A real-time method for heterodyne speckle pattern interferometry using the correlation image sensor (CIS) is proposed. The CIS demodulates the interference phase of heterodyned speckle wavefronts pixelwise at an ordinary video frame rate. The proposed method neither suffers loss of spatial resolution nor requires a high frame rate. Interferometers for out-of-plane and in-plane deformation are developed with a 200 × 200 pixel CIS camera. Experimental results confirm that the proposed method realizes real-time imaging of a rough-surfaced object under deformation. The average standard deviations of demodulated phase-difference images for the out-of-plane and in-plane interferometers are 0.33 and 0.13 rad, respectively. © 2010 Optical Society of America

1. Introduction

Speckle pattern interferometry (SPI) \cite{1-3} is a technique for measuring displacement, deformation, or strain of a rough-surfaced object from the interference phase between a speckled object wave and a reference wave or between two speckled object waves. The interference phase changes linearly to the displacement or deformation of the object. SPI has allowed easy use of image sensors in spite of lower spatial resolution than photographic film—in electronic speckle pattern interferometry (ESPI) \cite{1,2} for analog image sensors, or more recently, in digital speckle pattern interferometry (DSPI) \cite{3} for digital image sensors—because the speckle size can be adjusted by the aperture size of the imaging system \cite{4}. In DSPI, an interference phase image is computed from a phase-shifted sequence of speckle intensity images \cite{4-6}. This means that DSPI requires multiple frames for a single measurement and thus cannot perform real-time dynamic measurement of moving or deformed objects.

To overcome this limitation, it is a straightforward idea to employ high-speed cameras to increase the throughput of phase-shifting SPI, combined not only with discrete phase shifting \cite{7} but also with continuous heterodyning \cite{8,9}. This approach, however, tends to degrade the accuracy of demodulated interference phase, because high-speed imaging results in shorter exposure time, lower light intensity, and, therefore, lower signal-to-noise ratio in speckle interference images. To avoid this problem, it is necessary to use a high-power laser. Furthermore, high-speed cameras demand high-speed and large-volume frame grabbers. Real-time DSPI methods that employ conventional video image sensors have been reported as well. Bruno and Poggialini \cite{10} devised a method for estimating the phase change of successive intensity speckle images within a small region with respect to single-frame amplitude and phase speckle images. This method suffers a trade-off between spatial resolution and estimation accuracy. North-Morris \textit{et al.} \cite{11} developed a phase mask consisting of an array of 2 × 2 pixel retarder matrices with π/2 steps of retardance, which is attached in front of a video image sensor to realize four-step phase shifting simultaneously on the focal plane. Kiire \textit{et al.} \cite{12} proposed a method for simultaneously producing four separate fringe images with different phase shifts on an image sensor using a polarizing prism, a diffraction grating, and two lasers of different wavelengths. As a
drawback, these single-frame methods sacrifice spatial resolution of the image sensor.

The objective of this paper is to propose a real-time heterodyne SPI method using the time-domain correlation image sensor (CIS) [13]. The CIS produces temporal correlations between the intensity signal of incident light and the global voltage reference signals at each pixel, and outputs them as images at an ordinary video frame rate. It has been demonstrated that the CIS can simultaneously demodulate the amplitude and phase of heterodyned interference images at a video frame rate using three-phase sinusoidal reference signals [14–16]. The proposed method has advantages over previous real-time DSPI methods in terms of spatial resolution and frame rate, because speckle interference phase is demodulated pixelwise, whereas the frame rate can be kept as low as 30 frames/s. The proposed method first appeared in a previous paper [17], but it lacked reliable quantitative evaluation. Here we provide experimental results of quantitative evaluation obtained with a closed-loop-controlled piezoelectric linear stage to confirm the proposed method.

The paper is organized as follows. Section 2 proposes the real-time heterodyne SPI method based on the CIS and describes developed systems. Section 3 shows experimental results, and Section 4 discusses issues related to the results. Section 5 concludes this paper.

