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Multi-dimensional interferometric stage encoder using range-resolved interferometry

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Abstract

We present a novel approach to multi-dimensional optical stage encoding that utilises a single laser diode and single photodetector to resolve individual interferometers from a superpositioned interferometric signal and distinguishes them based on optical path difference using range-resolved interferometry. In this paper the principles behind this approach and a proof-of-concept setup demonstration, are presented. For a nominal stage motion of ±50 µm, 3-dimensional displacement measurements of a helical stage motion are presented. It is thought that this approach offers an attractive alternative to existing techniques, as it is compact, versatile and cost-effective.

Key Words: Interferometry, Range-resolved, Modulation, Displacement Measurement, Diode Lasers, Dimensional Metrology, Optical Encoder

1. Introduction

As technology advances, so does the need for high precision and versatile metrological methods. Modern production techniques used to produce nano-scale electronic and optical components require high-precision machinery, typically utilising optical positioning measurements capable of sub-nanometer resolution [1]. Whilst a variety of suitable linear encoders exist for single dimension measurements, multi-dimensional measurements require more sophisticated setups. Existing techniques such as pattern-based and interferometric encoders require multiple pattern strips [2] or optical access ports in order to measure multiple dimensions, while grating-based multi-dimensional approaches typically require complex setups [3], increasing the cost and alignment difficulty of these techniques. This current lack of low-complexity multi-dimensional optical encoding technique limits their potential applications in science and industry.

In this paper we present a novel approach to multi-dimensional optical stage encoding, utilising a range-resolved interferometric (RRI) technique [4] to measure simultaneous displacements for three Cartesian directions. This technique utilises a single optical access port to interrogate a series of multiplexed interferometers separated by unique optical path differences (OPDs), allowing for a compact, cost-effective optical stage encoder. We present a proof-of-concept setup that uses this technique to simultaneously measure displacements of a Piezo stage along three orthogonal axes, using a simple optical setup. In section two of this paper, the principle behind RRI is briefly discussed and how it is utilised in this application. In addition, the design of a proof-of-concept setup is presented, along with the hardware required. In section 3, measurements of stage motions over the ±50 µm range of a Piezo stage in 3-dimensions taken using the proof-of-concept design are presented.

2. Principle and Setup

2.1. Range-resolved Interferometry

Range-resolved interferometry (RRI) uses sinusoidal optical wavelength modulation resulting from injection current modulation of diode lasers to multiplex interferometric signals that are separated by unique OPDs. Constituent interferometers are created between a series of semi-reflective or reflective surfaces within a single optical beam and can be individually interrogated. By calculation of an appropriate, range dependant demodulation waveform, phase change measurements of each individual interferometer within the optical beam path can be resolved. This allows for standard interferometric measurements to be performed on each constituent interferometer simultaneously, provided they have unique OPDs, where any overlap in the OPDs of the interrogated interferometers would result in cyclic errors [5].

2.2. Setup

Using a simple optical setup consisting of two beamsplitters mounted on a 3-dimensional Piezo stage and three planar mirrors mounted orthogonally to one another around the stage, an appropriate optical configuration could be conceived in which the interferometers between each mirror and a fibre-tip reference could be interrogated. By numerically subtracting from these measurements, the measurement from an interferometer between an on-stage reference surface and the fibre-tip, 3-dimensional measurements of the stage displacement could be acquired. In order to obtain a strong reference signal back from the beamsplitters, the front surface of the first beamsplitter is polished to selectively remove the anti-reflective coating from this surface only, whilst maintaining the anti-reflective coating on the other beamsplitter faces. Figure 1 shows an illustration of this setup for three dimensions.

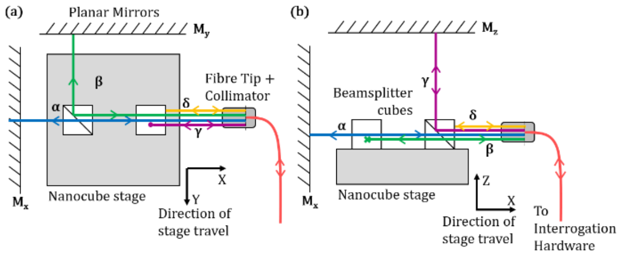

Figure 1. Schematic of the 3-dimensional stage encoder design with the geometric distances of the interferometers of interest, α, β, γ & δ highlighted. (a) shows a top-down view showing the X & Y dimension mirrors, with (b) showing a side-view of the setup and the X & Z mirrors.

