,600 pixels were used.




Magnification of imaging system: $M$ = 2.88
Module size: 241 × 46 × 27 mm$^3$



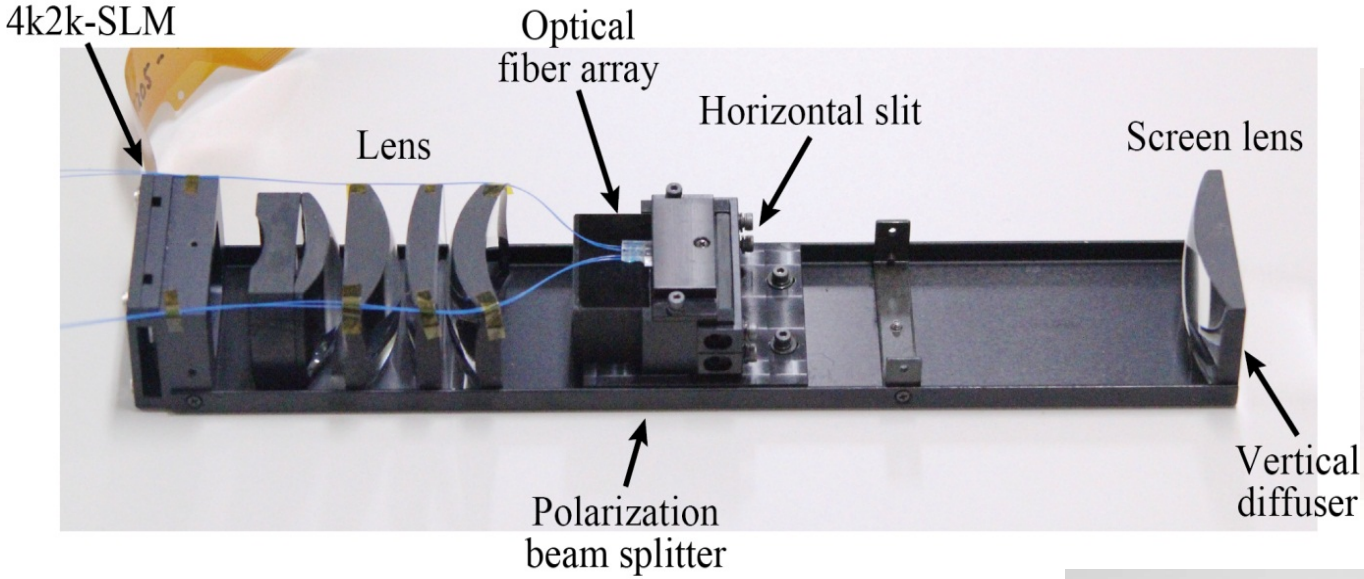
Optical fiber array
$K$ = 4

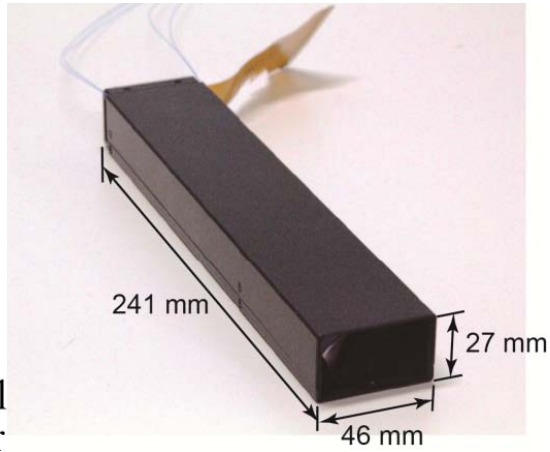


Micro lens array
N.A. 0.11 ⇒ 0.30

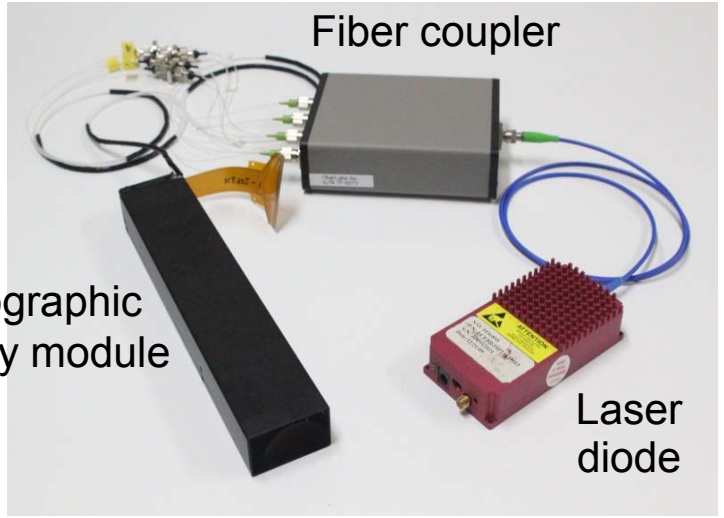
| | |
|---|---|
| Screen size | 2.0 in |
| Horizontal pixel pitch | 3.5 μm |
| Horizontal viewing angle | 11 ° |

