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Accuracy assessment of an industrial actuator

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Abstract

A commercial linear actuator equipped with a 0.1 μm resolution encoder was used as a contact displacement sensor with adjustable force. The accuracy of the position reading of the actuator was evaluated from experimental data taking into account the uncertainty contributions. The tests consisted of length measurements of grade 0 steel gauge blocks. Measurements with different values of contact force were performed to assess its influence. A statistical analysis of the experimental data was performed to support the accuracy assessment. Systematic effects were identified and corrected. An expanded uncertainty ($k=2$) lower than 1 μm was estimated.

1. Introduction

Dimensional measurements using contact sensors are affected by the measuring force applied by the measuring equipment. The systematic effect of the elastic deformation is compensated when the geometry of the contact and the material properties are known [1]. The uncertainties of the compensation may compromise the overall accuracy of the measurement especially when elastic deformations are high and the materials properties are not well defined, i.e. when measuring polymer parts. In this context, a measuring system with an adjustable measuring force is useful for defining the systematic effect of the contact force during the measurement.

The contact displacement sensor selected is a commercial linear actuator equipped with an encoder for a feedback control of the position. The system has been tested using reference artifacts and the uncertainty has been assessed using a statistical method compliant to the "*Guide to the expression of Uncertainty in Measurement*" (GUM) [2]. The main contributions to the uncertainty were identified using the *Procedure for Uncertainty Management (PUMa method)* described by ISO 14253-2 [3]. These statistical tools have

already been effectively employed in uncertainty estimations of measuring equipment [4-5].

2. Measuring process

2.1. Measuring system

- Actuator: the linear actuator is produced by SMAC Corporation (US). The main characteristics are listed in Table 1.

Table 1. Actuator features.

Dimensions / mm	70×55×25
Stroke / mm	10
Voltage supply / V	24
Maximum current / A	1.6
Encoder resolution / μm	0.1
Nominal force / N	3

The actuator is provided with a linear encoder, with a glass measuring scale, to feed a closed loop control. Thus it can move controlling the force, the position, the speed or the acceleration of the stem. A built in instruction package

allows to use it as contact displacement sensor (the stem moves slowly and stops as soon as the contact with an object is detected).

- Gauge blocks: grade 0 steel gauge blocks (ISO 3650 [6]) are used as reference object to be measured. The blocks are wrung together to cover 8 mm stroke with steps of 1 mm. The coefficient of thermal expansion (CTE) of the blocks is 11.5 ppm/°C, as reported in the calibration certificate.
- Metrology frame: the main frame consists of a main plate and supports made in invar, with a CTE equal to 1.6 ppm/°C. The actuator is fixed on the plate by means of two clamps. The gauge block is placed on a flat surface and the correct position on the plane is ensured by a three points contact.

2.2. Definition of the measuring task

The aim of the work is the determination of the metrological characteristics of the measuring system (described in detail in Section 2.1). Random and systematic effects are investigated under different conditions (measuring force and position of the actuator stem). The use of statistical tools allows for the separation of random and systematic contributions of the measurement errors.

The output signal of the system consists of the encoder counts. It can be transformed into length units applying a multiplicative factor to be defined from the measurements.

The contact force applied during the measurement is controlled by measuring the current consumption of the actuator. This force has been varied from 0 N to 3 N. The standard uncertainty of the force measurements is estimated to be 0.015 N, from a preliminary investigation using a calibrated load cell.

The experiments are performed in a metrology laboratory with a controlled ambient temperature. Even if the temperature on the measuring system is not directly measured, a reasonable temperature range may be defined basing on previous measurements.

The measurand is defined as the encoder output (i.e. the position of the actuator stem measured by the internal encoder) when the tip of the stem is in contact with the reference object.

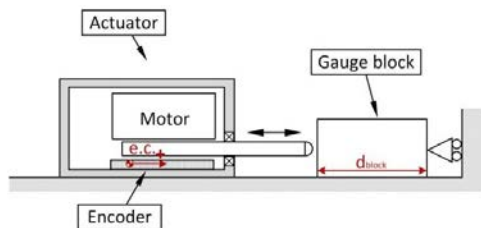The measuring setup is represented in a simplified form in Fig. 1.

Fig. 1. The measuring setup (e.c. = encoder counts, d_{block} = dimension of gauge block).

