Holographic Interferometry

Photonics Final Presentation

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Introduction

What is it holographic interferometry?

Holographic interferometry is a powerful optical technique that combines the principles of interferometry and holography.

- **Interferometry:** A family of techniques in which waves, usually electromagnetic waves, are superimposed, causing the phenomenon of interference in order to extract information.
- **Holography:** The science and practice of making holograms, which are three-dimensional recordings of a light field.

This presentation will explore the fundamental concepts behind holographic interferometry and its diverse applications.

Interferometry

Interferometry: The Basics

To understand holographic interferometry we should first be familiar with the basic principles of interferometry:

- Wave superposition
- Coherence requirements
- Types of interferometers (e.g., Michelson, Mach-Zehnder)
- Applications in metrology

Interferometry: Wave superposition

When two or more waves overlap in space, the resulting wave amplitude is the algebraic sum of the individual wave amplitudes.

For two coherent light waves with amplitudes E_1 and E_2:

$$E_{total} = E_1 + E_2 = A_1 e^{i(\omega t + \phi_1)} + A_2 e^{i(\omega t + \phi_2)} \tag{1}$$

- **Constructive interference:** When waves are in phase ($\Delta\phi = 0, 2\pi, 4\pi...$)
- **Destructive interference:** When waves are out of phase ($\Delta\phi = \pi, 3\pi, 5\pi...$)
- **Intensity:** $I \propto |E_{total}|^2 = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\Delta\phi)$

Interferometry: Wave superposition

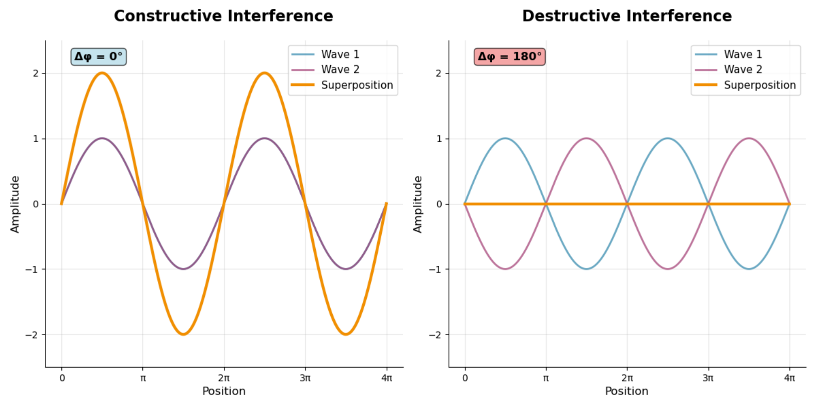

Figure 1: Illustration of wave superposition showing constructive interference (left) where waves add in phase to create larger amplitude, and destructive interference (right) where out-of-phase waves cancel each other.

Interferometry: Coherence requirements

For stable interference patterns, light sources must exhibit:

Temporal Coherence

- Light must be **monochromatic** (single frequency/wavelength)
- Coherence length: $L_c = \frac{\lambda^2}{\Delta\lambda}$
- Path difference must be $< L_c$ for visible fringes

Spatial Coherence

- Light source must be sufficiently **small** or **collimated**
- Ensures constant phase relationship across the wavefront
- Critical for uniform fringe visibility

Practical Sources

Lasers are ideal: high temporal and spatial coherence

LEDs/lamps require filtering and careful design

Interferometry: Coherence requirements

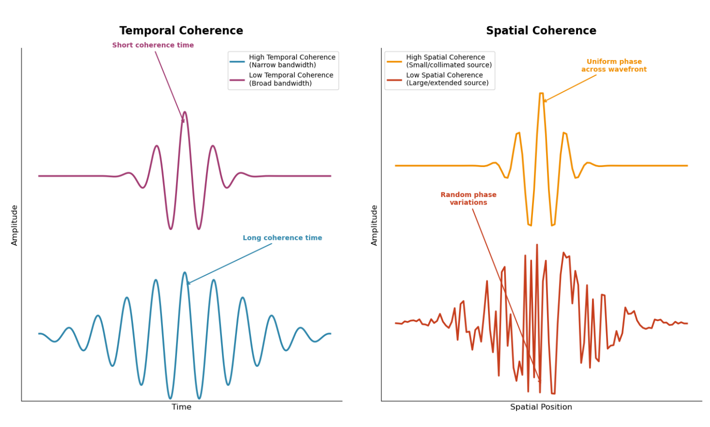

Figure 2: Demonstration of coherence requirements: temporal coherence (left) shows the need for monochromatic light with sufficient coherence length, while spatial coherence (right) illustrates the importance of wavefront uniformity for stable interference patterns.