# Modification of Module




Horizontal viewing angle : 11°
Screen size : 2.0 inches

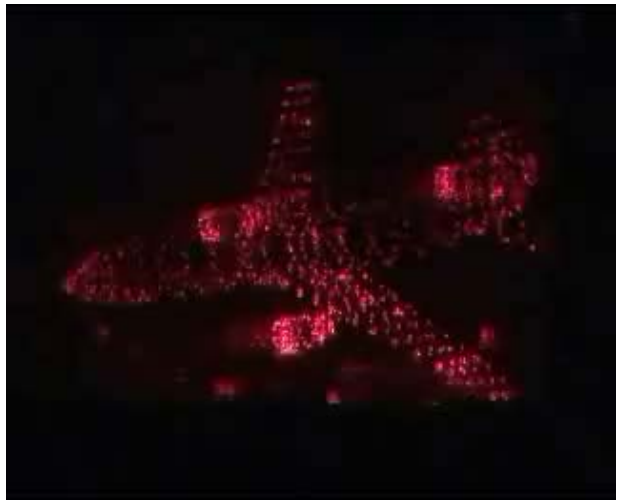



Compact optical system

# Reconstructed Image by Holographic Display Module

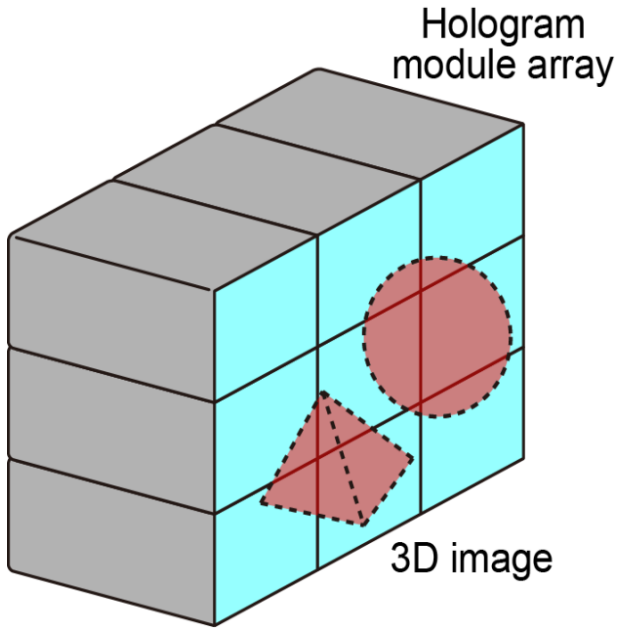
Apple

Teapot

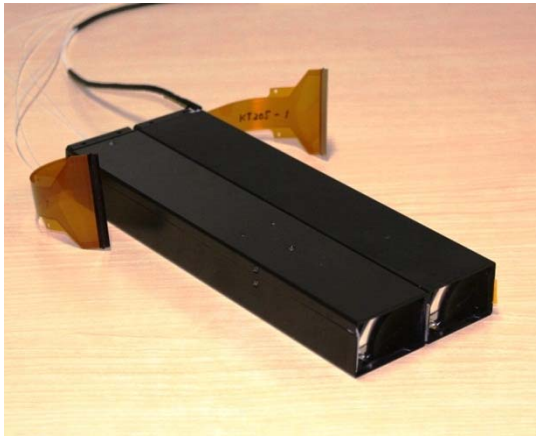


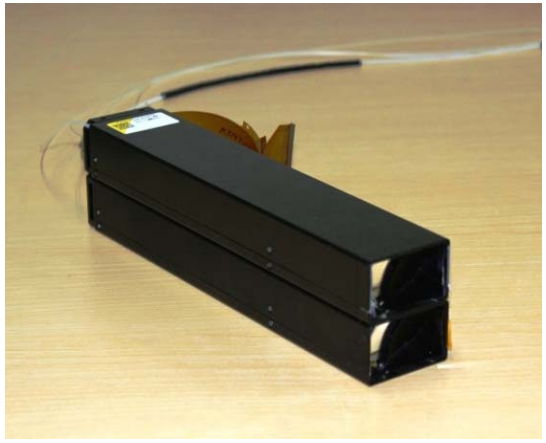
Plane

# Module Array to Increase Screen Size

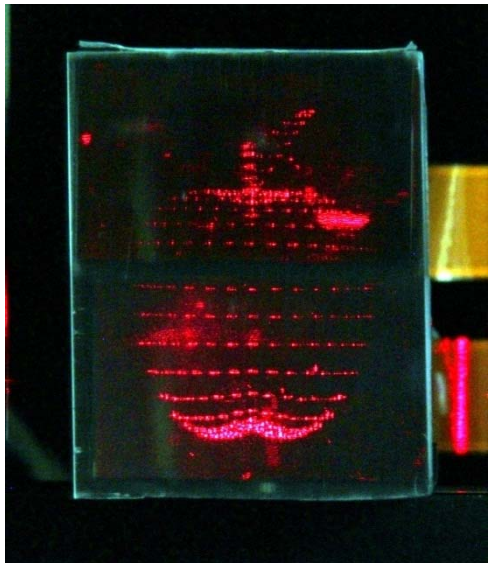



