A novel strategy for cost-efficient measurements with coordinate measurement machines

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Abstract. In this paper the choice of the best measurement strategy for coordinate measurement machines with multi sensor systems is investigated. A model is proposed which regards cost effectiveness as one main criterion for measurement strategies. The new model shows the dependencies between different cost fractions of the measurement. Therefore all cost fractions of multi sensorial measurement are determined and brought into relations. It is analysed how measurement uncertainty and speed of the measurement are connected and which ratio makes a measurement economic.

1. Introduction
One major task of metrology is the quality assurance of products. Increasing requirements to the specifications go in line with increasing requirements to the accuracy of coordinate measurement machines. Beside this the aspect, cost-effectiveness is getting more and more in focus. In economical difficult times, when companies are forced to reduce costs, quality assurance and with this the metrology as one part of it, have the chance to support this process. Beside methods of reducing the number of parts to be measured, the measurement itself has to be improved. Multifunctional and flexible measurement machines are one possible answer provided by the industry. One example are multi sensor coordinate measuring machines. Several sensors are integrated in one machine, which increases the field of applications. With increased flexibility of machines the education of the operator has to be better, too. The operator has to choose the right sensor with the right parameters to guaranty a precise and efficient measurement. To support the operator new support systems for measurement strategies are necessary. One approach for such a system is delivered in this paper.
2. State of the art

2.1. Definition

Measurement strategies contain all predefinitions of the operator to measure and analyse a measurement task. The following parameters are defined [1]:

- Definition of the coordinate system
- Probing strategy (number and position of the probing points)
- Touch probing sequence
- Measurement modus (Scanning or single point touch probing)
- Measurement speed
- Choice of the sensor (in multi sensor case)
- Illumination (for optical measurements)
- Criterion for analysing the measurement data
- and others

In normal case these parameters are defined by the operator. Depending on the knowledge of the operator the same measurement task can deliver different results.

To minimize human influence different standards have been established.

2.2. Standards

In the field of measurement strategies several publications and norms are published. Standards for using coordinate measurement machines are set by the Deutsches Institut für Normung (DIN). DIN12181-2 [2] deals with the calculation of the minimal number of touch points. DIN12780-2 [3] gives a limit for the maximum distance of touching points. DIN12781-2 [4] and DIN12180-2 [5] provide strategies for measuring the face of a plane or a cylinder.

2.3. Special approaches

Beside those standards different scientific works deal with field of measurement strategies. Main task of this research are automation measurements and optimizing the measurement strategy for special applications. An important work in the field of automation of measurements with optical coordinate measurement machines has been done by Toepfer [6], where the automation of focus, lightning and edge criteria is described. Approaches for determination of number and arrangement of measurement points are given by Bode [7], Gerlach [8] and Flack [9]. Buchholz [10] developed measurement strategies for micro gearwheels. A more general approach is given by Starczak [11].

The common goal of all introduced approaches is to reduce the measurement uncertainty of the measurement. The influence of measurement strategies to the uncertainty of the measurement is shown by Weckenmann [12].

3. Model for cost-efficient strategies

In contrast to most approaches the proposed method calls cost-effectiveness as its main goal. The philosophy behind this is to measure as precise as necessary and not as precise as possible. Basis for this model is the benefit equation

\[ G = E - K \]  

with \( G \) is the benefit, \( E \) is the proceeds and \( K \) are the costs caused by the measurement. Proceeds and costs depend on different parameters that are defined by the operator.
3.1. Costs of the measurement

The costs of the measurement are divided into cost for the preparation $K_V$ and cost for the execution $K_M$ of the measurement. The total costs of a measurement result from:

$$K = K_V + K_M$$  \hspace{1cm} (2)

Under condition that the time for preparation $t_V$ equals the busy time of the machine the costs for preparation $K_V$ result from:

$$K_V = t_V \times (k_p + k_{KMG})$$  \hspace{1cm} (3)

In this equation $k_p$ is the cost rate for employees and $k_{KMG}$ the cost rate for the machine. The time for preparation results from:

$$t_V = t_{d/all} + \left[ \sum_{i=1}^{m} t_Ei(x_{Sensor};CAD) + \sum_{a=1}^{b} t_{Va} \right] - \sum_{j=1}^{d} t_{Wj}$$  \hspace{1cm} (4)

with $t_{d/all}$ as time for loading the inspection plan, including times for creating the coordinate system and security areas. $t_Ei(x_{Sensor};CAD)$ is the time for handling the program to set parameters for each measuring point $i=1,...,m$ depending on the sensor and the existence of a CAD (Computer Aided Design) model of the object. In the case that no CAD model is available it also includes the time teaching in the element. $t_{Va}$ is the time for creating $a=1,...,b$ links between measuring points (e.g. for the measurement of the distance of two measurement points). $t_{Wj}$ represents teach in times of elements $j=1,...,d$ that used more than one times in the measurement procedure.

