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Optical deflection measuring system

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Abstract

A system for accurate real-time measurement of deflections was developed. A stable laser source is, by means of a single-mode fiber, coupled to an optical head located at one end of deformed structure. A detector circuit with a quadrant detector and processing electronics, located at the other end of the structure, communicates the resolved 2D position of the incident beam over a common digital bus. Experiments using interferometers were conducted in a climate-controlled chamber to evaluate system performance and verify the accuracy. A resolution of 0.1 μm is attainable in dynamic measurements. The system was calibrated and tested to yield measurement accuracy of ±0.8 μm for ±2σ probability over the measurement range of ±300 μm. Drift of the system in the experimental setup was determined to be less than 2 μm for measurement in both degrees of freedom within the 10 h period under constant environmental conditions.

Keywords: Optical deflection measuring; Real-time error compensation; Laser deformation measurement

1. Introduction

Optical methods have been used in various fields of science and industry in order to detect small deviations in position or angle. These systems often employ a laser source, producing an optical reference line, and a kind of position sensitive detector (PSD) to measure the deviation from the reference line. Different types of PSDs include segmented photodiodes, lateral-effect photodiodes and CCD detectors, among others. An autocollimator, e.g. such as described by Sohn et al. [1], uses a laser diode, PSD and a moving mirror to detect small changes in angle of the mirror. Armstrong and Fitzgerald [2] proposed an autocollimator comprising a CD player pick-up head and a reflecting surface. The head contains a laser source and photodiodes that can be used to establish the reflected beam deflection. Likewise, Fan et al. [3] used a DVD player head and a knife-edge principle in a straightness measuring system.

Similar systems were also used to measure geometrical errors of precision machinery, such as machine tools, coordinate measuring machines (CMMs) and others. When high accuracy is required, two different approaches can be used. First, errors can be avoided with a proper design of the machine by means of a rigid construction and close manufacturing tolerances. Second, they can be compensated for in real-time during machine operation. The latter method was found to be more cost effective than the traditional error avoidance approach and has been under constant development in recent years. Error compensation includes two different concepts, namely the off-line and on-line compensation. Off-line methods can improve the accuracy by applying either mathematical models of errors or previously established calibration data. Although effective only to a certain extent, calibration techniques were shown to significantly improve the accuracy [4].

Random non-repeatable errors caused by machine load, friction, environmental and other sources can, however, only be overcome by measuring and compensating them in real-time. Huang and Ni [5] presented an error compensation system for CMMs with a five DOF measuring system for *X* and *Y*-axes and a two DOF measuring system for *Z*-axis of the machine. The first unit contains a He–Ne laser, optical components to generate four separate beams and PSDs to measure vertical and horizontal straightness, roll, pitch and yaw errors. The *Z*-axis unit measures only the straightness errors due to space and weight limitations. Additional PSDs were used to compensate the lateral drift of the laser beam. The achieved accuracy of the system was 1″ for angle and 5 μm for translational errors. The

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problem of beam stability was addressed by Fan and Zhao in [7]. He used a fiber-coupled laser and a modulation circuit in order to diminish the lateral and angular beam drift. The resulting system stability was 0.3 μm at 1 m distance in 12 h period and the accuracy was 0.3 μm within ±100 μm range. Feng [6] also used a laser coupled to a single-mode optical fiber in straightness measurement system. The obtained repeatability was 1 μm at 1 m distance and the drift was 3 μm in 10 min period. Recently, Kuang et al. [8] introduced a four DOF measurement system with a fiber-coupled laser with an accuracy of the straightness part of ±2.5 μm and stability of 1.4 μm in 1 h interval.

In robotics, such systems were proposed to measure the deflections of a flexible robot structure. With lightweight manipulators, the assumption of rigid links is usually not valid. The existence of deflections and vibrations makes the measurement of the link deformations necessary. Attempts to measure deformations indirectly have been made, using strain gauges, fibre-optic and other sensors. Actual deflections are then inferred from these partial strain information by complex operations, which are often noisy and inaccurate. In this respect, optical methods are advantageous by measuring the deflections directly. Demeester and Van Brussel [10] presented a sensor system consisting of three laser diodes and three PSDs, mounted on opposite sides of a flexible link. Five components of total six DOF deflection are measured, excepting the elongation of the link. Xu and Tso [11] proposed an optical sensing system for measuring five DOF deflection of each flexible link and a compensation scheme to improve robot positioning accuracy. Yang [12] considered a simplified system, measuring only errors in the nominal motion plane, perpendicular to preceding joint axis. Tso et al. [13] demonstrated vibration control of a single flexible link by using a one-axis optical feedback system.

