# VERIFICATION OF THE ACCURACY OF A REAL-TIME OPTICAL 3D-MEASURING SYSTEM ON PRODUCTION LINE

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**Commission V, WG V/1**

**KEY WORDS:** Accuracy Verification, Real-time Optical Measurement, Industrial Production, Quality

## ABSTRACT:

Verifying the accuracy of a real-time optical 3D-measuring system on production line has been problematic in many senses. Reasons for this arise from the production line environment as well as the bureaucratic and political way of the customers in automotive industry. These problems cause significant and needles costs and divert the attention and discussion from relevant issues. In this article a verification method is introduced. The method draws its guiding principals from the quality control standards defined by European automotive industry. Also the VDI/VDE 2643-guideline is used in the verification as well as an empirical study on the accuracy of a optical 3D-measurement system. At the present day Mapvision 4D-measurement systems are verified with this method. Customers in automotive industry have in many cases accepted this method as a pre-acceptance criterion.

## 1. INTRODUCTION

### 1.1 Demand for technology

In the field of industrial quality control there is a considerable demand for accurate and flexible real-time optical 3D-measuring systems. This demand originates from shortening cycle times, increasing production volumes and tightening quality requirements. Also the increasing number of product variants demands a flexible measuring system. Many different variants or different products are produced on the same production line and therefore should be measured in the same measuring system. Traditional production line measuring methods include mostly a complex set of mechanical tactile probes or mechanically positioned non-tactile sensors. This kind of complex construction can be designed for only couple of pre-defined product variants at the most. If the product design changes after building and calibrating a measurement system which is based on accurate mechanical structure, a considerable modification work lasting several weeks must be done. Considerable portion of production lines have no on-line measuring system what so ever. Quality control on these lines is based on statistical predictions based on only a few random samples of the production. So a demand for a real-time, on-line, flexible and programmable optical 3D-measurement system is quite understandable.

### 1.2 Restrainers of introducing new technology

When introducing a new way of measuring to the industry, one of the major problems lies in the verification of the accuracy of this new system. The greatest problems occur when trying to verify the accuracy of an optical measurement system by comparing the results with a tactile mechanical measuring system, such as a coordinate measuring machine (CMM). This is due to the problematics in the definition what exactly each system measures. In the CMM measurements, at least in the industrial environment, a hole is assumed to be an ideal circle and is measured by few points touched inside the hole and on the surrounding surface. Even though these touched points are measured within microns, they might give completely wrong results of the hole position. This is due to the fact that a hole on an industrially produced part is never an ideal circle nor is the surface an ideal plane. Sometimes a bolt is measured by touching the outer threads. Clearly, the result depends whether the probe touches the top or bottom of the thread profile, especially if no correction algorithms are used. These are quite difficult and philosophical problems to discuss with people who have done the measurements this way for decades. Most of these problems have nothing to do either with the true accuracy of optical measurement systems or the capability to follow the production quality. The lack of understanding of new technologies concludes in serious doubt on the functionality of the system. This doubt is strengthened when having improper and unjust ways of testing and proving the capability of the new system. Therefore a verification method for an optical real-time production line 3D-measurement system is desperately needed.

### 1.3 Motivation for system manufacturers

For measuring equipment manufacturers it is important to have a clearly specified and standardized way of verifying the accuracy and functionality of the measuring system. The common principle at a production line construction site is that the final acceptance on production line equipment comes when the whole line is 100% up and running. As the final functionality of a production line can be prolonged for a long period of time, it is crucial that a pre-acceptance of the measuring system can be done as soon as the measuring system is ready. For these purposes a standardized verification method is needed.

## 2. STUDY ON THE ACCURACY OF A MAPVISION 4D-MEASURING SYSTEM

Before any kind of verification method can be introduced, there must be a realistic understanding of the potential accuracy of a measuring technology as well as factors which have effect on the accuracy of the measurement. This is why a study has been made on the accuracy of a real-time optical 3D-measurement system. Also a mathematical basis for theoretical accuracy should be presented so that a comparison between theoretical and true accuracy can be made. This tells how well the system is optimized and functions up to the potential of the technology.

