

Towards High Resolution Absolute Angle Sensing Using Dual-Wavelength Laser Speckle

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Abstract—We present a two dimensional angle sensor with greater than 0.01 degrees resolution, using dual-wavelength laser speckle. The technique uses speckle correlation of a double speckle pattern, determining absolute surface tilt from a single frame. A constructed sensor was used to measure a grid of 2D angles between $\pm 0.25^\circ$ rotating around both x and y axes. Sensor performance was limited by laser mode instability effects, however an analysis of measurements demonstrated that a stable mode output could achieve bias errors of less than 0.010° , and standard deviations of 0.003° around x and 0.021° around y .

I. INTRODUCTION

External position and orientation sensors are widely employed in robotic manufacturing, used alongside robots that typically have a very high repeatability but low absolute accuracy [1]. Angle sensing in particular is important in areas such as robotic drilling [2] and coating application [3], where perpendicularity to the work surface is important. In aerospace for example, the minimum required accuracy is 0.1mm for position and 0.5° for orientation [2].

There are a number of existing approaches to non-contact tilt sensing. One common method uses an arrangement of distance meters, which estimates the surface normal at the centre of the arrangement [4]. This can give real-time measurements, but the resolution is limited by the spacing of the distance meters, and the use of multiple detectors results in a relatively bulky system. Another, higher resolution, method is to scan the surface before work begins to create a 3D point cloud model [5]. This can be used to calculate the surface normal anywhere on the workpiece, but cannot account for any changes that occur once work has begun.

A number of laser speckle-based approaches to tilt sensing have also been proposed. Smíd *et al.* [6] describe a technique using two detectors to measure surface tilt using a small translation of the object, which can be used on flat or shaped objects. An approach using optical fractional Fourier transforms (OFRTs) was used by Kelly *et al.* [7] to measure combined tilt and translation of a surface, using before and after images.

These approaches each have their downsides, such as a bulky optical system, or only measuring the angle relative to a reference image acquired before rotation. We have previously reported the theory and concept of a dual-wavelength laser speckle approach [8], [9] that allows the measurement of

absolute angle relative to the detector without the need for a reference image. The work presented here demonstrates early results of the application of this technique to make higher resolution angle measurements, achieved by employing two lasers instead of a single laser operating in dual longitudinal mode output. The greater wavelength separation allows a greater theoretical resolution of 0.0028° , as compared to the roughly 0.1° achieved previously using a single laser diode [8].

Section II describes the concept of the sensor, giving an overview of dual-wavelength speckle and how it relates to surface tilt. The sensor design, including construction and signal processing, is detailed in Section III. Experimental results are presented in Section IV, where the sensor was tested by measuring a 2D grid of angles using a high resolution, six degrees of freedom (DOF) stage.

II. CONCEPT

Dual-wavelength speckle uses two collinear beams to illuminate an optically rough surface, producing a double speckle pattern. The two patterns are correlated but have a relative shift between them, the magnitude and direction of which relates directly to the tilt of the surface. Figure 1 shows an example of a speckle pattern recorded from a surface for two different illuminating wavelengths separated by around 0.5nm, then the double pattern recorded when illuminating the surface with both wavelengths simultaneously.

Figure 2 shows the arrangement of the sensor elements. The detector is placed directly opposite the laser spot, which is taken as the origin, O . The source is offset from the detector, in this case along the x axis. This distance from spot to detector is given by L_D , and the source position is described by the unit vector $\hat{s} = (s_x, s_y, s_z)$. The detector plane is assumed to be parallel to the surface at zero tilt.

