Chapter 8
Development of Mixed Reality Methods for Immersive Visualization of 3D Dynamic Optical Testing Measurements

Daniel Ruiz-Cadalso, Lorena Maria Genua, Jonathan Oliveira Luiz, Cosme Furlong, Lee Moradi, and Vladimir Vantsevich

Abstract Conventional techniques for visualization of optical experimental data, such as displacements and vibrations, as well as numerical simulations remain limited to 2D screens, lacking the opportunity for more intuitive spatial analysis. In this work, we are developing a methodology that explores the use of MR to overlay experimental optical measurement data directly onto the physical objects under analysis. Digital fringe projection and holographic interferometry techniques are applied to shape and vibration measurements, respectively, of real aerospace rotor blades subjected to dynamic loading conditions. The high-resolution, full-field displacement data is processed, applied to the shape measurement, and visualized in an MR environment using Microsoft HoloLens2 by a custom-developed application running on Unity, enabling users to directly interact with 3D data. This initial methodology demonstrates the potential of merging experimental data with numerical simulations for real-time investigation of actual components and facilitating the development of digital twins.

Keywords Mixed reality · Digital holography · Digital twins · Optical metrology · Non-destructive testing.

Introduction

Optical metrology is critical for non-destructive testing (NDT) in experimental mechanics, enabling precise, full-field measurement of displacement, strain, and vibration in a variety of engineering and biological applications. Techniques such as digital holographic interferometry, digital image correlation (DIC), structured light projection, and digital shearography offer non-contact, high-resolution measurements, and have been employed in a variety of applications [1], from NDT in the aerospace industry [2–4] to structural health monitoring, and biomedical imaging. Traditional visualization of data collected from these methods is often limited to two-dimensional (2D) representations on standard display screens, hampering a more intuitive spatial understanding of complex, dynamic data.

To address these limitations, mixed reality (MR) and digital twin technologies are being explored to enhance the way optical metrology data is analyzed and interpreted. By overlaying experimental data onto physical samples in a 3D interactive

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environment, users can intuitively explore and manipulate datasets in real-time. Prior work has demonstrated the use of augmented reality (AR) for visualizing holographic data obtained through DH [5]. Other studies have employed MR for ultrasonics imaging, where dynamics extracted from experimental data are directly overlaid on structures for real-time evaluation [6]. Digital twins in optical metrology are particularly useful in applications where real-time experimental feedback is used to update numerical models for better predictive capabilities [7, 8].

In this study, we propose a methodology that integrates mixed reality visualization with optical metrology techniques, specifically structured light projection and digital holographic interferometry. Our approach enables direct overlay of high-resolution experimental data and numerical simulations onto physical objects for real-time evaluation. The integration of MR tools allows users to interact with 3D full-field shape and displacement data, enhancing the interpretation of experimental and numerical results.

Materials and Methods

Mixed reality display

For mixed reality visualization, we utilize Microsoft HoloLens 2 [9], an optical see-through head-mounted display that enables real-time interaction with projected data [10]. The experimental optical metrology data can be processed using a custom-developed C# application running within Unity, which serves as the rendering engine for graphical data representation. The application, described in Figure 1, enables users to visualize and manipulate full-field displacement, strain, and vibration data overlaid on real test samples. Through custom Unity shaders and rendering techniques, high-resolution optical metrology data is spatially aligned with the physical object under investigation.