## 2.1 Mapvision 4D

In this study a Mapvision 4D-measuring system was used. This particular system has four cameras used in photogrammetrical measurement. All of the cameras are calibrated to one unanimous measuring volume (Niini, 2002). In principal, two calibrated cameras would be enough to determine a 3D-point. By adding cameras the 3D-point can be determined more accurately and the possibility of errors can be reduced. But most of all, when there are many cameras participating in the measurement task, the quality of the measurement can be controlled from the unanimity of all of the camera observations. This is the main principal of the patented Quality Index. This Quality Index gives the “fourth dimension” in addition to the x, y and z coordinates of a measuring point. The particular four camera system used in this study has a calibrated volume of 16 cm x 16 cm x 13 cm.

## 2.2 Theoretical accuracy

In convergent imaging, a coarse indicator of the object point accuracy, defined as the mean standard error σ of all object points, can be expressed as:

$$\sigma \approx \sigma_i q s \qquad (1)$$

Where σi is standard error of the image coordinate measurements, q is the network factor, and s is the average scale number. In this case, these can be assumed to have values: σ i= 0.03-0.04 pixels, q = 1.0, and s = 160 mm/768 pixels, for example, which gives a theoretical object accuracy of about 6-8 microns (Haggrén, 1992). Relative object accuracy is then about 1/25000-1/20000.

## 2.3 Study on the true accuracy with an ideal circle target

The only way of finding out the accuracy of a measurement system is to do measurements and then compare the measured values against something which is assumed to be accurately known. Altogether a little over 1000 measurements have been done in a study using the Mapvision 4D-measuring system mentioned above. Two different artifacts are measured. First an ideal circle target, which should give a representative idea of the accuracy of the system in ideal circumstances (see Figure 2a). This target is produced with high accuracy to be circular and planar. In the optical point of view it is ideal due to a clear contrast of black and white. The other artifact is a machined metal part having different kind of holes on it (see Figure 2b). This represents more or less a measuring task which Mapvision 4D-systems are designed for.

Measurements with the ideal circle target in this study, presented in Tuominen, 2007, can be divided in two categories: repeatability and displacement measurement. Displacement measurement results with the ideal circle target are not referred in this article. A more comprehensive study of displacement measurements were done with the metallic artifact, and a summary of those results can be found in this article, starting from 0.

### 2.3.1 Repeatability

Repeatability is studied by measuring the same target again and again without moving it between measurements. The number of average images used to create the measuring image has an effect on the accuracy due to the noise in the images. The target was measured 10 times and the deviation of each measurement from the measured average was used to present the repeatability. Depending on the amount of average images used, the repeatability (total range) varies from 1 micron to 14 microns. Also the Quality Index is presented in the same results. As seen from the results, the Quality Index quite well estimates the true accuracy of a measurement. (See Figure 1)

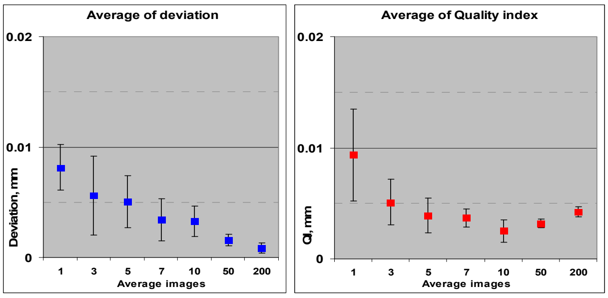

Figure 1. Results of the repeatability measurements done with the ideal circle target. Average +/- 1 sigma.

## 2.4 Study on the true accuracy with a metallic artifact

Study of accuracy with an ideal target might be misleading when discussing about a measurement system on a production line use. Mass produced parts, especially in automotive industry, are rarely ideal in any way. Many applications already on the market are based on target measurement. These applications, however, have nothing to do with production line measurement. So a study must be done on the accuracy with an artifact which somehow has the same kind of features that a mass-produced part has.

A metallic artifact was produced for this study (see Figure 2b). Main criteria were that it was in no way ideal. It had holes of different size and shape as well as a corner formed from edges. The surface of this artifact was quite shiny and reflecting. This way the measured artifact was just the opposite of a matt object preferred conventionally in optical measurements. Seven features were selected from the artifact (shown in Figure 2b). This kind of features would already give a good idea about the effect of feature size and shape to the accuracy.

With this artifact nearly 1000 measurements were done to study the accuracy of the measuring system. These measurements can be put in to three categories: repeatability-, displacement- and disturbance measurements. For the results of different kind of disturbances (change of illumination, surface impurities etc.) see the study in Tuominen, 2007. This study is however not as relevant for the verification method as the other two studies.

