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Displacement Measurement in the Vertical Axis of the Measuring Microscope using Laser Triangulation Sensor

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Abstract: The article deals with assessment of the suitability of using a laser triangulation sensor to measure the displacement in vertical axis of a measuring microscope. Data obtained from sensor calibration are used for determination of measuring range in which the smallest measurement error occurs. Linear approximation of the inverse calibration function is applied to correct systematic errors in reduced measuring range of the sensor. Residual measurement errors of corrected sensor output can be applied in uncertainty calculation for sensor future measurements.

Keywords: calibration; laser triangulation sensor; displacement measurement.

1. Introduction

Displacement measuring microscope is two-axis coordinate measuring instrument, whose construction is often composed of an optical microscope and a positioning stage. Measurements are obtained by direct comparison of the specimen dimensions to a linear scale in the x-y plane of the microscope. Mechanical stages often enable movement in both the x and y axes. Their displacement is precisely measured by particular measurement system, which is nowadays often composed of linear scales with pulse encoders or micrometric screws [1-3].

Measurements are performed in a non-contact manner, so there is no risk of skewing measurement of flexible parts or damaging sensitive parts. Measurement is possible even for targets with small or complicated shapes. It is not uncommon for measuring microscopes to be also equipped with displacement measuring system for the vertical axis. In this way, it is possible to measure some dimensional characteristics that were not previously possible to measure (e.g. hole depth), or it is not necessary to rotate the component during the measurement process (e.g. object with step).

Universal measuring microscope UIM-23 is opticomechanical instrument for precise linear and angular measurements. Measurement system equipped for both horizontal axes consists of glass linear scale and optical microscope, which is used to magnify and project linear scale on the screen. Targeting and focusing on the measured surface is provided by optical system beared on the mechanical arm, which is connected to y-axis stage. Maximum traveling distance for focusing system along the vertical axis is 50 millimetres. Position can be finely adjusted up to 4 millimetres by micrometric screw. It is possible to determine vertical displacement along the microscope optical axis by utilization of a calibrated fine focus adjustment on the microscope. However, it is not recommended for precise measurements.

The aim of this paper is to assess the suitability of using a laser displacement sensor

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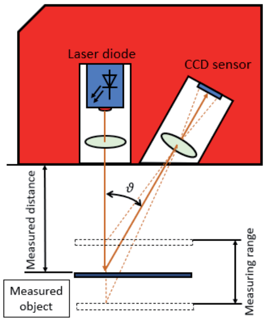
to measure the displacement of the optical system of the microscope in the vertical axis. Nowadays, laser displacement sensors are the most commonly used ones in the field of dimensional metrology as a result of their versatility. At moderate ranges, laser displacement sensors perform accurate and fast measurement and are easy to implement [4-6].

Metrological characteristics of sensor are evaluated from the experimentally obtained data in the calibration process. Based on the obtained data, a suitable measuring range that is least affected by measurement error is determined. Also, a formula to correct future measurements is expressed.

2. Calibration of measurement chain with laser displacement sensor

The sensor uses the principle of optical triangulation (Figure 1, left). Visible modulated point of light is projected onto the target surface. In dependency on distance, the diffuse element of the reflection of the light spot is imaged by a receiver optical element positioned at a certain angle to the optical axis of the laser beam onto a high-sensitivity resolution element (CCD). The controller calculates the measured value from the CCD-array. An internal closed-loop control enables the sensor to measure against different surfaces. The sensor outputs analogue or digital values.



Selected technical specifications	
Measuring range	200 mm
Start of measuring range	60 mm
End of measuring range	260 mm
Linearity	400 µm
Resolution	40 µm
Output	analog 4...20 mA digital RS422

Figure 1: Measurement principle and technical specifications of laser triangulation sensor.

Measurement chain with tested laser triangulation sensor for digital data output is shown in Figure 2. A PC with software belonging to the sensor is used as an evaluation and display unit. This way, we obtain readings directly converted to units of length. PC does not have an RS422 connector, therefore it is necessary to use a RS422/ USB converter.

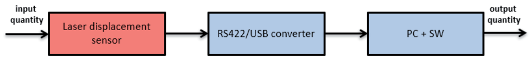


Figure 2: Measurement chain with laser displacement sensor

Calibration procedure structure is shown in Figure 3. Sensor is attached to the stand which allows its movement in the vertical axis. Measured distance between the sensor and the target surface is given by reference length gauge blocks. The output signal from the sensor is then processed by the converter and the measured distance is displayed in the software interface. Digital thermometer records temperature of gauge blocks. Their temperature varies from the reference temperature depending on the manual handling time, which affects their length. Obtained data are applied to compensate output values for errors caused by influence of temperature on length gauges.

