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Training program for the metric specification of imaging sensors

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ABSTRACT
Measurement systems in industrial practice are becoming increasingly complex and the system-technical integration levels are increasing. Nevertheless, the functionalities can in principle always be traced back to proven basic functions and basic technologies, which should, however, be understood and developed. For this very reason, the teaching of elementary basics in engineering education is unavoidable. The present paper presents a concept to implement a contemporary training program within the practical engineering education on university level in the special subject area of optical coordinate measuring technology. The students learn to deal with the subject area in a fundamentally oriented way and to understand the system-technical integration in detail from the basic idea to the actual solution, which represents the common practice in the industrial environment. The training program is designed in such a way that the basics have to be worked out at the beginning, gaps in knowledge are closed by the aspect of group work and the targeted intervention of a supervisor. After the technology has been fully developed theoretically, the system is put into operation and applied with regard to a characterizing measurement. The measurement data are then evaluated using standardized procedures. A special part of the training program, which is to promote the own creativity and the comprehensible understanding, represents the evaluation of the modulation transfer function of the system by a self-developed algorithmic program section in the script-oriented development environment MATLAB, whereby students can supportively fall back on predefined functions for the evaluation, whose implementation however still must be accomplished.

Section: RESEARCH PAPER

Keywords: Measurement education; measurement training; engineering education; hands-on pedagogy; image sensor characterization

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1. INTRODUCTION

Optical coordinate metrology is an essential part of industrial automation and inspection processes. Therefore, this subject area should play an essential role in today's engineering education in courses such as mechanical engineering, electrical engineering, computer science or engineering informatics. Thus, the question arises, how to efficiently teach essential contents, which are necessary for a successful handling of this topic in engineering practice. The requirements are that both the basics and the relevance have been understood, and that the systems engineering integration can be implemented on the basis of the learned knowledge and transferred into a functional system.

Group work and the targeted intervention of a supervisor play an essential role here. Not only in order to close existing knowledge gaps in a targeted manner, but also in order to train the cooperation in teams with corresponding social competence, which is inevitable in practice.

The central topic of the program is the metric characterization of imaging sensors. With regard to practice, two essential technological aspects can be taught through this. First, it is crucial for the implementation of a test system to be able to evaluate and classify geometric product specifications (GPS) characterized by the manufacturer of an image sensor, i.e., ultimately to be able to understand its test procedure. Secondly, this makes essential principles of image signal processing accessible and also provides a practical and comprehensible application case, which proves the usefulness of the methods and thus offers the motivation directly on the basis of the concrete example. The standard DIN EN ISO 10360 [1] is used as the basis for the methodical procedure; for coordinate measuring machines with optoelectronic sensors, the VDI standard 2617 [2] is used specifically. It describes the inspection of coordinate measuring machines by measuring calibrated test samples. This involves checking whether the measurement deviations are within the limits specified by the manufacturer or user. The test samples must be such that their properties do not decisively influence the parameters to be determined. The characterization is carried out on the basis of the principle described in [2] a circle measured at five different positions. For this purpose, a calibrated chrome standard and a through-light unit are used. After completion of the measurements, the results are to be statistically evaluated in accordance with the standard. In addition, the determination of the modulation transfer function (MTF) is intended to provide an assessment of the resolving capability of the overall system and to train an in-depth algorithmic understanding of 2D image processing.

2. THEORETICAL BACKGROUND

2.1. Problem description

The metrological problem with which the students are to be confronted is described in Figure 1. A calibrated sample with a circular ring (object) is placed as a normal on a light source. The circular ring passes (as a negative) through an optical system which consists of lenses and apertures. The image that is consequently created on the sensor surface deviates from the original image due to optical and mechanical influences. In addition, geometric quantization during scanning within the image sensor produces a further measurement deviation. All deviations in sum result in a total measurement deviation which has to be determined. Further it can be observed that with a change of the position of the object (5 different positions in [2]) due to the influences of the optics and mechanics the measured diameters of the circular rings differ. This also has to be quantified.

2.2. Analysis of measurement uncertainty

All image processing algorithms are already implemented in software, so that the diameter of the circular ring is output as the result of the measurement. The algorithms for edge detection are subpixel-based and very complex, therefore a more detailed description is not provided within this paper so reference is made to special literature [3]. More crucial for the metric testing of the image sensor system is the consideration of the measurement uncertainties. According to the formulas 1-3 the total measurement uncertainty can be determined.

