Light-field Display Technical Deep Dive
Strong technical team with deep experience in optical, mechanical, electrical, and software engineering.
• Definition and Significance of Light-field Displays
• Light-field Display Architecture and Properties
• Synthetic Light-field Rendering
• Heterogeneous Display Ecosystem
• Light-field Display Metrology
• Light-field Display Developer Kit
Definition and Significance of Light-field Displays
In a natural light-field we observe light reflected off objects, perceiving color and depth cues. An eye focuses a 3D scene on the retina as a 2D image, our brain reconstructs the 3D world.

In a synthetic light-field, we observe light projected from a surface that generates the same color and depth cues, thus we see the same object.
• Reproduces a 3D aerial image visible to the unaided eye without glasses or head tracking

• Binocular disparity, occlusion, specular highlights, and gradient shading and other expected depth cues must be correct from the viewer’s perspective as in the natural real-world light-field
Significance of Light-field Displays

• Human binocular vision and acuity, and the accompanying 3D retinal processing of the human eye and brain, are specifically designed to promote situational awareness and understanding in the natural 3D world.

• The ability to resolve depth within a scene, whether natural or artificial, improves our spatial understanding of the environment and as a result reduces the cognitive load accompanying the analysis and collaboration on complex tasks.
Background

- Originating with a DARPA Urban Photonic Sand-table Display challenge, core FoVI\(^3\)D team members participated in developing the initial Light-field Displays; Thomas was the computation architect on the program
- Core IP filed and the team continued to develop LfD technology
- Gen1 LfD systems built and installed in various research labs
- FoVI\(^3\)D formed to commercialize LfD technologies
- Extensive IP
  - Over 35 Issued and Pending Patents
  - LfD systems, Radiance Rendering Compute (MvPU), Distortion Correction Technologies, other
  - Proprietary Software

Light-field Display Developed by Zebra Imaging under the DARPA UPSD Program

https://youtu.be/blb0TUBoZwA
https://youtu.be/b_CKQN1t-e8
Quantified Benefits of Light-field Displays

Holograms versus traditional 2D methods proved overwhelmingly to increase retention and reduce the cognitive load when used in recalling complex medical anatomy. 

M. Hackett, Medical Holography for Basic Anatomy Training, 2013

JTAC reported greater confidence determinations of CDE, relative height of buildings, lines of fire and sight, and JTAC over-watch positions.

Evaluation of Holographic Technology in Close Air Support Mission Planning and Execution, John J. Martin AFRL, June 2008

The findings from these descriptive statistical comparisons indicate that the mean times from the search tasks performed by the individuals using the hologram were approximately 23 percent faster for target one, and 54 percent faster for target two.

N. Smith, SWAT Team Wayfinding in Laser Tag facility study, 2007
Light-field Display: Application Agnostic

**Interaction**
- Defense:
  - Command & Control
  - Airspace Management
  - Planning & Execution
  - Sensor Coverage Analysis
  - Multi-domain Situational Awareness

- Entertainment:
  - eSports (player and spectators)
  - Casual gaming
  - 3D internet exploration
  - Supplemental display for traditional media consumption

- Information Visualization:
  - Automobile Navigation
  - Engineering
  - Architecture
  - Design (film and game asset creation)
  - Oil & Gas Exploration
  - Population Data

- Medical:
  - Surgical Planning
  - Concept Visualization for Patients
  - Teaching
  - Diagnostics

**Collaboration**

**Visualization**
Light-field Display Architecture and Properties
What is a Light-field Display

• A light-field is a set of rays that pass through a plane in space and is typically defined for computer vision by a plenoptic function:

\[ L = P(\Theta, \phi, \lambda, Vx, Vy, Vz) \]

Direction Position

• Can be presented as a 2D raster image (Radiance Image) where each pixel represents the color, position, and direction of a ray within the light-field.

