UNCERTAINTY EVALUATION OF A 3D VISION SYSTEM: COMPARISON OF MONTE CARLO SIMULATION WITH A CLASSICAL EXPERIMENTAL CALIBRATION

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Abstract:
The Guide to the Expression of Uncertainty in Measurement has some limitations, especially for systems with complex mathematical models. In this article, two alternative methods to obtain the measurement uncertainty (Monte-Carlo simulation and calibration based on experimental measurement) are compared. These methods are widely used to calculate the measurement uncertainty of measurement systems. The advantages and disadvantages of these two methods are going to be studied estimating the uncertainty of the flatness measurement using a system based on laser triangulation. The measurement system captures images of the laser plane projected in the surface to be digitalized. The laser points in each image are identified and extracted and transformed into 3D coordinates to calculate the flatness of the surface. The influence of different factors will be characterized and the results of the estimation of the uncertainty with both Monte Carlo simulation and the calibration based on experimental measurement will be compared as well as the characteristics and requirements of each procedure.

Keywords: Measurement Evaluation and Verification, Uncertainty, Geometric error, Intelligent measurement

1. INTRODUCTION

Comparing the Guide to the Expression of Uncertainty Measurement (GUM) with the Monte-Carlo simulation, it can be observed that GUM approach exhibit more limitations than Monte-Carlo simulation [1]. GUM is applied when the measurand cannot be measured directly and a mathematical model allows expressing the measurand in relation with other input quantities [2]. The combined uncertainty can be calculated according to the propagation of uncertainty law (variances propagation) Once the input variables are characterized. Applied the propagation of uncertainty law can be a difficult task because most of the time it is a quite complex mathematical problem [2,3].

To overcome these limitations, Monte-Carlo simulations are suggested to be adopted in order to move from variances propagation to distribution propagation for the evaluation of the measurement result [4]. Other alternative to evaluate the measurement uncertainty is the calibration based on experimental measurements. In this case, the measurement of a well-known master piece is carried out several times and the results are analysed together with the variables of influence to estimate the uncertainty in measurement.

The mathematical model and the probability distribution of the input quantities are needed to run Monte-Carlo simulations. Random values of the output quantities are simulated with this information using a computer to finally obtain the associated uncertainty [2,3,5].

In this article, these two methods are going to be compared estimating the measurement uncertainty of a measurement system. The measurement system is based in laser triangulation and the surface of a master piece is going to be scanned to measure its flatness. The flatness of the master piece has been previously measured in a coordinate-measurement machine (CMM).

The aim of this paper is to compare the results obtained with both methods, Monte-Carlo simulation and the calibration based on experimental measurements.

The work presented consists in the calibration of the measurement system in order to obtain an estimation of the uncertainty for the measurement of flatness. Two different methods according with GUM [6] are tested. The experiments carried out to calibrate the system and to evaluate the influence of the input variables of the model are explained in section 3. The simulation needed when following the Monte Carlo method is explained in section 4.

2. MATERIALS AND METHODS

2.1 Description of the system

Two elements have been used to carry out the experiments: the measurement system and a master piece. The software needed to run the Monte Carlo simulation and to analyse the results have been developed too.

The master piece is a heat exchanger with a flat surface in one of its sides. The flatness of that surface has been measured in a CMM and serves as reference for the experiments.

The measurement system is based in laser triangulation and consists primarily of two components: camera and laser arranged in a fixture with a specific spatial configuration specially designed to measure the flatness of surfaces. The fixture is mounted on the carriage of a linear axis, which allows the movement of the camera-laser system along its axis. In this way the surface under inspection can be scanned.

The process can be divided in three steps: first step, the camera capture images of the laser projected in the surface that is located in the field of view of the system. At the same time, the axis translates the system linearly, Fig. 1. On second step, the captured information (images and positions from the axis) is processed resulting three dimensional points from the laser line in images. Finally, third step consists of obtain results from the analysis of the cloud of points digitalized. A more detailed explanation of the characteristics of the system can be found in [7].

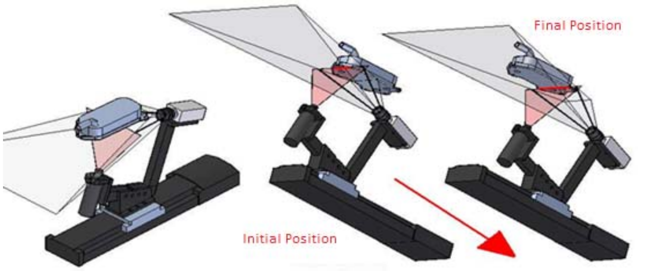

Fig. 1: Measurement system scanning the flat surface of the master piece.