2. Real-Time Heterodyne Speckle Pattern Interferometry with the Correlation Image Sensor

Real-time heterodyne SPI imaging systems based on the CIS are proposed. Figure 1 illustrates two types of heterodyne SPI system developed with a CIS camera, for measuring out-of-plane and in-plane deformation or displacement of a rough-surfaced object. In both interferometers, a linearly polarized beam from a He–Ne laser (λ = 632.8 nm, 7 mW) is passed through an electro-optic modulator (EOM, Conoptics Inc. M350-80), which is driven by a sawtooth voltage signal at a frequency υ, to result in a coaxial, orthogonally polarized pair of heterodyned beams with a beat frequency υ. The amplitude of the sawtooth signal was adjusted so that the retardation between the orthogonally polarized beams changes by exactly 2π. In the out-of-plane deformation interferometer in Fig. 1(a), the two beams enter a Michelson interferometer and generate speckle patterns, either on the target object or on a reference object with a rough surface. In the in-plane deformation interferometer in Fig. 1(b), the two beams are split by a polarizing beam splitter (PBS) and illuminate the target object from symmetrical directions with an angle α from the optical axis to generate speckle patterns. In both interferometers, the two heterodyned speckle patterns are imaged onto the CIS through an analyzer (POL) to generate beat signals oscillating at frequency υ. The beat frequency and the inclination angle in the in-plane interferometer were set to υ = 100 Hz and α = 45°, respectively, in the experiments. The F-number of the imaging lens was F = 2.8.

The CIS camera used in this paper consists of a 200 × 200 pixel CMOS CIS chip with a 40 μm pixel spacing [18], which is shown in Fig. 2(a). The CIS has three inputs of reference voltage signals gh(t) (k = 1, 2, 3) as depicted in Fig. 2(b), which are constrained with g1(t) + g2(t) + g3(t) = 0, and produce three outputs Qk(i,j) for the intensity signal of incident light at each pixel (i,j), denoted by f(t), as

\[
\begin{bmatrix}
Q_1(i,j) \\
Q_2(i,j) \\
Q_3(i,j)
\end{bmatrix} =
\begin{bmatrix}
\Delta Q_1(i,j) \\
\Delta Q_2(i,j) \\
\Delta Q_3(i,j)
\end{bmatrix}
+ \frac{1}{3}\begin{bmatrix}
f_1(t) \\
f_2(t) \\
\Delta f_3(t)
\end{bmatrix},
\]

(1)

\[
\Delta Q_k(i,j) = (f(t)g_k(t)) \quad (k = 1, 2, 3),
\]

(2)
beams interfering on a pixel \((i,j)\) of the CIS, denoted by \(u_{ij}\) and \(v_{ij}\), are expressed as

\[
    u_{ij} = U_{ij} \exp(i\phi_{ij}),
\]

\[
    v_{ij} = V_{ij} \exp[i(\psi_{ij} - 2\pi t)],
\]

where \(i\) denotes the imaginary unit, \(i^2 = -1\), \(U_{ij}\) and \(V_{ij}\) are random amplitude distributions, and \(\phi_{ij}\) and \(\psi_{ij}\) are random phase distributions. The interference of \(u_{ij}\) and \(v_{ij}\) results in an intensity beat signal \(f_{ij}(t)\) given by

\[
    f_{ij}(t) = |u_{ij} + v_{ij}|^2 + n_{ij}(t)
    = A_{ij} \cos(2\pi vt + \theta_{ij}) + B_{ij} + n_{ij}(t),
\]

where \(n_{ij}(t)\) accounts for noise contributions including ambient light, and can thus be considered uncorrelated with the three-phase reference signals \(g_k(t)\) in Eq. (3), so that \(\langle g_k(t)n_{ij}(t) \rangle \approx 0\) \((k = 1, 2, 3)\). Substituting Eqs. (6) and (3) into Eq. (2) yields

\[
    \begin{bmatrix}
        \Delta Q_1(i,j) \\
        \Delta Q_2(i,j) \\
        \Delta Q_3(i,j)
    \end{bmatrix} = \frac{T A_{ij}}{2} \begin{bmatrix}
        \cos \theta_{ij} \\
        \cos(\theta_{ij} - \frac{2\pi}{3}) \\
        \cos(\theta_{ij} - \frac{4\pi}{3})
    \end{bmatrix},
\]