The measurement uncertainty describes the deviation behaviour of the overall system. The total value of the measurement uncertainty is determined by the errors of the two essential assemblies, the mechanical and the optical measuring device, and results from:

$$U_{\mathrm{total}} = \sqrt{U_{\mathrm{mech}}^2 + U_{\mathrm{opt}}^2}\,. \tag{1}$$

Both mechanical and optical measurement uncertainty can be further divided into systematic and random measurement uncertainty. They result from:

$$U_{\mathrm{mech}} = \sqrt{U_{\mathrm{sys,m}}^2 + U_{\mathrm{random,m}}^2} \tag{2}$$

and

$$U_{\mathrm{opt}} = \sqrt{U_{\mathrm{sys,o}}^2 + U_{\mathrm{random,o}}^2}\,. \tag{3}$$

The systematic measurement uncertainty is usually specified by the manufacturer and is determined from comparative measurements with calibrated standards. Within the training program these are given to the students.

The random measurement uncertainty, on the other hand, is determined by several measurements carried out in the training program under the same environmental conditions and with the same test specimen. The standard deviation can now be calculated from the measured values obtained.

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}\,. \tag{4}$$

The random measurement uncertainty $U_{\mathrm{random,MS}}$ of the measurement series $U_{\mathrm{zuf,MR}}$ is now obtained, using the 95.4% confidence level.

$$U_{\mathrm{random,MS}} = \frac{2\,\sigma}{\sqrt{n}}\,. \tag{5}$$

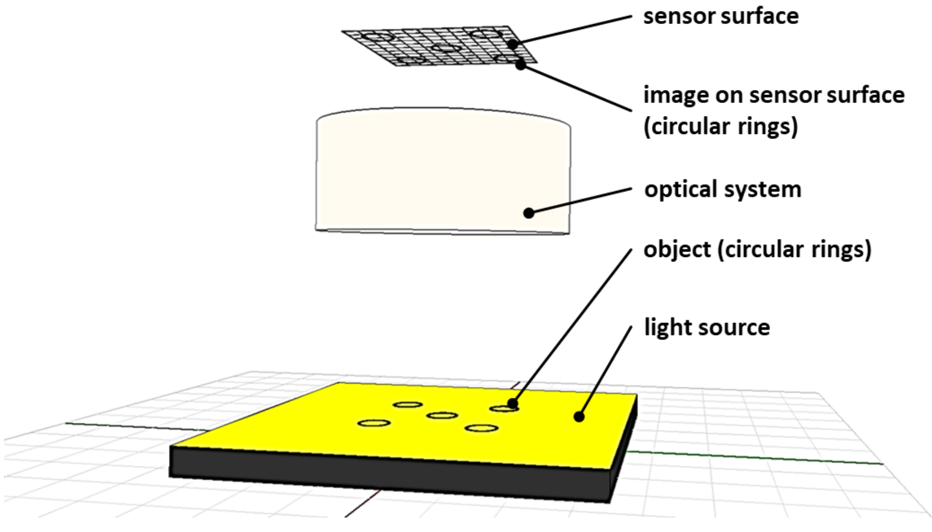

Figure 1. Schematic system description.

However, since the mechanical and optical measurement uncertainties in the measurement result cannot be separated directly with the available setup, the evaluation is simplified somewhat at this point and only predefined systematic deviations are included in the calculation of the total measurement uncertainty.

2.3. Modulation transfer function

There are several approaches to determine the modulation transfer function (MTF). The main approaches are part of the teaching in parallel to the designed training program and are presented in the lectures. A simple and practically easy to understand method is described in [4] and [5]. Thereby, the intensity differences (contrasts, $I_{\max} - I_{\min}$) of a search ray orthogonal to a rectangular signal are evaluated. If instead of the rectangular signal a sinusoidal signal is assumed, the contrast transfer function $CT(f)$ goes directly over into the modulation transfer function $MTF(f)$. Basically, the contrast ratios of the pattern in the image $K(f)$

$$K(f) = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \tag{6}$$

have to be put into the ratio to the contrast in the object space $K'(f)$.

$$K'(f) = \frac{I'_{\max} - I'_{\min}}{I'_{\max} + I'_{\min}} . \tag{7}$$

Plotted over the sampling points of the spatial frequency f as reciprocals of the line distances defined by the object, the MTF can thus be approximated

$$CT(f) = \frac{K'(f)}{K(f)} \approx MTF(f) . \tag{8}$$

For the calculations according to (6), (7) and (8), all values can be determined from the measurements, which is why these formulas must also be implemented by the students in the practical part. Complex examples for modulation transfer functions of spectral sensors are given in [6].

