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Optical fibre-coupled displacement and angle measurements using range-resolved interferometry

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Abstract

A novel approach to displacement and angle measurements that uses range-resolved interferometry to interrogate multiple interferometers is presented. Spatially offset beams are multiplexed onto the same delivery fibre using a very simple setup comprising of two stacked beamsplitters and the phase evaluation of these interferometers allows simultaneous measurement of both displacement and angular changes of a target surface. The operating principle of this technique and key design concepts are discussed. This approach, with its simple and compact fibre-coupled optical setup and ease of alignment, expands existing applications of laser interferometry, particularly for space-restricted environments, and its cost-effectiveness will be key to allowing widespread usage.

Keywords: Interferometry, Measurement, Optical, Metrology

1. Introduction

High precision angle and displacement sensors are paramount in many applications, including modern production techniques and scientific research where positioning and manipulation of components is essential. A wide variety of existing techniques have been used for angle measurements, including autocollimators [1] and interferometric techniques [2]. Here, interferometric approaches can offer high precision measurements with sub-nanometre resolution [3][4], however, interferometric approaches often require complex optical setups with numerous polarisation-sensitive components [5-7] such as waveplates, beamsplitters and analysers. This complexity is exacerbated as the system is extended to sense in multiple degrees of freedom. This current lack of simple, cost-effective solutions severely restricts the application of laser interferometry for angle and displacement sensing for both industrial and scientific applications.

In this paper a novel interferometric approach for performing combined angle and displacement measurements, requiring just a single diode laser and photodetector and an extremely simple optical setup is presented. Using a range-resolved interferometric technique [8] to demodulate multiplexed interferometric signals, simultaneous displacement measurements of two parallel beams is demonstrated, also allowing the calculation of angular changes. This paper expands previous work on multi-dimensional displacement measurements [9] into the realm of angle measurements, allowing for novel applications of laser interferometry, particularly in space restricted applications.

2. Principle and Setup

2.1. Range-Resolved Interferometry

Range-resolved interferometry (RRI) [8] is a signal demodulation technique that uses sinusoidal optical wavelength modulation, resulting from sinusoidal injection current modulation, of a diode laser. Using a single diode laser and photodetector, multiplexed interferometers can be interrogated by calculation of appropriate range dependent demodulation carrier waveforms, allowing for independent and simultaneous phase measurements from each interferometer. Standard interferometric displacement measurements based on phase change evaluation can then be performed for each constituent interferometer, provided these have unique optical path differences, where any overlap results in cyclic errors [10].

2.2. Setup

A simple optical setup was developed that uses two vertically stacked beamsplitters, and a planar mirror mounted on a pitch-yaw stage, interrogated with a weakly-focussed beam emanating from a fibre collimator, as shown in Fig. 1. By appropriate orientation of the beamsplitters, two parallel beams are created that are reflected from the planar mirror at reflections points M_1 and M_2, and back through the beamsplitters to the optical fibre. Here, a flat polished fibre tip is used so that evaluated interferometers are created between each of the beams reflecting from the mirror, and a beam reflecting from the fibre tip, labelled O. In addition, the interferometer between the front surface of the beamsplitter, R, and the fibre tip is interrogated to remove any motion signals caused by movement between the fibre tip and beamsplitter assembly. By numerical subtraction of the reference interferometer from the two mirror reflection interferometers,

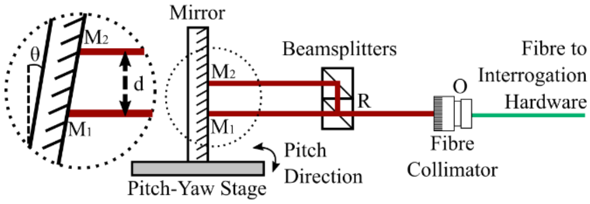

Figure 1. Schematic of the experimental setup used in this paper with reflection points O, R, M_1 and M_2 labelled. A close-up of the mirror incident points is shown on the left showing the pitch angle θ and the separation of the beams, d.

independent and simultaneous displacement measurements between the mirror and the reference surface can be performed for the two parallel beams.

In order to interrogate the optical setup, the interrogation hardware shown in Fig. 2 is used. A single discrete-mode laser diode, emitting at a wavelength of 1520.54 nm, is sinusoidally modulated through injection current modulation at a frequency of 24.4 kHz, with a resultant wavelength modulation amplitude of ± 0.3 nm. The laser emission is passed via a fibre-optic circulator to the optical setup. The returning light is incident on the InGaAs photodetector, and the resulting interferometric signals are demodulated in real-time by field programmable gate array (FPGA)-based signal processing hardware. A schematic of the interrogation hardware is shown in Fig. 2(a), along with photos of the fully-enclosed interrogation unit shown in Fig. 2(b) and of the experimental setup shown in Fig. 2(c).