Interferometry: Types of interferometers

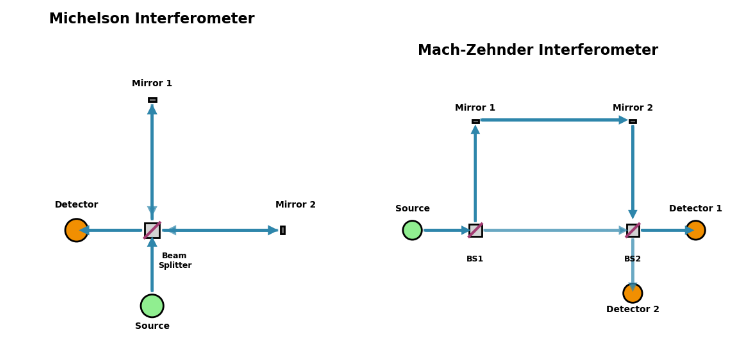

Figure 3: Left: Michelson interferometer - measures length changes by detecting phase shifts in interference fringes when one mirror moves, enabling nanometer-scale displacement detection. **Right:** Mach-Zehnder interferometer - compares optical path lengths between two separate beams, allowing measurement of refractive index changes, object thickness, or phase disturbances in one arm.

Interferometry: Applications in metrology

- **Length and distance measurement**
  Interference fringes shift as the optical path length changes (*nm* resolution or higher)
- **Surface profiling and surface**
  Comparing an optical surface to a reference flat or spherical surface to reveal deviations, roughness...
  (again, *nm* resolution or higher)
- **Refractive index measurements** (precise phase shift detection)
- **Wavefront Sensing**
  Comparing the phase of a light wave emerging from an optical system to that of a reference wave reveals wavefront distortions caused by imperfect mirrors or lenses.

Holography

Holography: Recording 3D Information

In order to fully understand holographic interferometry we should also revisit some key aspects of holography:

- Recording process (interference and diffraction)
- Reconstruction process
- Types of holograms (e.g., transmission, reflection)
- Key differences from traditional photography

Holography: Recording process

As explained, interferometry can be used to measure lengths and distances with high precision. If we measure planes (images) instead of single points we can create surface details and create 3D scans.

Holography: Recording process

Our simulation (conceptual):

- Shows how distance variations create interference patterns
- Projects 3D surface information into 2D views
- Demonstrates the *principle* of encoding 3D information in fringes

Real holography: Object beam (scattered from object) + Reference beam interfere on a *recording medium* (photographic plate/CCD). Our simulation is **educational** - it shows the concept but simplifies the actual recording process.

The complex fringe patterns demonstrate how 3D surface variations get encoded.

Holography: Recording process

Where are the light sources?

- **Front measurement:** Light source at position [0, 0, 3] - illuminating from +Z direction
- **Side measurement:** Light source at position [3, 0, 0] - illuminating from +X direction
- **Top measurement:** Light source at position [0, 3, 0] - illuminating from +Y direction

Each position acts as both:

- **Light source** (object beam origin)
- **Reference point** for distance measurements

Distance from source to each surface point determines the interference pattern recorded from that viewing angle.

Holography: Recording process

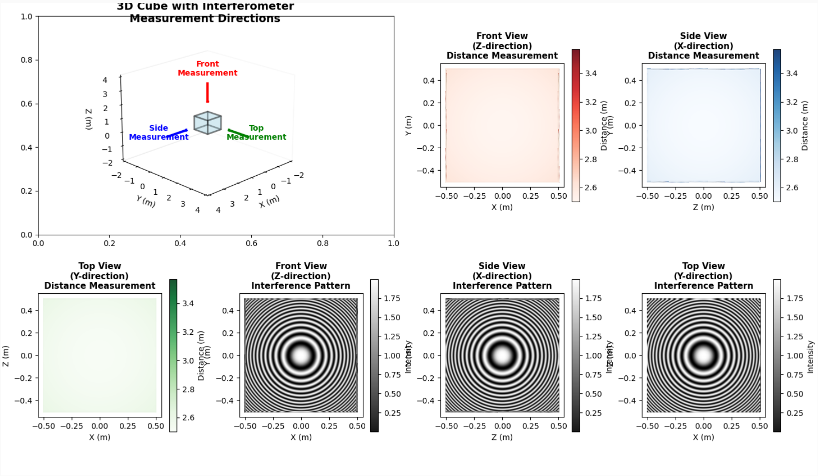

Figure 4: Interference patterns on flat surfaces of a 3D modelled cube.