Repeatability
Repeatability measurements were done in a similar way as the study with the ideal circle target. Four features (see features 1-4 in Figure 2b) were measured without moving the artifact. Also the effect of average images used in the measurement was studied. Accuracy of repeatability clearly depends on two variables: the amount of noise in the measuring images and the

size and articulateness of the measured feature. With the feature 4 (intersection of plane edges) the effect of image noise is considerable due to the quite indistinct appearance of the feature. With the smallest hole (feature 1) the accuracy of repeatability gets to the same level with the larger holes (features 2 and 3) when using 10 images as an average image. Quite interesting is that with these three features the accuracy of repeatability is in the same order of magnitude with the ideal circle target (see Table 1). Even though the repeatability measurements done here might not give understanding of the true accuracy in industrial applications, it still shows the stability of the system.

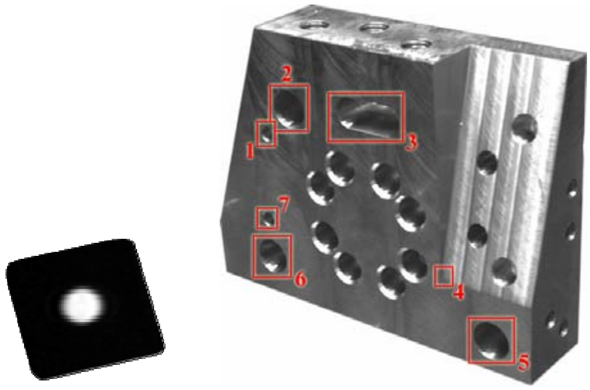

Figure 2 a and b. Ideal circle target (a) and the metallic artifact used in accuracy studies and the seven features which were measured (b).

| Avrg | Feat. 1 | | Feat. 2 | | Feat. 3 | | Feat. 4 | | Target | |
|---|---|---|---|---|---|---|---|---|---|---|
| img | μ | 1σ | μ | 1σ | μ | 1σ | μ | 1σ | μ | 1σ |
| 1 | 0.012 | 0.005 | 0.007 | 0.002 | 0.008 | 0.004 | 0.039 | 0.014 | 0.008 | 0.002 |
| 5 | 0.004 | 0.003 | 0.003 | 0.002 | 0.003 | 0.001 | 0.018 | 0.007 | 0.005 | 0.002 |
| 10 | 0.003 | 0.001 | 0.003 | 0.002 | 0.003 | 0.001 | 0.010 | 0.005 | 0.003 | 0.001 |
| 50 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.007 | 0.003 | 0.002 | 0.001 |

Table 1. Average and standard deviation of the accuracy of repeatability.

Displacement measurement
The most comprehensive study was made with a linear movement of small (0.2 and 0.1 mm) steps. The metallic artefact was attached to a three-axis micrometer device which was used to create the needed movements. The procedure was that seven features (seen on Figure 2b) were measured in the 0-position. Then the metallic artifact was moved a short step and measured again. The measurements of these short steps were continued until a total distance of 2 mm was moved. This was done with every axis of the micrometer device. These measurements were done first with 10 times 0.2 mm steps, then with 20 times 0.1 mm steps and finally with 10 times 0.2 mm steps while the metallic artifact was turned 180° around its middle point. From 10 to 50 average images were used in these tests to eliminate the effect of image noise.

The accuracy of the displacement measurement was defined as a deviation from the nominal movement given by the micrometer. The accuracy (deviation from nominal) in all of the displacement measurements with all the seven features was in average +/- 6 microns. The maximum deviations from nominal were 21 microns in average in all of the measurement sets. These results imply that when measuring a clear and distinct feature, such as a clean hole, the accuracy of the system can reach near to the level of the theoretical accuracy. The average deviations of each feature and each measurement set are seen in Table 2 Table 2. For more thorough analysis on the measurement results, see Tuominen, 2007.