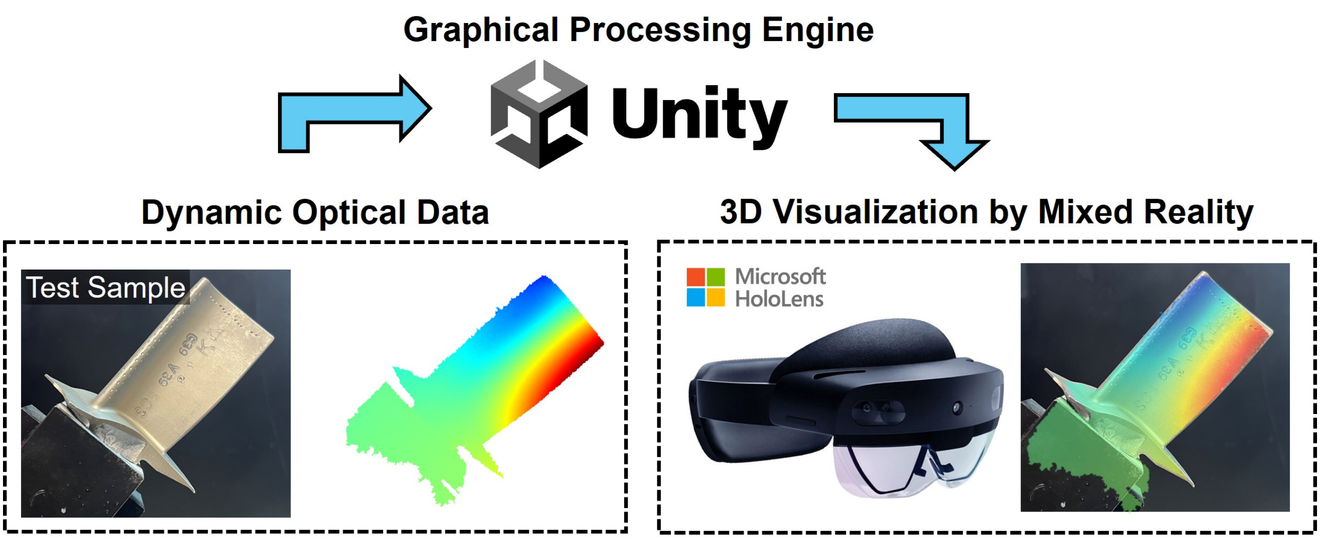

Fig. 1 Implementation of mixed reality tools for 3D visualization of dynamic optical data. The data is processed and imported into the Unity engine, and a custom-developed program runs the engine through the HoloLens 2.

Optical metrology techniques

Digital fringe projection

Structured light projection is a technique for recovering 3D shape information of an object's surface. In fringe projection, a structured fringe pattern with known phase and density is used. Our fringe projection system consists of two major components: a spatial light modulator (SLM) and a digital charged-couple device (CCD) camera. The SLM projects computer generated fringe patterns onto a sample of interest, and the CCD captures the fringe patterns on the sample. The camera is positioned at an angle from the projection axis in order to provide optical triangulation, which describes the sensitivity of the data. Due to optical triangulation, height, h, can be extracted via [11],

$$h = \frac{L\Phi}{2\pi f_0 D}, \tag{1}$$

where h is the height from the reference plane, L is the distance from the SLM to a reference plane, D is the distance from the SLM to the CCD camera, f_0 is the spatial frequency of the projected fringes, and Φ is the optical phase carrying shape information. The optical phase, Φ, is extracted via phase-shifting methods [12].

Digital holographic interferometry

Digital holography is an optical technique used to extract the amplitude and phase of light. In order to properly extract these parameters, digital holography uses the superposition of two unique coherent wavefronts which stem from the same light source but have each undergone diverse conditions in their respective paths. The recorded complex field, $\Gamma = Ae^{i\Phi}$, is reconstructed using phase-shifted holograms, either temporally or spatially [13]. The optical phase calculated from a single reconstructed field would yield static information; thus, changes to the optical phase are measured interferometrically via a double exposure (DE) method. The phase difference values are wrapped within $[-\pi,\ \pi]$ (mod2π). The phase can be unwrapped, and directly converted to displacements, d, by [12],

$$d = \frac{\lambda}{4\pi}\mathrm{unwrap}\left[\Delta\Phi\right], \tag{2}$$

where d is the displacement, λ is the wavelength of the source, and $\mathrm{unwrap}\left[\Delta\Phi\right]$ is the unwrapped optical phase.

Representative Results

Experimental results of optical methods

Shape measurements by structured light fringe projection

The results of structured light projection for shape measurements are shown in Figure 2. The fringe projection system captured the 3D surface profile of the sample with 5 MP spatial resolution and below 100 μm measurement accuracy. As shown in Figures 2a and 2b, the sample was illuminated using a spatial light modulator (SLM), and fringe patterns were captured