From the particular orientation of the reference system, the smaller is the gauge block under measurement the bigger the

output of the encoder. When performing the data analysis, the raw data values are rescaled as follows:

- The values are transformed from encoder counts into millimeters (1 e.c. = 10^{-4} mm).
- The values are shifted of a constant value to make the output relative to the bigger gauge block to coincide to zero. Consequently, all the values are nominally positive and represent a relative variation of the encoder output.

2.3. Experimental procedure

The calibration procedure consists in measuring the length of gauge blocks of 9 different dimensions (from 20 mm to 12 mm, with a step of 1 mm) with 8 different contact forces (nominally 0.17 N, 0.33 N, 0.50 N, 0.66 N, 0.83 N, 1.00 N, 2.00 N, 3.00 N).

The test is performed in the following way:

1. The gauge block is positioned.
2. The actuator is programmed to measure the gauge block with each of the different force level.
3. The gauge block is repositioned and step 2 is repeated. Step 3 is repeated 3 times.
4. The gauge block is replaced with another one of different dimension and steps 2 and 3 are repeated.
5. The whole procedure is repeated another time for a total of 6 repeated measurements for each combination of gauge block and measuring force.

3. Definition of the mathematical model

The mathematical model for the measured length D may be expressed by three additive terms, i.e.:

$$D = D_{scale} - \Delta L_{force} - \Delta L_{gauge} \tag{1}$$

where D_{scale} is the component of the measured length taking into account the thermal expansion of the glass measuring scale, ΔL_{force} is the deformation due to the contact force and ΔL_{gauge} is the thermal expansion of the measured gauge blocks.

The first term of the mathematical model (D_{Scale}) may be expressed as follows:

$$D_{scale} = (r - r_0) \cdot \alpha \cdot \left[1 + CTE_{scale} \cdot (T - 20) \right] \tag{2}$$

where r is the raw encoder output, r_0 is the reference for zeroing the encoder output, α is the transformation factor (from encoder counts to millimeters), CTE_{scale} is the thermal expansion coefficient of the glass measuring scale and T is the temperature of the whole system. Considering now directly the lengths of the blocks, equation (2) becomes:

$$D_{scale} = (L_{20} - L_{block}) \cdot \left[1 + CTE_{scale} \cdot (T - 20) \right] \tag{3}$$

where L_{20} is the length of the 20 mm gauge block used to zeroing and L_{block} is the length of the measured block. Since

some measured lengths are obtained by wringing two blocks of lengths L_1 and L_2, equation (3) becomes:

$$D_{scale} = \left[L_{20} - \left(L_1 + L_2 \right) \right] \cdot \left[1 + CTE_{scale} \cdot \left(T - 20 \right) \right] \qquad (4)$$

The second term of the mathematical model (ΔL_{force}) may be expressed as follows:

$$\Delta L_{force} = \left[\frac{3 \cdot \left(1 - v^2 \right)}{4 \cdot ra^{\frac{1}{2}} \cdot E} \right]^{\frac{2}{3}} F^{\frac{2}{3}} \qquad (5)$$

according to Hertz formulas in case of contact between a rigid sphere and a plane [7]. In this formula, F is the contact force, E is the Young modulus of the gauge blocks, v is the Poisson ratio of the gauge blocks and ra is the radius of the probe tip.

The third term of the mathematical model (ΔL_{gauge}) may be expressed as follows:

$$\Delta L_{gauge} = L_{block} \cdot \left[1 + CTE_{block} \cdot \left(T - 20 \right) \right] \qquad (6)$$

where CTE_{block} is the thermal expansion coefficient of the blocks, and L_{block} and T are defined above. When the measured length is obtained by wringing two blocks of lengths L_1 and L_2, equation (6) becomes:

$$\Delta L_{gauge} = \left(L_1 + L_2 \right) \cdot \left[1 + CTE_{block} \cdot \left(T - 20 \right) \right] \qquad (7)$$

So, according to equation (1), i.e. putting together the three additive terms of the mathematical model, it results:

$$D = \left[L_{20} - \left(L_1 + L_2 \right) \right] \cdot \left[1 + CTE_{scale} \cdot \left(T - 20 \right) \right] +$$
$$- \left[\frac{3 \cdot \left(1 - v^2 \right)}{4 \cdot ra^{\frac{1}{2}} \cdot E} \right]^{\frac{2}{3}} F^{\frac{2}{3}} + \qquad (8)$$
$$- \left(L_1 + L_2 \right) \cdot \left[1 + CTE_{block} \cdot \left(T - 20 \right) \right]$$

This complete model allows a thorough comparison among the effects of all the factors affecting the uncertainty of the measured length D.

