UNCERTAINTY ANALYSIS ON AN OPTICAL MACHINE WITH VISION SYSTEM FOR THREE-DIMENSIONAL MEASURING WITHOUT CONTACT

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Abstract - *In order to rise to the traceability of the optical machine equipped with a television camera CCD (Charge Coupled Device), the purpose of this paper is to evaluate the ability of the optical machine to provide measurements, the dispersions of which are compatible with the specified tolerances and the dispersions of the process that is measured. Referring to the principles of the Statistics Inference, the purpose is to verify that the performance of the optical machine is in conformity with what the builder have stated, both in reference to the capability of the optical machine measurement to be in a sufficiently little interval around the expected value and in reference to the measurement variability. The analysis of experimental data seems that the results are very appreciable. The paper presents the basic ideas for evaluating the uncertainty expression in a measurement process of an optical machine equipped with a television camera CCD: this will allow to qualify the optical machine in each part as well as on the whole, since till today no metrological traceability of this equipment in primary metrology is provided, neither in national (SIT) nor in international level (EA).*

Keywords - optical machine; VMM; CCD television camera.

1. INTRODUCTION

The study and the analysis of the optical machines with vision system (television camera), designed to perform three-dimensional measurements without contact, becomes important in order to identify their metrological characteristics (in relation to the characteristics that we have to measure on the product); besides they allow to define the measurement methodologies, the measurement evaluation, the choice of calibration methods, the detection of the traceability properties, the repeatability and reproducibility criterions to this end. This paper aims to evaluate the performance of the optical machine equipped with a television camera CCD.

The procedure applied requires the use of a certain number of convenient standards, each of them with a SIT certificate, in order to compare the measurement results with the certified values. In particular the performance evaluation of the optical machine is carried out through length measurements, so that we can provide a well defined traceability to the length unit (the metre). At the same time, the performance evaluation procedure of the machine is as much as possible in conformity with measurement procedures most frequently applied.

In such purpose we have based our study on two Norms, the EN – ISO 14 253 [1] and the UNI ISO 2854 [2].

Firstly we did a contemporaneous check of the capability of the optical machine measurement to be in a sufficiently little interval around the expected value and of the measurement variability. Successively we checked the same things separately, taking into account, respectively, the Prospect A' and the Prospect F of the Norm UNI ISO 2854.

Moreover the errors in the length measurement, must be in absolute value inferior of maximum allowed error, reduced of the calibration expanded uncertainty (in accordance with the Norm EN-ISO 14253-1).

2. MEASUREMENTS PROCEDURE AND EXPERIMENTAL DATA COLLECTION

Firstly the instrument is calibrated by using convenient masters whose values are assigned with reference to standards recognized as primary.

Successively we subdivided ideally the measurement instrument into two parts, the "machine system" and the "survey system" (i.e. the television camera CCD, which substitutes the "touch probe system" of the Co-ordinate Measuring Machine (CMM)): in this way we can analyse the two systems separately. In analogy with the CMM, the optical machines are indicated with the initials VMM (Vision Measuring Machine). Since these devices allows to measure the point in the space in Cartesian, cylindrical or spherical co-ordinates, therefore the measurement error is a three-dimensional error, the three independent axes are subjected separately to test, carrying out a limited number of tests, along the axes in the measurement volume of the VMM. In order to evaluate this phenomenon it is necessary to carry out a significant number of measurements and successively to proceed with the analysis of the experimental results to verify the performance of the machine; therefore for each axis we done two measurement types:

a) a certain number of points are chosen along each axis and for everyone of these points we repeated the measurement *n times*,

b) along each axis we made a length measurement and this measurement is repeated *m times*.

The procedure applied, both for the machine system and for the survey system, requires the use of a certain number of standards, each of them with a SIT calibration certificate.

It is necessary to evaluate the correspondence of the mean of the measurements with the reference values in ideal working conditions, in order to verify their influence as bias. The ideal conditions are:

- calibrated instrument;
- well-know and equipped with SIT calibration certificate measurand, uncertainty of which is negligible in comparison with the instrument uncertainty;
- experienced operator;
- measurement methodology rigorously applied;
- environment conditions constant: temperature of 20 ± 0.5 °C and humidity equal to 45 ± 1%.