where the dc term \(B_{ij}\) and the noise \(n_{ij}(t)\) are removed through temporal correlation. The speckle interference amplitude \(A_{ij}\) and phase \(\theta_{ij}\) are then demodulated by least-squares estimation from the single-frame temporal correlation images \(\Delta Q_k(i,j)\) as

\[
    A_{ij} = \frac{2\sqrt{2}}{3T} [ (\Delta Q_1 - \Delta Q_2)^2 + (\Delta Q_2 - \Delta Q_3)^2 ]^{1/2},
\]

\[
    \theta_{ij} = \tan^{-1} \frac{\sqrt{3}(\Delta Q_2 - \Delta Q_3)}{2\Delta Q_1 - \Delta Q_2 - \Delta Q_3},
\]

where \((i,j)\) is omitted for simplicity. When the change in the demodulated speckle interference phase \(\delta\theta_{ij}\), denoted by \(\delta\theta_{ij}\), has been obtained from two frames of temporal correlation images \(\Delta Q_k(i,j)\), the out-of-plane deformation \(\delta z_{ij}\) or in-plane deformation \(\delta x_{ij}\) of the object is estimated from the following relations:

\[
    \delta z_{ij} = \frac{\delta x_{ij}}{\tan \theta_{ij}}.
\]
3. Experimental Results

A. Accuracy Evaluation

Experiments were conducted on the interferometers in Fig. 1 for a sheet of white paper attached to a plate. This object was moved either in an in-plane direction or in an out-of-plane direction in 40 nm steps by a closed-loop-controlled piezoelectric linear stage (Nano Control TS102-G) with an accuracy of 10 nm. The difference image \( \delta \theta_{ij} \) between two speckle interference phase images was smoothed with a \( 5 \times 5 \) Gaussian filter in order to suppress the effect of speckle noise. The average speckle diameter is estimated by the formula \( \sigma = 1.22(1 + m) \lambda F \) [19]. The magnification factor \( m \) of speckle images was \( m \sim 2.3 \) and \( m \sim 4.4 \) in the out-of-plane and in-plane interferometers, respectively. These values, together with \( \lambda = 632.8 \) nm and \( F = 2.8 \), lead to estimates \( \sigma \sim 7 \) \( \mu \)m and \( \sigma \sim 12 \) \( \mu \)m for the out-of-plane and in-plane interferometers, respectively, which are smaller than the pixel spacing of the CIS, 40 \( \mu \)m.

Figure 3 shows an example of output images from the CIS obtained in the out-of-plane interferometer in Fig. 1(a). Figures 3(a)–3(c) show the average intensity image \( f_{ij}(t) \), interference amplitude image \( A_{ij} \), and interference phase image \( \theta_{ij} \), respectively, when the object was located at a base position. The value of phase is encoded as shown in Fig. 3(g). The pixels at which the interference amplitude is lower than a threshold appear in shades of gray in the interference phase image in Fig. 3(c), because phase cannot be defined for beat signals with amplitude that is too small. It is easy to observe random speckle patterns in these images. After the object was moved along the optical axis by 80 nm, the phase image changed, as shown in Fig. 3(d). The difference image between the phase images in Figs. 3(c) and 3(d) is shown in Fig. 3(e). Figure 3(f) shows the result of smoothing the difference image in Fig. 3(e).

Figure 4 shows a sequence of smoothed difference images of interference phase with respect to the phase image for the base position in Fig. 3(c), obtained in the out-of-plane interferometer in Fig. 1(a). It is easy to observe gradual phase changes with respect to the out-of-plane displacement of the object in these images. The mean and standard deviation of the smoothed phase difference over the central \( 50 \times 50 \) pixels were computed for displacement from 40 to 2000 nm. Figure 5(a) plots the mean of the smoothed phase difference against the out-of-plane displacement. Figure 5(b) shows the result of unwrapping the plot in Fig. 5(a), as well as a theoretical response predicted by Eq. (13) and the standard deviation of the smoothed phase difference. In Fig. 5(b), it is observed that the unwrapped mean phase difference follows the theoretical line, though the error of the unwrapped mean from the theoretical line increases for larger displacement. Furthermore, both the unwrapped mean phase difference and standard deviation periodically oscillate for every \( 2\pi \) change of the unwrapped mean. The average of the standard deviation over the whole displacement range was 0.33 rad, which amounts to a displacement of 17 nm.