3. MEASUREMENT SYSTEM DESCRIPTION

3.1. Measurement system

The system used for the experiment is shown in Figure 2. It consists of a monochromatic camera ①, a telecentric objective ②, a light table for measurement using the transmitted light method ③, a halogen-based light generator ④, and a stand construction in column design ⑤.

3.2. Measurement targets

Two samples are used for the training program. The first sample is shown in Figure 3 (left). In the sample, the metric dimensions are represented by circles. These circles are moved to the 5 positions described and the diameter of the corresponding circular ring is measured there in each case. The Second sample is a U.S. Air Force (USAF) test chart shown in Figure 3 (right), based on which the modulation transfer function is determined.

4. TRAINING PROGRAM CONCEPT

The training program is shown as a flow chart in Figure 4 and is described in detail below.

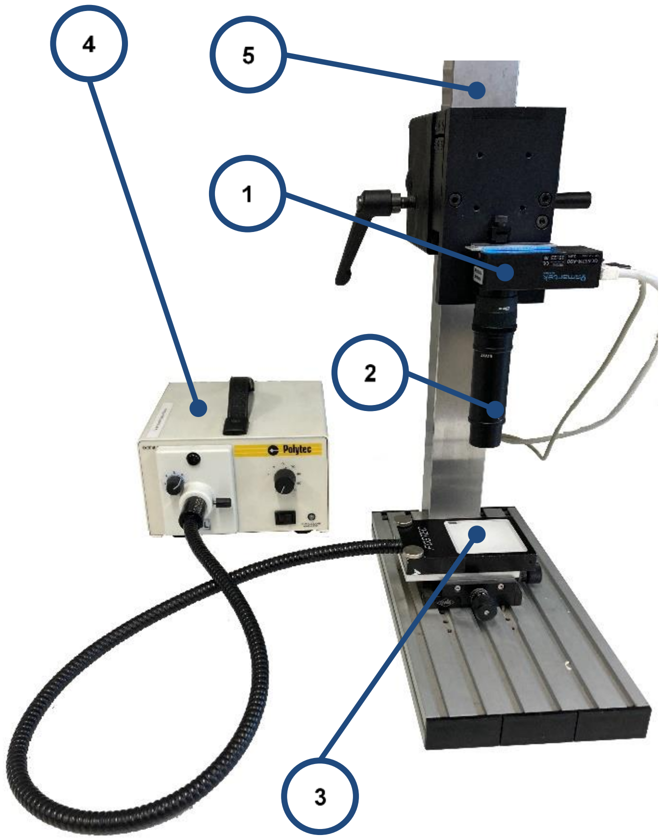

Figure 2. Measurement setup.

4.1. Preparation and general aim

The overall aim is to teach and consolidate the theoretical aspects. The theoretical basics are taught in preparation of the students in self-study. At the beginning of the training program, the supervisor checks the essential basics necessary for understanding the subject matter. Here it must be paid attention particularly on the part of the supervisor to recognize lack of understanding and to recognize possibly by further questions the actual knowledge conditions of the participants individually. Often misunderstandings or misinterpretations of the facts occur, which must be corrected. Interdisciplinary action should also be taken here, and basic mathematics or mechanics should also be addressed. Essentially, the following topics should have been learned at the end of the program:

Figure 3. Measurement targets. Circular rings chrome glass (left), USAF (right).

- knowing and understanding terms [1]
- understanding the necessity of characterisation concerning engineering tasks
- understanding measurement setup (incl. optics)
- understanding the measurement procedure
- reflection and deduce the causes of uncertainties in the measurement system
- evaluating und visualize the data
- encouraging the understanding of algorithms.

It is also important that the supervision always refers to the method of application and integration of the systems and components in the engineering practical task. In this way, the important practical relevance is continuously maintained. After verification of qualification and the elimination of misunderstandings, instruction is given in the measurement setup and operation of the software.

