Definition and Analysis of Uncertainty Contributors in the Dimensional Measurement of Bronze Sintered Samples

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Abstract
The paper concerns the definition and estimation of uncertainty elements. This topic is matched with Direct Metal Selective Laser Sintering used for manufacturing the samples.

The UNI ENV ISO 14253-2: 2003 standard deals with uncertainty sources in dimensional measurement. This paper treats just those ones regarding measurement procedure, measurement equipment and workpiece. The aim of this paper is estimating combined standard uncertainty.

Measurement repeatability, workpiece fixing and number of points for the definition of geometric elements arise from measurement procedure. Measurement equipment uncertainty is connected with Maximum Permissible Error. As far as workpiece uncertainty components, surface roughness, form error and temperature are checked.

Keywords:
Uncertainty Sources, CMM, DMSLS

1 INTRODUCTION

Process control and quality assurance in modern manufacturing depends more and more on Coordinate Measuring Machines (CMMs). For the last two decades CMMs have widely been replacing the traditional inspection methods and equipment. Besides information about measurand the process measurement aim is defining uncertainty representing a quality index of measurements.

Uncertainty evaluation methods are often very complex to perform due to innumerable sources of uncertainty. The GUM (Guide to the expression of Uncertainty in Measurement), published in 2000 [1], doesn't specify how to calculate this characteristic effectively. In some cases the risk of an unrealistic estimation of uncertainty is likely to arise.

In order to overcome these problems some standards have been developed, among them UNI ISO/TS 15530-3 [2], the aim of which is providing an experimental technique for simplifying the uncertainty evaluation of CMM measurements. In this experimental approach measurements are carried out in the same way as actual ones, but with calibrated workpieces or standards of similar dimension and geometry instead of the unknown objects to be measured. This method is simple to be performed, but there are also some limitations: high costs, the availability of artefacts with sufficiently defined geometrical characteristics and the possibility of being calibrated with uncertainty small enough.

Therefore, some alternative techniques have been studied without use of calibrated workpieces. The method developed in this paper starts from uncertainty sources classification of UNI ENV ISO 14253-2 [3]. Any possible effect which may affect a GPS (Geometrical Product Specification) measurement is considered and quantified as an uncertainty contributor, and, eventually, summed up to achieve the combined uncertainty. The most significant components are pointed out by measurement analysis. This paper doesn't regard the second part of the standard with the development of PUMA procedure, as there isn't a target uncertainty (U_T).

In literature, there are few papers discussing applications of the previous standard [4,5]. Particularly Heping made a mix of GUM and ISO 14253 concepts, without focusing attention on manufacturing aspects, examined in this paper.

2 PROCEDURE CHARACTERISTICS

The method shown in UNI ENV ISO 14253-2 standard consists in evaluating expanded measurement uncertainty, U, overvaluing uncertainty contributors, with $U \geq U_R$, where U_R is defined as the real measurement uncertainty, evaluated according to the GUM method. The procedure is characterized by these steps:

- Any uncertainty contributor is identified.
- Influence of each component is quantified by standard uncertainty u_{xx}, using type A or B evaluation.
- The combined standard uncertainty u_c attributed to the measurement result is obtained as square root of the sum of the squares of the uncertainty components:

  $$u_c = \sqrt{u_{x1}^2 + u_{x2}^2 + u_{x3}^2 + ... + u_{xn}^2} \quad (1)$$

  The previous formula is valid for a 'black box model' for uncertainty estimation when all the components are uncorrelated with sensitivity coefficients equal to ± 1.
- Expanded uncertainty is calculated because of the requirement of a higher level of probability. In GPS measurements the following formula is used:

  $$U = k \times u_c \quad (2)$$

  where k is the coverage factor [3].

Symbol	Interpretation
a	Limit of variation
α	Coefficient of thermal expansion
b	Coefficient for transformation of a in u_{xx}
h	Factor of safety
k	Coverage factor
n	Number of repeated measurements
s_x	Experimental standard deviation
$s_{\bar{x}}$	Estimated standard deviation
u_c	Combined standard uncertainty
u_{xx}	Standard uncertainty xx
U	Expanded measurement uncertainty
U_R	Real measurement uncertainty
U_T	Target uncertainty
X_i	Measurement result

Table 1: Symbols.

