3D Imaging Using Interferenceless Coded Aperture Correlation Holography

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Research Background

There are two fundamental approaches to capturing images: direct and indirect imaging. Direct imaging captures and creates an image in a single step, as seen in microscopes, cameras, and the human eye, where light strikes a sensor to record amplitude and frequency. In contrast, indirect imaging separates the capturing of light wave information from image recreation into two distinct processes (1).

Traditional digital holography requires two coherent light beams: an object wave that interacts with the subject and a reference wave that creates interference patterns on a sensor. This interference pattern is then numerically decoded to recover the object's three-dimensional information. Our experiment employs a simulated version of interferenceless coded aperture correlation holography (I-COACH), an innovative indirect method, that has the ability to capture 3D images from a single perspective (1,2).

I-COACH advances this technique by leveraging computational power to simulate the reference wave. Instead of analyzing interference patterns, I-COACH compares incoming object waves with a library of pre-recorded point spread functions (PSFs). These PSFs are created by shining light through a pinhole from known distances, illustrating how unaffected light propagates in the system.

Additionally, I-COACH utilizes spatial light modulators (SLMs) that modulate the phase of incoming light. This technology allows us to simulate different lenses using 2D bitmaps, known as phase masks. These phase masks overcome the physical limitations of traditional lens-based holography (3), giving the ability to probe the object in different ways.

Optical Setup

The I-COACH setup uses incoherent light emitted from an LED, which is focused onto a pinhole mounted on a motorized stage. This stage can move vertically in increments as small as 1.7 microns. A third lens collimates the light from the pinhole and directs it onto a beam splitter, allowing the light to interact with a spatial light modulator (SLM). The SLM modulates the incoming light and projects it onto an image sensor, where it is cross-correlated with a PSF library for reconstruction.

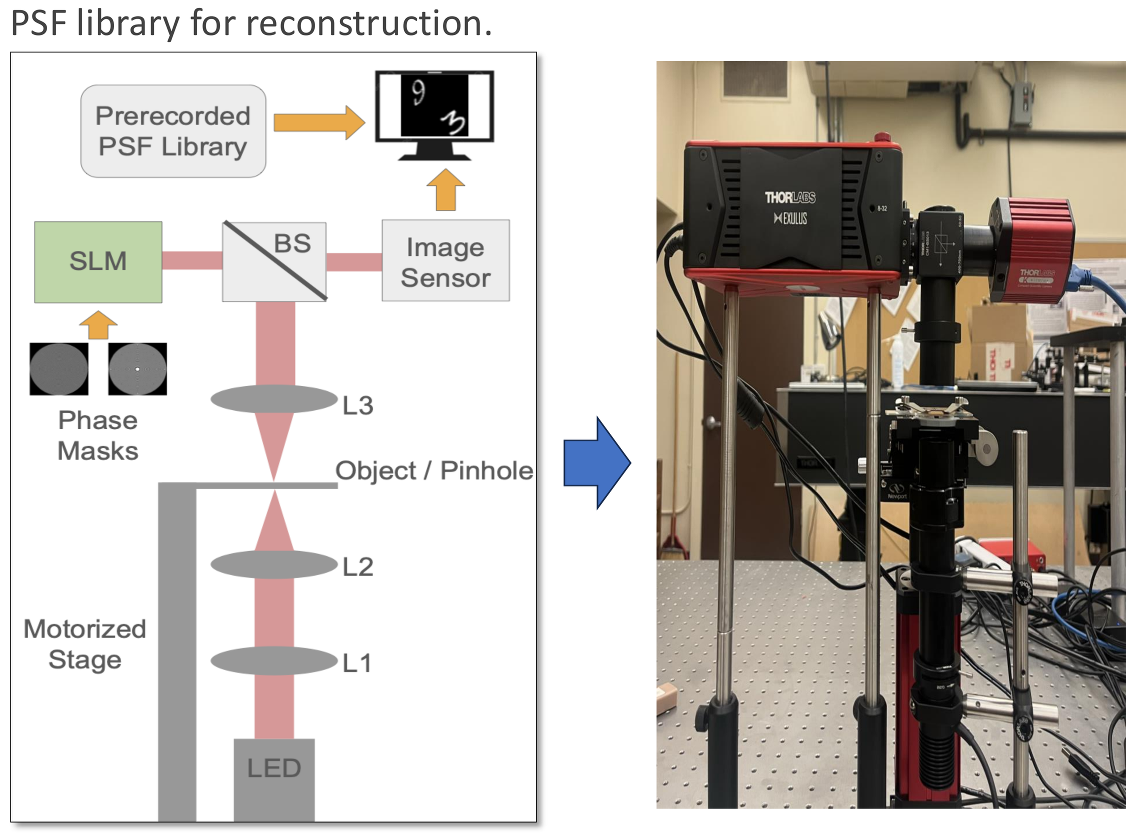
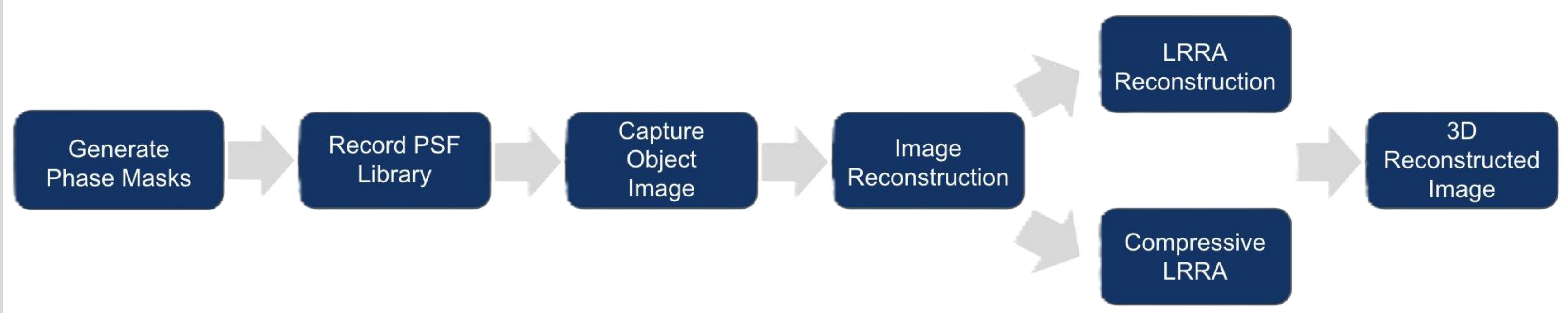