Multiple modules can be arranged two-dimensionally to further increase the hologram screen size.





Two modules



Reconstructed image

# *Creation of New Values Using 3D Displays*

*1. Faithful reproduction of object appearances*

*2. 360-degree 3D image reproduction*

*3. High-presence using 3D head-up display*

*4. Ultra-large screen 3D display*

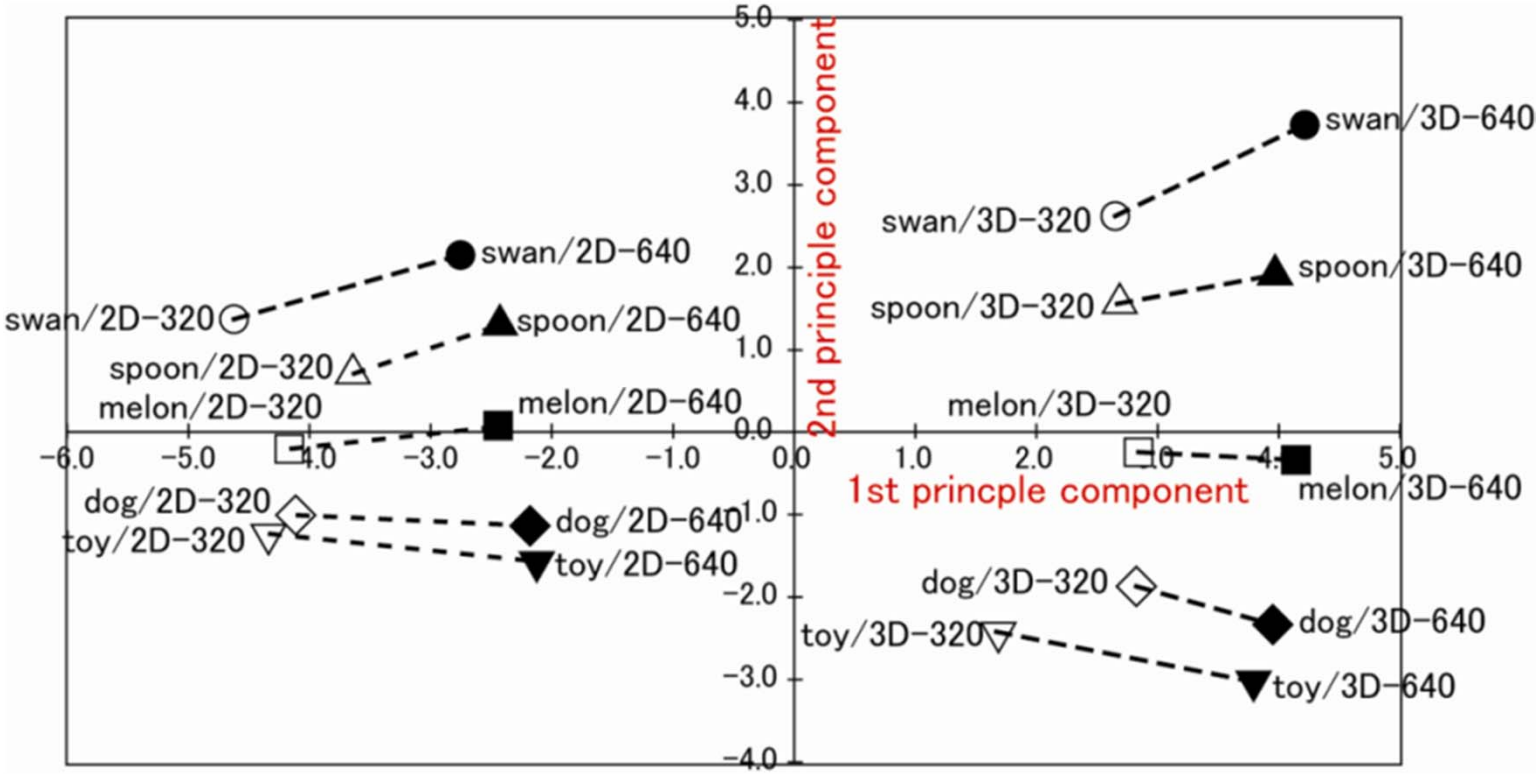
# Faithful Reproduction of Object Appearances