3 ESTIMATION OF UNCERTAINTY COMPONENTS

The estimation of uncertainty components may be carried out with two different methods, through a type A or B evaluation [3]. The type A method of evaluation uses statistical procedures to obtain u_{xx} from measurements data. Whereas in type B one the standard uncertainty is calculated by a method different from statistical procedures. Generally, the first type provides more precise estimations than the latter one.

3.1 Type A evaluation of standard uncertainty

Type A evaluation of standard uncertainty requires data from a series of observations. The experimental standard deviation and the mean one may be calculated using these expressions:

$$\bar{x} = \frac{1}{n} \times \sum_{1}^{n} X_i \quad (3) \qquad s_X = \sqrt{\frac{\sum_{1}^{n} (\bar{x} - X_i)^2}{(n-1)}} \quad (4) \qquad s_{\bar{X}} = \frac{s_X}{\sqrt{n}} \quad (5)$$

where $\bar{x}$ is the mean value of n statistically independent observations of the measurand X_i. When the evaluation of standard deviation is based on few measurements, the estimation could be undervalued. Consequently, a factor of 'safety' h, coming from Student's t distribution and function of measurements number, is used multiplying the standard deviation (Table 2).

Number of measurements n	Factor of safety h
2	7
3	2.3
4	1.7
5	1.4
6	1.3
7	1.3
8	1.2
9	1.2
>10	1

Table 2: Corrective factor in function of number of measurements.

Correct experimental standard deviation represents standard uncertainty when the measurement result comes from a single component value:

$$u_{xx} = s_{X,n} \times h \qquad (6)$$

Mean standard deviation is used for evaluating u_{xx} when the measurement result is calculated through n mean values:

$$u_{xx} = s_{\bar{X},n} \times h \qquad (7)$$

3.2 Type B evaluation of standard uncertainty

When the estimate value $\bar{x}$ of the measurand X is not obtained by repeated observations, the standard measurement uncertainty u_{xx} can be gained by collecting information connected with the measurement result. Information may include previous measurements data, experience or manufacturer's specifications. Given a limit of variation a, there is a relation between a and standard deviation. Making an assumption on the probability distribution of the measured quantity, it is possible to quantify standard deviation and, therefore, standard uncertainty as:

$$u_{xx} = a \times b \qquad (8)$$

where the parameter b is a function of the probability distribution. According to the UNI ENV ISO 14253-2, in most cases it is sufficient to use only three types of distributions for turning a limit of variation into a standard deviation. In particular:

- b = 0.5, for Gauss distribution;
- b = 0.6, for rectangular or uniform distribution;
- b = 0.7, for U-shaped distribution.

4 MEASUREMENT UNCERTAINTY CONTRIBUTORS

Errors or uncertainties in a measurement process consist in a mix of known and unknown errors originated by some sources or error contributors. These are variable case by case, because every measurement process is characterized by particular uncertainty components. However, it is possible to adopt a systematic approach. For instance, the UNI ENV ISO 14253-2 standard identifies 10 macro-categories of uncertainty contributors, as shown in Figure 1.

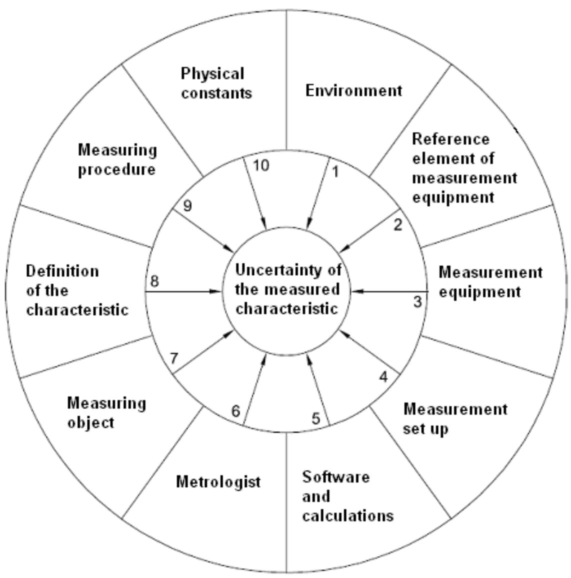

Figure 1: Macro-categories of uncertainty contributors [3].