The mathematical relationship between the speckle shift between the two patterns and the tilt of the surface depends on the geometry of the sensor (specifically L_D and $\hat{s}$), and the two wavelengths of the source [9].

$$A_x = \frac{\Delta\lambda}{\lambda_1} L_D (s_z + 1) \tan \theta_y + \frac{\Delta\lambda}{\lambda_1} L_D s_x \quad (1)$$

$$A_y = \frac{\Delta\lambda}{\lambda_1} L_D (s_z + 1) \tan \theta_x + \frac{\Delta\lambda}{\lambda_1} L_D s_y \quad (2)$$

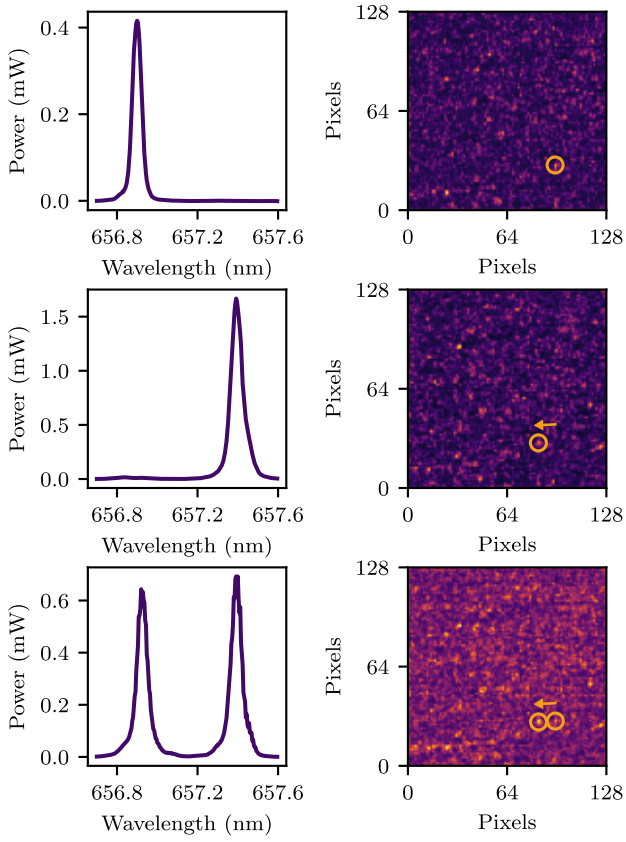


Fig. 1. Speckle patterns and corresponding laser spectra for two individual illuminating wavelengths, and finally a double speckle pattern from dual-wavelength illumination. The circle highlights the shift of a particular speckle in the pattern.

A_x and A_y are the speckle shifts in x and y , while θ_x and θ_y are the surface angles. The two source wavelengths are given by λ_1 and λ_2 , while $\Delta\lambda$ is the separation between them.

These equations can be rearranged to give three sensor constants. The first, C , is the responsivity or sensitivity of the sensor. A_{x0} and A_{y0} describe the speckle shift at zero surface tilt. For an on-axis source (i.e. directly opposite the spot, in line with the detector), these constants would both be equal to zero. In the case shown in Figure 2 where the source is offset in x only, A_{x0} is non-zero, and $A_{y0} = 0$.

$$C = \frac{\Delta\lambda}{\lambda_1} L_D (s_z + 1) \quad (3)$$

$$A_{x0} = \frac{\Delta\lambda}{\lambda_1} L_D s_x \quad (4)$$

$$A_{y0} = \frac{\Delta\lambda}{\lambda_1} L_D s_y \quad (5)$$

Using these three constants, the version of the theory used to calculate surface angles from measured speckle shifts can be written as follows.

$$\tan \theta_x = \frac{A_y - A_{y0}}{C} \quad (6)$$

$$\tan \theta_y = \frac{A_x - A_{x0}}{C} \quad (7)$$

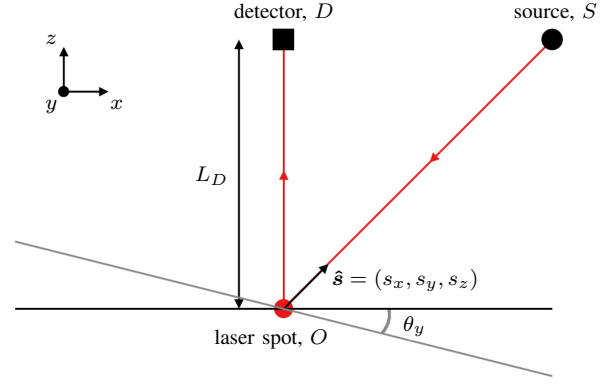


Fig. 2. Schematic diagram of the sensor, comprising of the source, detector, and laser spot. The distance L_D and unit vector $\hat{s}$ are used in the equations relating the surface tilt to speckle shift. θ_y is the surface tilt around the y axis.

