euspen's 18th International Conference & Exhibition, Venice, IT, June 2018
www.euspen.eu

Straightness and index sensor with sub-micron accuracy

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Abstract
Straightness measurements are important for machine axes correction or qualification. In this paper we investigate the accuracy of an optical straightness measurement system based on a fibre coupled laser beam pointing onto an image sensor. With sub-micron accuracy, such a simple and economic system is an interesting alternative to standard calibration techniques and can even be implemented on machines for real time correction. This paper investigates the achievable accuracy for measuring ranges up to 1.5m.

Keywords : Optical straightness measurement, sub-micron positioning system, error separation.

1. Introduction

Machine tools and measuring machines need to be calibrated with high accuracy. For this, the 6 degrees of freedom (DoF) of all stages need to be measured. Most of the machines use line scales or interferometers to measure the main component of a stage displacement, but relay on the accuracy and repeatability of the axis guidance to master lateral and/or angular displacements. In measuring machines with sub-micrometer accuracy, this can be insufficient and a dedicated real time measurement must be implemented [1]. Yaw and pitch can be measured using a 3 beam interferometer system, but roll and the two lateral displacements are more problematic to be measured with high accuracy. To ease this, we developed a simple high accurate straightness sensor using a fibre coupled laser beam pointing onto a digital image sensor. The idea is not new [2], but a complete investigation of its accuracy was to our knowledge not reported. This paper will investigate the accuracy and the application limits of such a system. Furthermore, we present an error separation method which can potentially reduce systematic errors.

2. Working principle

Four quadrant diodes are commonly used to find the centre of a laser beam spot, but to be implemented as straightness sensor, they need calibration. Position sensitive devices (PSD) don't require calibration apart from nonlinearity corrections but the light spot centre determination is fixed and cannot be influenced. Here we use a digital image sensor with the pixels acting as a ruler to locate the beam centre with sub-pixel accuracy since they are manufactured with lithographic precision. Different beam centre determination algorithms can be implemented and tested. Digital cameras are nowadays very cheap, much cheaper than a four quadrant diode, and very easy to use. Their only drawback is their power dissipation, which could lead to a thermal drift of the chip position.

For our setup, we used a Basler monochrome camera model daA1280-54um, which has a CMOS 1.2 M pixel chip with 3.75 µm square pixel size and a 1.2 W power consumption. The laser beam was issued from a single mode optical fibre pigtailed to a 670 nm laser diode. As the camera is quite sensitive, the laser diode is driven below its laser threshold, which also avoids some problems from coherent reflections. Two configurations were used:

- As index sensor with the bare fibre end is shining directly onto the CMOS chip at a distance ranging between 1 mm and 5 mm.
- As straightness sensor where the fibre end is fitted with an aspheric lens collimator (focal length 10 mm) in order to form a Gaussian beam with a Ø = 1 mm. With this configuration, the working distances can easily reach up to 1.5 m. Figure 1 depicts this later configuration of the straightness sensor.

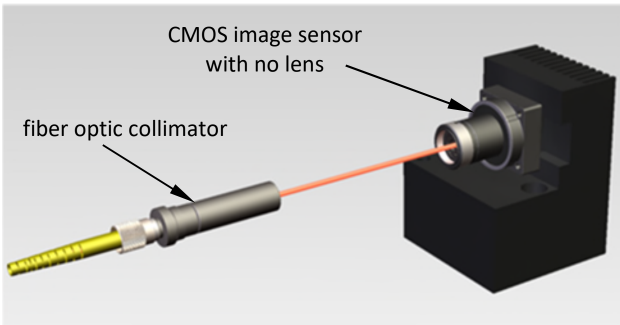

Figure 1 Configuration of the developed straightness sensor. The tube in front of the image sensors reduces stray light.

Special care was taken to obtain a very close to Gaussian beam shape. We verified that higher order modes in the fibre were not present. For the collimator, a high quality aspherical lens was used to avoid reflections and distortion of the wavefront by multiple lens systems. A poor lens quality can easily affect the beam shape and induce systematic errors. To assess the performance of the straightness sensor, an error separation technique can be applied to the measurement by rotating the fibre collimator and/or the image sensor 180 ° around the beam axis. The collimation of the beam was precisely adjusted such that the intensity at the beam centre and beam diameter varied less than 1 % over a 1.5 m travel range.

The algorithm used for finding the position of the beam centre is based on a simple intensity weighted mean. In order to reduce the sensitivity due to a possible inhomogeneous background illumination, an intensity threshold is implemented. Of course, before any measurement, the camera sensitivity is optimized to ovoid saturation and to obtain the best signal to noise ratio. More complex algorithms based on Gaussian fits were also tested but did not show any benefit with respect to the simple weighted mean method.

3. Static test

In order to test the fundamental accuracy of our system the bare fibre end was fixed directly to the camera housing, in the centre at about 2 mm from the camera chip surface. The centre of the light spot was then recorded to evaluate the fundamental accuracy of the system and the thermal drift of the camera as it warms up. The noise level of our measuring system is less than 10 nm (1 σ) and the drift during warm-up was less than 450 nm thanks to the central position of the chip respect to the camera mounting screws.

