

A Lensless Microscope-Based Sensor for 3D Displacement Measurement in Infrastructure Monitoring

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Summary:

We developed a cost-effective, compact lensless imaging system designed for 3D displacement tracking in the context of structural health monitoring. Lateral displacement is measured using phase-correlation-based image registration, while axial displacement is estimated from illumination-dependent image shifts using a geometric model. Experiments show lateral resolution down to 5 micrometers (x-y axes) and axial resolution of about 0.1 millimeters (z axis) over a dynamic range up to 18 millimeters. This instrument enables compact non-contact monitoring of microscopic 3D movements in cracks and joints.

Keywords: 3D displacement measurement, optical sensing, lensless imaging, phase correlation, structural health monitoring

Background and Motivation

Structural health monitoring of infrastructure requires reliable displacement sensing to enable long-term assessment of deformation and displacement. Conventional contact-based sensors include electrical crackmeters, vibrating-wire crackmeters, and fiber Bragg grating-based sensors. Despite their high sensitivity, these methods are typically deployed as point-wise measurements and most often provide one-dimensional information at each sensing location.

Vision-based non-contact methods have therefore attracted strong interest for displacement monitoring [1]. However, many existing optical approaches rely on bulky imaging optics and complex calibration, which restrict their use in compact field-deployable systems.

Lensless imaging offers a promising route toward miniaturized optical sensing [2,3]. In this field, phase correlation has been established as a robust method for sub-pixel displacement estimation [4]. Here, we combine these concepts and propose a compact lensless optical sensor based on a monochrome CMOS camera and a microLED array. The objective is to achieve 3D displacement sensing, where lateral motion (x-y axes) is measured by phase correlation and axial motion (z axis) is inferred from illumination-dependent image shifts under different LED positions.

Methodology and Instrument Design

The proposed instrument implements a compact lensless optical architecture for 3D displacement measurement using a QubeDot microLED array ($\lambda = 450$ nm), a patterned marker, and a Basler CMOS camera (daA3840-45um) in an in-line configuration. The marker is positioned between the illumination source and the sensor, so that each LED generates a distinct diffraction-based intensity pattern on the CMOS plane. Controlled displacement is introduced using a three-axis translation stage actuated by Thorlabs K-Cube DC servo controllers.

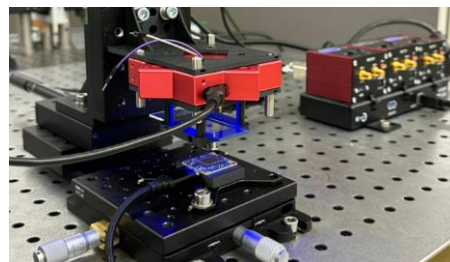


Fig. 1. Experimental setup of the proposed lensless displacement sensing instrument.

For two frames $I_a(x, y)$ and $I_b(x, y)$, the subpixel shift is obtained by phase correlation [4]:

$$(\Delta x, \Delta y), \rho = \text{PhaseCorrelation}(I_a, I_b) \quad (1)$$

where $\Delta x, \Delta y$ are pixel displacements and ρ is the correlation response. A key design feature is

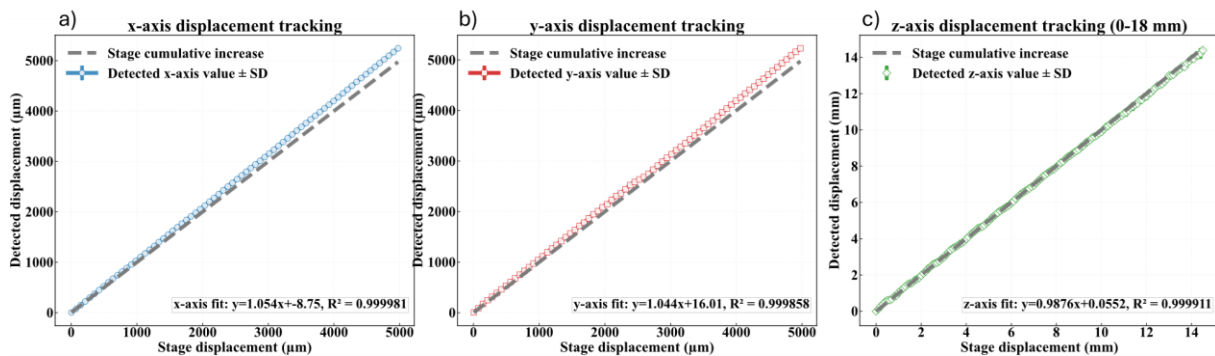


Fig. 2. Measured versus stage-referenced cumulative displacement for lateral (x, y) and axial (z) directions. a) x-axis displacement tracking; b) y-axis displacement tracking; c) axial displacement estimation over 0–18 mm.

the decoupled estimation of lateral and axial motion. Lateral (x-y) displacement is estimated from inter-cycle, same-pattern phase correlations, while axial (z) displacement is estimated from intra-cycle, illumination-dependent disparities. This separation reduces cross-axis coupling between lateral drift and depth variation.

Results

In the experiment, a motorized stage driven by three Thorlabs K-Cube DC servo controllers along the x, y, and z axes. The stage moved in fixed step sizes (5 μm in the x-y axes and 100 μm in the z axis). The measured displacements were recorded in real time and compared with a reference displacement of the stage to evaluate the measurement performance.

The displacement estimates follow the commanded stage motion consistently across all three axes. Under representative experimental conditions (CMOS pixel size of 2 μm, exposure time of 1000 μs, and microLED pixel size of 75 μm), the instrument achieves lateral (x-y) resolution down to 5 μm and axial (z) resolution of about 0.1 mm over a dynamic range up to 18 mm.

For detection speed, we tuned the camera readout by reducing the CMOS region of interest (ROI). In our setup with a Basler daA3840-45um, the full-frame mode (3840 × 2160 pixels) provided about 44 fps, whereas cropping to a small ROI (320 × 240 pixels) increased the acquisition rate to about 200 fps. Unlike reconstruction-based lensless or holographic axial methods [3], which rely on numerical propagation across multiple depth planes using wave-propagation models such as the angular spectrum method [5], our instrument estimates displacement directly from illumination-dependent pattern shifts. This avoids full image reconstruction and reduces computational complexity. Processing a 1 MP image via holographic reconstruction typically takes 0.2 s [5], while our instrument processes an image of the same size in only 0.008 s. This speed gain directly improves temporal resolution

for real-time displacement monitoring. This combined hardware–algorithm co-design enables compact, real-time, and repeatable 3D displacement sensing in a single optical head.

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