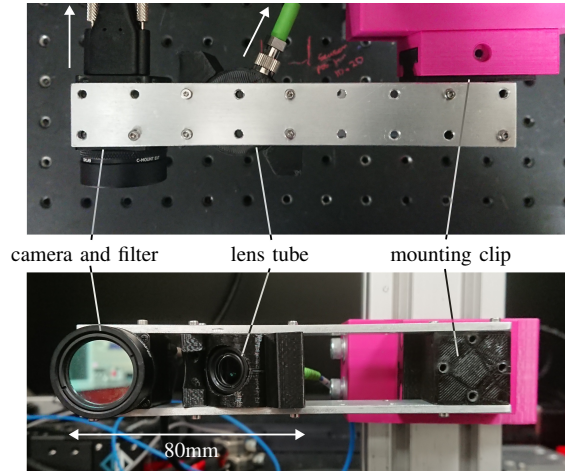
III. SENSOR DESIGN

The sensor presented here uses two FiberTecII Fabry-Perot (FP) laser diodes centred at 638nm (FTEC2-638-20) and 659nm (FTEC2-658-60), combined together into one output using a 50:50 wideband fibre coupler at $630 \pm 50\text{nm}$. The sensor head, shown in Figure 3a, has a lens tube with a 15mm focal length lens at 22mm from the fibre tip to decouple the light into free space. The camera mounted alongside it is an 8-bit monochrome CMOS camera (Ximea MQ013MG-ON), with a bandpass filter at $655 \pm 50\text{nm}$. The camera has a pixel size of $4.8 \times 4.8 \mu\text{m}$, and maximum image size of 1280×1024 pixels. The full width of the sensor head is around 80mm.

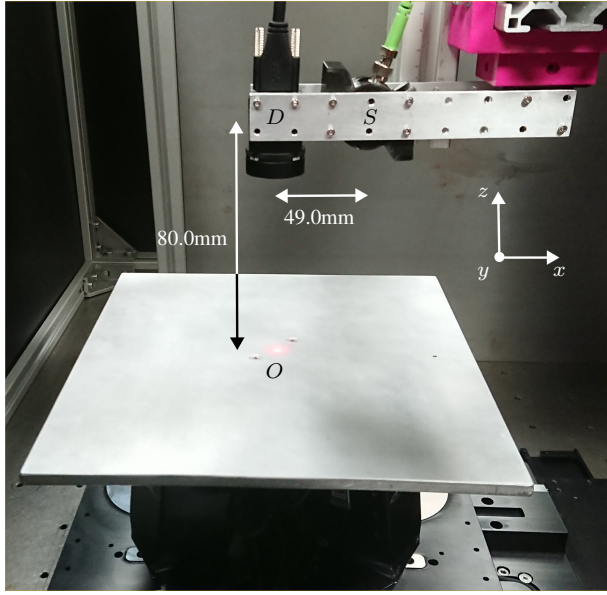
The long term laser stability of the two diodes was measured with a Yokogawa optical spectrum analyser (OSA). Over 2.5 hours, the standard deviation in the dominant wavelength of the 638nm diode was 10pm (centre wavelength 638.1nm), and 11pm for the 659nm diode (centred at 659.3nm). This gives a wavelength separation, $\Delta\lambda$, of 21.2nm. From equation (3), this will lead to a relatively large value for the sensitivity of the sensor, for instance larger than the $\sim 0.5\text{nm}$ wavelength separation seen in Figure 1.

The effect of wavelength instability on angular uncertainty depends on the angle being measured [8], but for the range of angles measured here is expected to be $0.0000^\circ - 0.0002^\circ$ in θ_x and $0.0114^\circ - 0.0117^\circ$ for θ_y .