Figure (1) The optical setup for I-COACH. L1,L2,L3 are convex lenses with focal length 2.54 cm. BS is a 50-50 beam splitter shining light onto a spatial light modulator (SLM).

Methodology

The I-COACH simulation starts by generating a set of phase masks for the SLM to function as a digital lens. These phase masks help create a library of PSFs, which model the interaction of a single light source with the system. This is beneficial for reconstruction, as an object can be represented by multiple point sources. The next step involves simulating an object to be captured by a camera. The resulting image is then reconstructed into a 3D representation using two algorithms: the Lucy Richardson Rosen Algorithm (LRRA) and the compressive Lucy Richardson Rosen Algorithm (Comp. LRRA). This simulated 3D reconstruction is depicted as two 2D images recorded at different planes.



Phase Mask Design

Phase masks are generated by applying specific functions to a 2D matrix, simulating lenses with various focal lengths. These lenses alter the PSF, thereby affecting image reconstruction. Some phase masks offer superior axial resolution, while others provide enhanced lateral resolution. By modulating light in ways traditional lenses cannot, phase masks enable novel methods of image reconstruction.

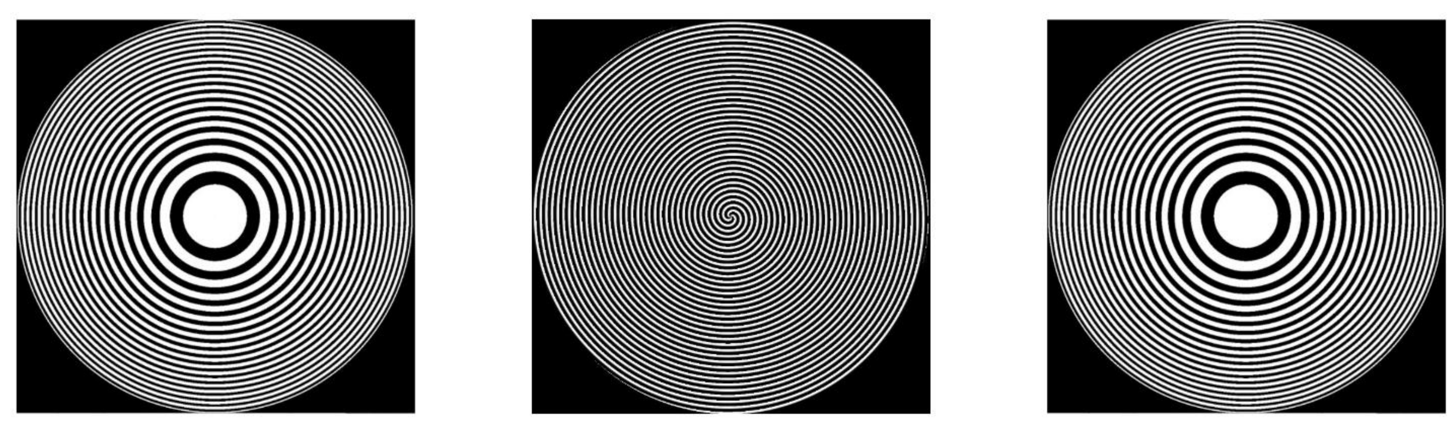


Figure (2) Three phase masks used to modulate light incident on the SLM. Diffractive lens f=5cm (left), spiral axicon (center), and diffractive lens f=50cm (right).

Image Reconstruction

The reconstruction of the 3D image involves cross-correlating the PSF with the simulated object. Two distinct image reconstruction techniques were employed, each yielding different results. The first technique, LRRA, iteratively refines the image by comparing the observed data with the expected PSF, enhancing the resolution at a specific plane. The second