5 EXAMPLE OF UNCERTAINTY EVALUATION

In order to consider an application of UNI ENV ISO 14253-2 standard, a measurement campaign has been carried out on a cylindrical sample (Figures 2-3), manufactured by EOSINT M270 laser sintering machine with a bronze based powder, DirectMetal 20. The sample is characterized by the name *cil/p02/h30/s2* and has the following nominal sizes:

cil/p02/h30/s2	
Height [mm]	32.00
External diameter [mm]	30.00
Internal diameter [mm]	26.00
Leading edge [mm]	2.00

Table 3: Nominal sizes of examined sample.

The nominal sample height, equal to 30 mm, is increased of 2 mm because of the leading edge, added to favour workpiece fixing on measuring machine. In this paper, as example, internal diameter of cylindrical sample is considered as GPS. The next paragraphs show the uncertainty components regarding measurement procedure, measurement equipment and workpiece (Table 4), and point out reasons for their choice.

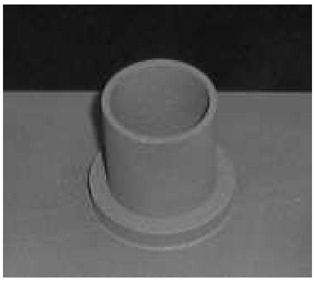

Figure 2: Sample on building platform.

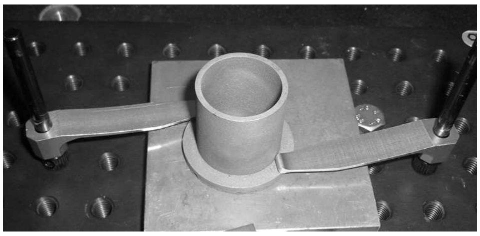

Figure 3: Sample on measuring machine.

6 UNCERTAINTY COMPONENTS CAUSED BY THE MEASURING PROCEDURE

6.1 Contributor connected with points density

The choice of points number during measurement procedure is vital for accuracy. Moreover, every geometric element requires a certain number of points to assure its full definition and there is a minimum number independent on element size. CMM identifies these features automatically, interpolating the coordinates of points.

Generally, in order to obtain a definite accuracy, it is necessary to consider the element size. In particular, there is an uncertainty component connected with the number of points, function of studied specification. To point out the influence of points number, a measuring campaign was performed on the external diameter of a cylindrical sample (Table 5).

As shown in Table 5, over a certain number of points diameter variation is not significant and, consequently, this parameter might not affect dimensional measurements. Choosing a limit value, the removal of this uncertainty source is possible. In the examined case 12 points are considered for every circle used for the construction of the cylinder with an external diameter of 30 mm. Adopting this principle for any circle or cylinder is possible, by making a proportion based on diameter:

$$30 : 12 = D : n \tag{9}$$

Therefore, u_{DEN} is negligible.

Uncertainty component (low resolution)	Uncertainty component (high resolution)	Name	Comments
u_{DEN}		Points density	Variation of measurement result in function of points number
u_{FIX}		Workpiece fixing	Study of workpiece deformations due to fixing tools
u_{RR}	u_{RES}	Resolution	Feature connected with scale resolution of CMM
	u_{REP}	Repeatability	Function of the results of successive measurements carried out under the same conditions
u_{MPE}	u_{MPE-E}	Maximum Permissible Error for size measurement	Connected with the error of indication of CMM for size measurement
	u_{MPE-P}	Maximum Permissible Error of probing system	Connected with the error due to the probing system during form measurements
u_{TD}		Temperature difference	Due to the temperature difference between workpiece and CMM
u_{ROU}		Roughness	Uneven surface finishing
u_{WE}		Workpiece form error	Imperfect roundness causes a radius distortion and, consequently, a diameter one

Table 4: Uncertainty components.