72-Direction Half-VGA Display

Because the SMV/HDD display can control the ray direction precisely, they can reproduce not only the depth of objects but also the appearances of objects, such as glare, transparency, softness, etc.

# Subjective Evaluation

The subjective evaluation was performed in order to evaluate the object appearances reproduced by the SMV/HDD displays.

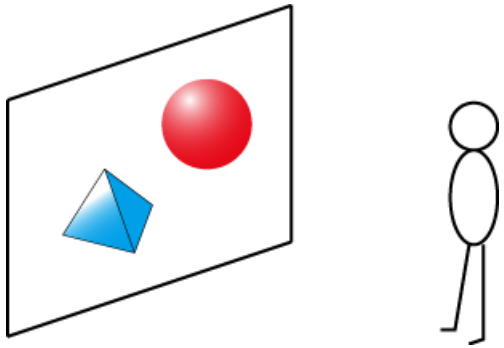



1st principle component: depth sensation
2nd principle component: appearances reproduction

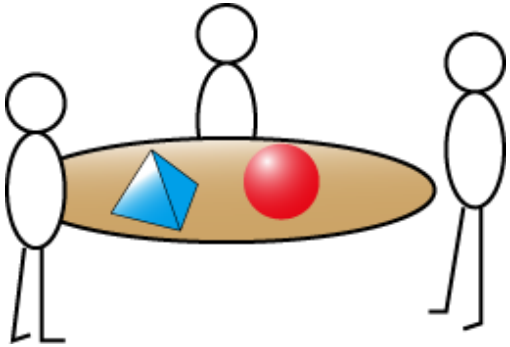
Y.Takaki and T.Dairiki, IDW 2005, 1777-1780, (2005)
Y.Takaki and T.Dairiki, Proc. SPIE **6055**, 60550X (2006)

