

REDUCING OPERATOR INFLUENCES ON RESULTS IN COORDINATE METROLOGY VIA A HOLISTIC QUALIFICATION CONCEPT

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Abstract: *In coordinate metrology, the operator has a significant influence on the measurement result. Therefore an adequate qualification for the correct performance of measurement tasks is a necessary precondition for reliable measurement results. To impart the required competencies in an efficient and sustainable way, preparative and accompanying measures of qualification have to be combined into a holistic concept adapted to the operator's needs and the requirements of industrial application. By mutual amendment of fundamental training in coordinate metrology and continuous learning via a workplace integrated assistance system, an efficient way is provided to reduce human influences on the measurement results and to increase their traceability.*

Key words: *Coordinate metrology, advanced vocational training, assistance system, workplace-integrated qualification, life long learning.*

1. INTRODUCTION

An efficient quality management is a condition for the success of a company. In order to choose adequate measures of quality management and to implement them according to the current circumstances, reliable information about products and processes are needed. These are mainly gained by procedures of manufacturing metrology. There, currently coordinate measuring machines are one of the most important measuring devices, due to their flexible applicability for the measuring of workpieces with complex shape and high demands on accuracy. Regarding the measurement uncertainty of coordinate measures, the influence of the operator outweighs by far the influences caused by environment, the work piece itself or the measuring machine.

To execute the measurement tasks correctly, the operator needs extensive knowledge, not only regarding the handling and programming of the machine, but also regarding the definition of a proper measuring and evaluation strategy and its correct execution. Misunderstanding or sheer lack of knowledge can lead to significant deviations of the measurement result. Thus, a proper qualification of the metrologist is an indispensable condition for achieving reliable and comparable measurement results. Considering the fast development in the field of metrology, the required competencies can not be gathered sufficiently via basic vocational education. In fact, continuous learning in advanced vocational training is demanded to maintain, deepen and enlarge the once achieved skills. Otherwise the knowledge will become inert or obsolete, e.g. after a revision of standards, and hence inapplicable. Therefore, it is necessary to provide a holistic concept for the gathering and maintenance of the needed

knowledge in an adequate and efficient way, adapted to the requirements of advanced training.

2. ANALYSIS OF EXISTING TRAINING OFFERS

Each measure of advanced vocational training has to fulfil requirements regarding on one hand the achievement of certain learning objective, on the other hand economical aspects as well as operational conditions of industrial working. It is necessary to assure via the chosen method of qualification, that the operator has sufficient knowledge to perform his measurement tasks correctly, and that he is able to apply this knowledge competently on a specific task. Also, the imparting of knowledge has to be maximal time and cost efficient. The chosen method has to provide enough flexibility for the learner regarding compatibility with other duties but also adaptation to existing competencies and specific professional experiences or concerns. To fulfil those requirements, an adequate methodology of training has to be defined.

Two main categories of measures to impart the necessary knowledge may be distinguished: Preparative measures of qualification that impart the necessary knowledge in a general way detached from a specific task, and integrative measures of qualification that provide needed information on demand close to its application.

2.1. Preparative measures of qualification

Preparative measures of qualification exist in a large variety, differing in the used methodology, e.g. face-to-face seminars, eLearning or combinations, as well as the imparted knowledge. Regarding the handling of the coordinate measuring machine – including utilization and

programming as well as maintenance – many courses are offered by the manufacturers of the machines. By these courses the participants mainly gain procedural knowledge for the actual performing of the measurement with their respective machine.

Courses imparting fundamental theoretical knowledge are provided by independent institutes but also by manufacturers. Yet, many employers are not aware of the necessity of training in theoretical basics. Therefore, the participation in courses is still the main and often the sole form of qualification for most operators. By attending adequate courses, it is possible to achieve comprehensive knowledge regarding both declarative knowledge about fundamentals and procedural knowledge about the handling of the machine. Yet, to transfer the gathered general information to a special task is often experienced as very difficult and is therefore prone to highly subjective or even erroneous interpretation. This situation can be eased to a certain degree by including into the education problem-based learning with practical tasks. But still the adaptability of knowledge is to be considered a critical aspect.