Nominal measuring range of displacement sensor is 200 mm (Figure 1, right). Accuracy of the displacement sensor is calibrated traceable to the SI, via reference gauge blocks, in 21 calibration points evenly distributed over the entire measuring range with 10 mm step. At each calibration point 10 values are recorded.

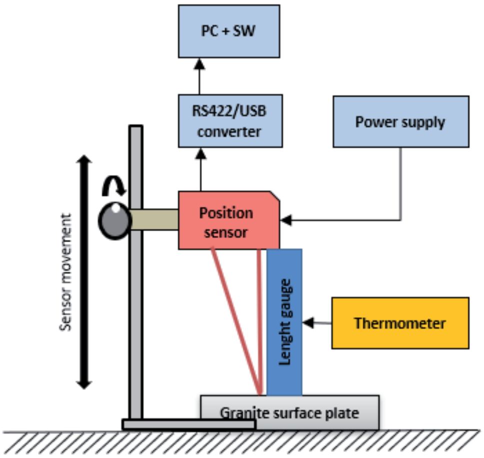


Figure 3: Calibration process structure

3. Evaluation of calibration process

The calibration of a measuring instrument allows determining the deviation of the indication of the measuring instrument from a known value of the measurand provided by the measurement standard, with associated measurement uncertainty [7-9]. Figure 4 shows the average calculated deviations from the measured value for all calibration points. The detected average deviations have an increasing tendency and it is possible to approximate them with the second degree polynomial regression. These data can be used as a basis for calculating the measurement uncertainty of the sensor in future measurements.

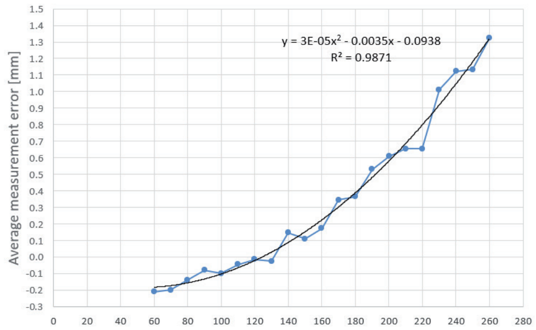


Figure 4: Average deviations in calibration points

In simplified mathematical model of calibration of position sensor, the deviation in any calibration point is expressed by the equation

$$e = L_{ind} + 60 - \left(L_N - \delta_G\right) \times \left(1 + \alpha \times \theta\right) \tag{1}$$

where: e – measurement error, L_{ind} – is indication given by evaluation unit, L_N – is nominal value of lenght gauge, δ_G – is systematic error of length gauge, α – is coefficient of thermal expansion of length gauges, θ – is difference between temperature of length gauges and reference temperature.

Due to measurement principle and design of the sensor, the indication given by evaluation unit must be corrected with constant 60, which represents offset of start of measuring range. Equation (1) can be also expressed as

$$e = L - L_G \times \left(1 + \alpha \times \theta\right) \tag{2}$$

where: L – is sensor output, L_G – is corrected value of length gauge.

3.1. Uncertainty calculation

Guidelines of the MSA-L/12 (EA-4/02 M:2013) [9] were followed to evaluate the calibration uncertainty of optical sensor. Uncertainty evaluation is based on a mathematical model of the calibration (2). If we consider all sources of measurement uncertainty to be independent, the combined standard uncertainty of the average measurement error is expressed as

$$u_C^2\left(\overline{e_i}\right) = A^2\left(\overline{L_i}\right) \times u_C^2\left(\overline{L_i}\right) + A^2\left(LG_i\right) \times u_C^2\left(LG_i\right) + A^2\left(\alpha_i\right) \times u_C^2\left(\alpha_i\right) + A^2\left(\overline{\theta_i}\right) \times u_C^2\left(\overline{\theta_i}\right) \tag{3}$$

where: $A(X) = \partial f\left(X_1, X_2, \ldots, X_m\right) / \partial X_i$ – are sensitivity coefficients, $u_c\left(\overline{L_i}\right)$ – is combined standard uncertainty of corrected sensor output, $u_c\left(LG_i\right)$ - is combined standard uncertainty of corrected value of length gauge, $u_c\left(\alpha_i\right)$ - is combined standard uncertainty of coefficient of thermal expansion, $u_c\left(\overline{\theta_i}\right)$ - is combined standard uncertainty of calculated temperature difference. Index i refers to calibration point. Its values are the same as a nominal value of a particular length gauge.

