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Computer-Based Holography

September 12 | Carsten Karbach, Jülich Supercomputing Centre (JSC)

Why computergenerated holography?

Source: `www.starwars-union.de`

Applications

- **3D Scientific Visualization**
  - **Natural** 3D viewing, focus on different depths, accomodation and convergence
  - **Correct perspective** for multiple viewers
  - No special glasses required
- Holographic optical elements

Challenges

Software

- Efficient, parallelized implementation
- $O(N^2 * log(N))$ FLOP per image in real time, with $N =$ px count of one edge, example $N = 10000 \Rightarrow 10^8$
- Multiple 2D Fourier Transformations for each image

Hardware

- Display with extremely **high resolution** required
- Pixel distance in magnitude of light wave

Content

Part I: Holography

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Holography

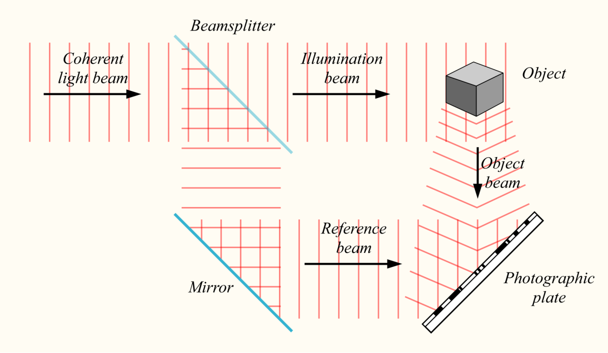
Definition

- Record entire light properties reflected from an object
- Store **intensity** and **phase** information
- Reconstruction of light field of the recorded object

History

1948 Dennis Gabor generates first hologram
1959 Improved hologram quality by Leith and Upatnieks
1960 Invention of laser, requirement for holograms
1966 First implemented algorithm for computergenerated hologram

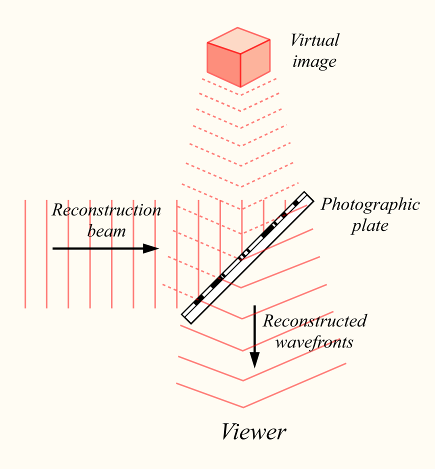
Hologram Recording



Source: `http://en.wikipedia.org/wiki/Holography`

- **Interference** of reference and object beam
- **Coherent** laser light generates standing waves
- Phase and amplitude of light are recorded

Hologram Reconstruction

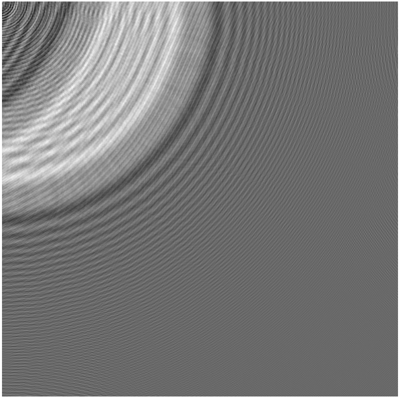


- Reconstruction beam is identical to reference beam
- **Diffraction** of reference beam by hologram
- **Virtual image** appears at position of recorded object
- **Real image** appears in front of the hologram

Source: `http://en.wikipedia.org/wiki/Holography`

Example hologram

Recorded object



Calculated fringe pattern

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Part II: Computergenerated holograms

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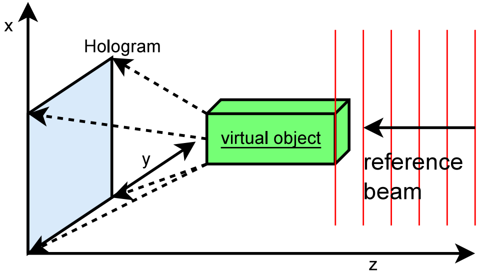
Computergenerated holograms

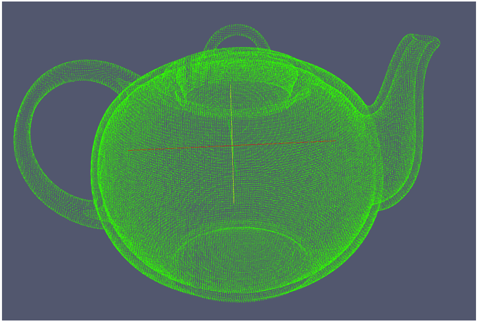
- Calculate fringe pattern on hologram plate
- Create holograms of virtual objects