| | | X | | | Y | | | Z | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | μ | 1σ | 6σ | μ | 1σ | 6σ | μ | 1σ | 6σ |
| 0.2 mm | 1 | 0.001 | 0.004 | 0.012 | -0.001 | 0.004 | 0.014 | 0.000 | 0.003 | 0.009 |
| | 2 | -0.002 | 0.002 | 0.008 | 0.009 | 0.007 | 0.021 | -0.003 | 0.004 | 0.011 |
| | 3 | -0.013 | 0.006 | 0.018 | 0.026 | 0.015 | 0.040 | -0.013 | 0.005 | 0.017 |
| | 4 | 0.006 | 0.004 | 0.012 | 0.009 | 0.011 | 0.035 | 0.013 | 0.010 | 0.031 |
| | 5 | -0.001 | 0.002 | 0.005 | 0.012 | 0.007 | 0.019 | 0.004 | 0.004 | 0.014 |
| | 6 | 0.002 | 0.002 | 0.004 | 0.004 | 0.003 | 0.012 | -0.008 | 0.003 | 0.009 |
| | 7 | 0.001 | 0.012 | 0.031 | -0.002 | 0.018 | 0.049 | -0.006 | 0.015 | 0.040 |
| 0.1 mm | 1 | 0.000 | 0.003 | 0.013 | 0.001 | 0.006 | 0.021 | 0.003 | 0.002 | 0.007 |
| | 2 | -0.002 | 0.002 | 0.012 | 0.010 | 0.006 | 0.020 | -0.003 | 0.004 | 0.014 |
| | 3 | -0.004 | 0.003 | 0.011 | 0.000 | 0.003 | 0.011 | -0.023 | 0.010 | 0.038 |
| | 4 | 0.009 | 0.005 | 0.019 | -0.008 | 0.011 | 0.041 | 0.008 | 0.014 | 0.046 |
| | 5 | 0.002 | 0.003 | 0.011 | 0.011 | 0.006 | 0.022 | 0.005 | 0.005 | 0.017 |
| | 6 | 0.000 | 0.002 | 0.008 | 0.003 | 0.002 | 0.007 | -0.006 | 0.005 | 0.020 |
| | 7 | -0.001 | 0.010 | 0.027 | 0.001 | 0.015 | 0.047 | -0.004 | 0.013 | 0.035 |
| 0.2 mm turned | 1 | 0.002 | 0.011 | 0.034 | 0.006 | 0.014 | 0.047 | 0.007 | 0.011 | 0.035 |
| | 2 | 0.003 | 0.003 | 0.008 | 0.014 | 0.007 | 0.022 | -0.002 | 0.003 | 0.010 |
| | 3 | -0.019 | 0.008 | 0.023 | 0.009 | 0.006 | 0.024 | -0.039 | 0.020 | 0.062 |
| | 4 | 0.004 | 0.009 | 0.028 | 0.007 | 0.008 | 0.032 | -0.021 | 0.014 | 0.036 |
| | 5 | 0.001 | 0.003 | 0.008 | 0.027 | 0.010 | 0.033 | 0.000 | 0.006 | 0.015 |
| | 6 | -0.002 | 0.002 | 0.007 | 0.019 | 0.008 | 0.024 | -0.002 | 0.006 | 0.015 |
| | 7 | 0.006 | 0.009 | 0.027 | 0.007 | 0.016 | 0.042 | 0.004 | 0.016 | 0.042 |

Table 2. Results of the displacement measurement with small steps for seven measured features

## 3. VERIFICATION METHOD

All the traditional verification methods for verifying the accuracy of a measuring system are based more or less on the repeatability of a measuring system or a correlation to another measuring system. Also quite widely used are methods which use a master part which is produced with very high accuracy. Then the verified measurement capability of a measuring system comes from the comparison between measured and "known" dimensions of this master part. These different approaches are sometimes combined.

Quite a good understanding of the factors which affect the accuracy of this optical 3D-measuring system had been created by the end of the study done in Tuominen, 2007. Also it was starting to be clear that there was no better way to confirm the true accuracy of a production line measurement system than to create accurately known movements and measure them. This comprehension is drawn from the fact that the main function for a production line measurement system is to accurately follow changes in the production parts, not to measure accurately some special master parts.

Still, a verification method must also be acceptable by the customer as well as the academic community. This is why this verification method of a production line optical 3D-measurement system should be based and fitted on already existing verification methods and standards.

### 3.1 VDI 2634 guideline

The VDI (Verein Deutscher Ingenieure) is a non-profitable organization which among other purposes creates nationally and internationally valid guidelines for different fields of technologies. These guidelines are sometimes referred even as international standards.

The VDI 2634 guideline is for verifying the absolute accuracy of optical measurement systems. This guideline does not take any consideration on which kind of measurement tasks are later carried out with the measurement system. Neither does it take any consideration on the accuracy of detecting local relative movements of a measuring point, which is the most important issue when studying production line measurement systems. Therefore this study is not usually needed for accepting production line measurement systems. Nevertheless, the VDI 2634 guideline gives a good method for evaluating the orthogonality, homogeneity and scale of the calibrated measuring volume of a system.