Regarding to all considered sources of uncertainties and methods of their evaluation, Equation (3) can be modified as follows

$$u_C^2\left(\overline{e_i}\right) = A^2\left(\overline{L_i}\right) \times \left(u_A^2\left(\overline{L_i}\right) + u_B^2\left(\overline{L_i}\right)\right) + A^2\left(LG_i\right) \times u_B^2\left(LG_i\right) + A^2\left(\alpha_i\right) \times u_B^2\left(\alpha_i\right) + A^2\left(\overline{\theta_i}\right) \times \left(u_B^2\left(\overline{\theta_i\left(T_\kappa\right)}\right) + u_B^2\left(\overline{\theta_i\left(T_a\right)}\right) + u_B^2\left(\overline{\theta_i\left(S\right)}\right)\right) \tag{4}$$

where: $u_A(X)$ – are uncertainty components evaluated by Type A evaluation of measurement uncertainty from the statistical distribution of the quantity values from series of measurements, $u_B(X)$ – are uncertainty components evaluated by Type B evaluation of measurement uncertainty, evaluated from probability density functions based on experience or other information, $u_B\left(\overline{L_i}\right)$ - is standard uncertainty that results from measurement step of the optical sensor, $u_B\left(LG_i\right)$ - is standard uncertainty that results from the inaccuracy of length gauge calibration, $u_B\left(\overline{\theta_i\left(T_\kappa\right)}\right)$ - is standard uncertainty that results from display resolution of digital thermometer, $u_B\left(\overline{\theta_i\left(T_a\right)}\right)$ - is standard uncertainty that results from the inaccuracy of digital thermometer, $u_B\left(\overline{\theta_i\left(S\right)}\right)$ - is standard uncertainty that results from the inaccuracy of temperature measuring probe.

Since standard uncertainties create an interval covering true value of measured quantity with a relatively small probability, it is necessary to introduce a quantity that would create interval with a higher probability of covering the true value. Expanded uncertainty is product of a combined standard uncertainty u_C and a coverage factor k larger than the number one. The factor depends upon the type of probability distribution of the output quantity in a measurement model and on the selected coverage probability [7-9]. Since we do not have enough data to calculate the type of probability distribution, we assume that measurement error is described by a rectangular probability distribution. For the level of confidence p = 95%, coverage factor k = 1.65. Expanded uncertainty is expressed as

$$U\left(\overline{e_i}\right) = u_c\left(\overline{e_i}\right) \times 1.65 \tag{5}$$

Simplified tabular form of uncertainty budget is shown in Table 1. Maximum calculated value of expanded uncertainty is equal to 0.047 mm for calibration point at the end of measuring range. We can consider this value as a calibration uncertainty in the whole measuring range. Combined standard uncertainty of corrected sensor output has the largest contribution to the expanded uncertainty. This is related to the resolution of the sensor, which may be finer when measuring range is reduced.

3.2. Determination of the suitable measuring range of the position sensor

From the calculated absolute values of errors (Fig. 4) in each calibration point, we compiled 17 intervals $\left(e_i, e_{i+40}\right)_{i=60}^{220}$, whose range corresponds with the required measuring range of 50 millimeters. From these intervals, we then selected the one in which the largest absolute measurement error is the smallest within all intervals. This condition is met by a measuring range starting 90 millimetres from the reflecting surface.

Inverse calibration curve for reduced measuring range (Figure 5, left), based on the original measured data, expresses relationship between measured value and sensor output estimated with linear regression, which leaves negligibly greater residual errors than polynomial regression. On the other hand, uncertainty calculation for linear regression is less complicated. Mathematical expression of the regression curve, also called inverse calibration function can be applied to correct sensor output for future measurements. In this case, equation (Figure 5, left) can be written as

$$L_{COR} = 0.998 \text{ x } L + 0.2661 \tag{6}$$

where: $L_{cor} = (L_G + e_{cor})$ – is corrected sensor output, e_{cor} – is residual error after correcting the sensor output.

The residual errors that result from correction of the sensor output (Figure 5, right) can be applied