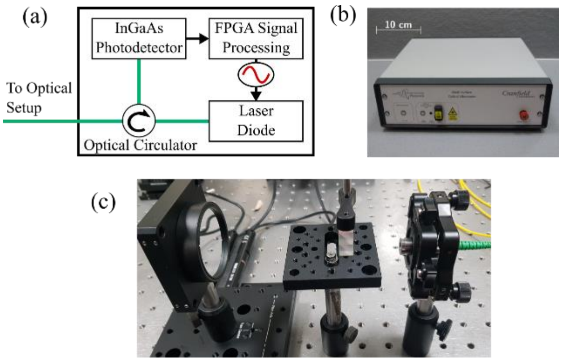

Figure 2. (a) shows a schematic of the hardware used in the paper. (b) shows a photo of the fully enclosed interrogation hardware, while the experimental setup used is pictured in (c).

3. Experimental Results

Using a pitch-yaw stage to adjust the pitch angle of the mirror, measurements were taken of the mirror displacement as observed by the two parallel beams reflected by the mirror and spatially separated by distance d = 10 mm. Over a ± 0.25° angular range, the mirror pitch was adjusted in increments of 0.05° and the phase changes in each interferometer were recorded. The measured displacements for each beam $\Delta(M_{1,2} - R)$ after the reference signal R has been removed are shown in Fig. 3(a). The resultant angle change can be calculated using Eq. (1), where θ_0 is a constant angular offset assumed to be 0° for this experiment.

$$\tan(\theta + \theta_0) = \frac{\Delta(M_1 - R) - \Delta(M_2 - R)}{d} \tag{1}$$

The angle change measurement from the interferometer is then compared to data from the pitch motor control encoder in Fig. 3(b). The inset, which includes a linear regression fit, confirms the linear relationship between the angle encoder and interferometer measurements. Of interest within the results from Fig. 3(b) is the slight scaling mismatch of approximately 3.0% between the encoder reported angle and the interferometer angle measurement. This could be caused by misalignment of the mirror to the pitch angle, such as a small rotation about the yaw axis, or a mutual misalignment of the beamsplitters. Errors in the uncalibrated angular stage encoders could cause additional uncertainties. Furthermore, the scaling mismatch could also be caused by a miscalibration of the laser emission wavelength, which would result in a systematic scaling error in the measured displacements and therefore the implied angle change. From the data shown in Fig. 3(b) an angle measurement noise standard deviation (over a 10 kHz bandwidth) of 1.5×10^{-5} degrees or ≈ 5.4×10^{-2} arcseconds can be calculated, which is of the same order of magnitude as commercial autocollimators [1].

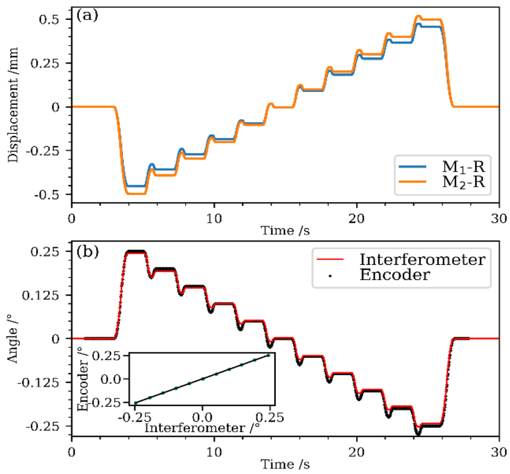

Figure 3. (a) Measured displacements for the two parallel beams incident on the mirror, with the reference interferometer R subtracted, for a series of stepped pitch angle changes. (b) shows the angle change calculated from these displacements measured by the interferometer, compared to data from the pitch motor stage encoder. In the inset in (b), the encoder measurements are plotted directly against the interferometer measurements, with a best linear fit plotted alongside.

4. Further Work

This technique shows great promise as a simple alternative to existing techniques for combined angle and displacement measurements. Whilst this particular configuration offers a single linear axis and a single rotational axis measurement, alternative optical configurations could be developed to allow for measurement of multiple rotational axes simultaneously in addition to linear displacement axes.

5. Conclusions

In this paper a novel approach to displacement and angle measurement using a range-resolved interferometric technique with a very simple optical setup has been presented. Using a proof-of-concept design, measurements of pitch angle changes obtained from displacement measurements of two spatially separated parallel optical beam paths multiplexed into a single interferometric signal, demonstrating an angle noise performance of 5.4×10^{-2} arcseconds at 10 kHz bandwidth, indicative of the potential usefulness and simplicity of the proposed approach.

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