N points	1	2	3	4	5	6	7
6	29.823	29.823	29.823	29.823	29.822	29.823	29.823
9	29.835	29.835	29.835	29.834	29.835	29.834	29.834
12	29.854	29.855	29.854	29.854	29.855	29.854	29.855
15	29.853	29.853	29.853	29.853	29.853	29.853	29.853
18	29.854	29.854	29.854	29.854	29.854	29.854	29.854
21	29.853	29.853	29.853	29.853	29.853	29.853	29.853

Table 5: External diameter in function of points number.

cil/p02/h30/s2							
Internal cylinder	1	2	3	4	5		
circleA	25.8938	25.8932	25.8960	25.8951	25.8944	Mean value [mm]	25.9005
circleB	25.9068	25.9065	25.9083	25.9066	25.9068		
circleC	25.9091	25.9112	25.9125	25.9121	25.9118	s_x [mm]	0.0011
circleD	25.8937	25.8929	25.8953	25.8957	25.8955		
circleE	25.8953	25.8957	25.8974	25.8977	25.9005	$s_{\bar{x}}$ [mm]	0.00047
Best-fit int. diam.	25.8993	25.8995	25.9015	25.9010	25.9014		

Table 6: Repeated measurements.

6.2 Workpiece fixing uncertainty

In order to evaluate this contribution, an analysis with a dedicated software was carried out quantifying sample deformations due to clamping strength. The cylinder is characterized by a leading edge, the aim of which is to favour fixing through clamps. As shown in Figure 3, the fixing system did not disturb the probe movement during the part program. Fixing force was not excessive and concentrated on the leading edge.

In order to verify that above-mentioned force hasn't caused deformations on the sample, a simulation with ANSYS software was developed. As input data, there were part geometry information and clamping strength (140 N). In output greatest displacements and related areas were displayed.

The greatest displacement in the measurement area was in the order of 10^{-2} µm. Therefore, ANSYS analysis has pointed out that deformations are negligible and it is possible not to consider fixing uncertainty effect.

$$u_{FIX} = 0\ \mu m \quad (10)$$

6.3 Uncertainty component due to repeatability

Repeatability is defined as the closeness of the agreement between the results of successive measurements of the same item performed under the same conditions. In general, these results might not all be the same. Therefore, repeatability is a source of uncertainty.

Repeatability topic is connected with resolution of measuring machine. Indeed, resolution error is included in repeatability one when the latter is greater. In order to verify this assumption, it is possible to use an expression from the above-mentioned standard [3]:

$$u_{RES} = 0.3 \times d \quad (11)$$

where *d* represents the resolution of measuring machine, which is equal to 0.1 µm. Consequently:

$$u_{RES} = 0.3 \times 0.1 = 0.03\ \mu m \quad (12)$$

A cylinder is the result of measurements by taking n circles at different levels. For the examined sample 5 circles made by 12 points are considered. Consequently, internal cylinder is the best-fit of these circles. Repeatability uncertainty component is calculated using a type A evaluation. Measurements are repeated for five times under the same conditions and the estimated standard deviation is considered with a corrective factor of safety equal to 1.4. The input data are shown in Table 6.

$$u_{REP} = 0.47 \times 1.4 = 0.66\ \mu m \quad (13)$$

Since $u_{RES} << u_{REP}$, the latter contributor is introduced in the expression of combined standard uncertainty.

7 UNCERTAINTY COMPONENTS CONNECTED WITH MEASUREMENT EQUIPMENT

The *Maximum Permissible Error* is an error which measuring machine makes because of its structural inaccuracies. They may be connected with:

- mechanical coupling;
- mechanical arm inertia;
- slacks of movement guides.

UNI EN ISO 10360-2 standard [6] distinguishes two different kinds of MPE: *MPE-E* and *MPE-P*. The first is connected with the error of indication for size measurement. Whereas the second specifies CMM error in the form measurements, when measuring straightness, flatness, roundness, cylinder form and free curves.

MPE-E uncertainty component can be calculated by an expression stated in calibration certificate, function of CMM:

$$MPE\text{-}E = 1.5 + (L / 333) \quad (14)$$

where 1.5 is in µm and *L* in mm. *MPE-E* is a function of the measurand and, consequently, is calculated only once. *L* is the mean value of the measurand shown in Table 6. Its uncertainty component is given by a type B evaluation [3] and *MPE-E* represents the limit of variation *a*. In this paper a U-shaped distribution is considered with *b* equal to 0.7.

$$MPE\text{-}E = 1.5 + (25.9005/333) = 1.58\ \mu m \quad (15)$$

$$u_{MPE\text{-}E} = MPE\text{-}E \times b = 1.10\ \mu m \quad (16)$$

As far as the second contribution, known as ‘probing error’, there is not information. However, it may be included in form error component next evaluated.