The source is placed at $S = (49.0, 0.0, 80.0)\text{mm}$ and the detector at $D = (0.0, 0.0, 80.0)\text{mm}$, which gives calculated sensor constants of $C = 4.925\text{mm}$, $A_{x0} = 1.388\text{mm}$, $A_{y0} = 0.000\text{mm}$. From these and the image size, the maximum measurable angle is calculated to be $\pm 15.23^\circ$. Figure 3b shows the sensor head mounted above a six DOF Alio Hybrid Hexapod stage (AI-HH-200XY-15Z-56R-ACS), which was used to measure the sensor performance. The stage can apply tilt angles of up to around 8° in magnitude, and has a resolution of 0.04arcsec and repeatability of 0.6arcsec.



(a) Sensor head



(b) Experimental setup

Fig. 3. Photo of (a) the sensor head seen from above and from the front, along with (b) the full experimental setup, with the sensor mounted above the Hexapod stage.

A. Signal Processing

The signal processing starts with a single frame taken by the camera, containing both speckle patterns. An example can be seen in the first image in Figure 4, which is a section of the full 1280x1024 pixel frame. The wavelength separation of the two patterns results in a difference in magnification as well as a relative shift; in this case the separation of 21.2nm gives a magnification factor of 1.0329. As such, the image is magnified by this factor and then correlated with the original, producing a correlation image like that shown in the right hand side of Figure 4. The location of the correlation peak relative to the centre gives the shift, (A_x, A_y) , between the two speckle patterns.

The correlation image also contains a blurred central peak, resulting from the correlation of the double speckle pattern

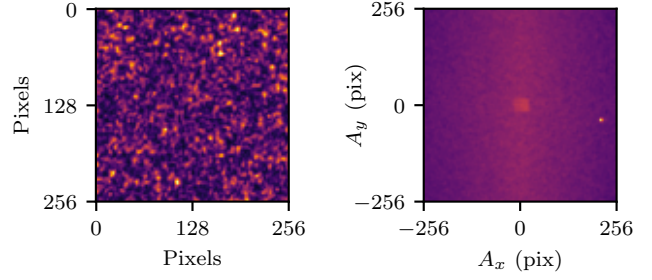


Fig. 4. Example dual-wavelength speckle image (left) and its correlation (right). The correlation peak is at $A_x = 208.35\text{pix}$, $A_y = 39.67\text{pix}$.

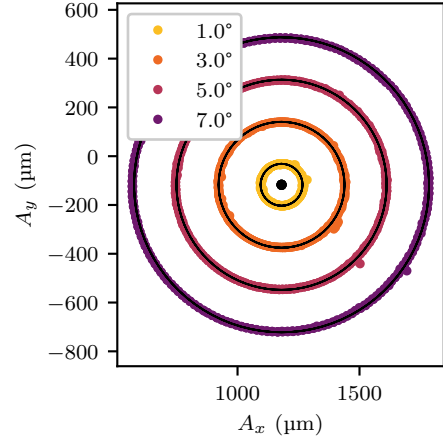


Fig. 5. Calibration data, consisting of measurements of speckle shift for fixed magnitude tilted profiles (1.0° , 3.0° , 5.0° , 7.0°) rotated through 360° three times in steps of 2° . The black lines show circles fitted to the measurements from each profile.

with itself. Due to the magnification of one image, this peak is spread over a region equal to the difference in width and height between the magnified and original images.

A 3-point Gaussian estimator [10] is used to find the peak position and hence pattern shift (A_x, A_y) . This uses the highest pixel in the image plus the two adjacent pixels in each direction to estimate the sub-pixel location of the peak. For the image in Figure 4, the values are $A_x = 208.35\text{pix}$ and $A_y = 39.67\text{pix}$. This estimator has an expected accuracy of 0.05 pixels, which translates to an expected angular uncertainty and resolution for the sensor of 0.0028° .

Once the speckle shift has been determined, the values are used in equations (6) and (7) to calculate the absolute tilt of the surface.

