Challenges for Next-Generation 3D Displays

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Faculty of Agriculture: Fuchu Campus

Faculty of Engineering: Koganei Campus

TUAT

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.

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

Virtual experiences

Robot manipulation

Design

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

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

Binocular disparity
the horizontal displacement in retinal images between the left and right 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.
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

Volume reconstruction
Stack of 2D images

Ray reconstruction
Multi-view, integral imaging

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.

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<tr>
<td>Binocular disparity</td>
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<tr>
<td>Accommodation</td>
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<tr>
<td>Motion parallax</td>
<td>o</td>
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</table>
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.

\[(3D \text{ resolution}) = \frac{(\text{Flat-panel resolution})}{(\text{Number of views})}\]

- Vergence
- Binocular disparity
- Accommodation
- Motion parallax

\[
\begin{array}{c|c}
\text{Vergence} & \bigcirc \\
\text{Binocular disparity} & \bigcirc \\
\text{Accommodation} & \times \\
\text{Motion parallax} & \bigcirc \\
\end{array}
\]
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.

When eyes focus on 3D images

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

When eyes focus on display screen

- 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
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 mm² (2.0 in.)
- Refresh rate: 48.5 Hz
**Flat-panel Type Super Multi-view Displays**

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

- 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

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

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interval of views</td>
<td>2.6 mm</td>
</tr>
<tr>
<td>Number of views</td>
<td>R 8 + L 8</td>
</tr>
<tr>
<td>Resolution</td>
<td>256 × 192</td>
</tr>
<tr>
<td>Screen size</td>
<td>2.57 in.</td>
</tr>
<tr>
<td>Observation distance</td>
<td>350 mm</td>
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</tbody>
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Developed with Seiko Epson

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.

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.

SMV256
Number of views: 256
Sixteen sets of 16-view displays are combined by multi-projection system.

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]

- S.H.
- T.N.
- Y.T.

Interval of viewpoints
- Real object
- 1 mm
- 2 mm
- 3 mm
- 10 mm

Distance to 3D image
**Other Super Multi-view Displays**

- **Windshield SMV display**
- **360-degree SMV display**
- **Large-screen SMV display**

Developed with DENSO

36-view SMV-WSD

High-speed RGB projector


Frameless modules are tiled.

Four modules are aligned vertically.

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 $\sim$1 μm.
2) To increase the screen size, the number of pixels must be proportionally increased.

\[
\Phi = 2 \sin^{-1} \left( \frac{\lambda}{2p} \right)
\]

Screen size:

\[
Np \times Mp
\]

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

Screen 40 in., viewing zone angle 30º ($\lambda = 0.6$ μm)

- Pixel pitch: $p = 0.97$ μm
- Resolution: $N \times M = 764,000 \times 430,000$

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

[AOM + 2D scanning]

MIT (U.S.A.)
SPIE 1212, 174 (1990)

Horizontal-Parallax-Only (HPO) hologram
Comparisons of Holographic Displays

- Ultra-high resolution SLM
- 1-D modulation (AOM) + 2-D scanning
- Multiple SLMs
- 2-D modulation (MEMS) + 1-D scanning
- Horizontally scanning holography using MEMS SLM

Institutions:
- MIT
- TUAT
- TAO, NICT
- SNU
- Bilkent Univ.
**Horizontally Scanning Holography Using MEMS-SLM**

**Screen scanning system**

Anamorphic imaging system:
- Horizontal: reduce pixel pitch → Viewing zone angle increases
- Vertical: increase image height

**Horizontal Scanning:**
- Increase image width → Screen size increases

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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**

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

- \( M_x = 0.183 \)
- \( M_y = 5.00 \)

**Horizontal scanner**

Galvano mirror
MicroMax™Series671
- Scanning frequency: 60 Hz
- Scan angle: ±18.1°
- Screen size: 3.5 in. (73.1 × 52.5 mm²)
- Number of elementary holograms: 222
Screen Scanning System: Reconstructed Image

- 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™ Series 671
Scan angle: ±6.8°
Scan frequency: 30 Hz
Mirror size: 95 × 170 mm²

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

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

cube

snowman
Accommodation Measurements

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

Results of Accommodation Measurements

Diopter [D] = 1/Length [m]

![Graphs showing accommodation responses to 3D objects for different distances.](image-url)
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 \times 30.0 \text{ mm}^2 (2.0 \text{ in.})
Reduced viewing zone width: 9.75 \text{ mm}
Viewing zone width: 437 \text{ mm} (at 600 \text{ mm})
Viewing zone angle: 40°
Frame rate: 60 \text{ Hz}

Number of hologram patterns: 222
Viewing-zone Scanning System: Reconstructed Images

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

Focus of camera was changed.

3D: +100 mm
TUAT: +30 mm
Circle: –100 mm
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.

360-degree Scanning System: Experimental System

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

Rotating screen
- Magnification: 5.71
- Screen size: 80 x 60 mm² (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)

### Graph

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<thead>
<tr>
<th>Pixels / frame</th>
<th>100 G</th>
<th>10 G</th>
<th>1 G</th>
<th>DMD</th>
<th>100 M</th>
<th>Super HV</th>
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**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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