The idea of the method is to have a rigid bar which has approximately the length of 2/3 of the diagonal length of the measuring volume. The bar has several targets on it which are suitable for optical probing. Between the targets several one-dimensional lengths can be determined. The dimension of this bar must be known to an uncertainty of 1/5 of the verified accuracy of the measurement system and this must be traceable to a national or international standard (VDI 2634). This assures the traceability chain up to the definition of the SI-unit meter (Hemming, 2007).

The certified bar is placed in different positions within the measuring volume as seen in Figure 3a. Different lengths are measured between the targets as seen in Figure 3b. By comparing the measured length and certified length we can calculate the length measurement error for each length as defined in equation (2).

The measurement system manufacturer, after experimental studies, defines a characteristic quality parameter for length measurement error E, which is a length dependent quantity, where A, B and K are constants and L is the length to be measured (see Equation (3) and Figure 4).

$$\Delta l = l_{measured} - l_{certified}. \tag{2}$$

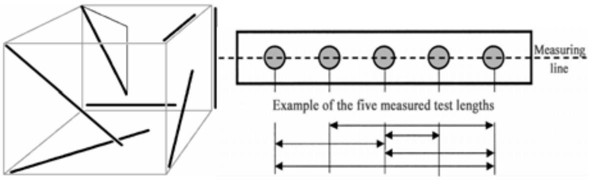

Figure 3a and b. Recommended measuring lines (a, left) and example of different lengths measured from the targets on the certified bar (b, right). Images modified from VDI 2634.

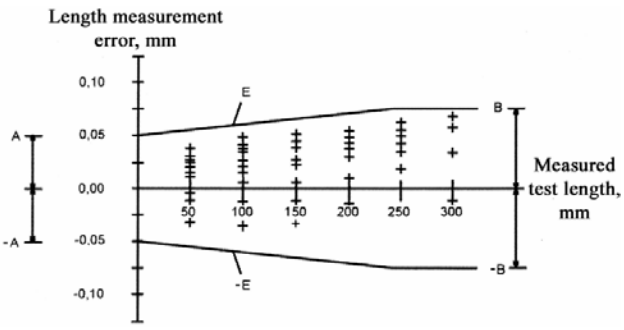

Figure 4. Example of length measurement error diagram. Image from VDI 2634.

$$E = A + K \cdot L \leq B \tag{3}$$

After carrying out the measurements, all the length measurement errors Δl are evaluated towards the length dependent E. The quality parameter is valid if no length measurement error Δl exceeds the maximum permissible length measurement error defined by E. If exceeding errors occur for not more than one measuring line, all distances on that one line can be re-measured once. For more details see VDI 2634.

### 3.2 Measurement System Capability Reference Manual

When trying to create a method which is acceptable by the customer, in this case mainly the automotive industry, it is important to know their current methods. The Measurement System Capability Reference Manual (MSCRM) has been created by a work group comprising people of Audi AG, BMW AG, Robert Bosch GmbH, DaimlerChrysler AG, Fiat Auto S.p.A., Ford-Werke AG, Adam Opel AG, Q-DAS GmbH, T.Q.M. Itaca s.r.l. and Volkswagen AG (Dietrich et. al. 1999). This manual is known to be used as a guideline for measurement system verification by the above mentioned companies. The manual is allowed to be freely used by anyone. This is why many other companies outside the distinguished list above use the manual as well. Therefore it represents quite well the expectations and standards of the customer. It is based on the commonly known MSA (Measurement System Analysis).

#### 3.2.1 Type-1 study

This study is used to decide if the measurement device is capable for its intended use under actual operating conditions. For this two indices, Cg (gage potential index) and Cgk (gage capability index), are created. For creating the Cgk, a measurement standard/master must be available whose true value is traceable to a national or international standard. If for technical reasons this kind of a standard is not available, Cgk is omitted. In this case only the repeatability Cg using a suitable measuring object is calculated. A suitable measuring object could be a stabilized part from the production series.

The indices Cg and Cgk are calculated in MSCRM as follows:

$$C_g = \frac{0.2 \cdot T}{4 \cdot s_g} \quad \text{and} \quad C_{gk} = \frac{0.1 \cdot T - \left|\bar{x}_g - x_m\right|}{2 \cdot s_g} \qquad (4) \text{ and } (5)$$

$T$ = specified tolerance range for measured feature
$s_g$ = standard deviation of the measurement values
$\bar{x}_g$ = average measurement value
$x_m$ = standard's true value

The selected measurement object (measurement standard or stabilized production part) is measured at least 20 times, preferably 50 times, with removing and re-inserting the measured object into the measurement system between every measurement. From the measurement results the Cg and Cgk values are calculated as described in equations (4) and (5).