Also, the learner after having finished the course is not supported in the maintenance of his competencies. Information often has to be gathered by self conducted inquiries in standards, books or internet. Of course this does not always lead to a satisfactory understanding of complicated subjects. So problems occurring in the gaining and interpretation of measuring results, whether between customer and supplier or between different sections of an organisation, are often caused by misunderstanding or sheer lack of knowledge. Hence, the direct impact of preparative learning offers on the reliability of measurement results is to be considered unsatisfactory.

2. 2. Integrative measures of qualification

The most common method of integrative qualification is the traditional on-the-job training by an expert, e.g. a foreman or a senior member of staff. By this method, the learner will have optimal support adapted to his needs and the actual context of work – provided the mentor has enough knowledge and experience regarding both the field of coordinate metrology and didactical aspects. If the expert himself has deficient or obsolescent knowledge, the training can not lead to the desired qualification. Also, during the period of qualification, the expert will not be available to perform his own tasks. To ease these problems, instead of experts various information or assistance offers may be used, such as guidelines or good practice examples or context-sensitive assistance-systems. Here, the operators eventually have to get used to the handling of the system first before using it for learning. For the execution of a measurement task without a profound preknowledge, it would be necessary for the operator to look up a lot of information for each step of the working sequence executing the measurement. This would be very time consuming and also frustrating for the operator as accordingly the progress of work will be very slow.

The knowledge gathered via integrative measures of

learning is adapted very well to the specific problem at hand and therefore immediately contributes to a correct performance of the measurement task. Yet, during the phase of basic introduction to the topic, the productivity is decreased considerably due to the efforts necessary to impart the required knowledge beforehand (Fig. 1).

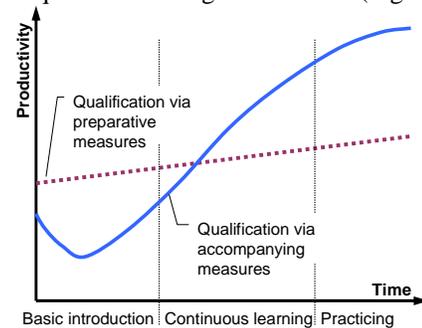


Fig. 1: Progress of productivity with preparative and integrative measures (Severing 1994)

Thus, pressure of time and cost efficiency in production prohibits a suitable gathering of background information, but enhances a sharp focus on the actually needed information. Therefore it is not recommendable to use integrative measures as a single source of qualification, as this would lead to a merely fragmentary understanding of the area. On long term, this would not enable the operator to solve other tasks on his own.

Taken as a sole source of qualification, neither preparative nor integrative measures provide the required comprehensive, efficient and continuous imparting of necessary knowledge. Therefore, it is necessary to blend both in a holistic concept with a strong view on adaptation to the operator's needs and requirements. In order to augment the respective advantages and extinguish the disadvantages, methods have to be chosen considerably out of the existing offers. Preparative learning offers have to give a profound basis for integrative qualification via the assisted execution of measurement tasks, during which additional information may be gained and the transfer of the gathered knowledge to the specific situation is supported.

3. PREPARATIVE QUALIFICATION VIA THE TRAINING CONCEPT EUKOM

The comparability of competences imparted in a training offer is very important for the sustainable assurance of an adequate level of qualification among the employees in coordinate metrology. This allows for a more reliable rating of the present skills of an operator. Therefore, the possibility to access a commonly accepted certificate is highly appreciated by the attendees of the training. This considerably increases the motivation to participate in the course actively and successfully. Thus, in order to define a concept of qualification it is necessary to choose an offer of preparative training which provides a standardized education. Although there are many offers for preparative training, most of them do not fulfil this

requirement. Rather they focus on specific topics and interests. Therefore the training concept EUKOM was developed by a consortium of institutes in several European countries to provide a Europe-wide harmonized training on basic knowledge for coordinate metrology. (Weckenmann et al. 2005). The training is divided into three consecutive levels according to the complexity of tasks the participants are expected to handle afterwards:

- A *CMM (Coordinate Measuring Machine) – User* is able to execute a measurement, if the measuring routine is already planned and prepared. Additionally, he is able to perform simple standard tasks on his own, where no complex planning operations are necessary.
- A *CMM-Operator* can execute a complete measurement task, including analysis of the task, definition of measuring and evaluation strategy and implementation of the measuring routine. Also he is able to estimate the uncertainty assigned to the measurement result and knows about ways to reduce adulterant influences.
- A *CMM-Expert* is able to plan, prepare and perform even very complex measurement tasks. Additionally he fulfils management functions in the administration and control of a measurement room. This level of qualification is usually taken only by metrologists who have been working several years in this area, fulfilling the tasks of a CMM-Operator.

For each level a curriculum is defined, which describes the contents of the section and the intended amount of information assigned to each topic (Table 1). To enable flexible learning, the course is based on a Blended Learning concept. Theoretical information is imparted via web-based modules that allow for self-controlled learning, adaptable to the pre-knowledge and interests of the individual participant. Time and place of learning can be adapted to other duties. Thus, the course offers the flexibility required for an efficient imparting of knowledge oriented on the constraints of advanced training.

The modules are provided via a web-based learning platform, which offers also possibilities for communication among the participants. During the self conducted work on the modules, a tutor is always available for support. The tutor needs experience and skills in measuring as well as pedagogical competencies, to support the learners adequately. After the end of the learning phase, a face-to-face-workshop is held, where the gathered theoretical knowledge can be applied to concrete tasks and exercises. There is also the possibility to discuss questions or problems. Each course is concluded with an examination, which forms the base for the receipt of the certificate. Additionally, a start workshop is offered. Here the learners are introduced to the concept of eLearning – which is still widely unknown in the target group – and to the handling of the platform. Also they get to know the other participants of the course. This strongly reduces difficulties regarding the unknown form of learning and the high demands on self organization of learning progress. As self-controlled learning is not yet very common in vocational training, an additional module is offered explaining basic

principles and helping the learner in structuring his own learning efforts.

Table 1: Curriculum of the EUKOM training concept

	Content	Time
Level 1: CMM-User	Start Workshop	1 d
	1-01 Measurands & units in coordinate metrology	2 h
	1-02 Location in plane	3 h
	1-03 Location in space	3 h
	1-04 Geometric features	3 h
	1-05 Geometric links	2 h
	1-06 Fundamentals of metrology and testing	8 h
	1-07 Basic elements of a CMM	4 h
	1-08 Types of CMM	2 h
	1-09 Preparation of measurements at CMM	3 h
	1-10 Stylus configuration and qualification	3 h
	1-11 Measurements with CMM	4 h
	1-12 Evaluation of measurements and statistics	3 h
	1-13 Accuracy	3 h
	1-14 Basics – Quality management	3 h
1-15 Self-organised learning	10 h	
Thematic Workshop with final examination		
Practical Experience		
Level 2: CMM-Operator	2-01 Overview – complete measuring sequence	3 h
	2-02 Overview – Geometry	2 h
	2-03 Tolerances of size	6 h
	2-04 Geometrical tolerances	16 h
	2-05 Measurement strategy	5 h
	2-06 Probing strategy	5 h
	2-07 CNC programming	4 h
	2-08 Evaluation	5 h
	2-09 Influences on measurement result	5 h
	2-10 Documentation	3 h
	2-11 Use of statistical parameters	5 h
	2-12 Statistic process control	5 h
	2-13 Basics – Inspection equipment monitoring	6 h
	2-14 Basics – Quality management	4 h
Thematic Workshop with final examination		
Practical Experience		
Level 3: CMM-Expert	3-01 Expert knowledge – Geometry	2 h
	3-02 Basics – Manufacturing	2 h
	3-03 Basics – CAD	6 h
	3-04 Expert knowledge – Datums	6 h
	3-05 Expert knowledge – Geometrical tolerances	16 h
	3-06 Optimized measuring sequence	6 h
	3-07 Expert knowledge – CNC programming	8 h
	3-08 Digital filtering and evaluation	6 h
	3-09 Stochastic	4 h
	3-10 Evaluation of measurement uncertainty	16 h
	3-11 Quality management	6 h
	3-12 Monitoring of CMM	12 h
	3-13 Quality costs	4 h
	3-14 Digitizing of freeform surfaces	6 h
	3-15 Good Coordinate Measurement Practice	8 h
	3-16 Measurement room management	4 h
Thematic Workshop with final examination		