B. Calibration

A calibration method was used with the completed sensor to verify the values of the sensor constants C , A_{x0} , and A_{y0} . 3D printed mounts of fixed magnitude, ranging from 1° to 7° in 2° steps, were continuously rotated such that a surface angle of constant magnitude and varying direction was applied to the sensor. The direction angles were incremented by 2° over three full rotations. The speckle shift at each point was measured,

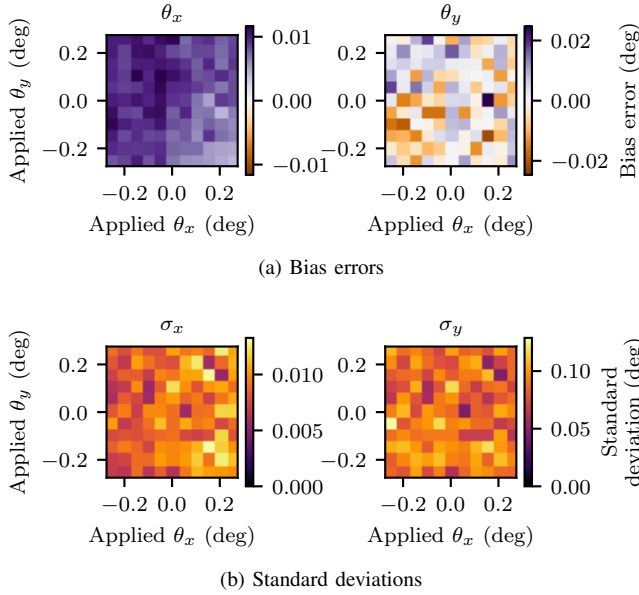


Fig. 6. Heatmaps showing the (a) bias errors and (b) standard deviations on a 2D grid of angles between $\pm 0.25^\circ$ (0.05° steps), calculated on 100 repeats.

using the signal processing method described above, and can be seen plotted in Figure 5.

A circle was fitted to each dataset, using a least squares fit, to determine their centre and radius. In each case, the centre of the circle is equal to the constants A_{x0} and A_{y0} , while the radius is proportional to C . For this sensor, the predicted values of the constants were $C = 4.925\text{mm}$, $A_{x0} = 1.388\text{mm}$, $A_{y0} = 0.000\text{mm}$. The calibrated values were $C = 4.924\text{mm}$, $A_{x0} = 1.180\text{mm}$, $A_{y0} = -0.117\text{mm}$.

IV. EXPERIMENTAL RESULTS

The Hybrid Hexapod stage shown in Figure 3b was used to apply a grid of 2D angles for the sensor to measure. The grid covered a range of $\pm 0.25^\circ$ in steps of 0.05° in both θ_x and θ_y . This is much smaller than the expected sensor range of 15.23° , but the focus of this experiment was investigating the sensor resolution. Each angle was measured 100 times, in such a way that the full series of angles was measured before returning to repeat each angle.

Figure 6 shows the full set of results, with the average bias errors (as compared to the applied stage angles) in Figure 6a and the standard deviations on repeats in Figure 6b. The average magnitudes of the bias errors across all angles were 0.007° in θ_x and 0.008° in θ_y . However, the standard deviations were a degree of magnitude higher in y at an average of 0.088° , though similar in x at 0.009° . These are higher than the expected values (from the combined laser instability and peak finding uncertainty) of $0.0028^\circ - 0.0030^\circ$ in θ_x and $0.0142^\circ - 0.0145^\circ$ in θ_y .

A further investigation into the stability of the laser diodes found that each laser had parasitic modes that were sometimes dominating the spectrum. Figure 7 shows a total of 10,000 spectra measured at 0.5s intervals over 2.5 hours. The first