Type-1 study states that if Cg and Cgk ≥ 1.33, the measurement system is capable. Note that if a verified measurement standard is not available, only Cg will be included in the assessment. If Cg and Cgk < 1.33, the measurement system is not capable. The case sg = 0 occurs only when some kind of an error appears or when the resolution of the measurement system is not high enough to recognize the existing influences. In any case of sg = 0 the measurement system is not capable. The equations and limit value of 1.33 originate from the statistical functions used for calculating the Cp and Cpk values, used in industrial process control. The required accuracy of a production line measurement system is dependent on the manufacturing tolerances, therefore it appears in the equations as well.

By setting the limit values of Cg and Cgk to the lowest limit value 1.33, the lowest possible manufacturing tolerance with which the measuring system would still pass the test can be solved for the particular measuring point. From this equation:

$$T_{\min} = 26.6 \cdot s_g \quad \text{, if Cg is used} \tag{6}$$

$$T_{\min} = 26.6 \cdot s_g + \left| \bar{x}_g - x_m \right| \quad \text{, if Cgk is used} \tag{7}$$

Large scale studies of real life processes have shown that in measuring processes, in industrial process control as well as in calibrations in laboratories, +/- 2sg is the true spread of the measurement device for repeat measurements. This is why 4sg is used in equation (4) and 2sg is used in equations (5) and (12) in stead of commonly used 6sg (or 3sg). (Dietrich et. al. 1999, p.18)

### 3.2.2 Type-2 study

This study is for systems which are subject to appraiser influence. When appraiser has no influence to the measurement, Type-3 study may be applied. Appraiser influence is possible to exclude if the measurement and loading of the part is automated completely (Dietrich et. al. 1999, p.20). The production line measuring system in interest is or can be always fully automated. Therefore Type-2 study will not be applied.

### 3.2.3 Type-3 study

This study is used to asses whether a measuring system is capable of measuring production parts. For this a value for a %EV index is calculated. %EV is defined as follows:

$$\%EV = \tfrac{EV}{RF} \cdot 100\% \tag{8}$$

RF = Reference Figure (or the specified tolerance range T)
EV = Equipment Variation

$$EV = 5.15 \cdot s_E \tag{9}$$

$$s_E^2 = \frac{1}{n \cdot (k-1)} \sum_{i=1}^{n} \sum_{j=1}^{k} (X_{ij} - X_{i\bullet})^2 \tag{10}$$

Xi• = average of measurements per part
Xij= measured value
n = number of parts
k = number of measurements per part

The test is carried out by selecting measurement objects ($n \geq 5$) which should spread across the manufacturing tolerance range. Also the number of measurements done per part ($k \geq 2$) must be defined, noticing the constraint of $n \cdot k \geq 20$.

For new measuring systems %EV ≤ 20% must be fulfilled for a capable measurement system status. For achieving a capable measurement system status for measuring systems already in use, %EV ≤ 30%. If these criteria are not fulfilled, the measurement system is not capable.

By setting the limit value of %EV to 20% and rearranging the equation (as done in type-1 study), the lowest possible manufacturing tolerance can be solved:

$$T_{\min} = \frac{25.75}{n \cdot (k-1)} \sum_{i=1}^{n} \sum_{j=1}^{k} (X_{ij} - X_{i\bullet})^2 \tag{11}$$

Note that capability proof from type-1 study must be achieved before carrying out type-3 study. Also it is stated in the MSCRM for both type-1 and type-3 studies that for very tight tolerances expectations may be made on a case-by-case basis.

### 3.2.4 Linearity

The linearity study is used to determine the “bias” of a measurement system over a specified range. Nevertheless, if a measurement system includes a linear reference standard, no linearity study is needed. This should be proved by the means of a certificate or testing. The Type-1 study alone is enough to fulfil this requirement (Dietrich et. al. 1999, p.27). Also following the VDI-guideline gives a quite comprehensive way of determining and verifying the linearity of an optical measurement system. So if the VDI-method is carried out, or if the Type-1 study is accepted, there should be no more linearity studies done.

## 3.3 Verification procedure with micrometer device

This method is based on the first version of the verification method using a micrometer device, presented in Tuominen, 2007. Still, the ways of calculating the parameters to be evaluated must be modified to correspond to the parameters used in the MSCRM, accepted by the automotive industry.