Due to the uniform structure and contents, the gained certificates are commonly accredited by employers all over Europe. Thus the training concept provides an efficient facility to gather comprehensive fundamental knowledge

for the correct execution of tasks in coordinate metrology.

4. INTEGRATIVE QUALIFICATION VIA AN ASSISTANCE SYSTEM

The intended measure for integrative learning shall offer an efficient facility to enhance the transfer and deepening of gathered knowledge. At the same time, it is a strong desire of both operators and their employers to constantly assure the correct execution of measurement tasks. These two aims can be reached efficiently by the use of a comprehensive and context-sensitive assistance system. Although there is a large variety of assistance offers, provided by the manufacturers of the measuring machine, these are not adequate to be used as a facility for continuous learning. Mostly they focus on support during the implementation of the measuring routine, but do not offer help at all for the planning of the measurement. Yet, the decisions made in this phase may most strongly influence the result of the measurement. Other solutions support the operator by providing automatically generated routines. Here it is very difficult for the user to understand the reasons for the made decisions. Therefore this will not lead to a better understanding of the underlying principles, but on the contrary hides the danger of too much trusting into the generated routine without further control. Therefore, a comprehensive assistance system was developed, that fulfils two main objectives during the performance of the measurement tasks: Ensuring the correct execution of the measurement task and providing required knowledge.

Ensuring the correct execution of the measurement task includes detecting and indicating errors of the operator or actions that are not congruent with specified rules. Thus, a lack or misinterpretation of knowledge can be identified and corrected. On one hand this enables the metrologist to gather information adapted to his own needs, on the other hand such supervision of his actions helps to assure the quality of the gathered measurement results. Yet of course the metrologist needs the freedom to choose his actions and must not be forced by the system in any way.

By providing knowledge required for the proper execution of the task, the assistance system on one hand offers a stimulation to remember the gathered information and to connect it to its actual usage. On the other hand it provides a possibility for continuous learning adapted to the respective problem. Provided the contained data and information is actualised regularly, the operator will be informed about developments relevant for his tasks, e.g. changes in standards. Thus, the decay of knowledge is prohibited and the relevance of information for the execution of a specific task is shown. Here, too, the operator needs enough freedom of control to which extent information shall be offered, so that it can be adapted to his specific state of knowledge or interest and to current constraints such as available time.

Beside these main objectives, a lot of requirements have to be met in order to provide an efficient assistance solution. These contain demands on hardware and software

as well as aspects of user friendliness in the use of the system.

4. 1. Structure of the assistance system

The two main objectives of the assistance system may be subdivided into a number of different functionalities. These were classified and compiled so that three basic components have been identified (Figure 2):

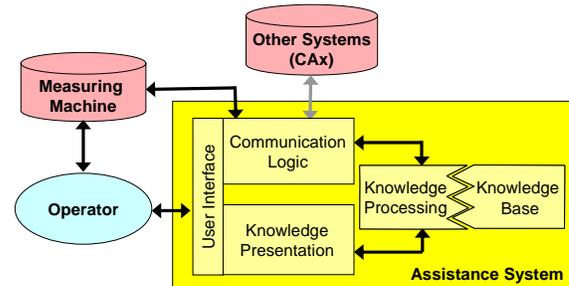


Fig. 2: Basic structure of the assistance system

- The *knowledge processing* offers active assistance, i.e. the component analyses input data and parameters, identifies mistakes and errors and determines presets for the current operation. It interacts with the knowledge base that stores all required information and decision rules.
- The *knowledge presentation* offers passive assistance, i.e. the component presents required information and thus supports the decision process and execution of the individual operations. It also provides background knowledge that can be accessed on demand.
- The *communication logic* serves for the interaction between assistance system, operator and coordinate measuring machine as well as for the data transfer with other systems relevant for the execution of the measurement task, e.g. quality-related data from a CAQ (Computer Aided Quality) system or design information from a CAD (Computer Aided Design) system. It also comprises the user interface and presents the data that are provided by the knowledge processing and the knowledge presenting component.