All previously mentioned optical systems have shown to significantly improve the accuracy of the mechanical structure. Nevertheless, they lack physical attributes (weight, dimension) or accuracy properties much needed for use in real machinery. Externally mounted sensitive components cannot be exposed to the industrial environment and may in different ways obstruct the operation of the machine. Moreover, an effective way to capture deflection data from multiple such systems is desired. In this paper, we present a solution with capability of static and dynamic measurement of deflections, developed for integration in precision mechanical systems at the University of Ljubljana. Simplicity, high accuracy and easy practical implementation were desired prime objectives. The system is distinctive for its small weight and compact dimensions, making it possible to locate it internal to a machine segment, robot or other structure. In this way, the normal functionality of the machine is unimpeded and at the same time, favorable operating conditions for the optical system can be attained.

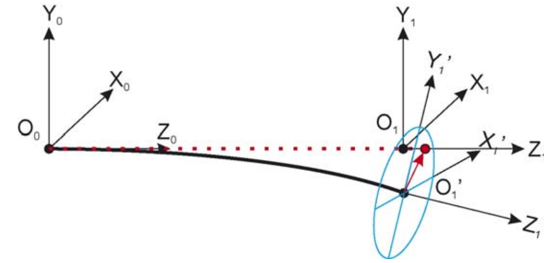

Fig. 1. A deformed link.

2. Deflection measurement system

2.1. Measurement principle

In Fig. 1, a single link of a flexible structure is shown. The coordinate frame O_0 is placed at one end of the link and coincides with an optical head producing a straight reference beam. At the other end of the link, a detector circuit establishes the position of the projected light spot in the O_1' coordinate frame. The deflection from the straight line can be represented by a transformation from coordinate frame O_1 to O_1'. Since the error components in *Z*-direction (the elongation of the link) are usually very small, they can be neglected [11] within defined temperature conditions. By using a single reference beam and a quadrant detector, the linear displacements in the plane perpendicular to the beam (*X* and *Y* translational errors) can be measured. Often, the rotations around *X*- and *Y*-axes can also be inferred from this information, e.g. when only gravitational loads are present, or by assuming the dominant mode shapes in oscillating structures [13]. Therefore, at most four of total six components of deviation can be identified.

When the segment is undisturbed, the reference beam hits the center of the photodiode, producing equal output in each of the quadrants. Any deviation of the detector in the plane perpendicular to the beam causes a displacement of the light spot (Fig. 2). The maximum deviation from the center position is limited by the spot diameter and is usually $< 0.9r$. A simple measure of the displacement can be found as:

$$dX' = \alpha \frac{(V_B + V_C) - (V_A + V_D)}{V_A + V_B + V_C + V_D} \quad (1)$$

$$dY' = \alpha \frac{(V_A + V_B) - (V_C + V_D)}{V_A + V_B + V_C + V_D} \quad (2)$$

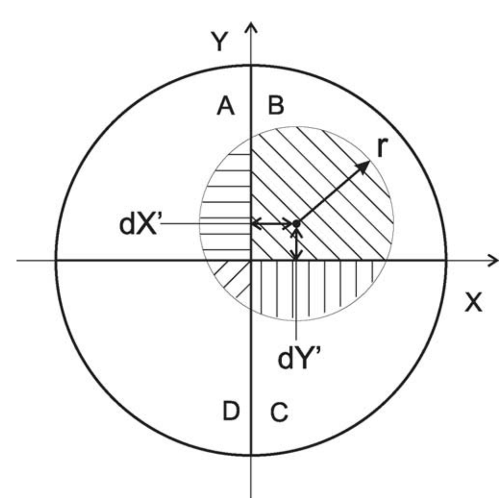

Fig. 2. A quadrant photodiode and an incident beam.

