UNCERTAINTY ESTIMATION FOR LASER TRIANGULATION HEIGHT MEASUREMENT

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Abstract:

According to the Guide to the Expression of Uncertainty in Measurement, measurement uncertainty in quality control is especially important, as the measured value determines either the acceptance or rejection of a product. As the coordinate measuring machines are not capable of 100% dimensional quality control, the use of optical methods is growing. The problem here is still the lack of methods for metrological verification. The available regulations and norms are not directly applicable for all optical measurement principles. One example is the laser triangulation method. It has been used in the in-process production control in height measurement (1D), profile reconstruction (2D) or complete 3D scanning for over 30 years.

This paperwork presents proposals of the procedure of measurements uncertainty evaluation for laser triangulation method. This method is designed for a semi-automatic determination of measure of the accuracy of shape reconstruction on the technical level and for a specific sensor. The process of the measurement in case of the laser triangulation method was divided into four sub-processes. The uncertainty for each of them can be estimated separately.

Thanks to the presented method, the process of the triangulation system accuracy evaluation is remarkably quicker, in comparison with the typical multiple measurement with the use of reference objects.

The correctness of the procedure was verified by the comparative research, which was based on the method of multiple height measurement of the set of block gauges.

Keywords: laser triangulation, measurement uncertainty

1 INTRODUCTION

According to recommendations of the GUM guidebook [1] each measurement has to be assigned its uncertainty. This recommendation becomes more and more common also in the industrial practice.

The methodology of optical measurement methods (especially 3D), became normalized thanks to the introduction of the VDI/VDE 2634 norm [2]. Nevertheless, this document is designed mainly for stereophotometry and for structural light techniques. Extensive theoretical analyses in the field of measurement uncertainty for the above are presented in [3, 4, 5], but none of them can be directly interpreted for 2D methods, like laser triangulation (ltm) [6]. In practice, scanning by ltm consists of successive profile measurements (2D sections), during the sensor movement. Uncertainty of 3D reconstruction is then a resultant of the positioning accuracy of the drive and the scanner precision. Estimation of these parameters in an independent way is definitely easier than considering this unit as a only one 3D measurement tool.

This article presents the *new method* of uncertainty evaluation for ltm. The main purpose here is the simplification of the process of uncertainty estimation for ltm. It will be possible for *automation* and only a *simple instrumentation* and *small set of test images* will be required.

2 METHOD

The 2D measurement model of laser triangulation method was designed (fig. 1) according to measuring chain [7, 8].

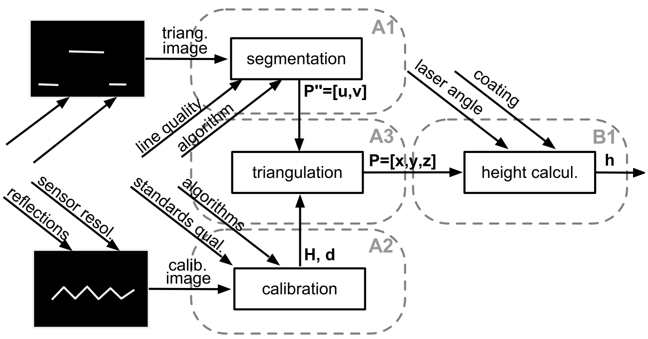

Figure 1: Measurement chain of laser triangulation method

It consists of four processes, where each one is significant for measurement uncertainty budget and will be studied as a separate analysis. Not all of these processes can be easily identified and modelled [8]. That is why the uncertainty of three of them (A1, A2, A3) is estimated by the experimental method (A), with the use of Monte Carlo simulation [9, 10], which is supplied by empirical data. Only one (B1) is analysed by the calculation method (B).

To determine the uncertainty of 3D geometrical reconstruction of point a juxtaposing of analyses (A1, A2, A3, B1) was made, which makes it possible to show the influence of each process on the uncertainty of final result. The result of the analysis A1 (fig. 2) is the uncertainty of laser line segmentation. This is the input parameter of the simulation A3 (fig. 4). The result of A2 (fig. 3) and A3 is the influence of calibration and reconstruction (fig. 4) on the accuracy of the determination of 3D coordinates of measurement points ($\mathbf{p}_i$). Their total uncertainty is the input parameter for the process of height calculation. B1 gives information about the measurement uncertainty of the objects height.