# 360-dgree Table-screen Display

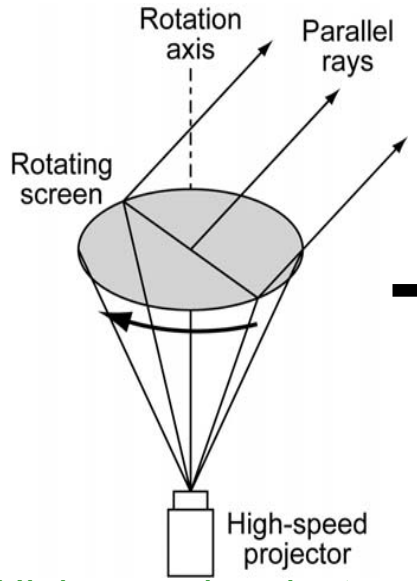
Present 3D display



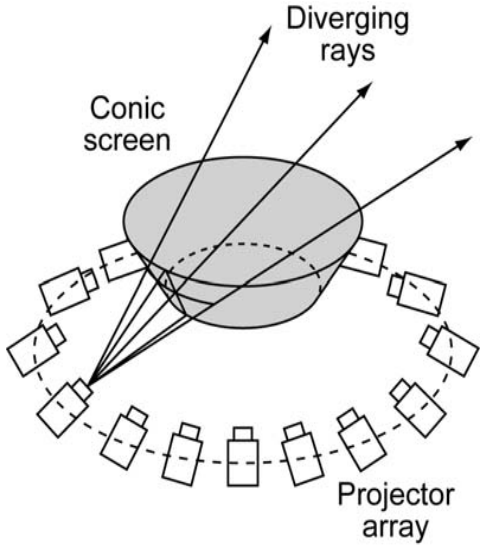
Future 3D display



Previous systems

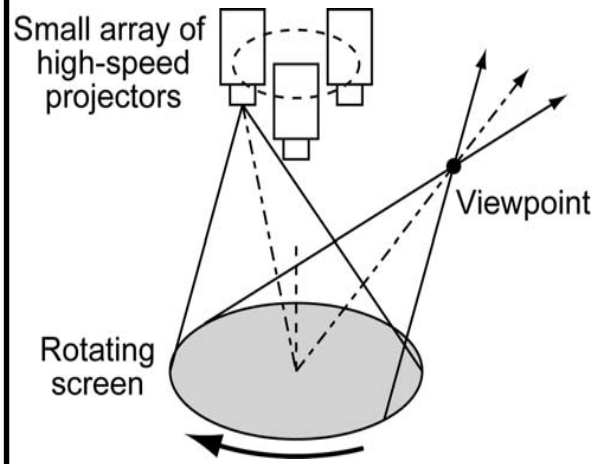



High-speed projector system



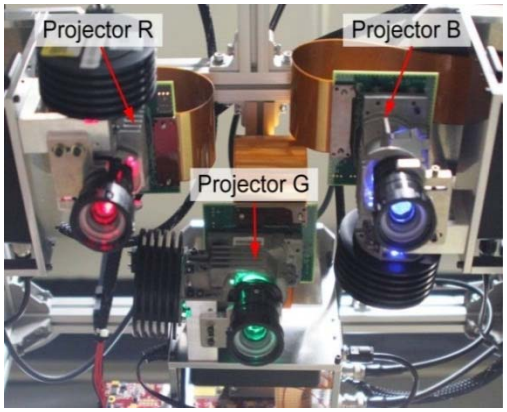

Multi-projector system

Proposed system



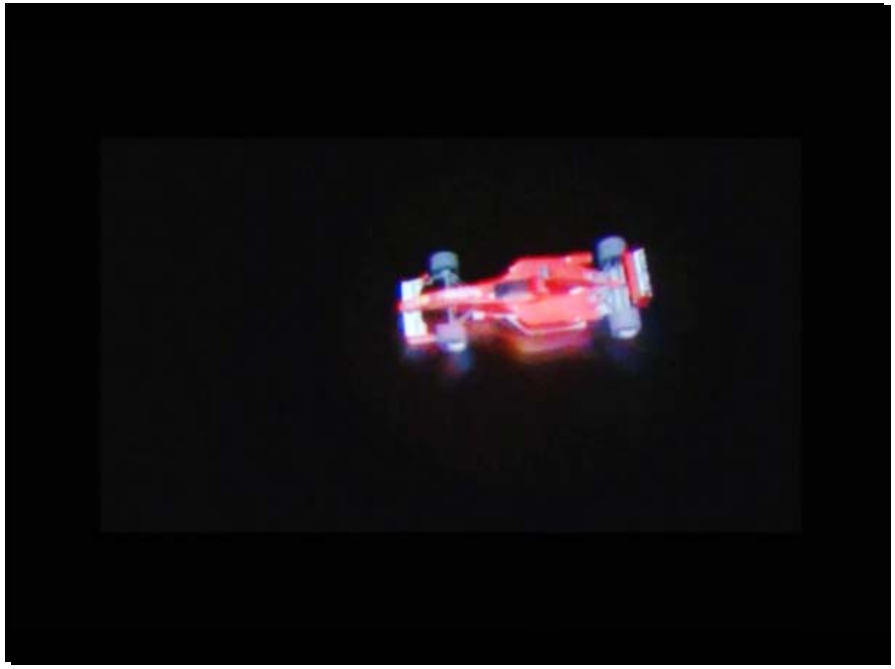

Small array of high-speed projectors

# 360-dgree 3D Image


Resolution: 1,024 × 768