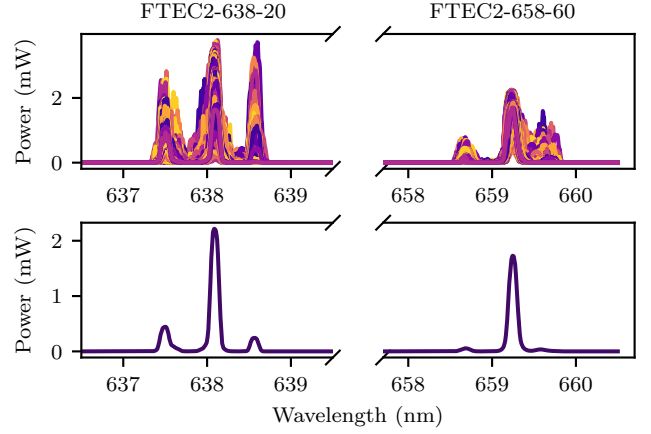


Fig. 7. Laser spectra recorded over 2.5 hours at 0.5s intervals (10,000 total). The top graph plots all spectra, while the bottom plots the average.

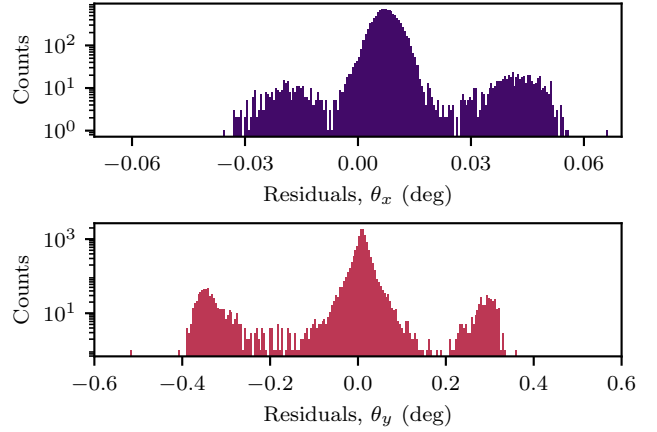
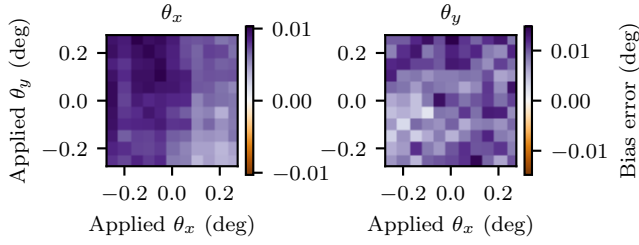


Fig. 8. Histogram showing the distribution of residuals in θ_x and θ_y before averaging (i.e. for raw data). The solid bars show measurements that are less than two standard deviations from the average, while the translucent bars give the whole distribution.

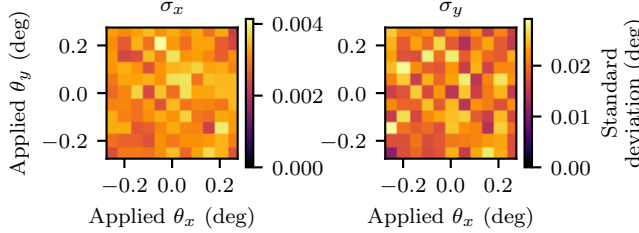
graph shows all spectra overlaid, and the central and parasitic peaks can be seen clearly. The lower graph shows the average of these spectra, which indicates that the central peak was still the most prevalent across measurements, especially in the 658nm laser.

For measurements where a parasitic mode was dominant, the discrete change in the wavelength spacing ($\sim 0.5\text{nm}$) will have resulted in a large difference in measured speckle shift as compared to the expected value. Correspondingly, these measurements will show a much larger error in the measured angle.

This interpretation is corroborated by the histogram shown in Figure 8. This gives the residuals in θ_x and θ_y across all individual measurements before averaging. The distribution (emphasised by the logarithmic axis) for each angle direction has a clear central peak surrounded by two side peaks, which would be expected from the changing laser modes causing a discrete jump in measurements.



(a) Bias errors



(b) Standard deviations

Fig. 9. Heatmaps showing the (a) bias errors and (b) standard deviations on a 2D grid of angles between $\pm 0.25^\circ$ (0.05° steps), after the filtering shown in Figure 8.