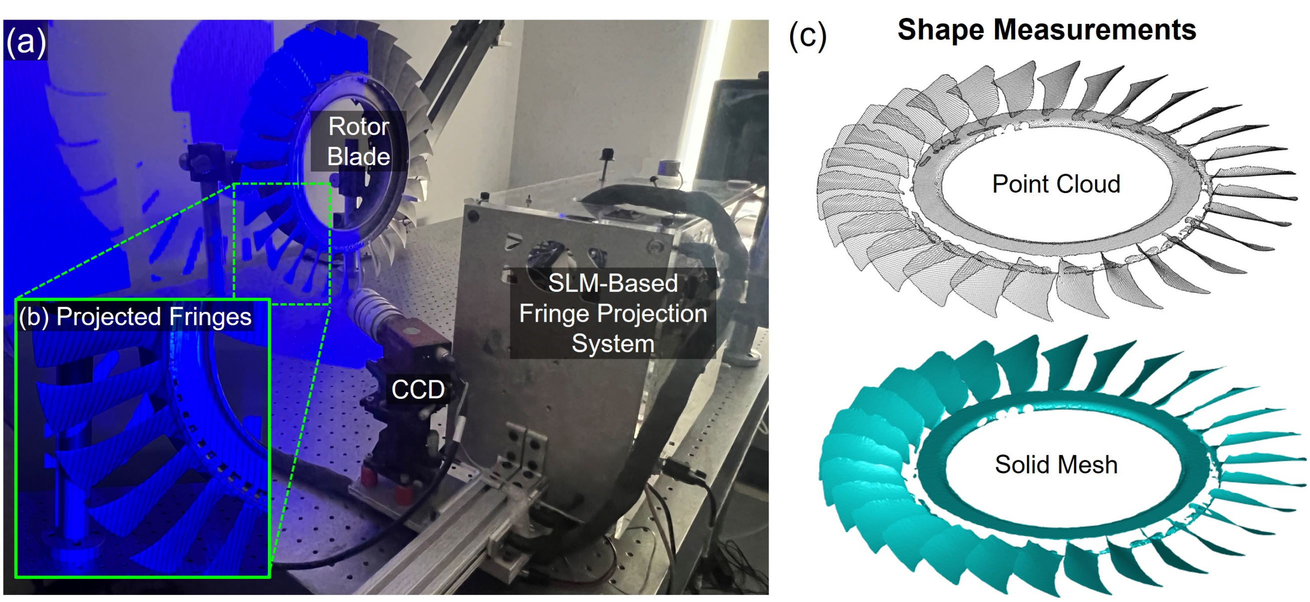

Fig. 2 Shape measurements by digital fringe projection: (a) system setup; (b) zoomed-in image showing the projected 460 nm fringes; and (b) 3D shape results as a point cloud as well as a solid mesh.

by a CCD camera positioned at an offset angle for triangulation-based reconstruction. The quantitative accuracy of shape measurement is assessed based on spatial resolution and phase-unwrapping techniques. Due to nondisclosure agreements, the specific dimensions of the sample cannot be provided, but the system demonstrated a shape measurement resolution in the sub-100 μm range. The extracted 3D mesh, shown in Figure 2c, provides precise surface reconstruction, which can be further analyzed in mixed reality environments for digital twin applications.

Vibration measurements by digital holographic interferometry

The vibrational displacement measurements obtained using digital holographic interferometry (DHI) are illustrated in Figure 3. The setup, shown in Figure 3a, features a custom-developed digital holographic system consisting of a compact and portable optical head, a 532 nm, continuous-wave, single longitudinal mode laser, and a 5 MP camera. The sample was loaded using a piezoelectric shaker attached along the circumference of the rotor's rim, inducing dynamic deformations, which were captured in real-time at 15 fps. The optical phase changes were processed to extract mode shapes and displacement fields down to approximately 26 nm in resolution. The results include displacement fields at a specific mode shape, shown in Figures 3b and 3c.