4. A priori uncertainty evaluation

It was evaluated the uncertainty of the measured length D before performing the measurements in order to identify the most significant factors. This is called *a priori* uncertainty evaluation.

4.1. Estimating the a priori contributions

In order to have an a priori estimate of the measured length D and its uncertainty, an estimate of the values of the independent variables of the mathematical model, shown in

equation (8), and their variabilities is required. According to GUM [2], the latter contributions may be evaluated as variability ranges (Type B evaluation) when standard uncertainties, obtained from repeated observations (Type A evaluation), are not available. By way of example, the working condition with a measured length D of approximately 6 mm and a nominal contact force of 0.17 N is considered. Table 2 shows the estimated values of the independent variables. The nominal lengths of gauge blocks L_1, L_2 and L_{20} are reported in the calibration certificate, as well as the value of the thermal expansion coefficient CTE_{block}. Instead, the value of the thermal expansion coefficient CTE_{scale} is taken from the literature, since it is not available from the technical specifications of the encoder. The temperature of the whole system T is estimated basing on the prior experience. The Poisson ratio v is taken from literature, as well as the Young modulus E. The radius of the probe tip ra is given in the technical specifications of the actuator, while F is the nominal value of the contact force.

Table 2. Estimated values of the independent variables.

Variable	Value
L_{20} / mm	20.0003
L_1 / mm	9.0003
L_2 / mm	5.0000
CTE_{scale} / °C^{-1}	8.0×10^{-6}
T / °C	21
v	0.30
ra / mm	1.50
E / N·mm^{-2}	2.05×10^5
F / N	0.17
CTE_{block} / °C^{-1}	11.5×10^{-6}

Table 3 shows the estimated variability of the independent variables. Only the variability of contact force F is known a priori as standard uncertainty (Type A evaluation). For the other independent variables, the variability range is exploited (Type B evaluation). By assuming rectangular distributions of width equal to the range, the corresponding variances may be calculated for each contribution by dividing the square of the range by the factor 12, as indicated by GUM. Then, the standard uncertainties are, of course, obtained by taking the square root of the corresponding variances.

The ranges for the lengths of the gauge blocks L_1, L_2 and L_{20} are derived from the limit deviations given in ISO 3650. As shown in the next session, these contributions are critical for the overall uncertainty of the measured length D, therefore grade 0 gauge blocks were adopted. In ISO 3650, the limit deviations are defined per length intervals, i.e. [0.5 mm, 10 mm], (10 mm, 25 mm], and so on. The measurement resolution of the encoder which also influences the length measurements has, however, a negligible effect. Instead, the effect of measurement repeatability is certainly significant, but it cannot be evaluated a priori. The range for the thermal expansion coefficient CTE_{block} is given in the calibration certificate. Instead, the range for the thermal expansion coefficient CTE_{scale} is taken from the literature,

being not available from the technical specifications. The range for the temperature T is estimated basing on the prior experience. The ranges for the Poisson ratio v and Young modulus E are taken from literature. The range for the radius of the probe tip ra is given in the technical specifications of the actuator. Finally, for the contact force F is known the standard uncertainty, from preliminary investigations by means of a load cell.

Table 3. Estimated variability of the independent variables. The variability range is given for Type B evaluations, while the standard uncertainty is given for Type A evaluations.

Variable	Range	Standard uncertainty
L_{20} / µm	0.28	
L_1 / µm	0.24	
L_2 / µm	0.24	
CTE_{scale} / °C^{-1}	$2.0×10^{-6}$	
T / °C	1	
v	0.04	
ra / mm	0.1	
E / N·mm^{-2}	$2.10×10^4$	
F / N		0.015
CTE_{block} / °C^{-1}	$2.0×10^{-6}$	

4.2. Uncertainty table

The uncertainty evaluation according to GUM and PUMa method may be properly organized in a tabular format, with reference to EA-4/02 M [8]. A small modification from this format has been introduced by substituting standard deviations with variances [9]; thus managing additive quantities which can be compared more easily. Table 4 shows the individual contributions to variance of output quantity D for the working condition considered in Section 4.1 (i.e. measured length D of approximately 6 mm and nominal contact force of 0.17 N).