2.2 Flatness measurement

As the following experiments and simulations aim the estimation of the uncertainty of the flatness measurement, the steps to measure flatness are showed in this point. Figure 2 shows a scheme of flatness measurement once the images have been captured.

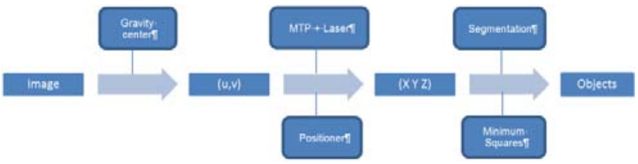

Fig. 2: Scheme of the measurement process.

The laser points are extracted from images using the weighted average method (WA). This method is widely use in subpixel estimation [8]. A point in image coordinates *(u,v)* is extracted from each column of image were the laser appears, Eq 1.

$$v_{sp} = \frac{\sum_{t=-m}^{m} w_{v+t} \cdot (v+t)}{\sum_{t=-m}^{m} w_{v+t}}; \qquad (1)$$

Where v_{sp} is the subpixel coordinate for a point of the laser line; w_v, is the level of grey in the pixel v; and m is the size of the window.

The search process is performed iteratively. First, the gravity center is searched in the column setting the window in 40 pixels (m=40). Afterwards, is calculated the gravity center with m=20 pixels starting from the gravity center obtained in the first iteration. Third iteration will be with m=10 pixels and in the last iteration m=7 pixels.

A condition is set to assure the existence of the analysed column whereby the level of grey sum must be higher than a threshold.

In figure 3, the result of the iterations using the WA method for a column is shown.

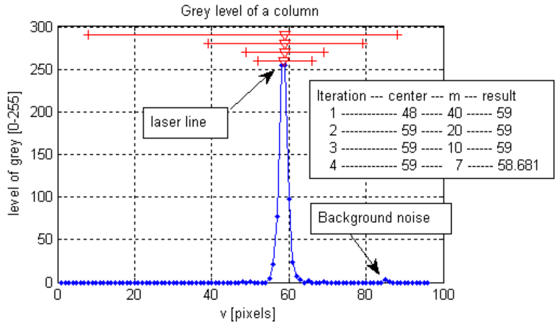

Fig. 3: WA method applied to a column. Red lines are the size of the window in each iteration.

Subpixel coordinates (u, v_{sp}) are extracted for each point of the laser line, figure 4.

Fig. 4: Above, image from the surface scan, red dots are used to mark the laser line dots. Below, detail of the laser in image, again red dots are used to mark the laser line dots.

Three dimensional coordinates (X, Y, Z) of the points of the laser line are obtained once (u, v_{sp}) are extracted from image. The perspective transformation matrix (PTM), obtained in the calibration of the vision system, is needed in this step. In order to reconstruct the cloud of points the position of the axis when the image was captured has to be applied to the (X, Y, Z) coordinates of the points. Finally the flatness of the scanned surface can be calculated applying minimum squares [7].

The influence of several factors appeared in this steps, such as image noise or errors in the position data, will be analysed in the next section.

3. CLASSICAL EXPERIMENTAL CALIBRATION

The calibration based on experimental measurements estimate the uncertainty of the inspection from the measurement of a well-known master piece. This master piece is measured several times, the results are analysed together with the variables of influence to estimate the uncertainty.

Three input variables are considered to estimate the uncertainty of the flatness results: the master piece measurement with a CMM, the calibration procedure and the measurement procedure. The difference of the result of the system and the flatness of the master piece is not contemplated because the correction obtained in the calibration will be applied to the flatness result in the measurement process. The combined standard uncertainty of the flatness measurement can be expressed according to the propagation of uncertainty law, Eq. 2.

$$u_c^2 = \left[\frac{\partial f}{\partial x_1}\right]^2 \cdot u^2(x_1) + \left[\frac{\partial f}{\partial x_2}\right]^2 \cdot u^2(x_2) + \left[\frac{\partial f}{\partial x_3}\right]^2 \cdot u^2(x_3); \qquad (2)$$

