INTRODUCTION
This paper discusses the performance of a 2 dimensional (2D) speckle displacement sensor used with measurement surfaces of various materials and characteristics. The sensor operates by projecting a collimated laser beam onto an optically rough measurement surface. Images of the resulting speckle pattern are acquired via a simple optical system and CMOS sensor. As the underlying measurement surface (and associated speckle pattern) displaces in 2D, measurement images are numerically correlated with an initial reference image to determine the 2D displacement in the plane of the measurement surface. The sensor in its present form is capable of sub-nanometer-position noise, X-Y measurements over a 250 μm X 250 μm measurement range, with update rates of 20-140Hz. The advantage of using a speckle sensor is that the sensor does not need a calibrated scale; the displacement of any optically rough surface may be measured. There are many possible applications for this technology, including but not limited to: monitoring stage drift, nanometer level positioning, monitoring metrology frame deflections, characterizing stage orthogonality/straightness, and (because of absolute measurements) mounting repeatability of measurement target.

Prior work has been conducted in the field of speckle correlation for measurement. Yamaguchi [1] et al demonstrated a 1D speckle correlation sensor for linear and rotation measurement with resolution linear and angular resolutions of 1 μm and 0.001°. Shilpiekandula [2] et al have discussed a speckle based sensor with resolutions 0.1 μm and 0.00029°.

SENSOR CONFIGURATION
We first give an overview of the sensor hardware and computational algorithms. Hardware includes the readhead optical design and custom electronics for position computation. The readhead (FIGURE 1) projects a collimated beam from a laser diode that illuminates the measurement area, an imaging lens, a pinhole aperture and a CMOS camera, all in a telecentric configuration. In a separate enclosure from the sensor readhead are the correlation electronics which include a Digital Signal Processor (DSP) for correlation computation, and hardware for communications between the readhead and PC.

The key algorithm operations are to quickly locate the vicinity of the correlation peak, and then to accurately determine the 2D location of the peak to sub-pixel accuracy via interpolation. Using proprietary curve fitting algorithms, the interpolation achieves a position noise value of better than 1/1000th of a pixel, or ~0.7 nm and an accuracy (defined as the reference position minus the report sensor position) of <±100 nm over the 250 μm 2D range. These algorithms are based on the assumption that the speckle image is uniform – i.e., that the size of the speckle features and level of background intensity are relatively constant over the full field of view. The measurement gap and tolerance of the sensor from the planar measurement surface is 4.5 mm ±0.05 mm. The dimensions of the current sensor prototype are ~40x40x40 mm.

FIGURE 1. Layout of readhead components.
TEST SYSTEM CONFIGURATION
Sensor accuracy testing is conducted on a 2D translational stage with Renishaw RLE10 plane mirror laser interferometers (158 nm signal period, 0.4 nm interpolated digital resolution) simultaneously measuring X and Y position of the stage. The interferometer beam paths are aligned with the sensor measurement axes to minimize Abbe error (FIGURE 2). Burleigh Inchworm piezo actuators are used to displace the Physik Instrumente X-Y magnetically preloaded roller bearing stage. The stage has been qualified with a laser interferometer to have angular deviations of less than 1 arcsecond over the 250 μm X-Y sensor test range. The test system is contained within a thermoelectrically temperature-controlled enclosure that is stable to ±0.03°C over 48 hours, FIGURE 3. The interferometers are compensated for changes in wavelength due to environmental variations using the modified Elden equation [3] (environmental compensation sensor resolutions: 0.01°C, 0.08 mbar, 0.0625% RH). Interferometer dead paths are shielded with clear acrylic tubes to reduce air turbulence.

The short term fixed position noise (1σ standard deviation of repeated fixed position measurements) of the test system is shown in FIGURE 4. It has a 1σ value of ~2.2 nm. The long term position drift over 48 hours is ~±33 nm with a 1σ value of ~11 nm, see FIGURE 5.
RESULTS

We present our results in terms of a number of performance parameters, including fixed-position noise, accuracy over the full range of travel (250 µm), and reproducibility of the sensor. Accuracy is defined as the difference between the reference interferometer position and the sensor’s reported position. Reproducibility is defined as the accuracy of the sensor when tested at different measurement surface locations.

In practice, we find that a number of surface materials, including randomly lapped stainless steels (SST), some ceramics and the backside (unpolished) of processed silicon wafers, yield images that closely match the assumption of speckle uniformity. We present test results for such surfaces showing that the sensor is accurate to within ±100 nm over the full 2D displacement range. Other surfaces, such as ground SST, milled Invar and patterned silicon wafers, yield images with anomalies, distinct directionality or repetitive patterns. Test results show that these surfaces can be successfully measured, although with reduced accuracy. Sample speckle images are shown in FIGURE 6.

The fixed position noise performance of the sensor is displayed in FIGURE 7. Tests have been conducted on lapped stainless steel, ceramic IC package and unpolished silicon wafer. The sensor maintains a fixed position noise 1σ <0.7 nm for these sample surfaces.
Reproducibility of the sensor on lapped SST is displayed in FIGURE 8. Accuracy tests are conducted by stepping the X-Y test system in a linear fashion in the X, Y and diagonal XY directions. At each step of the test, X and Y position readings are recorded from the sensor and the reference interferometers. The accuracy tests are conducted at a step size of 0.5 µm over the 250 µm range (a typical accuracy test takes ~8 minutes to complete). Test results from four different measurement locations are shown. The sensor accuracy deviation is less than ±100 nm for any of the four accuracy plots.

FIGURE 8. X and Y accuracy of the sensor is plotted from four different measurement locations on the same surface of lapped SST. All accuracy plots show less than ±100 nm of error. The top plots are for a test in the X motion axis direction, the bottom plots are for a test in the Y motion axis direction. X and Y accuracy is plotted for each test due to the 2D nature of the sensor.

FIGURE 9 displays the accuracy performance of the sensor when tested using ceramic IC package material and unpolished silicon as measurement surfaces. The peak-to-peak error is less than ±100 nm for these materials.

FIGURE 9. Sensor accuracy plots on ceramic IC package and unpolished silicon.

CONCLUSION
We have demonstrated the performance of a 2D speckle based displacement sensor with various measurement materials. The sensor in its present form is capable of <0.7 nm of fixed position noise, and accuracy and reproducibility of ±100 nm over a 250 µm X 250 µm measurement range with various measurement materials. 2D displacement measurements directly on native planar surfaces give this sensor a distinct advantage over other technologies. Trade offs in performance parameters (e.g. range/resolution) can be made to tailor the sensor to various applications.

REFERENCES