• The synthetic light-field is computed from a 3D model and is projected through an array of micro-lenses to create a 3D aerial scene for all viewers with the displays projection frustum.

**Hogel** (Holographic element): The combination of micro-lens and micro-image. The micro-image colors rays emitting from a point spot on the image plane and the micro-lens angularly distributes the light-rays.
Light-field Display Architecture

Primary Light-field Display subsystems:

- **Hogel Optics**: Array of microlenses responsible for angular distribution of light rays.
- **Relay Optics**: 
- **Photonics**: Array of SLMs that convert pixelized light-ray data into actual light rays.
- **Multi-view Computation System**: The subsystem that computes the light-field radiance image from a 3D model/scene.
Resolution in Light-field Displays

Spatial Resolution
Determined by size and pitch of micro-lenses. Higher density, smaller micro-lenses give higher spatial resolution.

Angular Resolution
Pixels per degree (Dr/FoV) Gives an indication of potential projection height capability. More than one ray/pixel per degree is desirable. Angular pitch is FoV/Dr.

Directional Resolution
Determined by the dimensions of the hogel. Assuming a square hogel, Dr^2 is the number of rays per micro-lens. More is better.
A hogel is the resulting combination of a lens element sitting above densely packed pixels that emit light into it. A viewer is only seeing one pixel through the lens at any time, depending on their viewing position.

Visualized above, each hogel is responsible for ~50 views of the overall scene. When aggregated, light emitting from the hogels forms a field of light rays.
Hogel Lens Properties

A synthetic light field’s 3D quality is driven by three properties (assuming perfect lenses):

**Why are the hogel optics so important**

The maximum spatial resolution depends on size, spacing, and arrangement of the Micro-Lens Array.

The higher the angular resolution, the better the opportunity to preserve detail as the light diverges from the hogel optics.

Field of view determines the display viewing space, and impacts the maximum display size.
Field of View

Vertically oriented display have the same challenge. Personal displays can get away with tighter FoV.

Display Field of View Considerations

Light-field displays is a ‘window’ to virtual content. Display size restricts content visibility.

Optics field of view restricts display’s effective size.

90° FOV

Narrow field of view restricts diversity of perspectives.

Wider field of view increases volume of windowed content – visible, but not from all positions.

45°

40° FOV

20°

90° FOV

0°

-20°

-45°
Challenge:
- Image blur decreases 3D aerial image fidelity
- MicroLens performance scales with design complexity:
  - Number of lens components
  - Number of curved surfaces
- Expensive to iterate on designs
  - Cost scales with complexity
  - Cost scales with size
- Hard to mold
- Lithographic processes are costly
- Current printed microlens array are of low quality – but there is progress
- SLM tiling introduces seams which inhibit the use of ‘hex’ package microlens arrays
A subcomponent of the microlens array are the baffles, which are designed to block light emitted in undesired directions (often referred to as cross-talk as it typically crosses to neighboring hogels).

- This light is primarily caused by the Lambertian emission of the pixels from the OLED source, which can cause ghost images and gamma reduction.
- Baffles between individual lenslets absorb this stray light, reducing or eliminating the artifacts it causes.

Baffles can be implemented as channels between lenslets, as stencils inserted between the primary and secondary array or both.
Each pixel in the radiance image is converted into a ray of light to be sent through the optical array.
To create large area photonics requires tiling of modulation devices (SLMs).