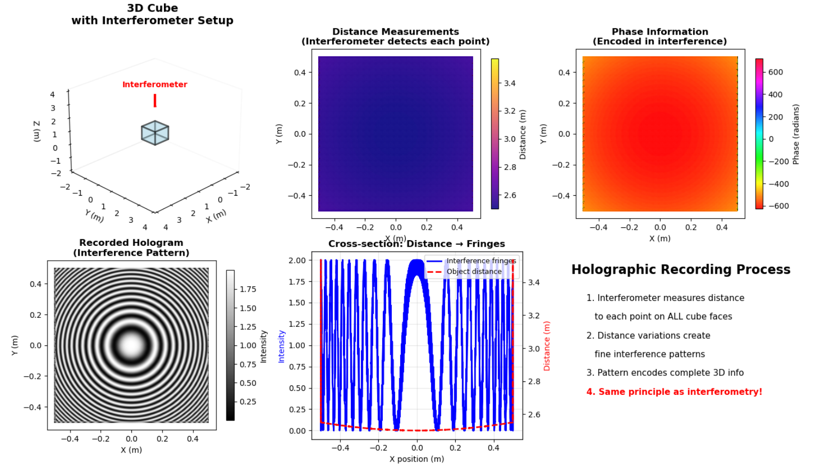

Figure 5: Difference between fringes and the equivalent distance measurement values on a 3D modelled cube.

Holography: Recording process

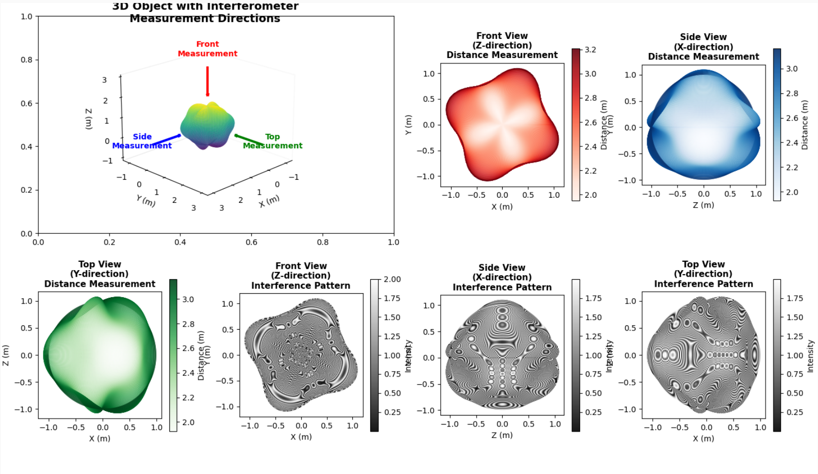

Figure 6: Interference patterns on flat surfaces of a 3D modelled complex volume.

Holography: Recording process

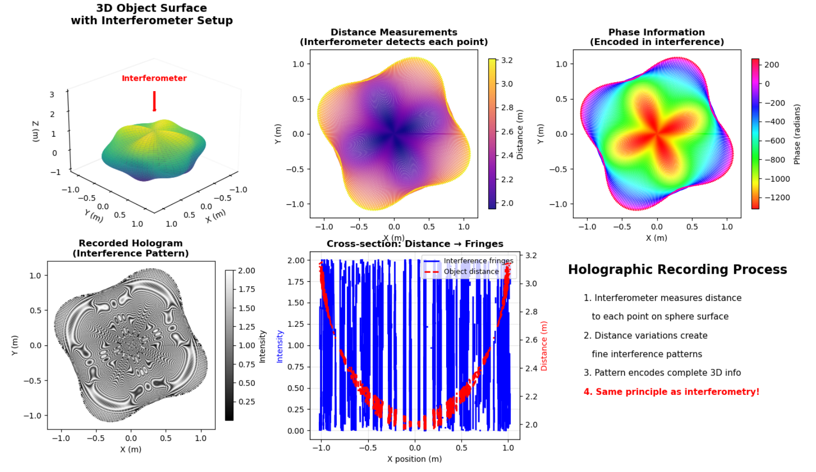

Figure 7: Difference between fringes and the equivalent distance measurement values on a 3D modelled complex volume.