2.1 Segmentation uncertainty

Segmentation — the process of finding the midline of light profile in the triangulation image — is one of the most important operations in ltm. It has strong influence on the final result [11]. The uncertainty of this process is estimated in the following way. A flat plate (flatness< 0.005), covered with antireflection coating, is photographed multiple times in a triangulation setup. The resulting profiles should be always a straight line, as the plate is flat. The difference (residual) between light profile on the image and best fitted line is used as an estimate of segmentation uncertainty (u_{seg}).

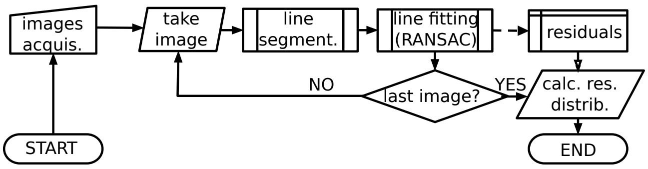

Figure 2: Schematics of A1 simulation

2.2 Calibration uncertainty

Calibration is the next major source of uncertainty [12]. To estimate its influence on the final measurement, the distance distribution (s_{e}) of series of 3D points ($\mathbf{p}_{\mathrm{A}}$, $\mathbf{p}_{\mathrm{B}}$), reconstructed from two random image points ($\mathbf{s}_{\mathrm{A}}$, $\mathbf{s}_{\mathrm{B}}$) with different calibration parameters ($\mathbf{H}_i$, $\mathbf{d}_i$) is used as the value of calibration uncertainty (u_{cal}).

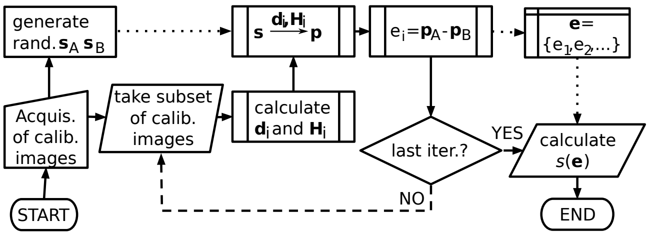

Figure 3: Schematics of A2 simulation

2.3 Reconstruction uncertainty

The analysis A1 gives information about the accuracy of the determination of the centre of laser profile. This data cannot be used for calculation of uncertainty of 3D points geometrical reconstruction, because it has to be processed by the reconstruction process (fig. 4). It is necessary to make a simulation based on Monte Carlo, which makes it possible to determine the influence of the distribution s_{seg} of points that were obtained from segmentation with accuracy u_{rec} of points reconstruction $\mathbf{p}_{\mathrm{i}}$ [13]. To do the simulation, random pair of calibration data ($\mathbf{H}$, $\mathbf{d}$), has to be selected, and input data for algorithm would be coordinates of random image point pairs ($\mathbf{s}_{\mathrm{i}}''$) generated according to standard deviation s_{seg} estimated in A1.

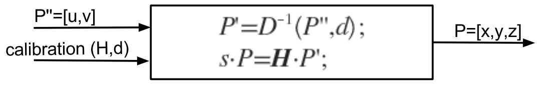

Figure 4: Triangulation reconstruction

3 EXPERIMENTS

The uncertainty of point $\mathbf{p}_{\mathrm{i}}$ measurements is evaluated as a complex uncertainty, calculated on the basis of results from A2 and A3 tests. These two processes are independent, so that is why there is all applied the equation (1).

$$u_{\mathbf{p}} = \sqrt{u_{\mathrm{rec}}^2 + u_{\mathrm{cal}}^2} \quad (1)$$

The height of the object measured is calculated according to the formula $h = h_i - h_0$, where

$$h_i = z(\mathbf{p}_{\mathrm{i}})\cos(\theta_{\mathrm{L}}) \quad (2)$$

$z(\mathbf{p}_{\mathrm{i}})$ is the Z-coordinate of point $\mathbf{p}_{\mathrm{i}}$, and θ_{L} is the laser angle. The base height h_0 is assumed as a value that was obtained from many measurements ($\gg 100$) on the calibration stage, thanks to which the accuracy in comparison to h_i can be assumed as a negligibly small (over ten times smaller) and it is invariable during measurements. The value and measurement uncertainty of the laser angle $\theta_{\mathrm{L}} = (0.6 \pm 0.2)^{\circ}$ were calculated by the multiple measurement (> 25). Because of the fact that these parameters are error-loaded, both of them are going to be taken into consideration in the uncertainty budget.