Instruction

1. Describe virtual object
2. Calculate light propagation
3. Produce hardware hologram
4. Hologram reconstruction

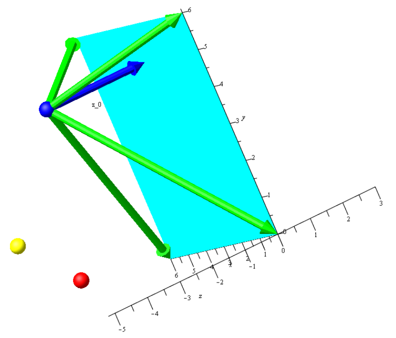
Modeling of virtual scene



- Discretize virtual scene with points
- Use each point as source of a **sphere wave**
- Electric field of sphere wave is $A * \frac{e^{i\left(\frac{2\pi r}{\lambda}+\phi_0\right)}}{r}$ with $r =$ distance from source to hologram pixel

Calculate CGH

Setting



Calculation

$$
\begin{aligned}
P_l &:= \text{source of sphere wave } l \\
p_{lm} &:= \textit{pixel}(l, m) \text{ on hologram plane} \\
U_l(P) &= \frac{e^{i\frac{2\pi r}{\lambda}}}{r}, \; r = |P - P_l| \\
R(P) &= \text{reference beam} = e^{i\frac{2\pi \langle \vec{k}, P - R_0 \rangle}{\lambda}} \\
H(p_{lm}) &= \text{eletric field on hologram plane} \\
&= R(p_{lm}) + \sum_{i=1}^{n} U_l(p_{lm})
\end{aligned}
$$

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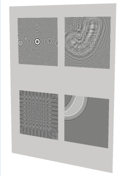
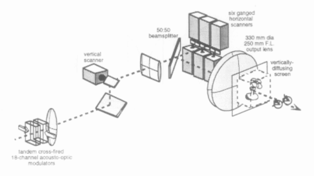
Reconstruction of CGH

Transparency film

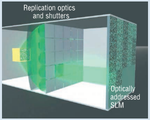


Print CGH with laser printer

Holovideo system

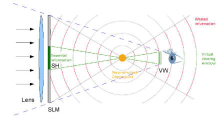


Active Tiling



Modular SLM with 10^8 pixels

SeeReal

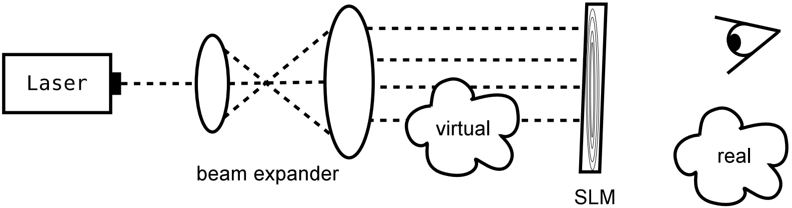


Subhologram

Image sources

- Holovideo: `http://xenia.media.mit.edu/~lucente/holo/36MB/persp.gif`
- Active tiling: Computer-Generated Holography as a Generic Display Technology, C. Slinger et al.
- SeeReal: Large holographic displays as an alternative to stereoscopic displays, R. Häussler et al.

Reconstruction setup



- Laser might be replaced with **LED**
- Light source is required to be **coherent**
- Virtual image visible behind SLM,
  real image in front of SLM

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Part III: Software design

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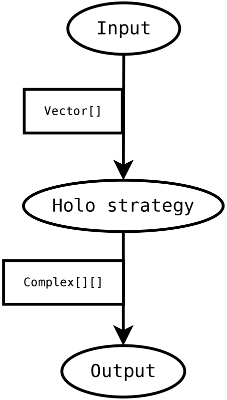
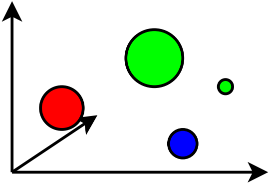
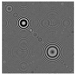
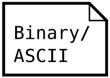
CGH application





Raycast / Fresnel / Fraunhofer
Fourier





CGH application – remarks

- Comparable with **VTK visualization pipeline**
- Input is a list of 3D vectors for **point sources**
  - generated
  - from file
  - 2D image as source
- **Strategies** for CGH calculation:
  - Raycast: Sum of sphere waves
  - Fresnel: Raycast using Fresnel approximation, avoids square roots
  - Fraunhofer: Raycast with Fraunhofer approximation
  - *Fourier*: Discretize volume into planes, run 2D DFT for each plane
- **Output** 2D image, binary / XML file

Parallelization

Approaches

1. Domain decomposition of 2D hologram
2. Decomposition of scene points, global sum
3. Time decomposition for dynamic images

Implementation

- Java prototype for testing
- C++/MPI implementation of approach 1 as efficient solution