4.2. Measurement process

The measurement is performed according to the instructions given in [2]. Regarding the training program, the meaningfulness has already been discussed in the basics and does not provide any knowledge gain for the student in the actual sense at this point. At this point, only the practical data is acquired, with which the evaluation and interpretation can be done afterwards. In the first step the 10 single measurements of the circular rings are carried out at 5 positions, which are reached by shifting the measuring object in the object field by means of the X-Y-stage. The software required for image acquisition is provided for the student and can be operated intuitively, and the circle diameters are also determined in this software. After determining the circle diameters, these values are saved in the background in a file, which can later be pulled into the evaluation software. The Second measurements is the capture of the USAF test chart, which is captured as a single image and then saved as an image file.

4.3. Evaluating the measurements

The evaluation of the measurement data is generally the most important and most insightful part of the training program. Here, the students learn how to evaluate data in an environment that is frequently encountered in practice. Both the measurement data of the circular diameters and the development of the MTF are implemented in the MATLAB environment.

In general, the necessary program text is available as cloze text and must be completed by the students at the essential points. This also promotes the algorithmic understanding of a sequential process. The first insight is the differentiation of the data types. The measurement data of the circle diameters are purely vectoral and 1-dimensional, the image data as 2-dimensional field. In addition, the image data are available as 8Bit integer, the measurement data are of the data type "double". For the evaluation of the circle data a script is available, which must be supplemented at some commented places only by the function for the computation of the standard deviation. Essential necessary standard functions and their arguments to be passed with syntax must be researched by the students themselves via the internal help and implemented in the main program. Experience shows that most students have enormous methodical deficits exactly at this point for independent problem solving.

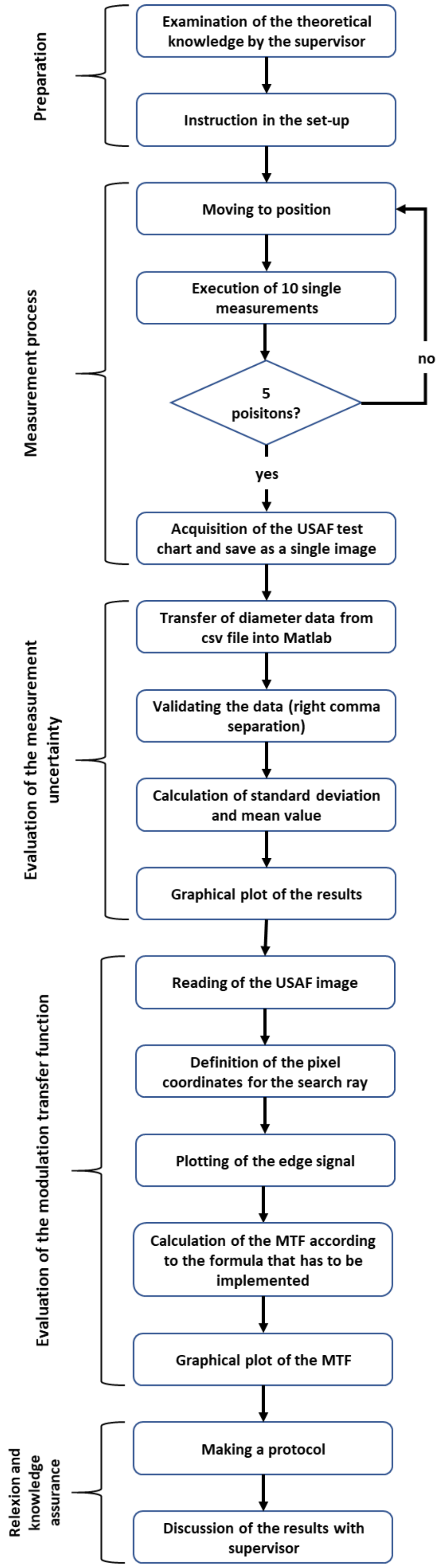

Figure 4. Measurement target 1.

4.3.1. Determination of the measurement uncertainty

The data obtained in the measurement serves as the basis for determining the measurement uncertainty. These are available in a csv-file (comma separated value) stored in the background by the image processing software and can be transferred to MATLAB with a function for reading in. Afterwards the data have to be validated. Unfortunately, problems occur again and again due to the comma-dot separation at the decimal point in the exchange with German-language software, which should be explicitly pointed out here. In the last step the calculation of the measurement uncertainty by standard deviations etc. takes place and are to be completed here after the appropriate equations by the students in the program text.