Frame rate: 22.222 kHz

| | |
|---|---|
| Number of projectors | 3 |
| 3D resolution | 768 × 768 |
| Number of views | 800/projector |
| Interval of views | 3.1 mm |
| Frame rate | 27.8 Hz |

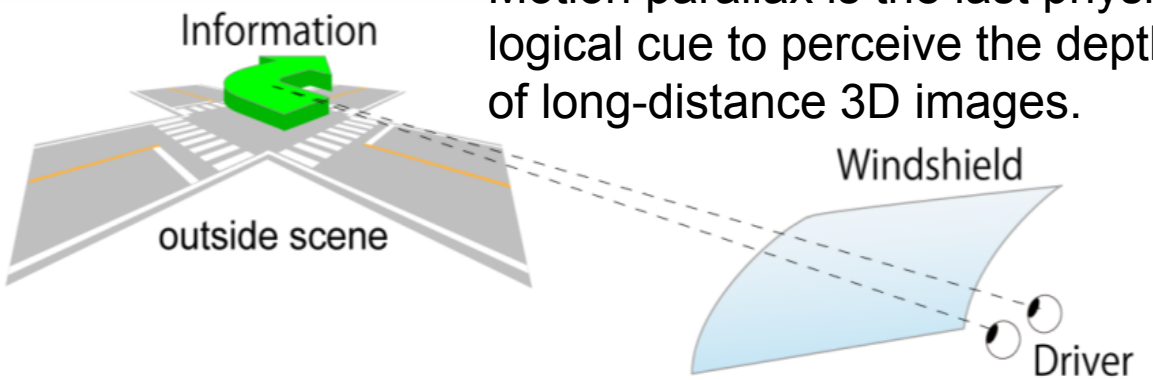


Y. Takaki and S. Uchida, Opt. Express **20**, 8848 (2012)

# High Presence Head-up Display

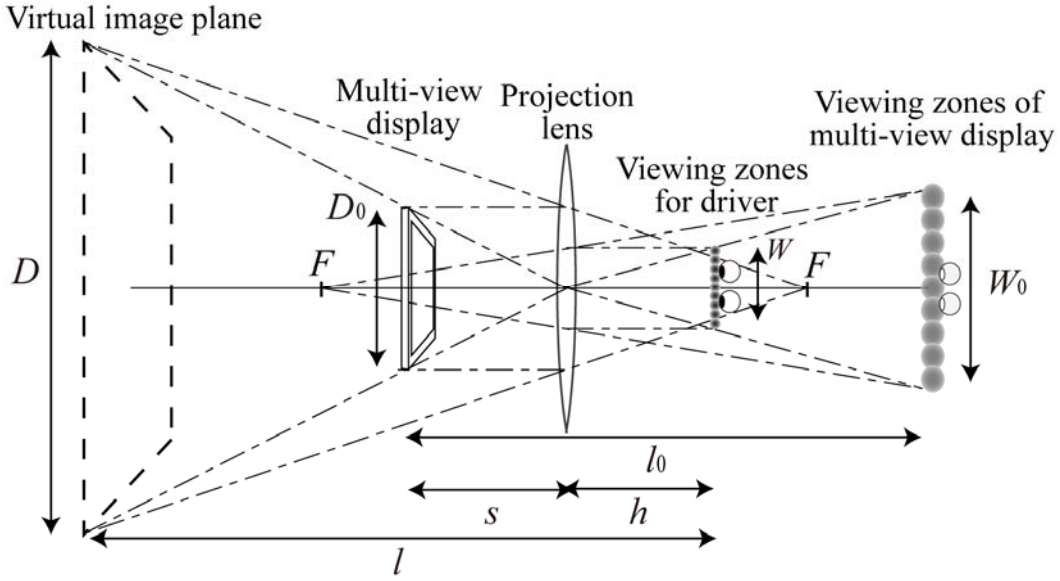
SMV windshield display: HUD for automobiles
Joint-development with DENSO Corp.