8 UNCERTAINTY COMPONENTS CONNECTED WITH WORKPIECE

8.1 Gradient temperature uncertainty

According to the ISO 1 standard [7], the measuring environment must be in defined conditions:

- temperature 20℃;
- humidity 45%.

CMM has a sensor checking workpiece temperature during measuring process. In order to reduce the gap between this value and room temperature, workpieces were put in CMM laboratory 24 hours before the measurements. The UNI ENV ISO 14253-2 standard uses linear thermal expansion equation for the evaluation of uncertainty:

$$\Delta L = \Delta T \times \alpha \times L \quad (17)$$

where:

- $\Delta T = (T_{\text{MEAN\_WP}} - T_0) = (T_{\text{MEAN\_WP}} - 20°\text{C})$, $T_{\text{MEAN\_WP}}$ workpiece mean temperature;
- $\alpha = 18 \cdot 10^{-6}\ \text{K}^{-1}$, coefficient of thermal expansion of DM20;
- L = measurand mean value.

As the example specification is a diameter, it is necessary to verify the previous formula. Instead of *L*, the circle length *C*, function of *Di*, is considered:

$$\Delta C = \Delta T \times \alpha \times C = \Delta T \times \alpha \times \pi Di \quad (18)$$

$$\Delta Di = \Delta T \times \alpha \times Di \quad (19)$$

The expression for a diameter is the same. ΔT and Di are mean values. The previous formula gives the limit of variation thereby a type B evaluation for uncertainty component is used with a U-shaped distribution (b=0.7). $T_{\text{MEAN\_WP}}$ obtained through five measurements is 21.2169℃:

$$\Delta Di = 1.2169 \times 18 \cdot 10^{-6} \times 25.9005 \cdot 10^{3} = 0.57\ \mu\text{m} \quad (20)$$

$$u_{\text{TD}} = \Delta Di \times b = 0.40\ \mu\text{m} \quad (21)$$

8.2 Calculation of surface roughness uncertainty

Surface roughness is one of the workpiece characteristics which may influence GPS [8]. For the quantification of uncertainty component connected with roughness, an experimental campaign was carried out with Zeiss Handysurf E-35A on sintered samples in order to obtain reference values for *Ra* and *Rz*.

cil/p02/h30/s2	*Ra [µm]*	*Rz [µm]*
Min	2.15	14.10
Mean	3.87	22.69
Max	6.30	35.80
s_x	1.17	6.01

Table 7: Roughness test results.

Table 7 sums up roughness data. For the calculation of uncertainty it is necessary to choose a type of roughness. *Rz* considers greater valleys and peaks on scanning length, whereas *Ra* evaluates a mean value on entire scanning path. In terms of CMM, because of probing system size, it is impossible to detect valleys, consequently *Ra* is a better estimator. Making reference to results of experimental campaign, a type B evaluation can be used with *Ra* mean value as limit of variation and assuming a rectangular distribution (b=0.6):

$$u_{\text{ROU}} = \overline{Ra} \times b = 2.32\ \mu\text{m} \quad (22)$$

8.3 Cylinder form uncertainty

Form error represents another uncertainty factor for workpiece under consideration. In particular, following the UNI 14253-2 standard, cylindricity, which measures the radius variation, is considered. A mean value of cylindricity was obtained through an experimental plan performed on sintered cylinders made of the same material (DM20).

$$CIL_{\text{MEAN}} = 0.0085\ \text{mm} \quad (23)$$

For assumption the effect on diameter is the double of cylindricity. Therefore, the limit of variation can be calculated as:

$$a_{\text{WE}} = 2 \times 0.0085 = 0.0170\ \text{mm} \rightarrow a_{\text{WE}} = 17\ \mu\text{m} \quad (24)$$

Obviously, a type B evaluation is adopted with a Gauss distribution (b = 0.5).

