Three-Dimensional Displays: Present and Future

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Outline

1. Introduction
2. Human Factors
3. Current 3D display techniques
   - two-view display, multi-view display
4. Future 3D display techniques
   - natural 3D display, integral photography, holography
5. Future Prospects
Why 3D?

2D displays have achieved sufficiently high resolution, high dynamic range, and high frame rate.
  Full HD resolution, 12-bit gray-level, 120 Hz frame rate

Is Super HDTV required?
  Resolution 7,680 × 4,320, Screen size 100”

The cinema industry has moved to 3D.
Audiences and profits have increased.
  "The Polar Express,"
  "Chicken Little,"
  "Beowulf,"
  "Center of the Earth,"
  "Bolt"…

ShoWest, March 2005

L to R: Doug Darrow (T), George Lucas, Robert Zemeckis, Randal Kleiser, Robert Rodriguez, James Cameron

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Advantages of 3D Displays

From “Image Screen” to “Image Space”

High presence, Ultra reality

Faithful reproduction of appearances (explained later)

Courtesy by URCF

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3D Perception by Psychological Factors

Perspective, Relative size, Superposition, Texture gradient, Shadow, Aerial perspective, etc.

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

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

Motion parallax
the change in a retinal image due to the movement of a viewpoint or an object

Harmony among these four factors is the key to developing comfortable 3D displays.
Two-View Display: Glasses Type

Two different images for the left and right eyes are displayed for the corresponding eyes.

Two images are separated using optical filters.

- Polarization filters: X-pol, RealD
- Wavelength filters: Anaglyph, Dolby 3D
- High-Speed shutters: XpanD

<table>
<thead>
<tr>
<th>Feature</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>Binocular disparity</td>
<td>○</td>
</tr>
<tr>
<td>Vergence</td>
<td>○</td>
</tr>
<tr>
<td>Accommodation</td>
<td>×</td>
</tr>
<tr>
<td>Motion parallax</td>
<td>×</td>
</tr>
</tbody>
</table>

3D Movie Theaters

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**Glasses Type Two-View Using Flat-Panel**

Polarization glasses technique

Time-multiplexing technique

- Liquid crystal shutter glasses
- 103” plasma
- Frame rate 120 Hz

Vertical resolution decreases by half.

_Nippon BS Broadcasting Corporation (BS11)_ is currently providing 3D TV programs for this type of display.

CEATEC 2008, Panasonic

Resolution does not decrease.

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RealD cinema technique

http://www.reald.com/

ZScreen changes the polarization of light between left and right-handed circularly polarized light.
Without using optical filters to separate two images, two viewpoints are located at a set distance from the display screen.

The viewing position is limited.

<table>
<thead>
<tr>
<th></th>
<th>Binocular disparity</th>
<th>Vergence</th>
<th>Accommodation</th>
<th>Motion parallax</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>○</td>
<td>○</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

The viewpoints appear periodically with typical glassless 3D displays.

→ Multiple viewers
→ Pseudoscopic image
A multi-view display generates more than two viewpoints.

The horizontal pitch of viewpoints is set to the inter-ocular distance (65 mm on average) or less.

Motion parallax is obtained.

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<tbody>
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<td>○</td>
</tr>
<tr>
<td>Vergence</td>
<td>○</td>
</tr>
<tr>
<td>Accommodation</td>
<td>×</td>
</tr>
<tr>
<td>Motion parallax</td>
<td>Δ</td>
</tr>
</tbody>
</table>

Probability of seeing pseudoscopic images decreases.

Jerky motion parallax reduces the presence and realism of 3D images.
Parallax barrier system

- High shape accuracy
- Low light efficiency

Lenticular lens system

- Shape deformation due to humidity and temperature
- High light efficiency

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Increase of Viewpoints

Step barrier technique

Slanted lenticular technique

Resolution is reduced both in the horizontal and vertical directions in order to increase the number of viewpoints.
Example: Glassless Two-View Displays


Sharp SH-251is  Sharp PC-RD3D  Mitsubishi Scan backlight 3D LCD  NEC LCD Technologies HDDP  Hitachi H001

Parallax Barrier  Lenticular  Parallax Barrier

Most of these products are 2D/3D switchable.
Example: Multi-View Displays

- 4D Vision
  - 8-view Parallax Barrier

- Sanyo
  - 4-view, 7-view Parallax Barrier

- Philips
  - 9-view Lenticular

- Toshiba
  - 12-, 16-, 30-view Lenticular

- NTT DoCoMo
  - 30-direction Lenticular

- Seiko EPSON
  - 8-view, 2.57” Lenticular

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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.

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All four physiological factors should function properly with a natural 3D display.