Where $u^2(x_1)$ is the uncertainty due to the measurement of the flatness of the master piece with a CMM; $u^2(x_2)$, is the uncertainty due to the calibration process; and $u^2(x_3)$, is the uncertainty due to the measurement process. Sensitivity coefficients are equal to the unit.

$$u^2(x_1) = \frac{I_0}{k_0}; \quad (3)$$

$$u^2(x_2) = \frac{s_c^2}{n_c}; \quad (4)$$

$$u^2(x_3) = \frac{s_m^2}{n_m}; \quad (5)$$

The value of $u^2(x_1)$ can be calculated from the calibration of the CMM, Eq. 3, where I_0 is the expanded uncertainty of the CMM measuring flatness is (I_0=0.005mm) with a confident level of 2 (k_0=2). The value of $u^2(x_2)$ can be evaluated using statistical methods from the results of repeated observations (ten measurements) of the flatness of the master piece, Eq. 4, where s_c^2 is the variance of the measures of the flatness of the master piece and n_c the number of measurement (n_c=10).

Measurement	1	2	3	4	5	6	7	8	9	10
Flatness (mm)	0.615	0.612	0.610	0.609	0.613	0.611	0.619	0.612	0.612	0.611
Mean	x	0.612								
Std. Dev.	sc	0.002								

Table 1: Measurement results and statistical analysis of the flatness of the master piece.

And finally, the value of $u^2(x_3)$ can be calculated from Eq. 5 considering the calibration conditions similar to the conditions in the measurement process, i.e. estimating $s_m^2 = s_c^2$ (the number of measurements to obtain a flatness result is 1 so n_m=1).

4. MONTE CARLO APPROACH

Monte Carlo simulation is an alternative to estimate the value of the uncertainty of the flatness measurement.

In Monte Carlo approach a suitable distribution is attributed to each input quantity. Principal input variables of the measurement system are briefly shown in section 2 for the case presented in this paper. These are the calculus of the subpixel coordinate with the WA method (calculus of (u, v_{sp})), the calibration results (PTM and equation of the plane of the laser for the calculus of (X, Y, Z) from (u, v_{sp})) and the data obtained from the linear axis. Before set the Monte Carlo simulation, the influence of each of the mentioned factors in the final result is analysed with the aim of determine the influence of the factor and, if the influence is significant, assign it a distribution.

4.1 Influence of the subpixel extraction

The WA method is used to obtain the subpixel coordinates of the laser in image. The output of the method is a subpixel (v_{sp}) value for each u coordinate. The WA method depends on the image noise in the area of the laser points. Therefore the variability of the estimation of the subpixel coordinates (v_{sp}) versus image noise is analysed in this subsection.

Ten images have been captured with the laser plane pointing the same area in all the images. In this experiment the single factor that can introduce variations to the results of the WA method (subpixel coordinates, v_{sp}), is the image noise. The WA results in 1100 points of the laser line in image have been compared with the 10 images. The standard deviation of the WA result for a pixel along the 10 images is calculated for the 1100 pixels of the laser line. The process results in 1100 values of standard deviation. The distribution of these values are shown in the histogram of the figure 5. The maximum value obtained is 0.093pixels.

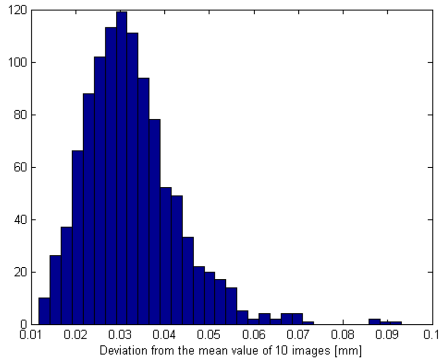

Fig. 5: Histogram of the differences of applied the WA method to 1100 points in 10 images. The differences of the results are due to the image noise.

The noise in image has been modeled as a perturbation on the subpixel coordinates obtained from WA method. The perturbation was characterized by a normal distribution with a standard deviation of 0.093pixels.

4.2 Influence of the 3D coordinates calculation

The transformation from image coordinates (u, v_{sp}) into (X, Y, Z) is made through the PTM which is the result of the calibration process of the camera-laser system. In this case variations of the results due to different PTM are not contemplated since the uncertainty of the system is studied for a period in which the system is working with the same PTM. Anyway, the study of the influence of the PTM in the flatness results is an interesting problem for future work.