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where V_A, V_B, V_C and V_D are the voltages proportional to illumination of respective photodiode quadrants and α is proportional to the beam diameter. These equations are exact only in case of a perfectly rectangular beam with a uniform intensity distribution. In reality, however, the circular shape and the beam intensity distribution cause significant non-linear deviations from these idealized equations, as it was discussed in [9].The beam diameter also influences the resolution of the measurement. A complete theoretical characterization of the displacement curve is difficult because of the Bessel distribution of the beam [6] and has only limited applicability on account of beam irregularities, caused by lens and scattered light. An experimental calibration is therefore necessary.

The plane of the PSD is expected to be normal to the laser beam. Nevertheless, the bending of the link will cause an angular deviation of the link and the PSD plane. This will introduce a cosine error in the measurement and effectively change the sensitivity of the detector to the lateral movement, since it is now inclined with regard to the reference beam. But the extent of this sensitivity variation is in most cases very small. If we assume a uniform profile of the link, the Eqs. (3) and (4) describe the lateral and angular deflections of the link under point load at the end of the link, respectively [14]:

$$f = \frac{Fl^3}{3EI_Y} \tag{3}$$

$$\alpha = \frac{Fl^2}{2EI_Y} \tag{4}$$

Here, f and α denote the lateral and angular deflections, F the applied force, l the length of the link and I_Y is the area momentum of the link cross-section. The relation between the two is therefore:

$$\frac{\alpha}{f} = \frac{3}{2}\frac{1}{l}. \tag{5}$$

The equation demonstrates that the ratio of angular to the lateral deflection is inversely proportional to the link length. Similar relation can be found for a load distributed along the link (e.g. gravity load). At link lengths, greater than 30 mm, the sensitivity change results in less than 0.01% reading deviation, so this effect can be neglected.

2.2. System components and operation

The main components of the system are presented in Fig. 3. The laser control unit drives the laser diode producing a visible output wavelength of 670 nm. A feedback circuit provides a constant optical power output of the laser diode, which is coupled to a single-mode optical fiber. This is known to reduce the lateral and angular drift of the beam common to laser diodes. The beam emanating from a single-mode fiber has a constant, Bessel distribution and does not suffer from any spatial drift. The optical fiber is terminated by an optical head containing a lens system. It collimates the light emerging from the fiber, producing a beam with an approximate diameter of 1 mm and 0.5 mrad divergence. Through usage of an optical fiber and stabile laser driver components [6,8], a high-quality reference beam of an adequate stability is generated.

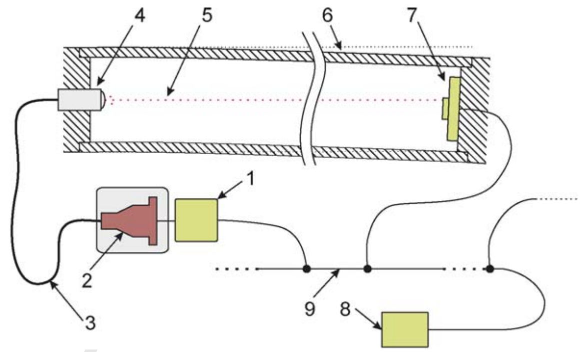

Fig. 3. Main system components: (1) laser driving unit, (2) laser diode, (3) optical fiber, (4) optical head, (5) reference beam, (6) deflected link, (7) detector circuit, (8) master circuit, and (9) digital bus.

The detector circuit board is placed at the other end of the measured segment. A schematic diagram of the detector assembly is shown in Fig. 4. The incident beam hits the quadrant photodiode, consequently generating four photocurrents, proportional to optical power over each quadrant. These small currents are then amplified and converted to voltages, to be added and subtracted as per Eqs. (1) and (2). A 16-bit ADC digitizes the values, which are processed and stored by an onboard microcontroller. The quantization step (1 LSB) of the A/D conversion in the current system corresponds to approximately 0.01 μm resolution.

The distinct advantages of this measurement device are its small size and low weight. Since the optical head is separated from the laser source by the optical fiber, its dimensions can be kept very small. This also has an additional advantage of dislocating the heat source from critical mechanical components. The compactness of the detector was achieved by developing small size electronic boards. Merely the components needed for the purpose were included and space efficient surface-mount technology was utilized. The components are located on two stacked boards, which were size-optimized to meet the dimensions as specified in Table 1. The finished prototypes of the optical head and the detector unit are pictured in Fig. 5. Because both main parts of the system, the optical head and the detector unit, are of small physical dimensions, they can be completely contained in the measured segment. The entire optical path of the reference beam is then held in an enclosed space with stable environmental parameters, therefore some disturbing factors that affect similar systems, namely the ambient lightning and air turbulence, can now be minimized. Two example applications of the system are shown on Fig. 6.