SLM technology imposes opto-mechanical constraints:

- **Pixel Density**: Directly drives the angular and spatial resolution of the display.
- **Luminance**: Brightness loss through optical stack.
- **Display Package**: Tiling micro-displays requires magnification to reduce seams created by packaging. Keep magnification to a minimal to maintain pixel density.
Radiance Image Computation
3D Model with Hogel Image Plane

Radiance Image
50^2 Hogels – 40^2 Pixels ("Rays") per Hogel

Resultant 3D Aerial LfD Projection
Radiance Image Rendering
Two traditional approaches to computing the radiance image

**Spatial x Directional**
- **Double Frustum**
  - Calculate each hogel independently

**Directional x Spatial**
- **Oblique Slice and Dice**
  - Calculate each direction across entire display and divide into hogels

Actually..., a third FoVIAN approach

**Bowtie Rasterizer**
- *Rasterize all hogels in parallel*
- *Custom bowtie frustum*
- *Single dispatch from host PC*
Double Frustum Light-field Rendering

Render all rays passing through a single lens from above and below

Pros
• Advantage of rendering a hogel natively
• Very parallelizable: each hogel is independent
• Large benefits from frustum culling

Cons
• Many (thousands) of render passes must be dispatched (OpenGL)
• Requires two passes of the geometry to create the ‘double frustum’
• Very small viewport
• Camera matrix must have a non-zero near plane (OpenGL), creating stitching singularity artifact

Double Frustum Near Plane Singularity

GPU double frustum showing hogel corruption

MvPU double frustum simulator showing hogel corruption

MvPU Bowtie frustum; no hogel corruption
Oblique Slice and Dice Light-field Rendering

**Pros**
- Large framebuffer size sometimes makes better use of GPU memory architecture
- Requires many fewer passes of the geometry, still hundreds to thousands of passes depending on directional resolution

**Cons**
- Adding more GPUs doesn’t reduce number of render passes
- Rendered pixels are not in a spatial form that can be projected through a portion of the micro-lens array
- Limited benefit from frustum culling, whole display oblique frustum is likely to intersect all objects
- May require resampling if the hogel arrangement is not a rectilinear grid
  - Inhibits on-the-fly transform
  - Resampling not cheap
Traditional Render Pipeline for Multi-view Systems

**2D Displays**
- Scene is described to the GPU
- Vertices → Viewpoint
- Vertex Lists

**Light-field Displays**
- Scene is described to the GPU
- Vertices → Viewpoint
- Only one hogel is rasterized at a time. The viewpoint and viewport change per hogel but the scene description remains the same.
- Vertex dispatch/transform dominates pipeline.

**GPU**
- Vertices
- Fragments
- Textures
- Pixels

**Large Viewport**
- Scene is rendered to the display

**1000s of very small viewports**
The host application scene is distributed to an array of computers, each of which renders a subset of the global light-field radiance image. Light-field Display interactivity and update rate are proportional to the complexity of the scene/model, the power/configuration of the rendering cluster and the size of the light-field display radiance image.
Magnitude of the Light-field Radiance Image

Size of Radiance Image - Examples

1m x 0.75m (90° FoV) Static Light-fields

- 1.0mm hogels, Dr = 256, ~300mm (1ft) usable depth
  
  \[1,000 \text{ hogels} \times 750 \text{ hogels} \times 256 \text{ rays} \times 256 \text{ rays} \times 3 \text{ RGB bytes per pixel} = \sim 150 \text{ Gigabytes per frame}\]

- 0.7mm hogels, Dr = 512, ~600mm (2ft) usable depth
  
  \[1,429 \text{ hogels} \times 1,071 \text{ hogels} \times 512 \text{ rays} \times 512 \text{ rays} \times 3 \text{ RGB bytes per pixel} = \sim 1.2 \text{ Terabytes per frame}\]

1m x 0.75m (90° FoV) Dynamic, Real Time, Light-field Display

- 0.5mm hogels, Dr = 128, ~150mm (6”-8”) usable depth – real time 30 fps rendering
  
  \[2,000 \text{ hogels} \times 1,500 \text{ hogels} \times 128 \text{ rays} \times 128 \text{ rays} \times 3 \text{ RGB bytes per pixel} = \sim 150 \text{ Gigabytes per frame}\]
  
  \[\times 30 \text{ fps} = \sim 4.4 \text{ Terabytes per second}\]

Conclusion: DO NOT MOVE PIXELS, don’t transport them, don’t store them. Render in hardware at the display instead.
Heterogeneous Display Ecosystem
Field of Light-Displays (FoLDs)

- Looking Glass Display
  - HPO Lenticular
  - Swept Volume Volumetric

- Actuality

- FoVI\textsuperscript{3D}
  - Light-field Micro-Lens

- MIT – Dr. Wetstein
  - Light-field Tensor

- Holografica
  - HPO Multi-view Zone

- Light-Space 3D
  - Multi-depth Plane Volumetric

- Leia/Red

- Multi-view Zone (LF?)