The main idea is simple. The similar feature of those to be measured in the real production line measurement task must be measured also in this verification procedure. For these measured features very accurately known movements, which represent the possible variations in production parts, must be generated. By measuring the moved position of each feature and comparing it to the nominal position calculated from the accurately known movements we can determine how accurately the measuring system can follow changes.

To create the movements a 3-axis micrometer device is needed. Also the accuracy of the whole micrometer device should be verified and certified to a national/international standard. The verified accuracy of the micrometer must be at least 1/5 of the verified accuracy of the measurement system. The micrometer device should be attached to a platform which can be moved into several different locations within the calibrated volume of the measuring system. Also it is important that positioning of the platform does not affect the measurement results. For this the platform should have targets which are ideal to measure. With these targets a coordinate transformation can be done so that each measurement is relative only to the platform which the micrometer device is attached, not to the absolute position inside the measuring volume. A good example of this kind of a device is seen in Figure 5. This particular device has been used for the pre-acceptance of a Mapvision 4D measuring system which is used for measuring Instrument Panel Supports (IPS) used in several car models of the Volkswagen Group. Parts attached to micrometer are sub-elements from the robot welded IPS.

Features which represent most comprehensively the features to be measured in the real production line measuring task must be created. The best way to accomplish this is to measure exactly the same physical features. This can be done by using sub-elements, from which the production part will be welded together on the production line. The sub-elements should be chosen so that they represent the complete measuring task most comprehensively. These chosen sub-elements are attached firmly to the micrometer device. It should be noted that the added weight of all the sub-elements attached to the micrometer should be less than the specified weight tolerance of the micrometer device.

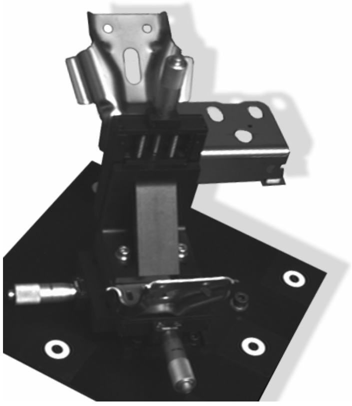

Figure 5. Micrometer device with attached sub-elements of the robot-welded IPS.

The measured features are measured in the 0-position. Then a set of movements are done according to Figure 6. One set of movements consists of 15 positions. There should be three sets of movements done, having altogether 45 measurements. All the movements should be in the range of expected variation of the real production and the length of a movement can vary between the three different sets. Also the three sets can be measured in different locations inside the measuring volume, if possible. From these known movements nominal positions for each feature in each measurement are calculated. The measured values are then compared to the nominal values.

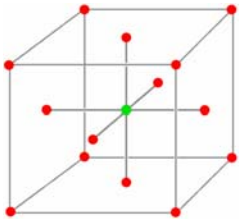

Figure 6. Movements done with the micrometer device.

As stated before, it is important to analyze the results in a form which is already accepted by the customer. Therefore the MSCRM is used as guiding basis. The C’gk (modified gage capability index) is calculated from the results with a slightly different approach. The nominal values of the certified master part are replaced with the nominal values drawn from the accurately (and certifiably) known movements of the micrometer. Also the standard deviation of the measurements can’t be directly used because the direct value of a measurement result varies dependent on the created movements. Therefore the used standard deviation is compensated with the nominal movements. The modified gage capability index (C’gk) is calculated as seen in Equation (12).

Following the guidelines derived from the MSCRM, if the calculated value for modified gage capability index, C’gk ≥ 1.33, the measurement system is capable.

Also from this test the lowest possible manufacturing tolerance can be solved as seen in Equation ( (13).

$$C'_{gk} = \frac{0.1\cdot T - \left|\bar{x}_{g-m}\right|}{2\cdot s'_g} = \frac{0.1\cdot T - \left|\frac{1}{n}\cdot\sum_{i=1}^{n}(x_{gi}-x_{mi})\right|}{2\cdot\sqrt{\frac{1}{n}\cdot\sum_{i=1}^{n}(x_{gi}-x_{mi})^2 - \frac{1}{n^2}\left[\sum_{i=1}^{n}(x_{gi}-x_{mi})\right]^2}} \tag{12}$$

$T$ = specified tolerance range for measured feature
n = number of measured positions
$\bar{x}_{g-m}$ = average difference between measured and nominal
$x_{gi}$ = measured value at position i
$x_{mi}$ = known value at position i
$s'_g$ = stdev of measurement values around the nominal values

$$T_{\min} = 26.6\cdot s'_g + \left|\sum_{i=0}^{n}(x_{gi}-x_{mi})\right|\cdot\frac{1}{n} \tag{13}$$

## 3.4 Verification in two stages

The problem of the traditional verification methods is that it either does not examine real production parts or if using real production parts it demands that the production is fully running and stabile. As stated in the beginning it is important to verify the accuracy of the measuring system as soon as it is delivered. When a measuring system is usually delivered the production is far from up and running. Therefore the verification must be divided into two chronologically separate stages, pre-acceptance and final acceptance tests.