Table 1. Uncertainty budget

i	$A(\overline{L_i})$	$u_c(\overline{L_i})$	$A(LG_i)$	$u_c(LG_i)$	$A(\alpha_i)$	$u_c(\alpha_i)$	$A(\overline{\theta_i})$	$u_c(\overline{\theta_i})$	$u_c(\overline{e_i})$	$\overline{e_i}$	$U(\overline{e_i})$
[−]	[−]	[mm]	[−]	[mm]	[mm. °C]	[°C^{-1}]	[mm. °C^{-1}]	[°C]	[mm]	[mm]	[mm]
60	1	0.014376	-1.000030	0.000054	-151.2	58 x 10^-8	-0.00072	0.149271	0.014379	-0.209	0.024
70	1	0.014376	-1.000022	0.000055	-126	58 x 10^-8	-0.00084	0.147161	0.01438	-0.198	0.024
80	1	0.014376	-1.000009	0.000059	-60	58 x 10^-8	-0.00096	0.144149	0.014381	-0.136	0.024
90	1	0.01459	-1.000011	0.00006	-80.9998	58 x 10^-8	-0.00108	0.144574	0.014596	-0.079	0.024
100	1	0.015771	-1.000004	0.000058	-29.9999	58 x 10^-8	-0.0012	0.142883	0.015778	-0.098	0.026
110	1	0.015417	-1.000014	0.000066	-132	58 x 10^-8	-0.00132	0.14543	0.015426	-0.043	0.026
120	1	0.015771	-1.000026	0.000067	-255.599	58 x 10^-8	-0.00144	0.148124	0.015782	-0.014	0.026
130	1	0.01494	-1.000019	0.000075	-204.1	58 x 10^-8	-0.00156	0.146494	0.014953	-0.025	0.025
140	1	0.015944	-1.000022	0.000076	-251.999	58 x 10^-8	-0.00168	0.147161	0.015958	0.147	0.027
150	1	0.015753	-1.000022	0.000072	-269.999	58 x 10^-8	-0.0018	0.147161	0.015769	0.110	0.026
160	1	0.016517	-1.000027	0.000079	-366.399	58 x 10^-8	-0.00192	0.148593	0.016535	0.175	0.028
170	1	0.01494	-1.000019	0.00008	-271.999	58 x 10^-8	-0.00204	0.146581	0.014961	0.346	0.025
180	1	0.015406	-1.000021	0.000082	-318.599	58 x 10^-8	-0.00216	0.147074	0.01543	0.365	0.026
190	1	0.01703	-1.000033	0.000084	-518.698	58 x 10^-8	-0.00228	0.149893	0.017056	0.531	0.029
200	1	0.015748	-1.000027	0.000085	-455.999	58 x 10^-8	-0.0024	0.148564	0.015778	0.610	0.026
210	1	0.02075	-1.000037	0.000091	-648.898	58 x 10^-8	-0.00252	0.150966	0.020777	0.656	0.035
220	1	0.020816	-1.000022	0.000092	-395.999	58 x 10^-8	-0.00264	0.147161	0.020842	0.654	0.035
230	1	0.026456	-1.000022	0.000093	-413.999	58 x 10^-8	-0.00276	0.147161	0.026478	1.011	0.044
240	1	0.025447	-1.000034	0.000094	-681.599	58 x 10^-8	-0.00288	0.15022	0.025475	1.123	0.042
250	1	0.021664	-1.000030	0.000095	-622.499	58 x 10^-8	-0.003	0.149182	0.021698	1.135	0.036
260	1	0.027975	-1.000030	0.000096	-649.999	58 x 10^-8	-0.00312	0.149212	0.028004	1.324	0.047

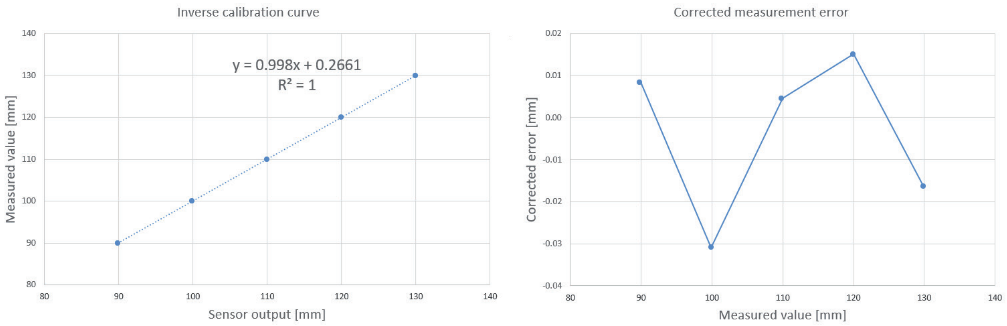


Figure 5 Correction of sensor output for reduced measurement range

in the calculation of measurement uncertainty for further measurements with an optical sensor.

4. Conclusion

The result of the calibration of measurement chain with triangulation sensor is determination of its measurement errors with associated uncertainty in the entire measuring range. Regarding to observed measurement errors, we have determined, that the most suitable measuring range of the sensor for displacement measurement in vertical axis of measuring microscope starts at a distance of 90 millimetres from the reflecting surface. Inverse calibration function determined for reduced measuring range may be applied for correction of sensor output for future measurements. In this case, absolute value of average error in reduced measuring range is less than 0.04 mm. The uncertainty of the average corrected errors was not calculated.

Based on the data obtained, laser triangulation sensor is suitable for use for the intended purpose. However, it is necessary to design a system for gripping the sensor to the optical system of the microscope. After mounting the sensor on the microscope it is also necessary to perform calibration procedure again to compensate for inaccuracies that may have occurred during installation.

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