<table>
<thead>
<tr>
<th></th>
<th>Two-view display</th>
<th>Multi-view display</th>
<th>Natural 3D display</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binocular disparity</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Vergence</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Accommodation</td>
<td>×</td>
<td>×</td>
<td>○</td>
</tr>
<tr>
<td>Motion parallax</td>
<td>×</td>
<td>△</td>
<td>○</td>
</tr>
</tbody>
</table>
The interval of viewpoints is made smaller than the pupil diameter, i.e. < 5 mm. A large number of parallax image (perspective projections) are displayed to corresponding viewpoints.

**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.”
**Project: Development of Natural 3D Display**

supported by SCOPE (Strategic Information and Communications R&D Promotion Programme) by Ministry of Internal Affairs and Communications, JAPAN, 2002-2006

3D Displays

- 64-directional ~QVGA
- 128-directional ~QVGA
- 128-directional SVGA

PC Clusters

- 64 PC for 64-directional display
- 16 PC for 128-directional display

Visual Function Measurement

- Accommodation measurement
- Accommodation+Vergence+Pupil diameter measurement (Jointly developed with TOPCON Corp.)

Research target: Exploration of Natural 3D Display Conditions

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HDD Displays

Multi-projection system

Flat-panel system
Multi-Projection HDD Display System

Modified 2D arranged multiple telecentric afocal imaging systems

Common lens

Vertical diffuser (3D screen)

2D display array  Lens array  Aperture array

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Prototype Multi-Projection HDD Displays

<table>
<thead>
<tr>
<th></th>
<th>64</th>
<th>128</th>
<th>128</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of ray directions</td>
<td>64</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>Horizontal ray angle pitch</td>
<td>0.34°</td>
<td>0.23°</td>
<td>0.28°</td>
</tr>
<tr>
<td>Horizontal viewing angle</td>
<td>21.6°</td>
<td>29.6°</td>
<td>35.7°</td>
</tr>
<tr>
<td>3D resolution</td>
<td>~QVGA</td>
<td>~QVGA</td>
<td>SVGA</td>
</tr>
<tr>
<td>Screen size</td>
<td>9.25”</td>
<td>13.2”</td>
<td>12.8”</td>
</tr>
</tbody>
</table>

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128-Direction QVGA Display

0.44” color LCD
(SONY LCX033AK)

16×8 LCD panels with modified 2D arrangement

Optical engine

Display system

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128-Direction SVGA Display

RGB LED
Nichia, NSSM016CT

0.49" LCOS
MD800 (MicroDisplay Tec.)
Resolution: 800 × 600
Frame rate: 180 Hz
(Field Sequential Color)

Small projector unit
26 × 38 × 63 mm³

16 × 8 projector units
with modified 2D arrangement

Display system

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3D Images by 64-direction QVGA Display

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Interactive manipulation of 3D images

Fingertip manipulation

3D drawing by fingertip

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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
**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 horizontally.
Slanted Subpixel Arrangement

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen size</td>
<td>2.57”</td>
</tr>
<tr>
<td>Number of viewpoints</td>
<td>16</td>
</tr>
<tr>
<td>3D resolution</td>
<td>$256 \times 192$</td>
</tr>
<tr>
<td>Pixel density</td>
<td>500 ppi</td>
</tr>
<tr>
<td>Width of subpixel</td>
<td>12.75 $\mu$m</td>
</tr>
<tr>
<td>Width of black matrix region</td>
<td>4.25 $\mu$m</td>
</tr>
</tbody>
</table>

Joint development with Seiko EPSON

Photograph of subpixel structure of fabricated LCD panel

### Prototype Flat-panel HDD displays

<table>
<thead>
<tr>
<th></th>
<th>72</th>
<th>72</th>
<th>30*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of ray directions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal ray angle pitch</td>
<td>0.38°</td>
<td>0.38°</td>
<td>0.71°</td>
</tr>
<tr>
<td>Horizontal viewing angel</td>
<td>27.6°</td>
<td>27.6°</td>
<td>21.2°</td>
</tr>
<tr>
<td>3D resolution</td>
<td>320 × 400</td>
<td>640 × 400</td>
<td>256 × 128</td>
</tr>
<tr>
<td>~half VGA</td>
<td></td>
<td>~VGA</td>
<td></td>
</tr>
<tr>
<td>Screen size</td>
<td>22.2”</td>
<td>22.2”</td>
<td>7.2”</td>
</tr>
</tbody>
</table>

*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: 9.46°

72-directional HDD display
- N: 6
- M: 12
- Number of ray directions: 72
- Number of 3D pixels: 320 × 400
- Horizontal ray angle pitch: 0.38°
- Horizontal viewing angle: 27.6°
- Screen size: 22.2"

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3D Images by 72-direction Display