A multitude of such detector units can be connected to a digital bus, all communicating with a single master unit. The exact moment when the deflection data is converted and stored can be defined by asserting the common trigger signal, thus synchronizing the measurement of all detector units. Alternatively, the measurement can be software triggered by an external controller or the detected position can be continuously output with the maximum sample rate. The master board contains the hardware facilities and protocols to transfer all deflection and control data to an external controller or computer. At this stage it is equipped

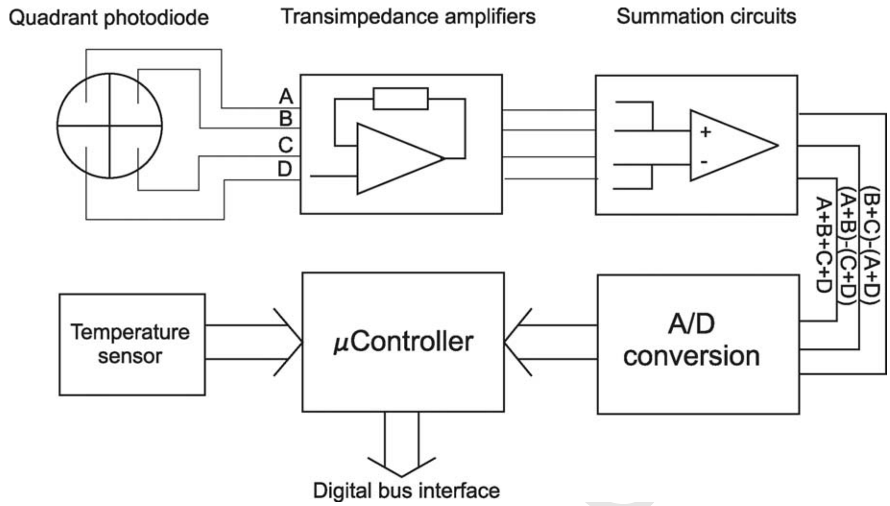

Fig. 4. Detector circuit board components.

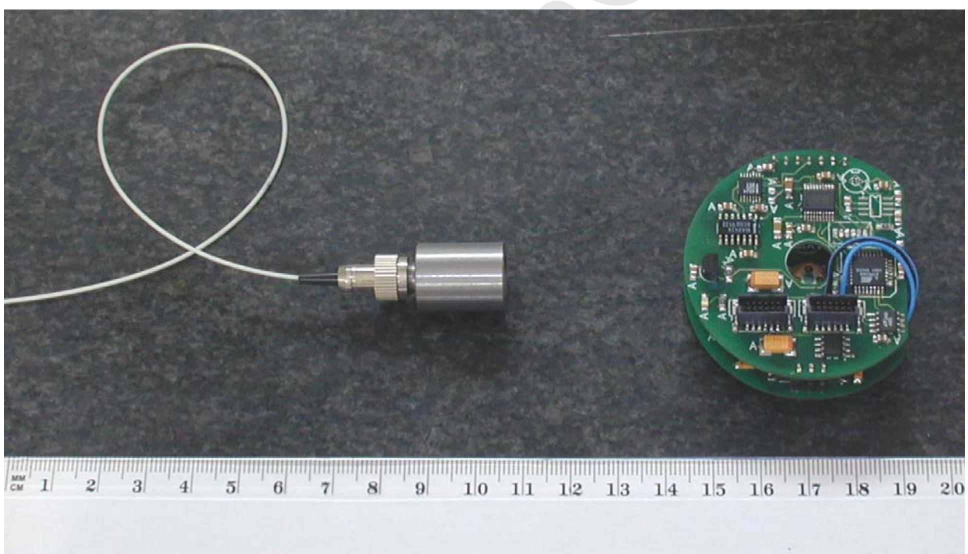

Fig. 5. The finished optical head and detector components.