A similar experiment was conducted on the in-plane interferometer in Fig. 1(b). Figure 6 shows a sequence of smoothed difference images of interference phase. Figure 7(a) plots the mean of the smoothed phase difference over the central \( 50 \times 50 \) pixels against the in-plane displacement. Figure 7(b) shows the result of unwrapping the plot in Fig. 7(a), as well as a theoretical response predicted by Eq. (14) and the standard deviation of the smoothed phase difference over the central \( 50 \times 50 \) pixels. In Fig. 7(b), the unwrapped mean phase difference follows the
theoretical line much better than the plot in Fig. 5(b), with the error from the theoretical line including periodic oscillation barely visible. Only the standard deviation exhibits slight oscillation for every $2\pi$ change of the unwrapped mean. The average of the standard deviation over the whole displacement range was 0.13 rad, which amounts to a displacement of 9 nm.

B. Example of Real-Time Imaging

Next, real-time imaging of an object under deformation was conducted on the in-plane deformation interferometer in Fig. 1(b). Figure 8 provides a schematic of the object, which consists of (left) a piezoelectric actuator (NEC Tokin AE0505D08) and (right) a fixed frame. The imaged area is marked by a broken square, which covers the junction of both parts. The actuator could extend and shrink only toward its left because its right end was blocked by the fixed frame. Figure 9 shows a sequence of smoothed difference images of speckle interference phase captured over 16 successive frames or 1.92 s. Each frame is labeled at the top left with the start time of capture of the image. Figure 10 shows the profiles of the smoothed phase difference after phase unwrapping along the horizontal white lines in the images in Fig. 9. The middle part of the plot in Fig. 10, which corresponds to the border between the piezoelectric actuator and the fixed frame, is not shown because the interference phase is not well defined due to low interference amplitude in this part. In Figs. 9 and 10, the left parts show significant changes caused by the extension of the actuator toward its left. In Fig. 9, the area of the actuator also exhibits gradation from the left to
the right, especially in the later time, in which the phase difference is larger on the left-hand side of the actuator than on the right-hand side. This is also recognized in the profiles in Fig. 10, which not only shift upward uniformly but also have steeper slopes decreasing toward the right with time. These observations are considered to suggest the presence of horizontal extension strain within the actuator, as well as uniform displacement toward the left. It is also observed in Figs. 9 and 10 that the right part displays slight changes of phase difference in the opposite direction to the left part. It is possible to regard this phenomenon as representing the displacement of the fixed frame toward the right, as a result of an external force applied by the extending actuator.

4. Discussion

A. Sources of Measurement Errors

Comparing the unwrapped mean phase difference in Figs. 5(b) and 7(b), the error from the theoretical line is present almost exclusively in the results for the out-of-plane interferometer in Fig. 5(b). This phenomenon can be explained as follows. The out-of-plane interferometer, which is based on a Michelson interferometer, is more vulnerable to disturbances such as vibration, mechanical drift, and temperature change than the in-plane interferometer, because the disturbances affect the object and reference waves independently, and thus cannot cancel each other in the interference image. In the in-plane interferometer, by contrast, disturbances have the same influence on both object waves, which are generated on the same object, and thus easily cancel out in the interference image.

The periodic oscillation of the standard deviation of phase difference in Figs. 5(b) and 7(b), and that of the unwrapped mean phase difference in Fig. 5(b), for every 2π change of phase difference, can be attributed to insufficient calibration of the CIS. Such oscillation may occur if the three temporal correlations in the CIS outputs are unbalanced. One possible source of this imbalance is nonzero offset, as discussed in Appendix A. This oscillation can be suppressed by more elaborate calibration of the CIS.