The optical machine used to manage the analysis is the Quick Vision Ace 200 model with Power Turret, that presents the three type of lighting (coaxial, diascopic and annular) and the automatic motorized focalization. The measurement field of this machine on the axes X, Y and Z is: 200 mm for the X and Z axis and 150 mm for the Y axis. The equipment called Quick Vision is produced by Japan's Mitutoyo. The linear measurement error indicated by Mitutoyo is ±3 μm. The considered optical system is characterized by an high resolution, trough two turrets, one with 1x, 2.5x and 5x fixed lens, and the other with 1x, 2x and 6x (this last can be programmed) with an auto-calibration function. However in this study we considered uniquely the 2.5x lens.

In particular for the check of the axes X and Y, we considered a point every 20 mm along each axis (in this way we are able to cover all the measurement field) and we repeated the measurement of each point 30 times. Therefore the used master, is a 200 mm graduated crystal rule equipped with SIT calibrate certificate. Besides, along each of the two axes we have done a length measurement for 30 times, using to this end as standard a slide for pixel calibration, equipped with SIT certificate: in particular we considered the 4 mm square. This choice was made in order to use a square doesn't enter in the television camera field and therefore it was necessary a movement of the machine in order to carry out the requested measurement. The procedure used to make the length measurement and then repeated 30 times for each of the two axes, is as follows (like fig. 1 shows):

- straight line *a* measurement;
- point H measurement;
- distance R measurement.

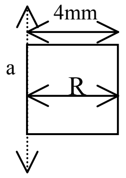

Fig. 1 – Procedure used to make the length measurement along the axes X and Y

Since the measurement field of this optical machine used along the Z axis is 200 mm, we considered for the Z axis 10 points along the axis (respectively to 0mm, 20mm, 40mm, 60mm, 80mm, 100mm, 120mm, 140mm, 160mm, 180mm; also in this case we have a point every 20mm, so we can cover all the measurement field) and we repeated the measurement 30 times for each point. The used material standard is constituted by a series of plain-parallel gauge blocks, equipped with a SIT calibration certificate. Also for the Z axis we made finally a length measurement for 30 times using to this end always the same series of plain-parallel gauge blocks as standard. The procedure used to make the length measurement, repeated 30 times, is the following: we found the 0mm point, then the 80mm point and after this we evaluated the distance.

At this point we considered the "survey system" i.e. we proceeded to check the television camera performance. To this end we used a slide for pixel calibration (equipped with SIT calibration certificate) as Master and in particular we used the 0.8 mm square: we did this choice to try to place the square into the television camera measurement field; in this way it is not necessary a movement of the machine in order to carry out the length measurement that we want to make and so the machine must remain motionless during these measurements series. This procedure allows to isolate the television camera behaviour from the rest of the machine and so it is possible to check the television camera performance. Also in this case, in analogy with the previously described procedure to check each of the three independent axes of the VMM measurement volume, we made two measurement types, that, taking into account fig. 2, can be explained as follows:

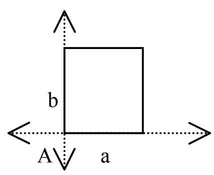

Fig. 2 - Procedure used to make the A point measurement

Firstly, we chosen to shift the machine co-ordinates to a new reference origin and so to assume as origin of the axes the point indicated with A in fig. 2; the procedure used to make the measurement of the point A is based on the intersection of the two straight lines indicated with a and b in fig. 2. In conclusion the procedure, that we have repeated for 30 times in order to obtain 30 repetitions of the A point measurement, is as follows:

- straight line *a* measurement;
- straight line *b* measurement;
- calculus of the intersection between the two straight lines *a* and *b*, i.e. point A measurement.

After the definition of the new axes origin, we made 30 measurements for each of the considered points (A, B, C, D) and this was obtained by constructing an appropriate programme which simultaneously measures the co-ordinates of each of them. This programme was repeated 30 times, obtaining in this way 30 measurements for each of the considered point. The procedure used to construct the programme and to obtain the co-ordinates of the 4 points is the following (taking into account fig. 3):

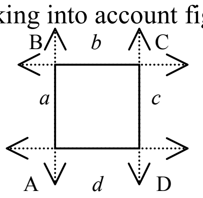

Fig. 3 - Procedure used to make the measurement of the points A, B, C, D

- straight line *a* measurement;
- straight line *b* measurement;
- straight line *c* measurement;
- straight line *d* measurement;
- calculus of the intersection between the two straight lines *a* and *b*, i.e. point B measurement;
- calculus of the intersection between the two straight lines *b* and *c*, i.e. point C measurement;
- calculus of the intersection between the two straight lines *c* and *d*, i.e. point D measurement;
- calculus of the intersection between the two straight lines *d* and *a*, i.e. point A measurement.