- Hologram Phase (Wavefront)
Today’s Display Environment: A Growing Problem

1. Multiple Display Types
2. Increasing Resolutions
3. Novel Displays Require Multiple Simultaneous Views

2D
1 VIEW

AR / VR
2 - 24+ VIEWS*
*Vergance accommodation forces multiple views.

VOLUMETRIC
20+ VIEWS
- Multi-depth plane
- Swept Volume

LIGHT FIELD
1000’s OF VIEWS
- Holographic
- Tensor
- Lenticular

Single View  Multi-view  Extreme Multi-view
Current Graphics Rendering: The Tightly Bound Display

- Server
- Client System
- Display

Data

3D Data Service

3D App + Render Engine

HOST APP

CPU

GPU

streaming PIXELS
from GPU to display

Draw commands from CPU to GPU
1. 2D video is captured with the expectation that the downstream display offers a single point of view.
2. 3D visualization requires actual 3D real-world coordinates in three-dimensional space.
Tomorrow’s Heterogeneous Display Ecosystem

1. 3D Data Service sends data to any device initiating a request.

2. **CPU**
   - **PUBLISHER**: 3D App running on any single device issues ObjGL commands agnostically.

3. **SUBSCRIBERS**
   - Rendering occurs at the display via MVPU allowing unique rendering requirements to be met.
Object Graphics Library (ObjGL)

TODAY
Traditionally, a host application creates a 3D scene for viewing on a 2D monitor. As such, the host application system has responsibility for rendering to that display device. If the underlying display technology changes or evolves, the host application has to adapt. The host application and display are tightly bound.

FUTURE WITH HDE
Within the Heterogeneous Display Ecosystem, the host application that creates a 3D scene is loosely bound to the display environment. Responsibility for rendering is placed with the display. The host application broadcasts its 3D scene data in a display agnostic manner via ObjGL; the display receives the scene data and renders the views required by its architecture and projection system internally via the MvPU.

Consider, for example, an eSports application/game broadcast from a Netflix-like server. The game is streamed without regard to the types of visualization devices present within the ecosystem. Whether a viewer wants to wear a head mounted display (HMD) for a first-person perspective at ground level or a group of viewers surrounds a Light-field Display (LFD) for a bird’s-eye view of the entire scene, the host application is unaware. The host application and the display technology are free to evolve independently.
MvPU Development

If the Phase II framerate goals can be obtained with OTS GPUs, then custom Phase III MvPU may only be necessary to reduce SWaP.

**Phase I**
- MvPU reference algorithm developed in C/C++
  - FoVI3D currently has a working reference simulator for Bowtie rendering a LfD radiance image

**Phase II**
- MvPU OpenCL port of reference to desktop GPU
  - x86/x64 CPU
  - AMD VEGA GPU
  - Focus on extreme multi-view rendering for collaborative display
- MvPU OpenCL port of reference to mobile GPU
  - Exynos ARM CPU
  - Mali GPU
  - Focus on shallow multi-view rendering for personal/mobile display

**Phase III**
- MvPU FPGA Accelerator
  - Exynos ARM CPU
  - Mali GPU
  - MvPU FPGA
  - Preserves GPU for normal rendering
  - MvPU is responsible for multi-view rendering for 3D displays
Calibration and Metrology
Example of uncalibrated hogels projecting a blurry image.