For a comprehensive assistance these components have to interact well-adjusted, so that active and passive assistance complement each other.

4. 2. Definition of a methodology for the execution of tasks in coordinate metrology

It is a precondition for a comprehensive assistance, that the execution of measurements can be based on a uniform and methodical procedure. Thus, it is possible to provide assistance and information targeted on the currently prepared work step. A methodical procedure allows for an efficient execution of tasks, so that no iteration has to be done and no mistakes occur, which are caused in a non-systematic approach. Thus, the definition of a methodical procedure contributes as well to a uniform and comparable

approach as to a target-oriented and efficient working. Based on this methodology, the assistance system can provide the operator with an important orientation guide. Since for a successful application the assistance has to be adapted precisely to the currently executed work step, a methodology is required that describes and systematises the different steps in detail. A procedure for the execution of a task in coordinate metrology consisting of seven steps is widely accepted (Weckenmann & Gawande 1999):

- Analysis of the measurement task
- Determination of the measuring strategy and evaluation strategy
- Planning the measurement and setting up the inspection plan
- Preparation of the measuring routine
- Execution of the measurement
- Evaluation of the measurement results
- Estimation of the measurement uncertainty

Based on these steps, a detailed methodology has been developed. This includes all individual operations in a defined sequence, which leads to an effective execution of the measurement task and which avoids the subsequent modification of already defined parameters. It can be used both as a basis for the intended assistance system, but also as a guideline for the efficient and systematic execution of measurement tasks without support by a system.

After defining the methodology, for each step it has been identified which support by the assistance system would be useful for the operator. This includes for example the composition of data to be presented - either immediately when reaching this step or on demand as background information - or the specification of test routines to check if the operator has given all required data (Beetz 2006, Weckenmann et. al. 2005).

Thus, the interaction of operator and assistance system is carefully designed to provide optimal support during all steps of the execution of the measurement task. Based on the developed structure and methodology, a prototypical system was realised. Some simplifications were made, but without reducing the utilisability. So the prototype may be used to test the developed concept.

5. COMBINATION OF ACCOMPANYING LEARNING AND FUNDAMENTAL TRAINING

To achieve a sustainable learning effect, it is useful to transfer gathered knowledge to actual use in close time. On the other hand, the learner has to have sufficient basic understanding first before trying to solve an actual task, in order to avoid an overstraining. That would be discouraging and therefore inhibiting for the further learning process. Therefore it is recommended to augment the difficulty and complexity of the actually set task adapted to the existing knowledge of the learner. This way, the possibility of gathering additional knowledge can be used optimally, as the interest of the learner for further information is stimulated by a better understanding, but he is also free to concentrate on his actual task and the usage

of current knowledge.

5.1. Schedule of learning contents

The idea of continuously increasing requirements fits well with the system of three successive levels in the training concept EUKOM.

Table 2: Combination of preparative training and integrative learning with the assistance system