4. Index sensor test

In a second experiment, the fibre end was mounted on a 2 axis transvers displacement stage placed at a fixed 2 mm distance from the chip surface. The position of the stage was actively regulated using its own controller looped using its integrated line scale and a transvers trajectory of 500 nm up, 5 x 100 nm steps down followed by a trajectory of 500 nm down, 5 x 100 nm steps up was programmed. Figure 2 shows the displacement of the centre of the spot of light measured by the camera. One can notice that the 100 nm steps are clearly resolved despite the slow back and forth fluctuation of the stage with a 50 nm amplitude.

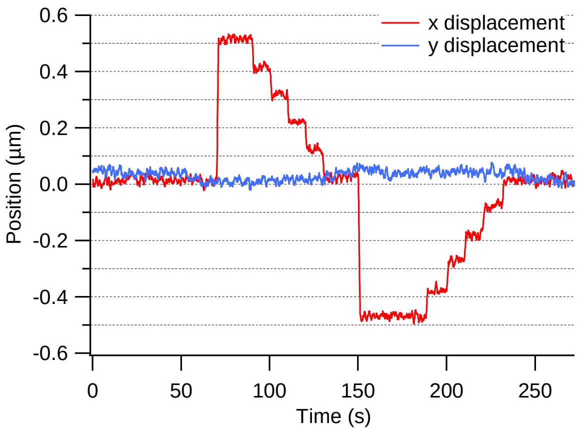

Figure 2 Trajectory of 5 x 100 nm steps down, and 5 x 100 nm back is clearly resolved despite the slow 50 nm oscillation of the stage.

With this accuracy, such a system can be used as a position sensor for small displacements or as an absolute index sensor for machines using an incremental displacement measuring system.

5. Straightness sensor test

The straightness experiment configuration depicted in figure 1 was realized with a collimator to image sensor distance ranging from 0.1 m to 1.5 m. The straightness measured by the sensor was compared with the straightness of the displacement stage which was calibrated using conventional methods, i.e. a tactile probe measuring a ceramic straight edge. Electronic levels were used to measure the angular errors and required for correcting the influence due to the Abbe offset of the straight edge. The measurement results shown in figure 3 were determined for a 300 mm displacement along a y-axis. The two systems agree within 150 nm for translation along the z-axis (Tz), and within 400 nm for a translation along the x-axis (Tx) which was severely influenced by a large Abbe offset.

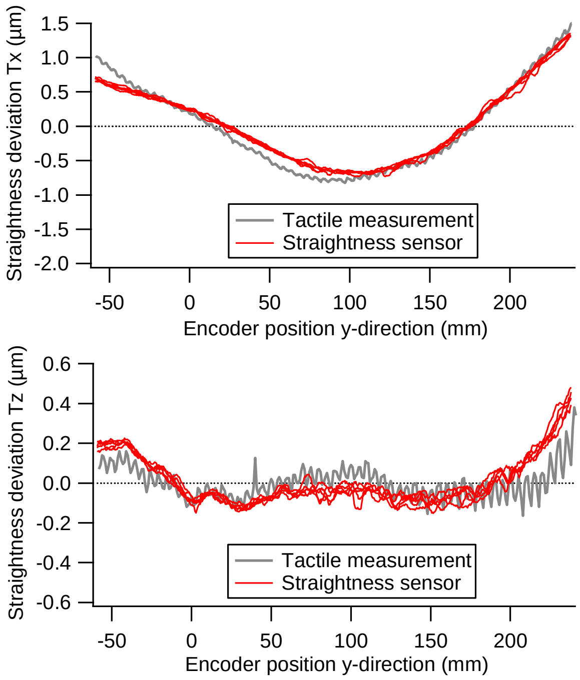

Figure 3 Evaluation of the straightness sensors on 300 mm displacement stage in y-direction. The straightness sensors (red curves) are compared to tactile measurements obtained on a straight edge (grey curves).

The beam pointing stability was investigated at longer distances. In a climatised laboratory, the air turbulences induced a fluctuation (1 σ) of 40 nm at 200 mm, 190 nm at 1 m and 310 nm at 1.5 m.

6. Conclusion

This study showed that our proposed very simple index and straightness system can reach a very high accuracy. If the thermal warm-up of the camera is mastered, the index sensor can clearly achieve 50 nm accuracy, whereas the straightness sensor can achieve 150 nm accuracy over a 300 mm travel range. An error separation method by turning the source beam 180° around the propagation axis was used to determine the beam profile influence. Performances over even longer distances are still under investigation. The sensor system is cheaper and less cumbersome to use than conventional tactile or interferometric systems, it can be an interesting alternative for machine calibration or for an in-situ real-time measuring system.

References

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[2] Cuifang Kuang et al 2007 Meas. Sci. Technol. 18 3795