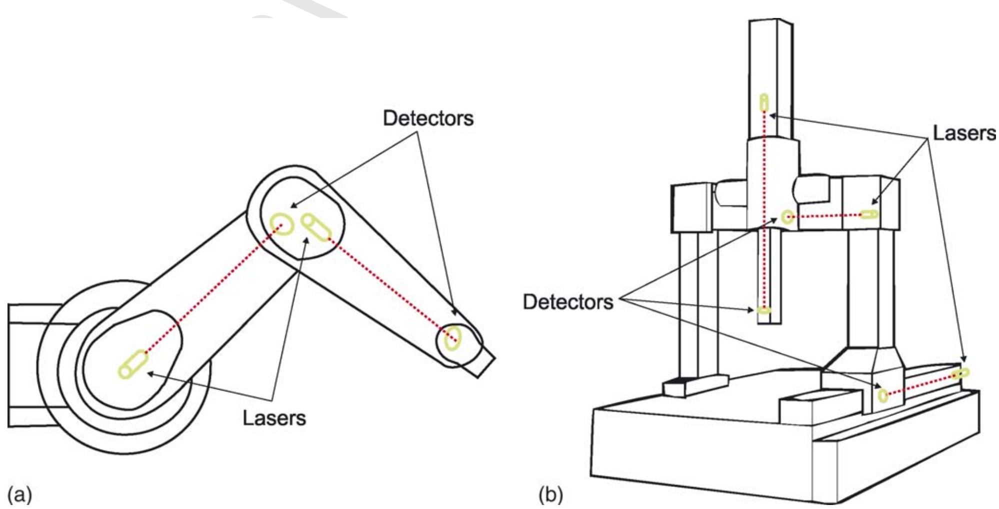

Fig. 6. Example applications of the measuring system: (a) in a robot and (b) in a CMM.

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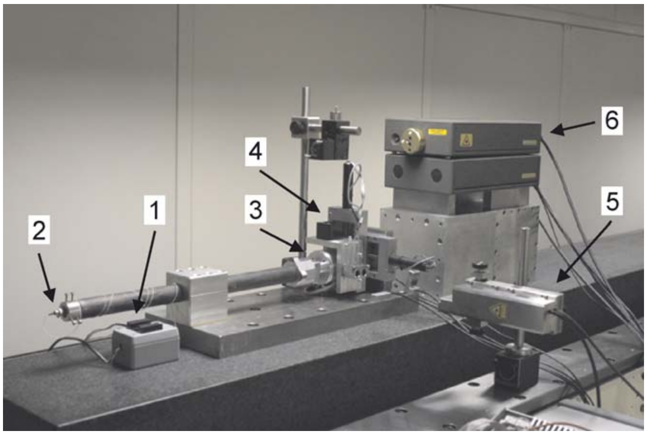

Fig. 7. Experimental system setup: (1) laser unit, (2) optical head, (3) detector, (4) micropositioning stages, (5) *X*-axis interferometer, and (6) *Y*-axis interferometer.

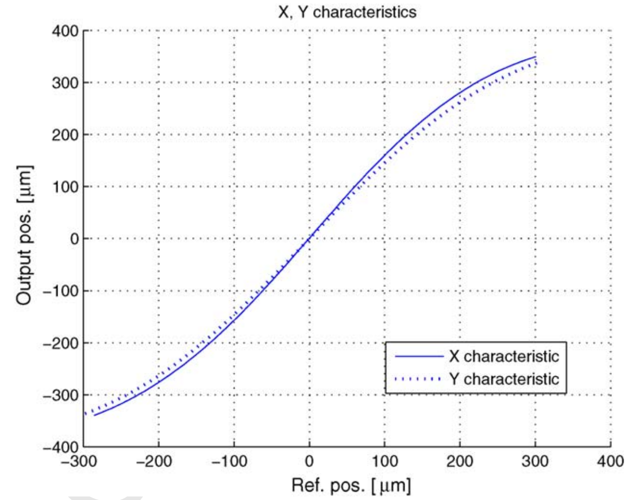

Fig. 8. *X* and *Y* detector response.

with an USB interface, enabling the system to be connected to any personal computer and capture data with a 1.2 kHz sampling frequency.