TABLE I
MAXIMUM AND MEAN ABSOLUTE BIAS ERRORS ACROSS ALL ANGLES

Bias errors (deg)	Max, θ_x	Mean, θ_x	Max, θ_y	Mean, θ_y
Unfiltered	0.012	0.008	0.025	0.007
Filtered	0.010	0.007	0.015	0.009

In order to get a clearer picture of the potential performance of the angle sensor, these histograms were used to filter out measurements with residuals greater than two standard deviations away from the average. The solid histogram bars in Figure 8 show the remaining measurements, whose distribution fits very closely to the central peak while excluding the two side peaks.

The heatmaps of results after filtering are shown in Figure 9. The mean bias errors across all angles are very similar, though the maximum bias error has dropped from 0.012° to 0.010° in θ_x , and from 0.025° to 0.015° in θ_y . The distribution of errors in θ_y has also changed, with a much clearer trend of positive bias errors across all measurements. This suggests a positive bias error in both θ_x and θ_y that was not fully accounted for during calibration. The comparison of the absolute bias errors before and after filtering is given in Table I.

The standard deviations have improved significantly after the above histogram filtering, as expected. The mean value across all angles has decreased from 0.009° to 0.003° in θ_x , and from 0.088° to 0.021° in θ_y . These are much closer to the expected uncertainties calculated from the laser instability and peak finding, as given alongside the experimental results in Table II.

The higher standard deviation in θ_y is expected from the error analysis on the wavelength stability, and is effectively due to the larger value of A_{x0} causing a fixed increase in

TABLE II
MAXIMUM AND MEAN STANDARD DEVIATIONS ACROSS ALL ANGLES

Standard deviations (deg)	Max, θ_x	Mean, θ_x	Max, θ_y	Mean, θ_y
Expected range	0.0028 – 0.0030		0.0142 – 0.0145	
Unfiltered	0.013	0.009	0.129	0.088
Filtered	0.004	0.003	0.029	0.021

expected errors. However, the laser stability analysis only takes into account the changes due to small shifts in wavelength of the central mode. As described above, there are points where the error is much larger, caused by the discrete jumps between laser modes. Although we have tried to remove these values to better investigate the sensor performance, it is likely that the imprecise filtering technique has not removed every anomalous datapoint. As such, these values may still be skewing the data, and this effect would be seen predominantly in the errors on θ_y rather than θ_x , which aligns with the results in Table II.

Further work would benefit from more stable laser sources, removing the need for post-processing of data. An investigation into the geometry and sensor wavelengths should also be undertaken to minimise the effects of laser instability. However, the low bias errors seen across the filtered results demonstrate the potential of this approach for measuring angles in the order of tens of millidegrees.

V. CONCLUSION

This paper has presented a non-contact angle sensor for measuring two dimensional surface tilts from a single frame. The technique employs dual-wavelength laser speckle, where two different wavelengths are used to illuminate a surface, each producing a correlated but shifted speckle pattern. The magnitude and direction of the shift between the two patterns is directly related to the surface tilt, via the equations given in Section II.

We have tested the technique for a high-resolution version of the sensor (expected 0.003°), which was achieved using a wide wavelength separation of 21.2nm. Experimental results were limited by mode instability in the lasers used for the sensor, and as such measurements were post-processed to remove outliers caused by changes in the dominant mode. This gave an idea of the potential performance of the sensor, with standard deviations of 0.003° in θ_x and 0.021° in θ_y , and bias errors of 0.007° in θ_x and 0.009° in θ_y .

This has improved on our previously published work which demonstrated a 1D angle sensor with accuracies of around $\pm 0.14^\circ$, though over a larger range of 45° [8]. The sensor presented here was demonstrated for two-dimensional angles, and is more compact than our previous version, having a total width of around 80mm. This makes it well suited for the target application of robotic manufacturing.

Further work should focus on the laser mode stability, which was shown to be the main source of errors in the data presented here.

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Data supporting this study are openly available from the Cranfield Online Research Data Repository (CORD) at [10.17862/cranfield.rd.24592725](https://doi.org/10.17862/cranfield.rd.24592725)

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