B. Effect of Unresolved Speckles

When each individual speckle cannot be resolved by a single pixel, multiple speckles are averaged by a pixel. This causes a problem of speckle decorrelation, especially in the in-plane deformation interferometer, even if the shift of speckles is as small as the average speckle diameter. It also decreases the contrast of speckle interference images and thus...
degrades the accuracy of phase demodulation. The experimental results in Subsection 3.A, however, confirm that even if the average speckle diameter was much smaller than the pixel size of the CIS, the proposed heterodyne SPI method still worked well. This is probably because the beat signals of the speckle wavefronts were detected by the CIS pixels with large enough amplitude to allow well-defined speckle interference phase, although multiple speckles are considered to have been averaged by a single CIS pixel. The smallness of the displacement of the object also reduced the effect of speckle decorrelation on the measurements. In the in-plane deformation interferometer, the unit displacement of 40 nm of the object is transferred to the shift of the speckle wavefronts by 176 nm on the focal plane. This shift is much smaller than not only the pixel size (40 μm), but also, the average speckle diameter of 12 μm, and thus is considered to have had little influence on speckle decorrelation. It has also been observed in another experiment, however, that speckle decorrelation became prominent in the in-plane interferometer for displacement of the object as large as about 5 μm.

5. Conclusion
A real-time heterodyne SPI method using the CIS was proposed. Based on this method, real-time imaging systems for measuring out-of-plane and in-plane deformation were developed with a 200 × 200 pixel CIS camera. The experimental results confirm that the proposed method demodulated the interference phase of heterodyned speckle wavefronts pixel-wise at an ordinary video frame rate without loss of spatial resolution and successfully realized real-time imaging of a rough-surfaced object that is being deformed. It is expected that the proposed method will be useful for measuring transient deformation, strain, or stress of moving objects.

Appendix A: Effect of Imbalance in CIS Outputs on Phase Demodulation
Suppose that the three temporal correlations \( \Delta Q_k(i, j) (k = 1, 2, 3) \) in Eq. (10) have nonzero offsets \( \epsilon_k \ll \frac{1}{2} TA \). Equation (10) is then modified as

\[
\begin{bmatrix}
\Delta Q_1 \\
\Delta Q_2 \\
\Delta Q_3
\end{bmatrix}
= \frac{TA}{2}
\begin{bmatrix}
\cos \theta \\
\cos \left(\theta - \frac{\pi}{3}\right) \\
\cos \left(\theta - \frac{4\pi}{3}\right)
\end{bmatrix}
\begin{bmatrix}
\epsilon_1 \\
\epsilon_2 \\
\epsilon_3
\end{bmatrix}
\]  

(A1)

where \((i, j)\) is omitted for simplicity. The denominator and numerator on the right-hand side of Eq. (12) are then expressed by

\[
2\Delta Q_1 - \Delta Q_2 - \Delta Q_3 = X + \Delta X,
\] 

(A2)

\[
\sqrt{3}(\Delta Q_2 - \Delta Q_3) = Y + \Delta Y,
\] 

(A3)

where

\[
X = \frac{3}{2} TA \cos \theta,
\] 

(A4)

\[
\Delta X = 2\epsilon_1 - \epsilon_2 - \epsilon_3,
\] 

(A5)

\[
Y = \frac{3}{2} TA \sin \theta,
\] 

(A6)

\[
\Delta Y = \sqrt{3}(\epsilon_2 - \epsilon_3).
\] 

(A7)

The errors \( \Delta X, \Delta Y \) in \( X, Y \) introduce an error \( \Delta \theta \) in speckle interference phase \( \theta \) as

\[
\tan(\theta + \Delta \theta) = \frac{Y + \Delta Y}{X + \Delta X}.
\] 

(A8)

Since \( \Delta X \ll X \) and \( \Delta Y \ll Y \), \( \Delta \theta \) is then estimated as

\[
\Delta \theta \approx \frac{X \Delta Y - Y \Delta X}{X^2 + Y^2} = \frac{2}{3TA} \left[ \sqrt{3}(\epsilon_2 - \epsilon_3) \cos \theta - (2\epsilon_1 - \epsilon_2 - \epsilon_3) \sin \theta \right] = \frac{4}{3TA} \rho \cos(\theta + \beta),
\] 

(A9)

\[
\rho = [(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_3 - \epsilon_1)^2]^{1/2}, \quad (A10)
\]

\[
\beta = \tan^{-1}\frac{2\epsilon_1 - \epsilon_2 - \epsilon_3}{\sqrt{3}(\epsilon_2 - \epsilon_3)}.
\] 

(A11)

Equation (A9) reveals that the estimation error \( \Delta \theta \) in speckle interference phase \( \theta \) is a periodic function of \( \theta \) with a period of \( 2\pi \).

References