Example of calibrated hogels projecting a crisp image.
**Spatial Calibration:**
Maximize clarity of projected content

**Color / Brightness Calibration:**
Minimize visibility of distracting tiling artifacts
Light-field Display Metrology

Physical Metrology Pipeline

- Projection
  - Projection of 3D Metrology References
- Capture
  - 2D Image or Data Capture
- Quantization
  - Construction of Metrology Databases
- Qualification
  - Analysis & Reports

Registration and Calibration of Test Environment

100mm

Large Calibration and Metrology Gantry

Image Plane

Light field Volume
Defining the Volume

- Normalized voxel database of metrology
- Of some pre-defined resolution – number of hogels along an axis?
- Populated from multiple perspectives
- Each voxel has a plurality of metrics
- Database stores measurements collected from multiple viewing angles
Spatial Accuracy

Measurement of the 3D positional precision of geometric primitives in the projected 3D volume

$$\text{Abs. Error} = \sqrt{(x_e-x_m)^2 + (y_e-y_m)^2 + (z_e-z_m)^2}$$
Spatial Resolution

Measurement of the spatial detail in the 3D FoLD projection volume and a partial qualification of the FoLD’s plenoptic description.

\[ L = P(\Theta, \phi, V_x, V_y) \]
9-Tile ZMD Spatial Accuracy
Display Artifacts Make 3D Metrology Hard
Display resolution requirements depend on viewer’s distance: angular sub tense of features

Snellen scale – widely familiar measure of angular acuity:

20/20 = 6/6 = 1 arc minute feature

Snellen volume: a 3D display’s projection volume in which a typical user can resolve a target level of detail

Similar evaluation of VR headsets being performed by Oliver Kreylos (doc-ok.org)
Snellen Volume

Equivalent 20/x rating vs content height for viewer at 0.7 m

<table>
<thead>
<tr>
<th>Display</th>
<th>Usable Volume</th>
<th>Interstitial Pixel Grid Feature Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZMD</td>
<td>---</td>
<td>0.8mm*</td>
</tr>
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<td>+/- 7cm</td>
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<td>Static Hologram</td>
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*will detract focus from displayed virtual object

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Feature Size

ZMD: 0.8mm*
DK2 (Wilcox): +/- 7cm .05mm
New (min. spec.): +/- 8cm .05mm
New (max. spec.): +/- 13cm .05mm
Static Hologram: +/- 20cm .03mm
Today's Demo: DK2

DK2: Light-field Display

- Light-field Display
- Object Graphics Library
- Multi-view Processing Unit
- Heterogeneous Display Ecosystem

729 cubic centimeters of active 3D light field display volume projection

Projected 3D model
Demonstrating:

**Lucas** - The highest resolution light-field display yet created.

**GEN 1**
- 90° field of view
- 1.6 mm hogel diameter
- 80 x 70 hogel display
- 76 x 76 views per hogel

**DK2 Wilcox**
- 90° field of view
- 1.0 mm hogel diameter
- 80 x 80 hogel display
- 110 x 110 views per hogel

**DK2 Lucas**
- 60° field of view
- 0.5 mm hogel diameter
- 168 x 168 hogel display
- 55 x 55 views per hogel
Light-field Display Developer Kit

Lab Prototype Display With
~1.0mm Plastic Micro-Lens

LfD DK2

LFD Developer Kit with
~0.5mm Glass Lens Solution
First Quarter 2018
Technical Challenges

• **Pixel Density**
  • Need very high pixel density to achieve spatial angular requirements

• **Optical Manufacturing**
  • High precision optics to preserve ray detail

• **Light-field Computation**
  • Ginormous number of samples-rays/pixels

• **Display Agnostic Format**
  • Future proof for novel display architectures

• **Metrology**
  • Capture, quantification, standardization
Socialize the significance of light-field display technology and what FoVI\textsuperscript{3D} is doing about it.