Under the condition that the time for the execution of the measurement $t_M$ equals the busy time of the operator the costs for the execution of the measurement $K_M$ result from:

$$K_M = t_M \times (k_p + k_{KMG})$$  \hspace{1cm} (5)

with

$$t_M = t_{Ein} + t_K + t_{KS} + t_A + n \times \left( \sum_{j=1}^{k} \sum_{i=1}^{m} t_{ij} + \frac{s_{Verf}}{v_{Verf}} + t_{TW} + t_{U} \right)$$  \hspace{1cm} (6)

where is $t_{Ein}$ the warm up time of the machine, $t_K$ the time for the calibration of the machine, $t_{KS}$ the time for creating the coordinate system and $t_A$ the time for mounting the test piece. To this the sum of $t_{ij}$, the time for measuring objects $i=1,...,m$ with the sensor $j=1,...,k$, plus the time for positioning, represented by the distance between measuring objects $s_{Verf}$ divided by the speed for the positioning $v_{Verf}$, added by $t_{TW}$, which is the time for changing the sensor, and $t_{U}$, the time for changing the test piece, if more than one is measured. This sum is multiplied by $n$, which is the number of pieces.

3.2. Proceeds caused by the measurement

On the positive site of equation (1) there are proceeds. Proceeds are achieved when parts are sold to the customer. Those proceeds depend on the output of the measurement. There are four possible cases for the selling company:

- conformable test piece is measured correctly
- conformable test piece is measured wrong and considered scrap
- non-conformable test piece is measured correctly and considered scrap
- non-conformable test piece is measured wrong and delivered to the customer

In case one the measurement causes proceeds, as the piece can be sold. Cases two and three cause internal costs, as the parts have to be reworked. In case four external cost plus costs for the wrong delivery are generated. The view can be widened up by including the customer measurement and decision process. The customer of course has the same choices in its incoming goods inspection.

The financial consequences can be calculated with:

\[
E_K = \sum_{i=1}^{n} m_i \times e - \sum_{i=1}^{n} m_i \times k_i
\]  

(7)

and

\[
m_i = m \times p_i
\]  

(8)

In this equation \(E_K\) is the proceeds, \(m_i\) is the amount of pieces of each decision \(i=1,\ldots,n\), \(e\) is the proceeds rate, \(k_i\) is the cost rate of each decision, \(m\) is the total amount of pieces and \(p_i\) is the probability of each decision.

The probability of the decisions can be calculated with convolution integrals [13]. It depends on the average and the standard deviation of the production and measurement process.

**4. Results**

The proposed method calls cost-effectiveness as its main goal. The philosophy behind this is to measure as precise as necessary and not as precise as possible. To calculate the probabilities for equation (7) convolution integrals are used. Those integrals deliver probabilities depending on average value and standard deviation of the measurement. Those parameters are strongly influenced by the measurement strategy. The more points are used for the measurement, the smaller are average value and standard deviation. But by measuring more points the times for preparation and measuring grow, that increases the costs of the measurement.

Figure 1 shows this relation. The broken line represents the proceeds caused by the measurement, the pointed line stands for the costs of the measurement and the full line represents the benefit.

Precise measurements guaranty a save information on the conformity of the measured probe. One risk is that conformable test pieces are tolerated too strict and because of the precise measurement are considered scrap. At the same time the cost of precise measurements are very high. This is why the benefit line starts with negative values. By lowering the precision of the measurement it gets cheaper. But it also increases the risk that non-conformable pieces are not detected and get to the customer what means costs for service and callbacks. This lowers the proceeds.

The result of the proceed line and the cost line is shown by the full line, the benefit line. It rises as long as cost are going down and the measurement is still precise enough that high proceed can be achieved. After the benefit line passes its maximum, costs for the measurement decrease, but the measurement is not precise enough. Wrong decisions can follow, wrong measured parts may be delivered to the customer, external cost rise. The maximum of the benefit line represents the cost optimal measurement strategy.
5. Discussion and future prospects
This paper shows a new approach for finding a cost optimal measurement strategy. As cost
effectiveness is one major task for the industry quality assurance has to contribute this. The model first
sums up all cost categories in a cost equation and fits this equation with the proceedes. By matching
costs and proceeds a cost optimal measurement strategy can be calculated.
Cost efficiency of the measurement can only be realized by minimizing the cost of the
measurement. For this purpose the measurement times especially have to be reduced. A closer look at
equation (6) shows that many of the time categories depend on the measurement machine, such as
warm up time, calibration time and other. Only a few parameters can be influenced by the operator.
These are the travel time on the measurement object. This is restricted by travel speed of the machine.
But the overall distance can be reduced by bringing the measurement point in a distance minimal
order. A second parameter that can be influenced is the time for changing the sensors of multi sensor
coordinate measuring machines. In this case especially the number of changes and the time in the
measurement program has big influence on the measurement time. A third parameter that is influenced
by the operator is the time for measuring one measurement point. This time depends for example on
the number of touch points and influences the measurement of the measurement. Another leverage is
the mounting time for measuring piece. Especially in the case of serial measurement of many objects
this factor effects the measurement time.
The minimization of those factors will be subject of future researches.

6. Acknowledgements
We thank the Faculty of Mechanical Engineering for the support. We express our gratitude to the
research program Innoprofile which is funded by the BMBF (Federal Ministry of Research and
Education).
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