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

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

Specifications

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3D resolution</td>
<td>640 × 400</td>
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<td>Number of ray directions</td>
<td>72</td>
</tr>
<tr>
<td>Horizontal ray angle pitch</td>
<td>0.38°</td>
</tr>
<tr>
<td>Horizontal viewing angle</td>
<td>27.6°</td>
</tr>
<tr>
<td>Screen size</td>
<td>22.2”</td>
</tr>
</tbody>
</table>
SID Display Week 2009

3D Images by 72-direction VGA Display

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 SID Display Week 2009

**Accommodation Measurement**

![Auto refractometer](image)

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

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Enhancement of Eye’s DOF

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

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.
### Time-Multiplexing Display Module

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of images</td>
<td>15</td>
</tr>
<tr>
<td>Resolution</td>
<td>XGA</td>
</tr>
<tr>
<td>Frame rate</td>
<td>60 fps</td>
</tr>
<tr>
<td>Number of gray levels</td>
<td>5 bits</td>
</tr>
<tr>
<td>Frame rate of DMD</td>
<td>900 fps</td>
</tr>
<tr>
<td>Number of LEDs</td>
<td>15</td>
</tr>
</tbody>
</table>

### Optical Engine

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of images</td>
<td>60</td>
</tr>
<tr>
<td>Horizontal display angle pitch</td>
<td>0.31°</td>
</tr>
<tr>
<td>Horizontal viewing angle</td>
<td>18.3°</td>
</tr>
<tr>
<td>Resolution</td>
<td>XGA</td>
</tr>
<tr>
<td>Frame rate</td>
<td>60 fps</td>
</tr>
<tr>
<td>Number of modules</td>
<td>4</td>
</tr>
</tbody>
</table>

**Light source array**

**Aperture array**

**Time-multiplexing display module**

**Common lens**

**Vertical diffuser**
The appearances of objects, such as glare, gloss, transparency, softness are the results of reflection, refraction, and diffusion of rays on the object surfaces.

Natural 3D displays precisely control the ray directions so that they can faithfully reproduce the appearances of objects.
Subjective Analysis

Principle component analysis shows that natural 3D displays provide higher appearances and higher presence than 2D displays.

1st principle component: presence, reality

2nd principle component: appearances

2D-320: 2D, 320 × 400
2D-640: 2D, 640 × 400
3D-320: HDD, 320 × 400
3D-640: HDD, 640 × 400
Ray Saving

2D display: rays diffuse on the display screen
3D display: directions of rays are controlled
When the positions of viewers' eyes can be detected, only rays entering viewers’ eyes are produced. \(\rightarrow\) **Rays can be saved**

3D displays have the potential to be extremely low-energy displays.
Integral Photography

Integral photography offers full parallax (horizontal parallax + vertical parallax.)

The resolution of the flat-panel display must be extremely high.

| Binocular disparity | ○ |
| Vergence            | ○ |
| Accommodation       | × |
| Motion parallax     | Δ |

When ray sampling satisfies the SMV or HDD display conditions, accommodation will work and motion parallax will become very smooth.
Holography is an ideal 3D display technique, because it reconstructs the wavefront of light.

The pixel pitch of a display device needs to be ~1 μm.

In order to increase the screen size, the number of pixels must be proportionally increased.

<table>
<thead>
<tr>
<th>Perception</th>
<th>Example</th>
</tr>
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<tbody>
<tr>
<td>Binocular disparity</td>
<td>○</td>
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<tr>
<td>Accommodation</td>
<td>○</td>
</tr>
<tr>
<td>Motion parallax</td>
<td>○</td>
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</tbody>
</table>
Horizontal-parallax-only (HPO) holography dramatically reduces the number of pixels required for a display device.

Horizontally scanning holography reduces the horizontal pixel pitch to 2.5 μm.

Image size: 70 × 50 mm², Viewing angle: 15°
**Evolution and Future Prospects**

- Glasses-type two-view
- Glassless two-view
- Multi-view
  - Vertical parallax oriented: Integral photography
  - Resolution & presence oriented: Natural 3D horizontal parallax
- Natural full parallax
- Holography horizontal parallax
- Holography full parallax

- Effective content creation

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Standardization of stereoscopic displays

Recent signs of expansion of the 3D market
- 3D movie
- Internet ads
- Medical field
- 3D display
- And others...

Recent movements in standardization and active involvement by Japan
- IEC: Discussions for standardizing measuring methods of 3D displays.
- ICDM: Discussions on measurement methods in 3D stereo subcommittee.

Reducing visual fatigue and motion sickness in 3D images

ISO International Workshop on Image Safety organized by Japan
- Photosensitive seizures
- Visually induced motion sickness
- Visual fatigue from stereoscopic images

Ergonomics point of view
Quality control
Image safety

Support
Promotion
Thank you !