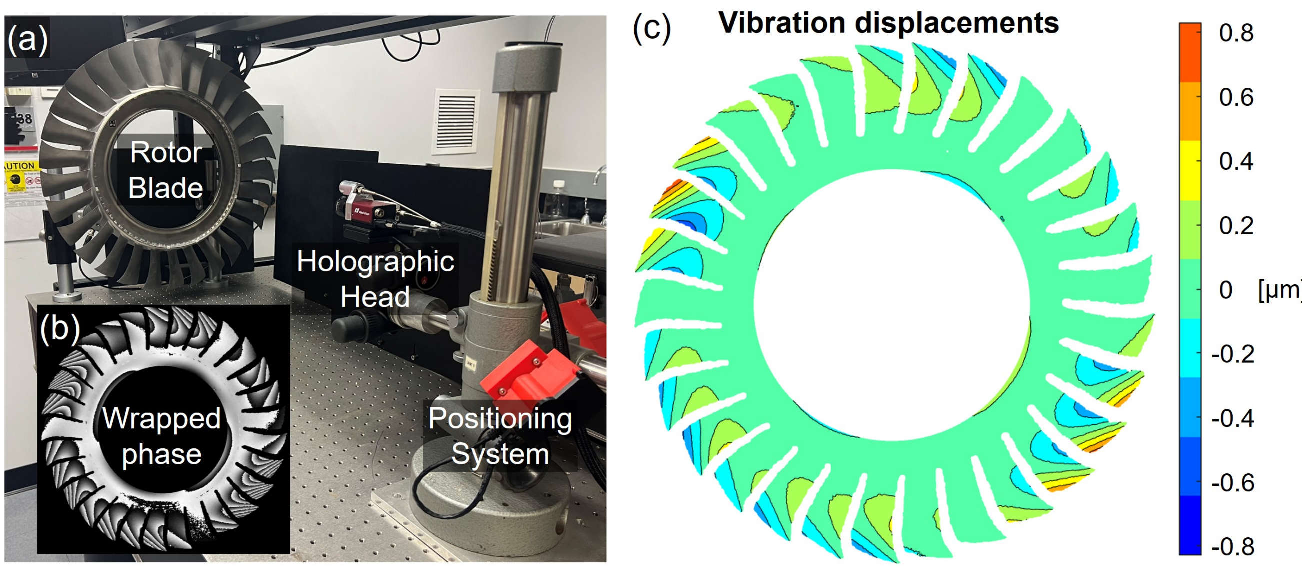

Fig. 3 Vibrational displacement measurements by digital holographic interferometry: (a) system setup; (b) wrapped optical phase of the complete rotor blade; and (c) displacement fields of one mode shape.

Visualization of rotor vibrations by mixed reality

The final experimental demonstration involved using mixed reality visualization to project optical metrology data onto an actual rotor sample, as depicted in Figure 4. Figure 4a shows the 3^{rd} person view of the user interacting with the optical data in real-time. The displacement data obtained from digital holographic interferometry was mapped onto the rotor surface in real-time, as shown in Figures 4b, 4c and 4d, allowing users to interactively examine mode shapes and vibrational characteristics. The data visualization was performed using manual placement within the MR environment, with plans for future automation through image-based registration. The frame rate of the MR display was maintained at 60 Hz, ensuring smooth rendering, with occasional and short dips to 30 Hz, while the accuracy of holographic data alignment was within millimeter precision. Future developments will enhance automatic registration techniques for improved data alignment.