Following the recommendations of GUM [1], the uncertainty of the reconstruction process will be calculated according to equation (3).

$$u_{\mathrm{h}} = \sqrt{\cos^2(\theta_{\mathrm{L}}) \cdot u_{z(\mathbf{p}_{\mathrm{i}})}^2 + \left(-z(\mathbf{p}_{\mathrm{i}})\sin(\theta_{\mathrm{L}})\right)^2 \cdot u_{\theta_{\mathrm{L}}}^2} \quad (3)$$

4 RESULTS

Tests for A1 analysis were executed for fifty triangulation images of the flat plate.

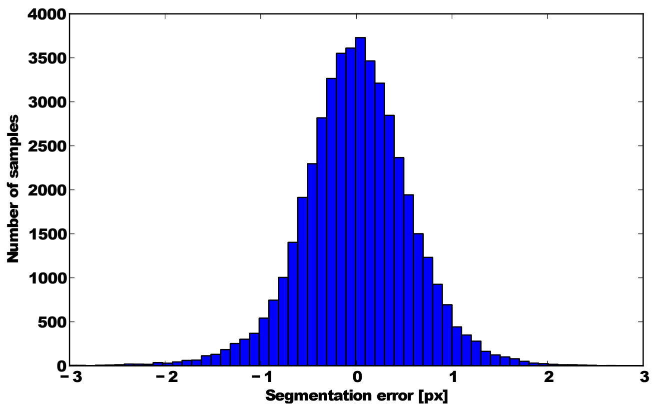

Figure 5: Histogram of accuracy of line segmentation

Standard deviation for the error distribution (fig. 5) is s_{seg}=u_{seg}=*0.57px*.

The A2 analysis gives information about the influence of the calibration process on the reconstruction result. The measure of this is the standard deviation s_{cal}. This value depends on nominal points distances (fig. 6). From the analysis of the errors distribution, a standard deviation of the populations of distances between pairs of points $s_{\mathbf{e}}$ for the nominal distance $e_{\mathrm{nom}} = 14\mathrm{mm}$ on u_{cal}=*0.014mm (@14mm)*, was calculated.

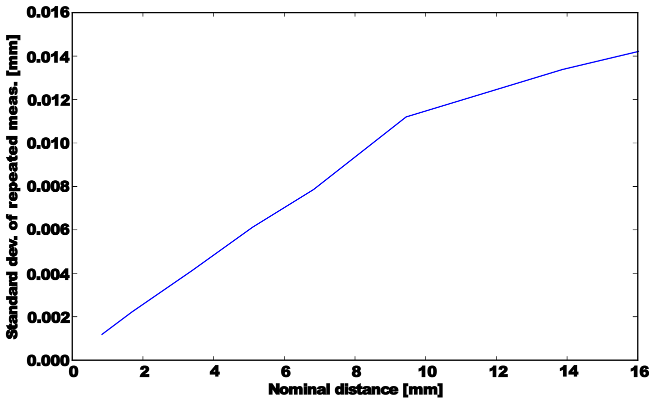

Figure 6: Standard deviation of distance measurement caused by repeated calibrations

The result of the analysis A3 is presented in figure 7. Standard deviation of distances between pairs of points in space ($\mathbf{p}_{\mathrm{A}}$, $\mathbf{p}_{\mathrm{B}}$) is not dependent on the nominal distance and points positions on the image (fig. 8) and it amounts u_{rec}=*0.048mm*. It is confirmed by the Bartlett test for the equality of variances [14, 2012-09-20].

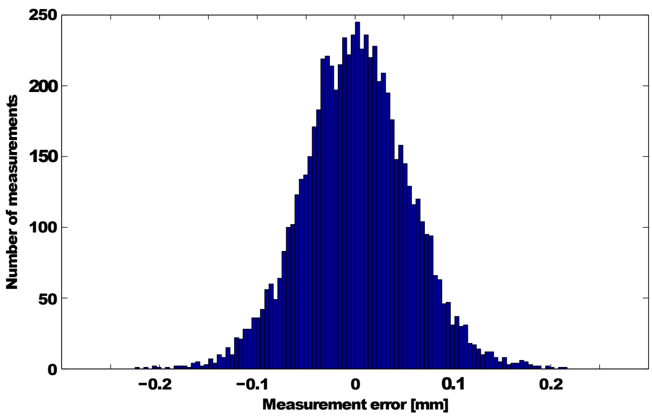

Figure 7: Histogram of distance measurement errors

The expanded uncertainty of height measurement, according to the B1 analysis can be estimated as u_{P}=0.05mm, $U_{\mathrm{h}} = k \cdot u_{\mathrm{h}} = 2 \cdot 0.058 \simeq 0.12\mathrm{mm}$. This value is for measurements of elements in the range of $Z = 1 \div 14\mathrm{mm}$.

Results obtained in simulations are presented in table 1.