Part IV: CGH examples

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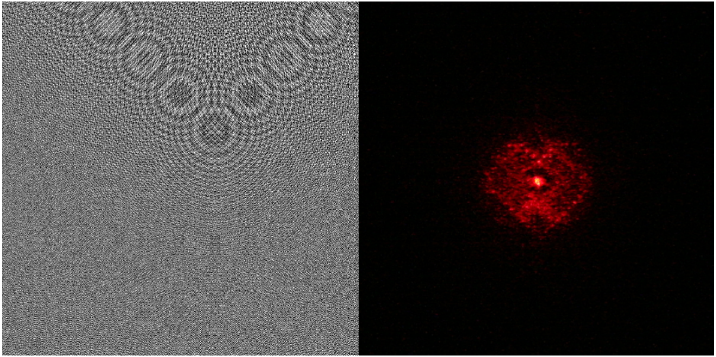
Transparency film

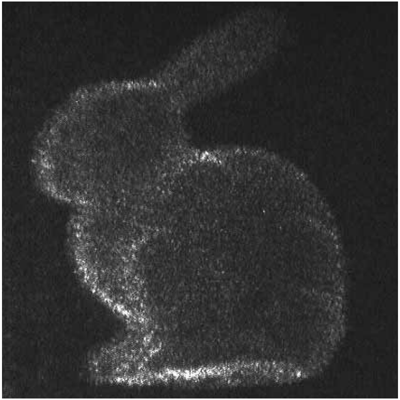
- CGH printed with **laser printer**, reconstructed with **laser pointer**



Source: Computer Generated Holography, J. Wendt

CGH with GPUs

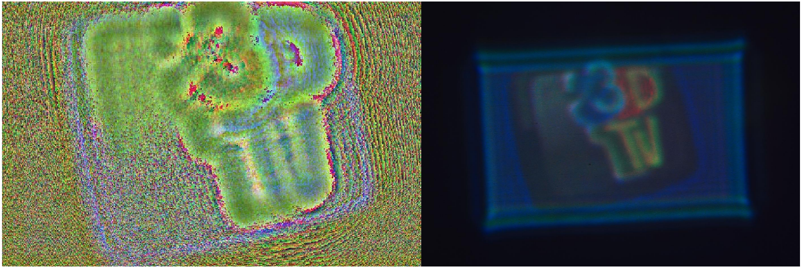
- CGH calculated with **graphic hardware**, reconstruction with Brillian 1080 SLM



Source: Computer generated holography using parallel commodity graphics hardware, L. Ahrenberg et al.

Full color CGH

- Three layer CGH,
  reconstructed with **LEDs** and HoloEye SLM



Source: Color Holographic Reconstruction Using Multiple SLMs and LED Illumination, F. Yaras et al.

SeeReal prototype

- CGH using sub holograms and eye tracking

Source: Holographic 3-D Displays – Electro-holography within the Grasp of Commercialization, S. Reichelt et al.

Part V: Outlook

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Conclusion

- Holography uses light interference and diffraction for reconstruction of a 3D-scene
- Promising visualization method
- Modeling concept of holography with sphere waves
- CGH calculates interference pattern of virtual scene
- Parallel approach for calculation of CGH

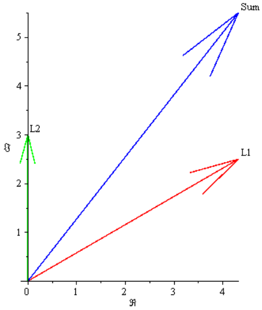
Outlook

- Performance analysis of parallel implementations for CGH generation
- Requirement for reconstruction: affordable SLM
- Integration of CGH rendering into existing visualization software

Modeling of light waves

Complex light

- Light wave defined by **electric field** $E(t)$
- $E(t) = A\, cos(\omega\, t + \phi)$
- Light has amplitude A and phase ϕ
- Complex notation $E(t) = A\, exp(i\,\phi)$ simplifies calculations
- Interference: $A_1 \mathrm{e}^{i\phi_1} + A_2 \mathrm{e}^{i\phi_2}$
- Diffraction: $A_b * A\mathrm{e}^{i\phi}$



Hologram – Derivation I

- Interference of object wave and plane wave of reference beam
- $|H|^2$ is intensity stored in hologram

$$
\begin{aligned}
\text{Reference beam} : R &= A * e^{i\phi} \\
\text{Object beam} : O &= B * e^{i\sigma} \\
\text{Interference} : H &= R + O \\
\Rightarrow |H|^2 &= (R + O) * (\overline{R} + \overline{O}) \\
&= |R|^2 + |O|^2 + O * \overline{R} + R * \overline{O}
\end{aligned}
$$

Hologram –Derivation II

- Assumption: coherent light

$$
\begin{aligned}
R * |H|^2 &= R * \left(|R|^2 + |O|^2 + O * \overline{R} + R * \overline{O}\right) \\
&= R * (|R|^2 + |O|^2) + |R|^2 * O + R^2 * \overline{O} \\
&= \text{reference beam} + A^2 * O + R^2 * \overline{O} \\
&= \text{reference beam} + \text{virtual image} + \text{real image}
\end{aligned}
$$

- Diffraction of R by interference pattern $|H|^2$
- Virtual image looks identical to recorded object
- Real image is distracting overlap