technique, Comp. LRRA, incorporates compressive sensing principles to further improve the reconstruction quality by reducing noise and artifacts. By performing multiple image reconstructions at different planes, a comprehensive 3D image can be obtained. This approach allows for detailed visualization of the object's structure, providing a precise and high-resolution 3D representation.

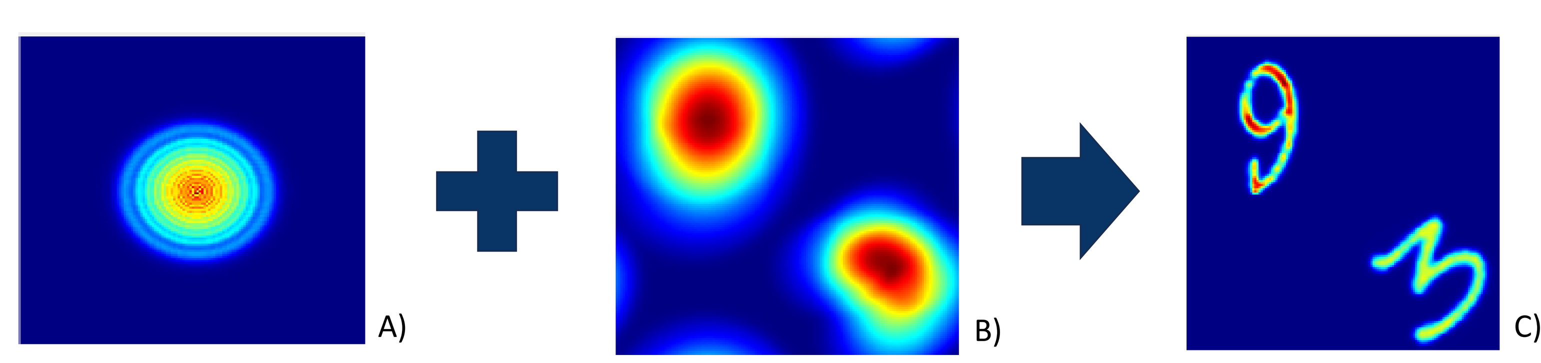


Figure (3) A prerecorded PSF (A) is cross correlated with a 2D object image (B) to be reconstructed into a 3D image (C).

Results

After simulating two objects at different planes, one at 4 cm and another at 5 cm, three different phase masks were used to reconstruct the 3D object. The simulation demonstrated that phase masks significantly influence the point spread function (PSF), and altering the vertical distance of the pinhole also impacts the results. The object intensity, which is the 2D information recorded by the camera, is captured on a single plane and does not provide 3D information.

Both the Lucy Richardson Rosen Algorithm (LRRA) and the compressive Lucy Richardson Rosen Algorithm (Comp. LRRA) were employed to reconstruct the images at both planes. The simulation revealed that Comp. LRRA offers higher lateral resolution while maintaining the same axial resolution as LRRA. This means that Comp. LRRA can provide finer details along the horizontal axis without compromising the depth information.

Additionally, the simulation showed that different phase masks provide varying lateral and axial resolutions. Some phase masks enhance the lateral resolution, offering sharper details across the horizontal plane, while others improve axial resolution, providing better depth perception. This variability allows for diverse perspectives on the original 3D image, enabling a more comprehensive understanding of the object's structure.