$$u_{\text{WE}} = a_{\text{WE}} \times b = 8.5\ \mu\text{m} \quad (25)$$

9 COMBINED STANDARD UNCERTAINTY

In the previous paragraphs each uncertainty component is evaluated. the synthesis of these results is combined standard uncertainty. It is estimated that no correlation occurs between the contributors, therefore the expression of u_c is:

$$u_c = \sqrt{u_{DEN}^2 + u_{FIX}^2 + u_{RR}^2 + u_{MPE}^2 + u_{TD}^2 + u_{ROU}^2 + u_{WE}^2} = 8.91\ \mu\text{m} \quad (26)$$

Using a coverage factor equal to 2 (with a 95% confidence level of the interval), expanded measurement uncertainty can be calculated as:

$$U = k \times u_c = 8.91 \times 2 = 17.82\ \mu\text{m} \quad (27)$$

Table 8 represents a summary of uncertainty budget. To detect the influence of each uncertainty contributor, their squares are considered. Table 9 shows the importance of macro-categories on u_c. It is possible to point out that workpiece components are dominant. These data suggest that it is necessary to elaborate some strategies for the reduction of uncertainty.

The greatest contributor connected with cylindricity error expresses difficulties in laser sintering process. The solution may be a change in process or exposure parameters (beam offset, shrinkage factor, powder layer) to avoid form error and sintered parts shrinkage.

Two other components of less importance in the same macro-category may be reduced prolonging the stay of samples in measurement room with a better acclimatization and performing some post-process operations, like shot-peening, to improve surface finishing.

Component name	Evaluation type	Distribution type	Measurements number	Limit of variation *a* [μm]	Distribution factor *b*	Uncertainty component u_{XX} [μm]
u_{DEN} – Density of points						0.00
u_{FIX} – Workpiece fixing						0.00
u_{RR} – Resolution/Repeatability	**A**		5			0.66
u_{MPE} – Maximum Permissible Error	**B**	**U-shaped**		1.58	0.7	1.10
u_{TD} – Temperature difference	**B**	**U-shaped**		0.57	0.7	0.40
u_{ROU} – Workpiece roughness	**B**	**Rectangular**		3.87	0.6	2.32
u_{WE} – Workpiece form error	**B**	**Gauss**		17	0.5	8.5
Combined standard uncertainty u_C						**8.91**
Expanded measurement uncertainty ***U***						**17.82**

Table 8: Summary of uncertainty budget.

Component name	Source of uncertainty	Uncertainty component u_{XX} [μm]	u_{XX}^2 [μm^2]	Percentage of u_C^2 [%]
u_{DEN} – Density of points	Measuring procedure	0.00	0.00	0.5
u_{FIX} – Workpiece fixing		0.00	0.00	
u_{RR} – Resolution/Repeatability		0.66	0.44	
u_{MPE} – Maximum Permissible Error	Measurement equipment	1.10	1.21	1.5
u_{TD} – Temperature difference	Workpiece	0.40	0.16	98.0
u_{ROU} – Workpiece roughness		2.32	5.38	
u_{WE} – Workpiece form error		8.5	72.25	
Combined standard uncertainty u_C		**8.91**	**79.44**	**100.0**

Table 9: Influence of uncertainty macro-categories.

10 CONCLUSIONS

Along with the publication of the GUM and ISO 14253 standard series, the use of measurement uncertainty is becoming more and more wide in manufacturing area.

This paper has analysed the opportunity of adopting a systematic approach for uncertainty evaluation of a GPS. The UNI ENV ISO 14253-2 standard is used for this aim. It provides hints on uncertainty sources macro-categories and useful expressions for the uncertainty budget. Other standards (UNI CEI ENV 13005 and UNI ISO/TS 15330-3) have been published about measurement uncertainty calculation, but the first is complex to perform and the second needs the use of calibrated workpieces.

The example covering the evaluation of measurement uncertainty gives information on changes in measuring procedure, but also points out critical aspects of manufacturing process (for instance form error). It emerges that metrological side may go hand in hand with productive one and measurement result can give some concrete advice.

The definition of uncertainty components is function of measuring task, thereby this analysis is not exhaustive. Future works will concern the development of procedures for quick quantification of further uncertainty contributors.

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