3. Experiments

3.1. Experimental setup

To characterize, calibrate and validate the new measurement system as proposed in Sections 2.1 and 2.2, an experimental setup as pictured in Fig. 7 was employed. The optical head was fastened to one end of a 0.6 m long carbon-fiber tube having 23 and 30 mm outer diameter, respectively. The practical implication of the tube was to contain the laser beam in stable (non-turbulent) environment and was not actively deformed. Instead, the detector was moved in the measuring plane by means of two Physik-Instrumente M-150.10 micropositioning stages, arranged in a *X*–*Y* configuration. The measured resolution of the stages was approximately 0.2 μm and the bidirectional repeatability 2 μm. The detector was contained in aluminium housing and fastened to the positioning stages, which were, in turn, fixed to the base steel plate together with the tube and optical head. The whole setup was then rested on a massive granite table, providing a stable and vibration-free support.

To accurately measure the actual relative position of the detector, two laser interferometer systems were used. The horizontal movement was measured by the Heidenhain ILM-1131 interferometer and the vertical by Renishaw ML10 + EC10 system. The stated resolutions of the reference measuring systems were 0.1 and 1 nm, respectively. In the laboratory environment, the accuracy of these systems is 0.1 μm, which was sufficient for the intended experiments. The retroreflectors were rigidly

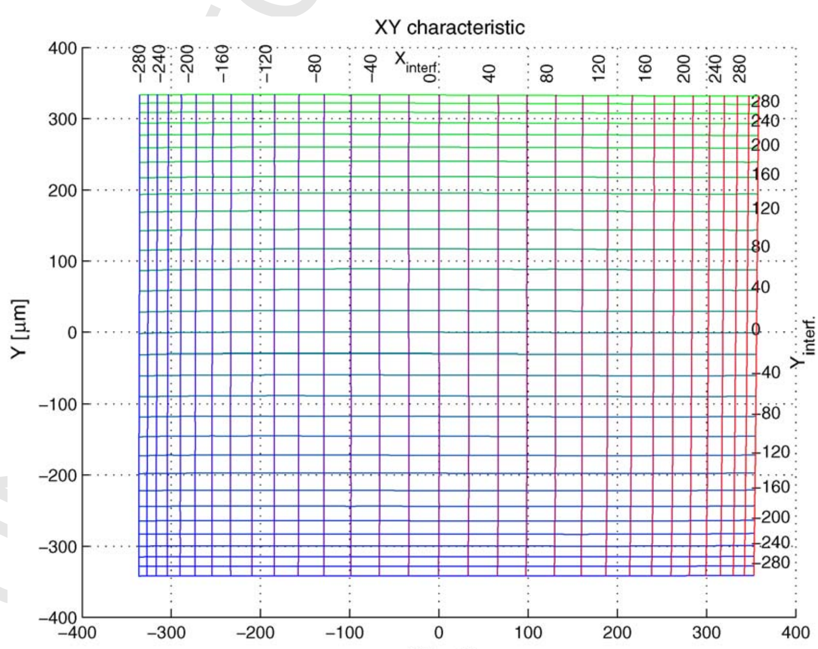

Fig. 9. 2D detector response.

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mounted to the detector housing in the axes of quadrant photodetector in order to minimize errors caused by angular deviations of positioning stages.

The measuring setup was located in a climate-controlled chamber [15] at the Institute of Production Engineering, TU Graz, to avoid temperature induced deformations of the critical elements. A desktop PC was used to control the positioning stages and retrieve the captured data from deflection measurement system and both interferometers. A common trigger signal was used for exact synchronization of all measuring systems. At the same time, the temperature values of the surrounding air and the steel base were also acquired. A PC application for unattended execution and control of measuring sequences was developed, creating an automated calibration and test system. Therefore, it was possible to avoid any possible external disturbance to the measurements.

3.2. Results and discussion

The purpose of the experiments was to assess basic system characteristics, calibrate it and evaluate its accuracy properties. First, one-dimensional response curves of the detector were recorded (Fig. 8). Detector response in *X*-direction was measured with *Y*-axis in center position and for *Y*-direction with *X*-axis in center position. The curves were found concordant with theoretical predictions. With increasing distance from central region with good linearity, the sensitivity is falling because of circular beam shape and its distribution. The slight difference in sensitivity of *X*- and *Y*-axis originates from beam ovalness and deviations in analog electronics. Unwanted properties such as hysteresis and dead-zone were below the limit of detection. The position resolution of the system depends on well definable and measurable factors, such as electronic noise and A/D conversion resolution as well as on random circumstances, such as thermal conditions and air turbulence in the light path. The former amounts to less than 0.05 μm and the overall resolution was experimentally verified to be 0.1 μm in conditions, as specified in Section 3.1. In static measurements, the resolution can be increased by time averaging techniques.