Successively, we made a length measurement for 30 times both along X axis and along Y axis (remember that the co-ordinates system it was shifted and that the origin is in A); the procedure used for each axes, repeated for 30 times for each axes, is as follows:

- for the length measurement along X axis, taking into account the fig. 4, we have:

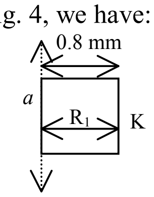

Fig. 4 - Procedure used to make the length measurement along the X axis

  - straight line *a* measurement;
  - point K measurement;
  - distance R_1 measurement.
- for the length measurement along Y, taking into account the fig. 5, we have:

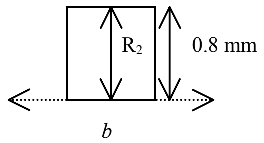

Fig. 5 - Procedure used to make the length measurement along the Y axis

  - straight line b measurement;
  - point H measurement;
  - distance R_2 measurement.

3. EXPERIMENTAL DATA ELABORATION

The experimental data were analyzed by using the principles of *Statistics Inference.* Through the valuation of the frequencies and the relative frequencies of the values obtained from the measurements, we can construct the statistics variables, which allow to carry out the study of the phenomenon variability through the estimate of the parameters which characterize the population considered (like the mean, the variance, etc., of the population). This is solved through the estimate of the corresponding sample parameters or statistics (like the mean, the variance, etc., of the sample): this is one of the main aspects of the Statistics Inference.

Referring to the principles of the Statistics Inference, the purpose is to verify that the performance of the VMM is in conformity with builder statement, both in reference to the capability of the optical machine measurement to be in a sufficiently little interval around the expected value and in reference to the measurement variability. To such purpose we have based our study on two Norms, the EN – ISO 14 253 [1] (how to proceed to decide the conformity or non-conformity of the product characteristic, when this characteristic is measured with inevitable uncertainty) and the UNI ISO 2854 [2] (data statistics interpretation, methods for the values estimate and tests for means and variances).

Firstly we done a contemporaneous check of the capability of the optical machine measurement to be in a sufficiently little interval around the expected value and of the measurement variability. We have supposed that the mean *M* of the population coincides with the conventional true value (that is the conventional true value is the central value) and so we have proceeded to verify this hypothesis by constructing the bilateral confidence interval around the estimated value, in accordance with the Prospect B' of the Norm UNI 2854. Then we have checked that the determined confidence interval is into the Zone of Conformance (based on the Norm EN ISO 14 253), taking into account what the builder declared. It's necessary to observe that the Zone of Conformance changes from point to point and from axis to axis. In particular the problem is not to check if the population mean is equal to the assigned value, but to determine the limits into which presumably and reasonably we can suppose that the value *M* is contained. In this way we associate a probability or a "confidence level" equal to (1-α) to the statement that the limits calculated includes the true value of the parameter that we estimate (note that α is the "significant level"). We consider the most common values for (1-α) that are 0.95 and 0.99, that is respectively α=0.05 and α=0.01. If we denote with X the random variable, that represents the measurement result of the Quick Vision optical machine of which we must check the performance, the true conventional value of the measurement made is:

$$M = E\{X\} \tag{1}$$

i.e. M is the expected value of X.

The check tests was carried out for each axis of the measurement volume of the VMM and for the television camera, by using suitable reference standards on which we make the measurements; each of these standards is equipped with its SIT calibration certificate, where the uncertainty u_s is specified that we must associate to the standard in each situation of measurement. Therefore, by taking into account that for the optical machine used the uncertainty declared by the builder is ±3µm, we can recognized three zones, like the fig. 6 shows and like the Norm EN ISO 14 253 says:

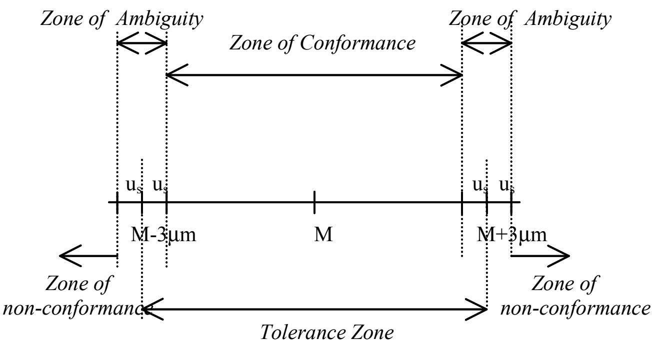

Fig. 6 – Definitions related to conformance, non-conformance, tolerance and ambiguity zone.