4.3 Influence of the accuracy of the linear axis

The linear axis translates the vision system while it scans the surface under inspection. The capture of each image is synchronized with the capture of position data. Therefore, a distance between images can be calculated and the cloud of points obtained from each image can be translated that distance. Translation is applied in the linear axis direction measured in the frame of the three dimensional points (this direction is obtained in the calibration of the camera-laser system, see [7]). An experiment has been carried out to study the influence of the positioning error of the axis in the flatness results. The experiments began from the measurement of the master piece. The measurement process is repeated with the same images but adding a normal distributed perturbation to the position data. Three repetitions have been done with different standard deviation of the perturbation (5, 10 and 50µm). The flatness results are similar in all the cases. The maximum variation is 1 µm with the third perturbation that is far away from the linear axis behavior (accuracy of 5µm from the calibration report). The influence of the accuracy of the linear axis is despised after analysed these results.

4.4 Monte Carlo simulation

Monte Carlo simulation to calculate the measurement uncertainty can be ran after determining and characterizing the influence of the different factors of the measurement process. In this case, there has been only one factor with significant influence. This is the noise in image that has been characterized by a perturbation on the subpixel coordinates obtained from WA method (normal distributed and 0.093pixels of standard deviation). The measurement process is simulated with a number of over 10^5 iterations. The flatness results, that have a normal distribution, allow to calculate the measurement uncertainty according with GUM (k=2). The distribution of the flatness results along the iterations and the evolution of the uncertainty estimation as a function of the logarithm of the iterations are shown in figure 6.

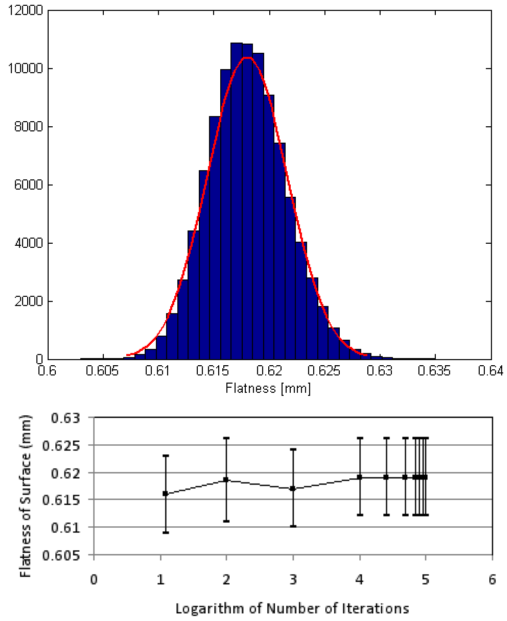

Fig. 6: Above: Distribution of the occurrence frequency for the flatness of surface with 10^5 (with coverage factor k=2). Below: Evaluation of the Number of Iterations: Values of flatness and uncertainty as a function of logarithm of the number of iterations.

4. RESULTS AND DISCUSSION

Two values of the uncertainty of the flatness measurement have been estimated. The uncertainty estimated by the classical experimental method has been 0.008mm (k=2). In this case, the uncertainty of the master piece, the uncertainty due to the calibration process and that one due to the measurement process have been considered according to the propagation of uncertainty law.

The uncertainty estimation obtained after Monte Carlo simulation is 0.007mm (k=2). The influence factor taken in account for the simulation has been the image noise after neglected other shown in figure 2.

Both methods estimate similar results but the material requirements are different for each other. For the classical experimental method a well-known master piece is needed which can be expensive to get and to maintain. The surface characteristics of this master piece should be as similar as possible to those of the surface for which the uncertainty value is calculated (because the measurement system is based in industrial vision). This may involve the need of a different master piece for each type of surface to verify with the system. On the other hand, the Monte Carlo simulation needs an estimation of the image noise distribution of the surface and the image coordinates of a scan as input data to get a value of uncertainty of the process.

5. CONCLUSIONS

On the basis of the results we can observe that values obtained by the two techniques used for calculating the uncertainty are very similar. Monte-Carlo simulation gives reliable results. Furthermore, it is clear that applying GUM can be an unapproachable solution considering all the variables that can affect the function when a measurement system is based in industrial vision.

Thus, when it is necessary to calculate the uncertainty of a system that have a complex mathematical model, it is preferable to apply Monte-Carlo simulation if we can detect and quantify the significant sources that affect the system.

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