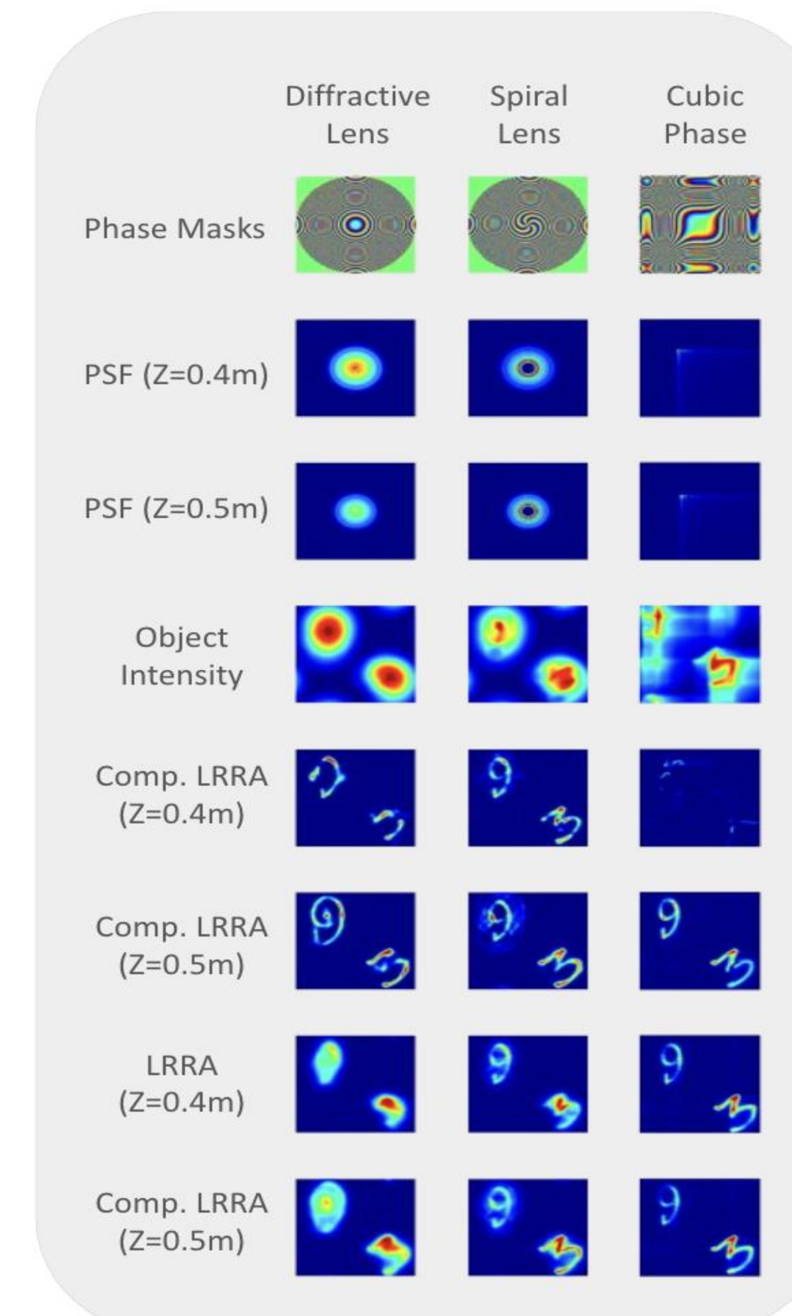


Figure (4) A simulated 3D object being reconstructed in 2 different planes using LRRA and Comp. LRRA.

Conclusion

The simulation conducted in this project effectively demonstrates the viability of I-COACH as a method for capturing high-quality 3D images. By utilizing digital phase masks, incoherent light, and PSF libraries, I-COACH offers greater flexibility and freedom compared to traditional holography techniques. The ability to modulate light using digital phase masks allows for innovative approaches to image reconstruction that were previously unattainable with conventional lens-based methods.

Our results highlight the significant impact of phase masks and pinhole positioning on the point spread function (PSF) and, consequently, on the quality of the reconstructed images. The use of the compressive Lucy Richardson Rosen Algorithm (Comp. LRRA) has proven to be a viable and effective algorithm for image reconstruction, offering higher lateral resolution while maintaining axial resolution.

Furthermore, the simulation underscores the importance of optimizing phase masks and reconstruction techniques to achieve the best possible image quality. By leveraging computational power and innovative algorithms, I-COACH can overcome the limitations of traditional holography, paving the way for future advancements in 3D microscopic imaging.

References

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