The uncertainty of the reference standard causes a Zone of Ambiguity in the definition of the specific: this zone is symmetric as regards the specific limits and it has half-width equal to the calibration uncertainty. In accordance with the Norms in argument, we verify that the constructed confidence interval is into the Zone of Conformance. The confidence interval is deduced by taking into account the "frattili" of the t - Student distribution (Prospect IIa of the Appendix B in the Norm UNI ISO 2854) in relation to the free degree ν available. We can write:

$$\Pr\left\{\bar{x}-\left[\frac{t_{1-\frac{\alpha}{2}}(\nu)}{\sqrt{n}}\cdot s\right]\le E\{X\}\le \bar{x}+\left[\frac{t_{1-\frac{\alpha}{2}}(\nu)}{\sqrt{n}}\cdot s\right]\right\}=(1-\alpha)\cdot 100\% \quad (2)$$

where, if n is the number of the sample elements (i.e. the number of the observations done) and x_i (i = 1,…,n) are the recorded values, we have that:

- s is the standard deviation (mean square error), that in accordance to the Norm in argument we consider to evaluate as follows:

$$s=\sqrt{s^2}=\sqrt{\frac{\sum_{i=1}^{n}(x_i-M)^2}{n}} \quad (3)$$

- $\bar{x}$ is the mean of the sample, evaluated as follows:

$$\bar{x}=\frac{\sum_{i=1}^{n}x_i}{n} \quad (4)$$

- $t_{1-\frac{\alpha}{2}}(\nu)$ is the "frattile" of the t -Student distribution.

On the ground of the free degrees $\nu = n-1$ that are available, we check on the "frattili" table the value of $t_{1-\frac{\alpha}{2}}(\nu)$ and so we can evaluate the confidence interval. Then we consider two case, i.e. (1 - α) = 0.95 and (1 - α) = 0.99 (necessarily to the value 0.99 correspond limits more large, to which we can attribute greater confidence).

So that the hypothesis is checked, it must appears the situation qualitatively showed in fig. 7:

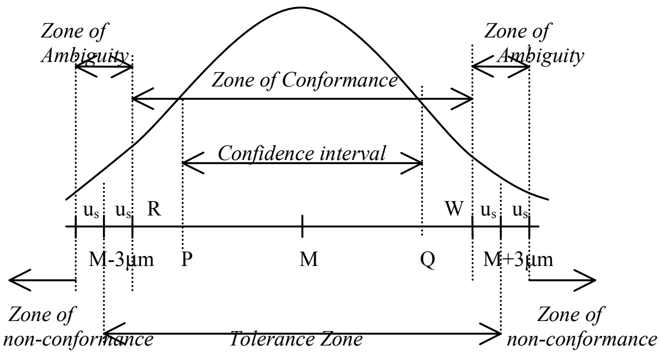

Fig. 7 - Confidence interval

where P and Q are the limits of the confidence interval with:

$$P=\bar{x}-\left[\frac{t_{1-\frac{\alpha}{2}}(\nu)}{\sqrt{n}}\cdot s\right] \quad \text{and} \quad Q=\bar{x}+\left[\frac{t_{1-\frac{\alpha}{2}}(\nu)}{\sqrt{n}}\cdot s\right] \quad (5)$$

In the bilateral case that we are studying, the area under the curve in the left of P and in the right of Q is equal to α/2, because the area under the curve into the confidence interval constructed like we have shown is equal to 1-α.

Now we can check the capability of the optical machine measurement to be in a sufficiently little interval around the expected value and the measurement variability separately, taking into account the following fig. 8 and, respectively, the Prospect A' and the Prospect F of the Norm UNI ISO 2854:

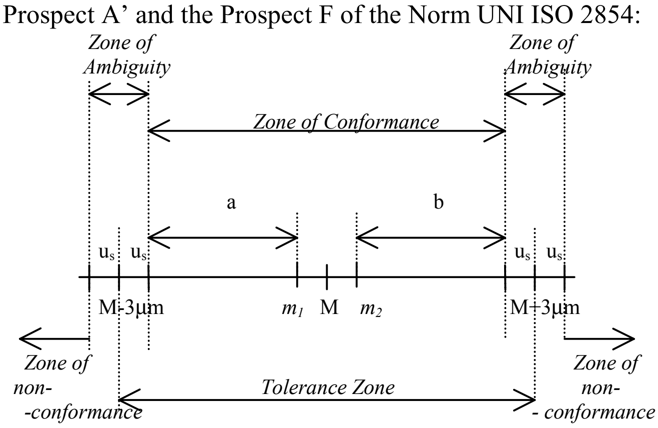

Fig. 8 - Check of the capability of the optical machine measurement to be in a sufficiently little interval around the expected value and of the measurement variability

We must reason like follows:

1. to check the capability of the optical machine measurement to be in a sufficiently little interval around the expected value, we can choose two values very close to M, at the right and in the left of M (m_1 and m_2) and then we check that the estimated mean value $\bar{x}$ be into the interval [m_1, m_2]; the hypothesis is rejected if:

$$\bar{x} < m_1 - \left[\frac{t_{1-\alpha}(\nu)}{\sqrt{n}} \cdot s\right] \quad \text{or} \quad \bar{x} > m_2 + \left[\frac{t_{1-\alpha}(\nu)}{\sqrt{n}} \cdot s\right] \qquad (6)$$

2. to check the measurement variability, taking into account in fig. 8, we must check that the variance is into a or b, that is:

$$k^2 \cdot s^2 \le a^2 = b^2 \quad \text{i.e.} \quad s^2 \le \left(\frac{a}{k}\right)^2 = \left(\frac{b}{k}\right)^2 \qquad (7)$$

and we can consider different situations in relation with the different values of the covering factor k (k = 1, 2, 3). Then using the "frattili" of the χ^2 distribution (i.e. the values $\chi^2_{1-\alpha}(\nu)$ reported in relation with the free degrees both for the bilateral and for the unilateral case in the Prospect III in Appendix B, Norm UNI ISO 2854), we can say that the hypothesis is rejected if:

$$\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{\left(\frac{a}{k}\right)^2} > \chi^2_{1-\alpha}(\nu) \qquad (8)$$

where $\chi^2_{1-\alpha}(\nu)$ is the "frattile" of the χ^2 distribution, k is the *coverage factor* and we have chosen a=b. Note that in the calculations that we have made, we have assumed that $|m_1| = |m_2| = \left(\frac{1}{10}\right)|a| = \left(\frac{1}{10}\right)|b|$.

Finally the measurement uncertainty for its indication must be calculated, based on a mathematical measurement model and on the suggestions provided with the Norm UNI CEI ENV 13005 [4]. The VMM performance check is a necessary condition, but it is not sufficient to guarantee the optical machine measurement results traceability; in fact using the optical machine for the conformity check of the pieces/instruments, the measurement result is traceable if, besides the optical machine check in accordance with the Norms in argument, it is also documented the uncertainty evaluation. Moreover the errors in the length measurement, must be in absolute value inferior of maximum allowed error, reduced of the calibration expanded uncertainty (in accordance with the Norm EN-ISO 14253-1).

4. PRELIMINARY EXPERIMENTAL RESULTS

Referring to the model shown for the experimental data elaboration and taking into account the fig. 7 and the fig. 8, for each measurement of points of the X axis we determined the mean of the samples $\bar{x}$, the standard deviation s and the values R and W.

Then we determined the limits P and Q of the Confidence interval with (5), by considering the case α = 0.05, i.e. $\frac{t_{1-\frac{\alpha}{2}}(\nu)}{\sqrt{n}} = \frac{t_{0.975}(29)}{\sqrt{30}} = 0.373$ according to the Prospect IIb in Appendix B of the Norm UNI ISO 2854, for n = 30. For example, the experimental results are shown in Table I for the measurements of five points along X axis.

We verified that in this case the confidence interval is into the Tolerance Zone and into the Conformance Zone, i.e. we verified respectively that:

a) P > M - 3μm and Q < M + 3μm;
b) P > R and Q < W.

Table III – Confidence interval and conformance check for X axis

M (mm)	**P** (mm)	**Q** (mm)
20	19.99905	19.99925
40	39.99851	39.99871
60	59.99840	59.99860
80	79.99739	79.99757
100	99.99988	99.99705

The experimental results obtained seem to be appreciable enough both in relation to the capability of the optical machine measurement to be in a sufficiently little interval around the expected value and to the measurement variability. This drives us to believe that the method could deserve further attention inside more complicated models.

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