Next, a 2D characteristic was measured (Fig. 9). Because of the above mentioned small irregularities in beam distribution and analog electronics, the response curves in *X*-axis direction depend on *Y*-axis coordinate and vice versa. For this reason, a 2D response calibration is necessary for accurate results. The procedure for acquiring Fig. 9 was as follows. The response curves of the detector in *X*-direction were recorded and the *Y* position was then shifted for 20 μm repeatedly across the measurement range in order to obtain the horizontal lines. The same was done with *Y*-axis for the vertical lines. The resulting curves in Fig. 9 are plotted in uncalibrated space, according to Eqs. (1) and (2). The *X*- and *Y*-axes represent the detector output coordinates and the plotted horizontal and vertical arrays correspond to actual positions as measured by the interferometers. It is evident that the sensitivity is falling with increasing distance from the center point. With the measurement range chosen as $-300\ \mu\text{m} < X, Y < 300\ \mu\text{m}$, the sensitivity on the edge is about one-third of maximum (center) sensitivity.

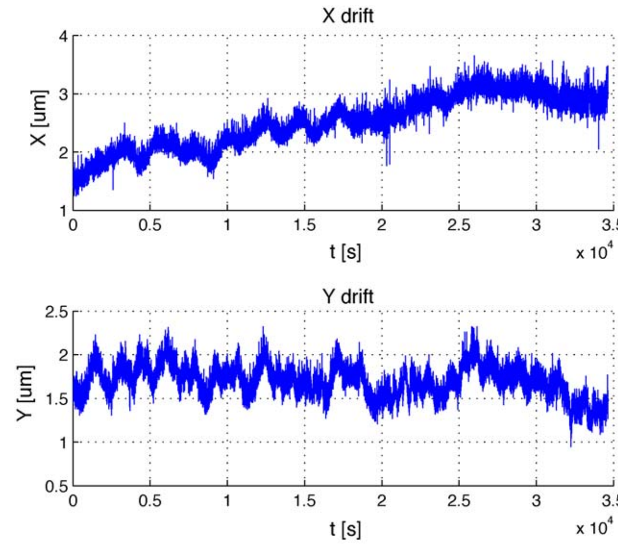

Fig. 10. Position drift of the system.

The system drift was also measured. In a thermally stable environment, the position was measured for a period of 10 h with 1 Hz sampling frequency. The positioning stages were left fixed in approximate center position of the detector. The results, shown in Fig. 10, indicate position reading drift of less than 2 μm for *X*-axis and 1 μm for *Y*-axis in the stated interval of 10 h. The likely sources of positional drift are mechanical deformations caused by the remaining temperature changes and small spatial deviations of the laser beam. The drift quantified here does not prevent higher degree of accuracy in shorter period of time. Successive calibrations, if possible, could bring the short term stability within 0.5 μm over 30 min time interval.

Finally, the system accuracy was tested. The data acquired for 2D characteristics presented in Fig. 9 was used to calibrate the system, after which the detector was moved into 400 random positions, uniformly distributed in the measuring range. The position output from our detector was calculated using 2D interpolation of the calibration data, and the true positions were measured simultaneously by the interferometers as reference values. The resulting positional deviations of successive measurements are in Fig. 11. It can be seen that the maximum error after detector calibration was 1.3 μm for the *X*-axis and 1 μm for the *Y*-axis. Slightly better agreement of the measured and reference position is visible in the *Y*-axis results. Also, small drift is present in *X*-axis position, since the duration of measurement was more than 30 min. The statistical distribution of the errors is in Fig. 12. As expected, the shape of the distribution is close to Gaussian (dashed line in the graphs). The standard deviations of the error data for *X*- and *Y*-axes amount to $\sigma_X = 0.4$ and $\sigma_Y = 0.35$, respectively. We can therefore expect with approximately 95% ($\pm 2\sigma$) certainty the measurement result is within ±0.8 μm of the true value. These values could be further improved by applying better calibration and position estimation methods, e.g. spline instead of linear interpolation. Again, accuracy can be further enhanced in static or quasi-static conditions by averaging the measurements in a sufficient time interval.