Table 4. Uncertainty table for the measured length D (expressed in millimeters) for a specific working condition.

x_j Symbol	Value	$u(x_j)$	c_j	$u_j^2(D)$	v_j	$u_j^4(D)/v_j$
L_{20}	20.0003	$8.1×10^{-5}$	1.0	$6.5×10^{-9}$	100	$4.3×10^{-19}$
L_1	9.0003	$6.9×10^{-5}$	-1.0	$4.8×10^{-9}$	100	$2.3×10^{-19}$
L_2	5.0000	$6.9×10^{-5}$	-1.0	$4.8×10^{-9}$	100	$2.3×10^{-19}$
CTE_{scale}	$8.0×10^{-6}$	$5.8×10^{-7}$	6.0	$1.2×10^{-11}$	100	$1.4×10^{-24}$
T	21	$5.8×10^{-1}$	$-1.1×10^{-4}$	$4.3×10^{-9}$	100	$1.8×10^{-19}$
v	0.30	$1.2×10^{-2}$	$2.6×10^{-5}$	$9.2×10^{-14}$	100	$8.5×10^{-29}$
ra	1.50	$2.9×10^{-2}$	$1.3×10^{-5}$	$1.5×10^{-13}$	100	$2.2×10^{-28}$
E	$2.05×10^5$	$6.1×10^3$	$1.9×10^{-10}$	$1.4×10^{-12}$	100	$1.9×10^{-26}$
F	0.17	$1.5×10^{-2}$	$-2.3×10^{-4}$	$1.2×10^{-11}$	100	$1.5×10^{-24}$
CTE_{block}	$1.15×10^{-5}$	$5.8×10^{-7}$	$-1.4×10^1$	$6.5×10^{-11}$	100	$4.3×10^{-23}$
D	5.9999		$u^2(D)$	$2.0×10^{-8}$	Σ	$1.1×10^{-18}$
			$u(D)$	$1.4×10^{-4}$	v_D	392
			p	95%		
			$t_p(v_D)$	2.0		
			$U(D)$	$2.8×10^{-4}$		

Symbols of independent variables appearing in the mathematical model and their values are written down in column x_j. Entries in column $u(x_j)$ are the standard uncertainties for each contribution, while values in column v_j represent the relevant degrees of freedom, which are set to 100 in absence of specific information. Coefficients of sensitivity c_j may be evaluated either by partial derivation, or numerically, and eventually contributions $u_j^2(D)$ of variance of dependent variable D can be calculated. By taking into account all these information, it is possible to get the expanded uncertainty $U(D)$.

By examining the values of the column $u_j^2(D)$ in Table 4, the weights of the different uncertainty contributions are determined. The ranges for the lengths of the gauge blocks L_1, L_2 and L_{20} are the major contributions. Indeed, passing from the adopted grade 0 gauge blocks to grade 2 gauge blocks, the expanded uncertainty (at 95% confidence level) increases from 0.28 µm to 1.0 µm. Instead, the expanded uncertainty does not change significantly when considering other combinations of contact force and measured length.

5. A posteriori uncertainty evaluation

The experimental data are composed by 72 series of 12 data points for every combination of gauge block and measuring force. Their values represent the raw output of the encoder. Given the experimental data, it is possible to obtain an a posteriori estimate of measurement uncertainty.

Firstly the Chauvenet criterion is used to identify suspected outliers (i.e. measurement accidents). The method is applied within each single series in order to consider only the variability relevant to each set of measuring conditions. The method considers the residuals of each repetition from the average value of all repetitions. Outliers are then replaced by the median value of the series.

Experimental data are then rescaled according to Section 2.2, the transformation factor being 10^{-4} mm/count. The shift is defined as the average of all measurements for the 20 mm gauge block. Systematic effects linked to rescaling are identified as and compensated later in the analysis. The differences between measured values and the reference value (i.e. residuals R) are calculated for each data point. For each series the average and the standard deviation of the residuals are calculated and used in the subsequent analysis.

Before evaluating measurement uncertainty, systematic effects are corrected [2]. The influence of measuring force is calculated as elastic deformation according to equation (5). The calculated values (listed in Table 5) are then subtracted from residuals R.

Table 5. Systematic effects due to measuring force.