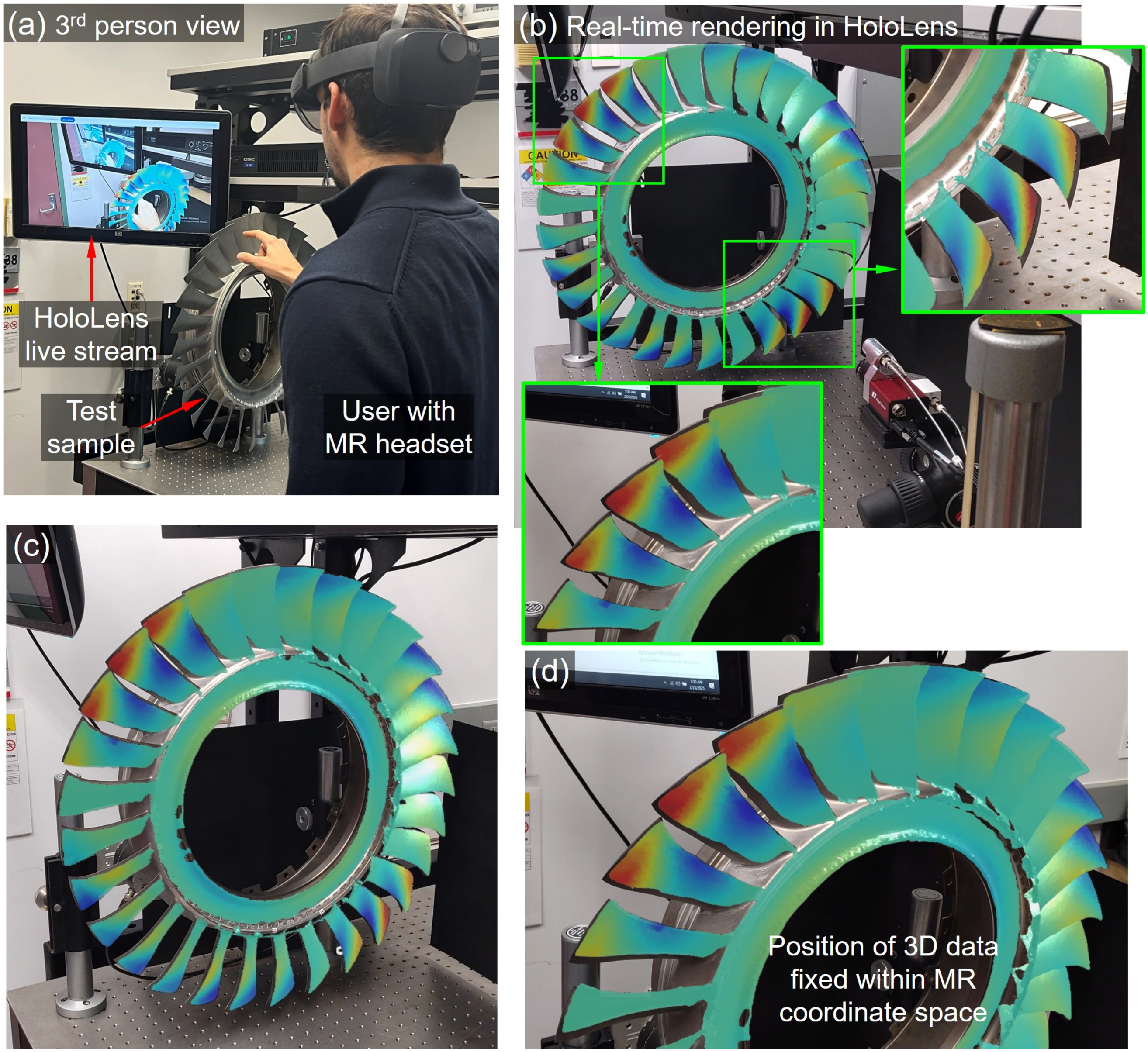

Fig. 4 Augmented visualizations of digital holographic interferometry data by mixed reality methods using HoloLens technology: (a) image of the user from a 3^{rd} person point of view, while displaying the live stream of the HoloLens results using first mode shape; (b) snapshots taken via the HoloLens stream; (c) overlay of entire dynamic optical data on the real sample; and (d) different angle of view.

Conclusions and Future Work

This study demonstrates the integration of mixed reality with optical metrology techniques, including structured light projection, digital holographic interferometry, and high-speed digital image correlation. By leveraging HoloLens 2 and Unity, we successfully visualized full-field 3D experimental data in an interactive MR environment. The results highlight the potential of MR for intuitive interpretation of dynamic optical measurements, offering a more immersive and spatially accurate representation of experimental data compared to conventional 2D visualization methods.

Despite the promising results, several challenges remain in the implementation of MR-based optical metrology visualization. The handling of large datasets poses computational challenges, requiring efficient processing methods to ensure real-time rendering. Additionally, the accurate registration of data with the geometry is crucial for precise alignment of MR overlays with physical samples. Another challenge lies in real-time synchronization, as improvements in frame rate stability and spatial accuracy are necessary for seamless integration and user interaction.

Future work will focus on enhancing the automatic placement of MR data using image and shape registration techniques, which will improve alignment accuracy and reduce manual intervention. The integration of shape measurement techniques with dynamic metrology is another key area of development, enabling a more comprehensive digital twin representation. Additionally, modifying geometry visualization using exaggerated displacement fields can enhance the spatial understanding of the optical data, making it easier to interpret dynamic behaviors. The potential for real-time modal correlation through MR will also be explored, further strengthening the capabilities of digital twins in predictive analysis. Overall, this research lays the foundation for MR-enhanced optical metrology, offering significant advancements for applications in nondestructive evaluation, biomechanics, and structural health monitoring.

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