Motion parallax is the last physio-logical cue to perceive the depth of long-distance 3D images.




36-view SMV-WSD

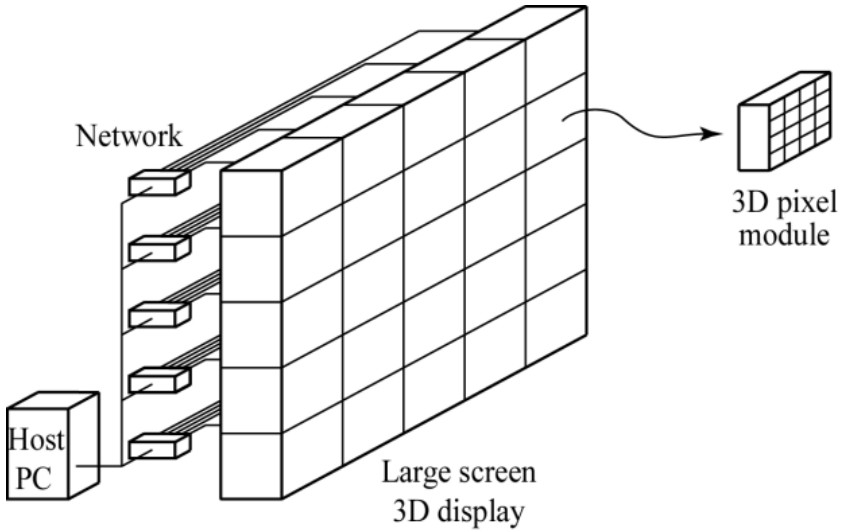
Combination of flat-panel system and virtual imaging system

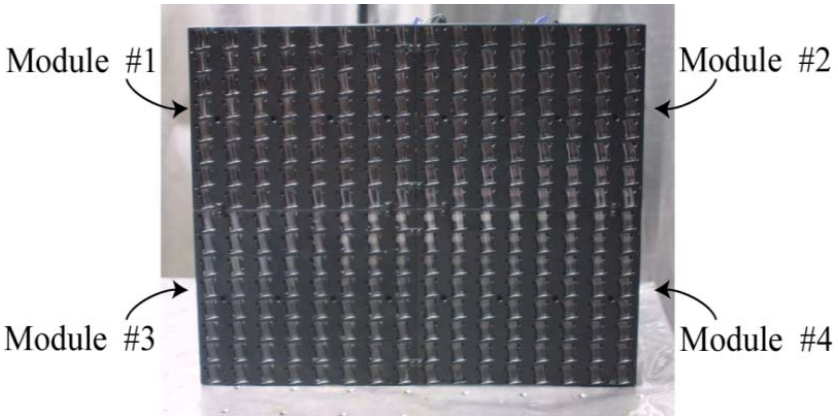


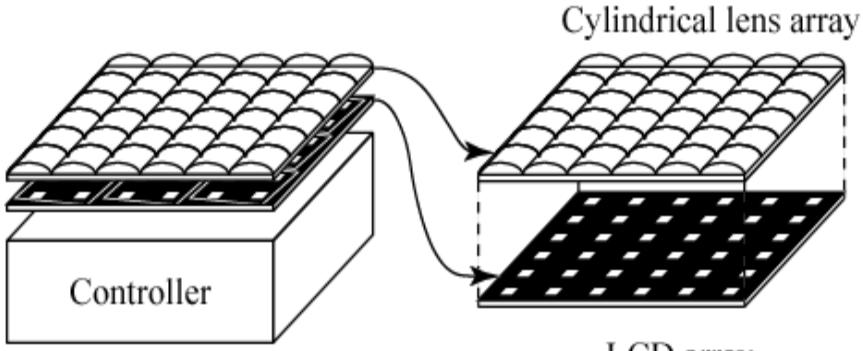


Y. Takaki et al., Opt. Express **19**, 704 (2011)

# Ultra Large Screen Display

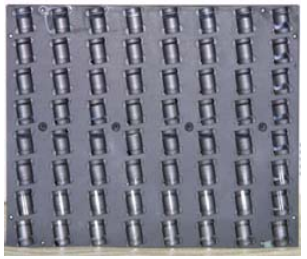




3D pixel module

LCD array

Lens array



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