Nominal Force / N	Deformation / µm
0.17	0.06
0.33	0.09
0.50	0.12
0.66	0.15
0.83	0.17
1.00	0.19
2.00	0.31
3.00	0.41

Box-plots in Fig. 2 show the scatter of the residuals corrected for the force effect ($R_{corr,F}$) as a function of measuring length, underlining a clear trend. The latter represents the metrological characteristic of the actuator, showing a sensitivity error with a negligible nonlinearity.
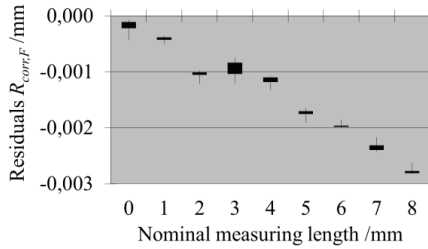

Fig. 2. Box-plots of residuals $R_{corr,F}$ vs. measuring length.

Therefore, linear regression between nominal measuring length and residuals is performed to quantify the influence of length, according to the model:

$$R_{corr,F} = a_L \cdot L + b_L \qquad (9)$$

where L is the nominal measuring length, a_L and b_L are the coefficient of model. Residuals corrected from the systematic influence of the measuring length ($R_{corr,FL}$) are calculated as:

$$R_{corr,FL} = R_{corr,F} - (a_L \cdot L + b_L) \qquad (10)$$

According to GUM, the correction of the sensitivity error results to have, in the worst case, a standard uncertainty of about 0.06 μm. Box-plots of residuals corrected for systematic effects of measuring length and force ($R_{corr,FL}$) are shown in Fig. 3.
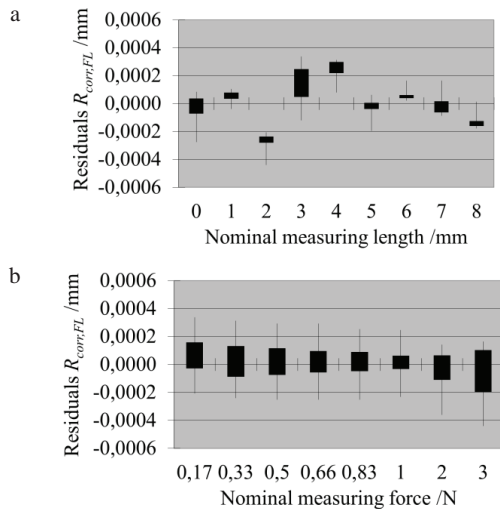

Fig. 3. Box-plots of residuals $R_{corr,FL}$ vs. measuring length (a) and measuring force (b).

Residuals $R_{corr,FL}$ appear to be almost unaffected by the two factors considered. This is confirmed by the normal probability plot, shown in Fig. 4, which does not highlight substantial discrepancies from normality. So, the standard deviation of the residuals $R_{corr,FL}$, equal to 0.17 μm, is taken as measurement repeatability. Combining the latter contribution with the standard uncertainty relevant to the previous correction (equation (10)) and the standard uncertainty relevant to all the factors considered in the a priori evaluation (Table 4), it is obtained a combined standard uncertainty equal to 0.23 μm. In this way, the a posteriori estimate of expanded uncertainty (at 95% confidence level) of measured length D is 0.46 μm.
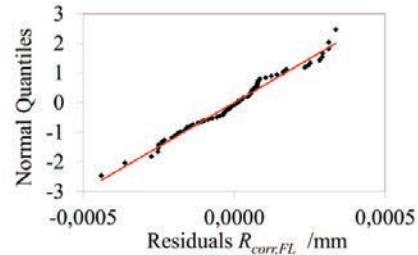

Fig. 4. Normal probability plot for residuals $R_{corr,FL}$

6. Conclusions

A commercial linear actuator, equipped with an encoder for a feedback control of the position, was used as a contact displacement sensor. Thanks to the adjustable measuring force, the systematic effect of the contact force during the measurement was taken into account. In order to determine the metrological characteristics of the measuring system, the calibration consisted in length measurements of steel gauge blocks with different contact forces. It was defined a complete mathematical model for the measured length, taking into account the thermal expansion of the glass measuring scale, the deformation due to the contact force and the thermal expansion of the measured gauge blocks. An a priori uncertainty evaluation, performed according to GUM, enabled to identify the most significant factors affecting uncertainty of the measured length. The limit deviations for the lengths of the gauge blocks resulted to be the major contributions. Accordingly, grade 0 gauge blocks were selected. Then, considering experimental data, a systematic sensitivity error was identified and modelled, subsequently the measurement repeatability was evaluated. In this way, an expanded uncertainty (at 95% confidence level) of measured length of about 0.5 μm was obtained.

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