	Measure of qualification	Objective
Training on basic level	Course on basics (CMM-User)	Basic understanding of the coordinate measuring machine Preparation and execution of simple measurement tasks
	Course on handling of the specific CMM by manufacturer	Execution of measurements with prepared measuring routine
	Execution of tasks supported by the assistance system: Execution and evaluation of measurements Preparation of simple tasks	Transfer of newly gained knowledge to actual tasks Gaining of background knowledge for better understanding
Working experience		
Training on advanced level	Course on advanced knowledge (CMM-Operator)	Interpretation of product specifications Planning, preparation and execution of complex measurement tasks
	Course on programming of the specific CMM by manufacturer	Implementation of measuring routines
	Execution of tasks supported by the assistance system: Planning and execution of complex measurement tasks	Transfer of newly gained knowledge to actual tasks Gaining of advanced knowledge for special applications Deepening the understanding of underlying principles
Working experience		
Training on expert level	Course on expert knowledge (CMM-Expert)	Management and administration of measurement rooms Calculation of measurement uncertainty Planning, preparation and execution of highly complex measurement tasks
	Course on maintenance and of the specific CMM by manufacturer	Inspection of accuracy of the measuring machine
	Execution of tasks supported by the assistance system: Planning and execution of highly complex tasks	Avoiding mistakes out of typical human weaknesses Refreshing and actualising of specialised knowledge

Regarding the defined levels of qualification, the CMM-Operator may profit most of the support by an assistance system. He has to perform complex tasks that require a lot of knowledge, but he does not yet have the

deep experience of a CMM-Expert. But also CMM-Users may profit strongly, as they are reminded of the proper execution of their tasks and have access to further information, if they are interested. Thus, they can enlarge their knowledge continuously and raise accordingly the complexity of the tasks they perform as a preparation for taking the next level of a CMM-Operator.

For CMM-Experts the assistance system is mainly to be seen as source of support to avoid mistakes out of typical human weaknesses, such as lacking concentration or forgetfulness. By that, the system may help to assure the execution of complex measuring tasks on a constantly high level, and provide a possibility to adjust to recent developments in order to avoid obsolete knowledge.

Thus, the tasks have to be selected carefully and with a continuously raising degree of difficulty. Then the assistance system will be a valuable source for learning, aiming at different objectives in every phase of qualification (Table 2).

5.2. Requirements on the use of integrative measures

Beside an adequate selection of tasks, the constraints during the assisted work on the set problems also have to allow for learning. If the situation does not enable self-guided working and a comprehensive considering of the advice offered by the assistance system, but only a strict processing of instructions, a learning process will not be possible. Then the learner will not be able to gain the intended deeper understanding of gathered knowledge. These requirements can be divided in several basic aspects (Severing 1994):

- The tasks should on one hand require transfer and adjustment of general knowledge to the actual situation in an entire specific way, but on the other hand they should be solvable in a systematic way.
- The environmental conditions have to allow for concentrated working. This includes, among other aspects, an acceptable level of noise as well as general requirements on human working conditions.
- The organisational constraints of the workplace have to allow for learning accompanying working. This requires especially a certain degree of freedom in the performance of assigned tasks, regarding both the needed time and the general scheduling.

In a typical working environment in coordinate metrology, these requirements are to be regarded as principally met. Yet, it is necessary that the employer supports the learning process and therefore allows for the required freedom. This grant will be rewarded immediately by a higher motivation of the employees and a better traceability and accuracy of the achieved measurement results due to a deeper understanding of the underlying principles.

6. CONCLUSION AND OUTLOOK

By the combination of preparative and integrative

measures into a holistic qualification concept, necessary competences for the proper execution of measurement tasks can be imparted in an efficient way, adapted to the requirements and constraints of advanced vocational training. An adequate election of an offer for preparative learning enables the learner to gain profound knowledge about fundamentals and principles. Here harmonized training courses allow to rate the basic competencies reliably on the basis of acquired certificates. Assistance systems as instruments of integrative learning provide an effective possibility to immediately raise the accuracy and traceability of measurement results.

For an efficient use, it is necessary to combine systematic learning via preparative training with problem-based learning via the assistance system adapted to the currently available pre-knowledge of the learner. Thus the transfer of general information on a special task is supported and a deeper understanding of the underlying principles is facilitated. Additionally, continuous learning is enhanced, accompanying daily work or even being an integrated part of it. To this aim, the developed prototypical assistance system has to be fully implemented and integrated into the common working environment. Thus, a closer connection between learning and working may be realized, leading to a continuous enlargement of knowledge and consequently to a continuous raising of the reliability of gathered measurement results.

7. ACKNOWLEDGEMENT

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