High resolution holographic image synthesis for future display eyeglasses

Praneeth Chakravarthula

UNC Chapel Hill
Eyeglasses-Style Near-Eye Display Optics

- Wide field of view
- High resolution
- Accommodation support
Eyeglasses-Style Near-Eye Display Optics

- Wide field of view
- Moderate resolution
- Accommodation support

**Holography** is the only demonstrated technology for getting everything

Maimone et al. 2017
Basics of Digital Holography
Principle of Holography
Principle of Holography
Principle of Holography

Step 1: Recording
Principle of Holography

Step 1: Recording
Principle of Holography

Step 1: Recording

Step 2: Playback
Principle of Holography

Step 1: Recording
Principle of Holography

Step 1: Recording

Step 2: Playback
Holographic Image Formation

Incident light modulated by Hologram H
Holographic Image Formation

\[ z = \mathcal{P}(H) \]

Propagates to result in the final field \( z \) and final image \( |z|^2 \)
Heuristic Hologram Phase Retrieval

Phase Hologram

Reference

Reconstruction

Reconstructed Image
Double Phase Encoding Hologram

Phase Hologram

Reference

Reconstruction

Reconstructed Image
Wirtinger Holography

\[ \nabla Err(\Phi) = \text{Re}\left(-j \exp^{-j \Phi} F^\dagger (FL)^* F \nabla f\right) \]

Phase Hologram

Reconstructed Image

Reference

Reconstruction
Wirtinger Holography
Wirtinger Holography Overview

1. Differentiable forward model
2. Compute complex Wirtinger gradients
3. Optimize for phase holograms
Step 1: For a penalty function $f$,

Compute complex Wirtinger gradients

Optimize for phase holograms

$z = \mathcal{P}(H)$

$Err = f(|z|^2, I) = f(z)$
Step 1: For a penalty function $f$, compute the error

$$z = \mathcal{P}(H)$$

$$Err = f(|z|^2, I) = f(z)$$
Step 1: For a penalty function $f$, compute the error between the holographic reconstruction and
Step 1: For a penalty function $f$, compute the error between the holographic reconstruction and the target image
Step 1: For a penalty function $f$, compute the error between the holographic reconstruction and the target image

\[
z = \mathcal{P}(H)
\]

\[
H(\Phi) = c \exp^{i \Phi}
\]

\[
Err = f(|z|^2, I) = f(z)
\]
Step 1: For a penalty function $f$, compute the error between the holographic reconstruction and the target image

\[ z = \mathcal{P}(H) \]

\[ H(\Phi) = c \exp^{j\Phi} \]

\[ Err = f(|\mathcal{P}(H(\Phi))|^2, I) \]
Step 2: Construct the cost function

\[ \Phi_{opt} = \min_{\Phi} f(|P(H(\Phi))|^2, I) + \gamma ||\nabla \Phi||^2_{\text{Err}(\Phi)} \]
Step 2: Construct the cost function to minimize the error

\[ \Phi_{opt} = \min_{\Phi} \left\{ f(|\mathcal{P}(H(\Phi))|^2, I) + \gamma \|\nabla \Phi\|^2 \right\} \]
Step 2: Construct the cost function to minimize the error with optional regularizer

$$
\Phi_{opt} = \min_{\Phi} \underbrace{f(|\mathcal{P}(H(\Phi))|^2, I)}_{\text{Err}(\Phi)} + \gamma ||\nabla \Phi||^2
$$
Step 2: Construct the cost function to minimize the error with optional regularizer to obtain the optimal phase

$$\Phi_{opt} = \min_{\Phi} \left\{ f(|P(H(\Phi))|^2, I) + \gamma ||\nabla \Phi||^2 \right\}_{Err(\Phi)}$$
Differentiable forward model → Compute complex Wirtinger gradients → Optimize for phase holograms

We can use standard optimizers if there is a gradient

\[
\Phi_{opt} = \underset{\Phi}{\text{minimize}} \left\{ f\left( |P(H(\Phi))|^2, I \right) + \gamma \| \nabla \Phi \|^2 \right\}_{\text{Err}(\Phi)}
\]

\[
\frac{d(Err)}{d\Phi} = \frac{df}{dz} \frac{dz}{dH} \frac{dH}{d\Phi}
\]

Step 2: Construct the cost function to minimize the error with optional regularizer to obtain the optimal phase
Holomorphic function: Complex function that is complex differentiable

Derivative of holomorphic real-valued function is always **ZERO**

\[
\Phi_{opt} = \min_{\Phi} f(\overbrace{|P(H(\Phi))|^2, I}^{Err(\Phi)}) + \gamma \| \nabla \Phi \|^2
\]

\[
\frac{d(Err)}{d\Phi} = \frac{df}{dz} \frac{dz}{dH} \frac{dH}{d\Phi}
\]

Derivatives of any order are **NOT DEFINED** for our objective function
Differentiable forward model → Compute complex Wirtinger gradients → Optimize for phase holograms

Two important properties of gradient:

1) Direction of maximal rate of change
2) Is zero at stationary points

\[ d(Err) = df(z) = Re\langle \nabla f, dz \rangle \]

REFER TO MY SIGGRAPH Asia 2019 PAPER AND SUPPLEMENT

Step 3: Define approximate gradient and compute Wirtinger derivatives for each propagation model
Step 4: Optimize for holograms using off-the-shelf methods.

Standard off-the-shelf optimization methods

1) Quasi-Newton
2) Stochastic gradient descent
Simulation Results
Simulation Results

Target

Modified GS (Peng et al. 2017)

Double phase (Maimone et al. 2017)

Our Method
Simulation Results

Target

Modified GS
(Peng et al. 2017)

Double phase
(Maimone et al. 2017)

Our Method
Prototype Hardware Results
Prototype Hardware Results

- **Target**
- **Modified GS**
  (Peng et al. 2017)
- **Double phase**
  (Maimone et al. 2017)
- **Our Method**
Prototype Hardware Results

Target

Modified GS
(Peng et al. 2017)

Double phase
(Maimone et al. 2017)

Our Method
Prototype Hardware Results

Target

Modified GS (Peng et al. 2017)

Double phase (Maimone et al. 2017)

Our Method
Perceptually Optimized Holography

Optimize for deep learning based perceptual losses

Learned Perceptual Image Patch Similarity (LPIPS)

( Zhang et al. 2018 )
Perceptually Optimized Holography

Target  L2 optimized  MS-SSIM optimized  LPIPS optimized
Cascaded Superresolution Holography
Prototype Hardware Results

Target

Modified GS
(Peng et al. 2017)

Double phase
(Maimone et al. 2017)

Our Method
Real World Deviations
Ideal Wave Propagation
Real World Wave Propagation
Compensating real world deviations via Hardware-in-the-loop phase retrieval

|--------|--------------------------------------------|--------------------------------------------------|-------------|

Upcoming at SIGGRAPH Asia 2020
Compensating real world deviations via Hardware-in-the-loop phase retrieval

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Upcoming at SIGGRAPH Asia 2020
Differentiable forward model → Compute complex Wirtinger gradients → Optimize for phase holograms

Wirtinger Holography

Praneeth Chakravarthula
www.cs.unc.edu/~cpk