5 DISCUSSION

The verification of the proposed method was executed by the comparison with a typical method, which is based on the analysis of measurement errors of the references objects

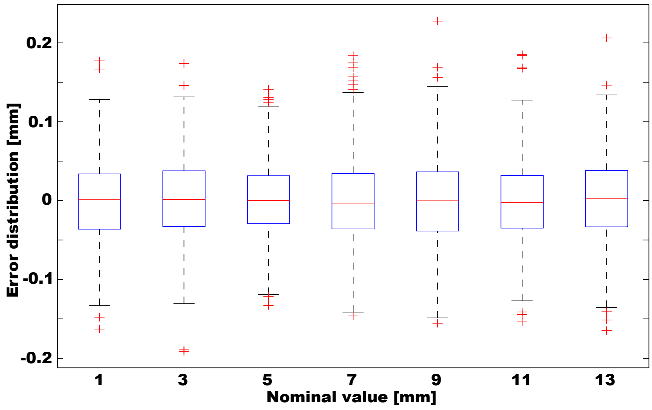

Figure 8: Distance measurement errors for nominal values

Table 1: Summary of analysis

An.	Result	Value	Inp. to
A1	Segmentation unc. u_{seg}	0.57px	$\rightarrow$A3
A2	Calibration unc. u_{cal}	0.014mm	$\rightarrow$B1
A3	Reconstruction unc. u_{rec}	0.048mm	$\rightarrow$B1
B1	Height meas. unc. u_{h}	0.058mm	—

(gauge blocks). As a result, a graph (fig. 9) containing information about the standard uncertainty of measurement for a given nominal height, was prepared.

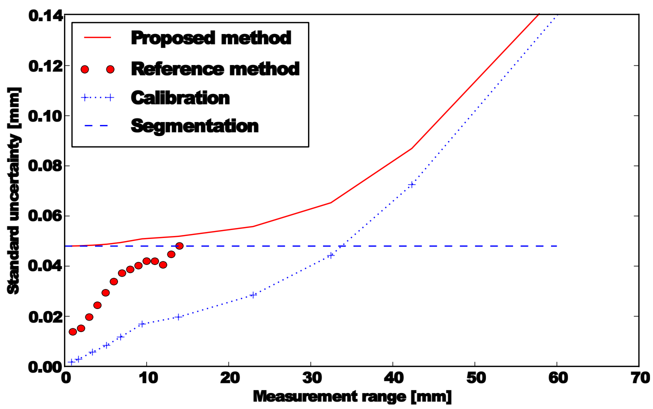

Figure 9: Comparison of standard measurement uncertainty estimated with two methods

As it can be interpreted from figure 9, measurements made by the proposed method are overestimated (in comparison to the reference method) in the area of small nominal values. It results from the fact, that the uncertainty of the segmentation in this area has a main influence on the final uncertainty. In the reference method it is taken into consideration only in case of a small area of an eyeshot where plates are situated and what is more, the surface of plates is always situated at the same angle to the camera. At the same time, the semi-automatic procedure requires the study of the segmentation algorithm for a whole measurement area, so it means taking the quality of the segmentation on the peripheries of the area into account, where measurements are not executed. Additionally, it requires the placing of the sample surface at different angles, which influences the segmentation quality. That is why there is a recommendation to configure the system for which the measurement uncertainty has to be estimated by the method proposed here. It has to be done during errors evaluation in a most similar way to the measurement conditions (especially parameters: the angle and the region of interest –ROI).

6 CONCLUSION

In this article, a new, semi-automatic method of measurements uncertainty evaluation for the laser triangulation method, was presented. This method is recommended in case of the simplified evaluation of the accuracy of the system. The procedure requires the collection of series of evaluation images, which are then used during the simulation. The analysis of the accuracy according to the proposed procedure does not require other devices than are required during the calibration of the system and a flat plate, whose surface is similar to the surface of the object scanned. Additionally, the simplified method makes it possible to evaluate the quality of the measurement for a given and specific surface and not for the surface of the reference objects (e.g. gauge blocks).

The comparison of the obtained results shows that this is a protective method, which means that it overestimates the values of the uncertainty. As opposed to the applied reference method, the uncertainty is estimated for the 3D geometrical points reconstruction and not only for the height measurement. The uncertainty that was calculated is connected only with the 2D triangulation sensor and the calculation for a 3D measurement system, which has additional drive, has to be executed separately with taking the accuracy of applied control systems into consideration.

Thanks to the advantages described above, the proposed method could be implemented as a process parallel to the calibration, with the use of the same set of images.

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