### 3.4.1 Pre-acceptance test

The pre-acceptance verification procedure for Mapvision measuring systems is meant to be as comprehensive and as realistic as possible, even though it is usually done before any automatically produced production parts are produced.

Even though the state of readiness of the production line prevents the use of all of the tests described in MSCRM, the type-1 study can be carried out also with a hand-welded prototype part. If there is a measuring report from CMM, this can be used as a “true value” in the type-1 study even though this raises the questions of reliability of the CMM-measurement. This can be done if the system is calibrated with this particular part. Any other correlation between measurement systems should be only suggestive and not referred as part of pre-acceptance.

Second part of the pre-acceptance test is carried out following directly the micrometer procedure described in 3.3.

Carrying successfully out these two tests the capability is tested for repeatability measurement (Cg), repeatability measurement referenced to CMM (Cgk) and absolute measurement of changes, simulating the variation in production (C’gk ). The availability of measurement report from CMM defines whether the repeatability referenced to CMM (Cgk) is calculated in the type-1 study. If all of these calculated indices exceed or are equal to value 1.33 the measurement system is capable in the pre-acceptance stage and should be pre-accepted.

### 3.4.2 Final acceptance test

After the production line is up and running, at least up to a level where robot welded parts are produced and are stabile, the final acceptance test can be carried out with the measurement system. For this the type-1 and type-3 studies are carried out referring to MSCRM. If the studies are completed acceptably the measurement system should be accepted as capable. It should be noted that correlation to CMM (or any other measuring systems) is not in any form an acceptance criterion. Using industrial CMM-measurements of industrially produced parts as a true value (for example in the type-1 study) is incorrect and reveals the lack of understanding of industrial measurements and therefore props up the unjustified role of the CMM as the God-Given-Truth.

If the measuring task consists of measuring large unanimous geometries, also a linearity test of the calibrated volume should be carried out according to the VDI. Such measuring tasks could be the absolute measurements of surfaces extending across the whole calibration volume. For this kind of measuring tasks acceptance from the VDI test is needed for the capable measuring system status. If there are no measuring tasks fitting this description this test should not be done.

## 4. CONCLUSIONS AND DISCUSSION

When creating a verification method for the accuracy of a measurement system there are two important factors to be taken into notice. First the tests which are done have to assess the true accuracy of a measurement system in similar conditions in where the measurement system will be used. Secondly, the verification method must be acceptable from the party which will approve or disapprove the measurement system as capable to measure.

In this article these two important factors are taken as fundamental guiding principles. Previously the micrometer based test was not enough to automatically get the acceptance from the customer. Even though this test convinced the customer, the lack of commonly accepted way of defining and presenting the results withheld the official acceptance. On the other hand the commonly accepted test defined in the MSCRM was not doable at the time of delivery of the measurement system because of the incompleteness of the production line. The idea of the verification method described in this article arose from the idea of combining the benefits of both of these tests in an unanimous way.

One of the biggest problems in introducing this new method will be the credibility of the software for calculating and presenting the results. The problem is that in automotive industry the qs-STAT software from Q-DAS Inc. has reached the status of a de facto standard and is commonly used to present measurement results. The tests described in the MSCRM are supported by the qs-STAT. In a short timeframe it will be impossible to include this new method in qs-STAT. So the only way to introduce this new method for verification is to develop a software component for the acceptance. Getting the approval to use this software in the pre-acceptance will be debatable, even though the final acceptance can still be done traditionally with qs-STAT.

The organisations in the field of automotive industry are very conventional and big. As known, big ships turn slowly. One thing is to introduce a new measuring technology. Another thing is to introduce the idea of acceptance tests of measurement systems done in the way defined by measurement system manufacturer. For this it is important to have the idea published and raise discussion widely across the field of automotive industry as well as across the academic field of science. Anyhow, getting common approval for this new way of verifying the accuracy will clearly be a challenge.

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