Holography: Reconstruction process

To view the 3D information stored in the hologram, we reverse the recording process:

Illumination with reconstruction beam:

- Shine light (typically the same wavelength) through the recorded hologram
- The interference pattern acts as a **diffraction grating**
- Light diffracts in specific directions based on the fringe patterns

Wavefront reconstruction:

- The diffracted light recreates the **original object wavefront**
- Observer sees a true 3D image floating in space
- Different viewing angles reveal different perspectives

Holography: Reconstruction process

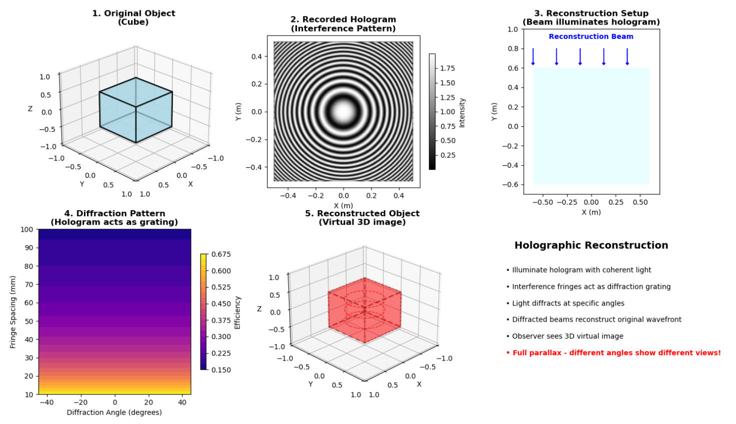

Figure 8: Reconstruction of the measured hologram of the 3D modelled cube.

Holography: Reconstruction process

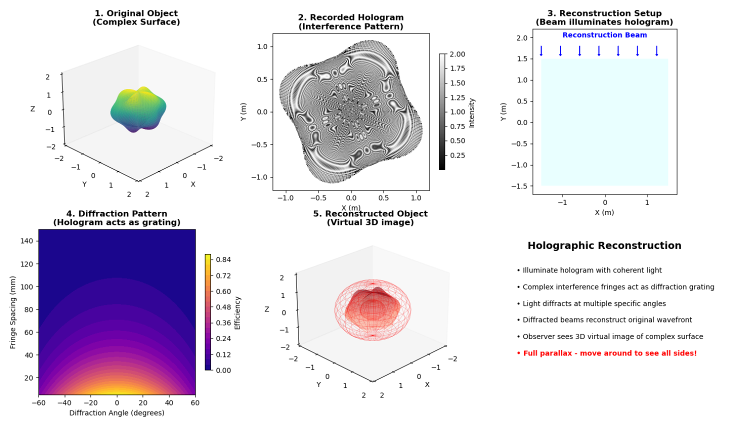

Figure 9: Reconstruction of the measured hologram of the 3D modelled complex volume.

Holography vs Traditional photgraphy

Traditional Photography:

- Records only **2D intensity** information
- Single viewing perspective
- Loses all depth information
- Flat projection of 3D world
- Cannot reconstruct original light field

Holography:

- Records **3D wavefront** information
- Multiple viewing perspectives encoded
- Preserves complete depth information
- **All visible surfaces** from recording direction
- Reconstructs original light field

Holography vs Ray-Tracing

- Holography captures 3D information **just like ray-tracing** - limited by optical visibility
- But uses **interferometry & diffraction** instead of computational algorithms
- Each recorded interference pattern encodes distances to all visible surface points
- Reconstruction reverses the process using wave optics principles

Physics of Holographic Interferometry

Physics of Holographic Interferometry

Now we can combine the concepts and explore the underlying physics of this optical technique.

- Double-exposure method
- Real-time method
- Time-averaged method
- Fringe formation and interpretation
- Sensitivity and measurement capabilities

Double-exposure method

Real-time method

Time-averaged method

Fringe formation and interpretation

Sensitivity and measurement capabilities

Industrial Applications

Industrial Applications

This section will showcase the practical uses of holographic interferometry.

- Non-destructive testing (NDT)
- Stress and strain analysis
- Vibration analysis
- Flow visualization
- Surface contouring and deformation measurement

Industrial Applications: Non-destructive testing

Industrial Applications: Stress and strain analysis

Industrial Applications: Vibration analysis

Industrial Applications: Flow visualization

Industrial Applications: Surface and deformation measurement

Conclusion

Conclusion

A summary of the key concepts presented.

- Recap of holographic interferometry principles
- Advantages and limitations
- Future outlook and potential advancements