In Figure 1, the geometrical distances corresponding to the interferometers of interest are denoted as α, β, γ & δ, with the former three referring to the optical paths between each mirror and the fibre-tip reference, and the latter referring to the optical path between the front surface of the beamsplitter and the fibre-tip, providing the on-stage reference measurement. Notably in this setup, the fibre collimator is the only optical access port required by this setup, with the interrogation hardware able to be placed a distance away, allowing for remote measurements. In order to interrogate this setup, a single discrete-mode laser diode (λ ≈ 1520.5nm) has its emission wavelength sinusoidally modulated by injection current modulation at a frequency of 24.4 kHz, with a wavelength modulation amplitude of ± 0.3 nm. The emitted light is guided through an optical circulator via a single-mode lead to the optical setup shown in Figure 1, and the returning light is circulated to an InGaAs photodetector. The resulting interferometric signals are demodulated in real-time using field programmable gate array (FPGA)-based signal processing hardware. Figure 2 shows a schematic of the interrogation hardware along with a photo of the fully-enclosed interrogation unit developed and manufactured at Cranfield, an example of an interferogram captured by the system and the range view output of the RRI interrogation unit.

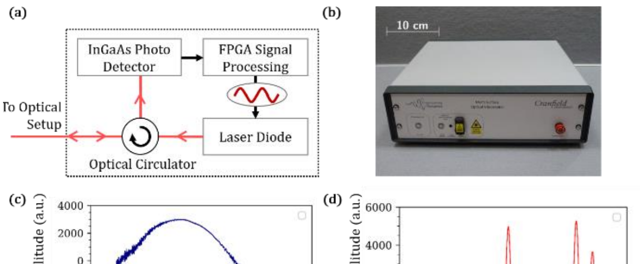

Figure 2. (a) shows a schematic of the interrogation hardware used, and (b) shows a photo of the fully enclosed interrogation unit. (c) shows an example interferogram captured by the system and (d) shows the range view output of the RRI system, showing peaks at the optical path differences present in the interferometric signal shown in (c).

3. Experimental Results

Over the ±50 µm nominal operating range of the stage, displacement measurements were taken for a series of 3-axis motions. In two of the axes, sinusoidal and co-sinusoidal motions of the stage were performed in closed-loop operation using feedback from the strain-gauge encoder of the stage, resulting in circular motion in this plane. This was combined with a linear motion of the stage in the third axis, resulting in a helical motion. This was repeated for each pair of axes for a total of three helical motions with results shown in Figure 3.

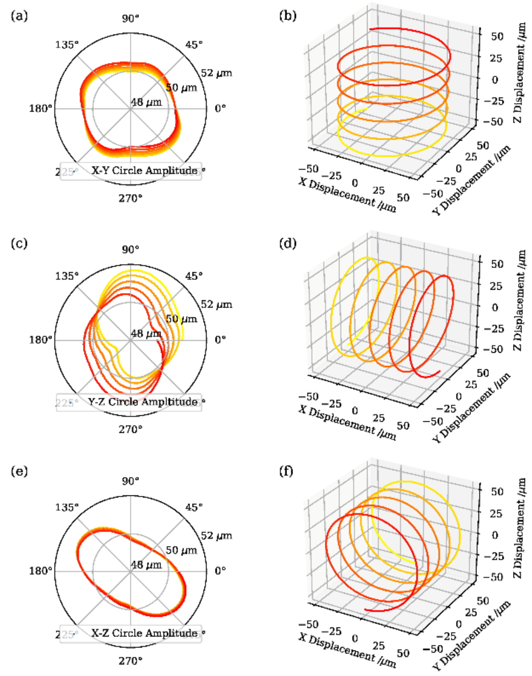

Figure 3. Measured displacements of helical motions of the Piezo stage. (a), (c) and (e) show polar representations of the amplitude of the X-Y, Y-Z and X-Z circular planes respectively. (b), (d) and (f) show 3D representations of the measured displacements.

Of interest within these results is the skew of the polar plots and offset of each circle within the plots. It is thought that the "footprint" shape of each plot is due to non-perfect stage motion, while the offset could be caused by misalignment of the beamsplitters or the mirrors to the measurement axis, with further analysis required to determine the exact cause. From static noise measurements over a bandwidth from 1 Hz to 10 kHz typical noise standard deviations of 3.5 nm are achieved. This, however also includes mechanical stage vibrations present.

4. Further Work

This technique shows great promise as an alternative to existing techniques for multi-dimensional stage encoding. Although this proof-of-concept demonstrates one particular application of RRI, variations of this setup could be extended to allow the simultaneous measurement of other degrees of freedom, for example angular measurements by evaluating the measurements from two spatially offset beams for each mirror.

5. Conclusions

In this paper we have presented a novel approach to multi-dimensional positional encoders, using a range-resolved interferometric system and a compact, simple optical setup. Using a proof-of-concept design we have presented simultaneous, 3 dimensional measurements of a 3D stage motion, demonstrating the feasibility and benefits of such an approach for science or industrial applications.

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