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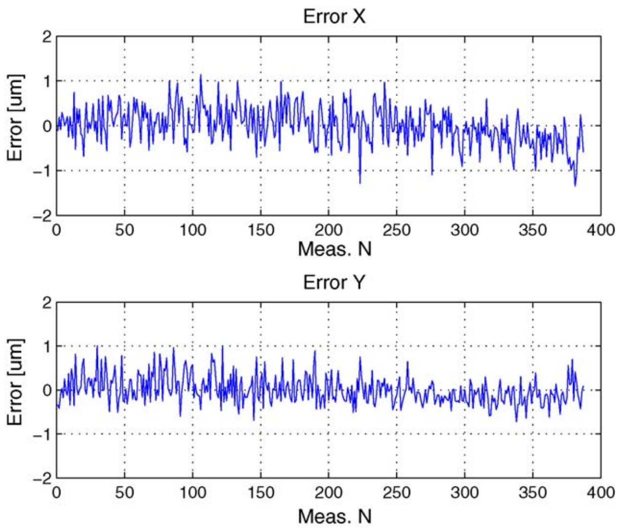

Fig. 11. Measurement error in test points.

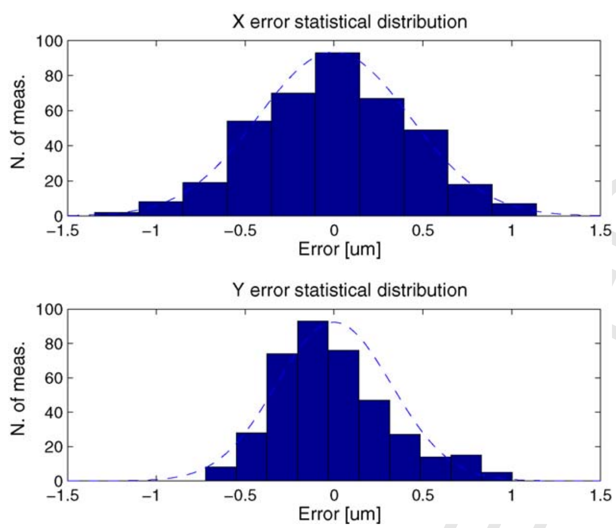

Fig. 12. Statistical distribution of measurement error.

The accuracy alleged here applies to the specific detector unit in the calibration setup. The misalignment of the PSD relative to the detector mounting has been taken into account by the calibration procedure. However, care must be taken when positioning the detector unit into the target system. The out-of-plane rotation of the unit will cause an observable cosine error if the mounting error is greater than 1.5°. Likewise, the in-plane rotation error will exceed the resolution limit of the system if the misalignment is greater than 0.02°. By careful mounting, these errors can be minimized.

Table 1
System characteristics

Range	X, ±300 μm; Y, ±300 μm
Resolution	0.1 μm
Accuracy (±2σ)	±0.8 μm
Maximum sample rate	1.2 kHz
Trigger response time	<20 μs
Trigger modes	Software, hardware, continuous
Optical head dimensions	⌀15 mm × 30 mm
Optical head weight	20 g
Detector dimensions	⌀52 mm × 10 mm
Detector weight	25 g

The system properties are gathered in Table 1. It must be noted that the measurement range, now equal to ±300 μm could optionally be adjusted simply by changing the beam diameter. By increasing it, the range is correspondingly expanded, provided that the beam diameter remains smaller than the detector radius. Doing so, however, also proportionally reduces the positional resolution and accuracy.

4. Conclusion

An optical measuring system, capable of direct measuring of two translational degrees of freedom was presented, suitable specifically for measuring deformations in mechanical components. The system is composed of optical head producing a stable reference beam, and a detector board with digital interface. The system was calibrated and the resulting accuracy was found to be adequate for applications in precision systems. The verified value of resolution is at least 0.1 μm and the error distribution shows a standard deviation of 0.4 μm. Stability tests in temperature-controlled environment indicate positional drift under 2 μm in 10 h in both DOF. Real-time static and dynamic measurements with sampling rates up to 1.2 kHz are possible. Multiple laser-detector sets can be connected to a single master board, thus measuring arbitrary number of DOF in a flexible mechanical system. The fact that the only necessary components in the affected structure are the modestly dimensioned optical head and detector unit, makes the integration of the system feasible in existing and future machinery. Being under the focus of commercial partners, a number of industrial applications is emerging.

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