4.3.2. Determination of the MTF

More detailed understanding is required to calculate the MTF. It should be noted that within the training program only the MTF of the entire system is to be determined. Of course, this would also be possible for each individual component in the beam path. However, the goal is to get a pragmatic overview of the resolving power of the entire system. In addition, the time required should also be kept within reasonable limits. The necessary data are available as a single image, which must first be read in.

In the next step, the relevant signals must be extracted from the image data set as one-dimensional signals. This is done manually by defining the start and end points of the search beams. Afterwards, the students represent these signals as a simple plot for illustration purposes. To write the necessary functions would go beyond the scope of the training program, therefore these functions are predefined.

After extracting the vectoral data, the students calculate the MTF according to the relationships presented in the basics. Here it is also important to understand the signal properties of the overall image (contrast ratios) and to calculate them with appropriate functions from the field. Also, here the necessary program text is available as gap text. Calculations for visualization of the search rays in the image etc. have been predefined. As a result, the MTF is plotted graphically.

4.4. Reflexion and interpretation of the data

The main focus of the training program is the graphical representation of the evaluated data. For each result a plot is to be created, which illustrates the data. Figure 5 shows an exemplary graphical representation of the statistical values of 10 single measurements at the 5 relevant positions. The graph shows the histogram and the distribution function fitted in it (red curve). On the basis of the compression of the curve the meaning of the standard deviation as a scattering parameter of the data can be read off immediately. The knowledge gain is secured by the graphic connection of the data thus finally and is to be summarized a protocol.

All results are finally discussed with the supervisor on the basis of the graphs. Thus, the learning result is secured by the renewed repetition and purposeful discussion of substantial qualitative characteristics, particularly in the curves. Experience shows that qualitative progressions can be memorized very lastingly through graphically illustrated relations.

5. INTEGRATION INTO TEACHING

The present concept will be integrated into teaching as a fixed element from the time of publication. However, initial test sessions with students for the evaluation of the concept were performed before. These preliminary tests with a total of 4

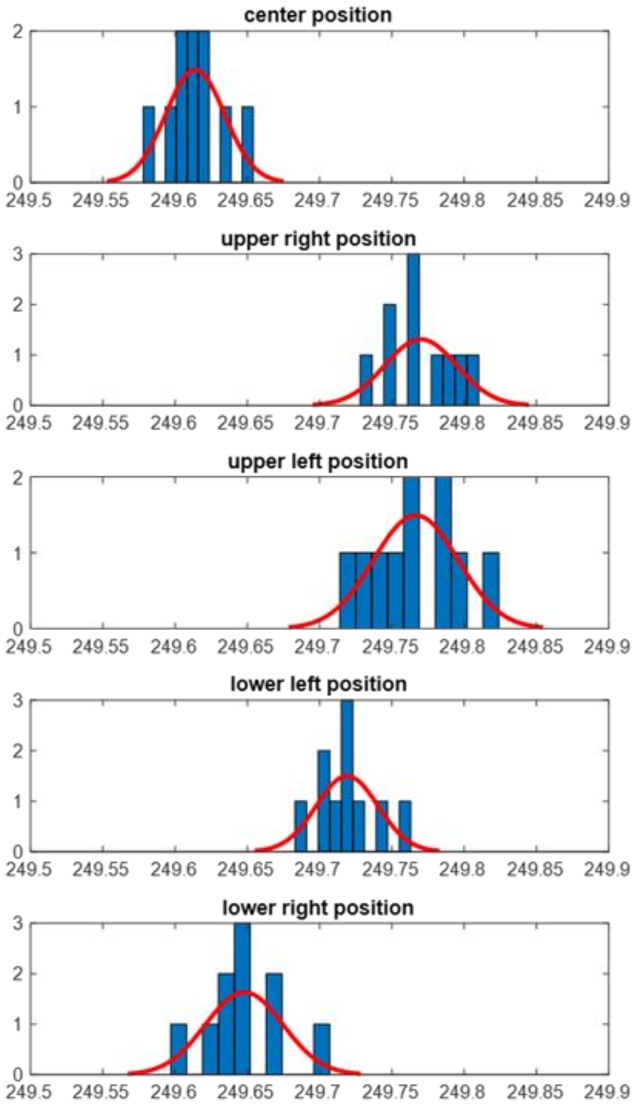

Figure 5. Measurements on 5 positions (target 1).

groups had three main reasons. First of all, it was to be determined whether the test could be completed at all by the students in the appropriate time. All 4 groups managed to complete the task within the set time frame of 3 hours. The second reason is to estimate the suitability. The students were asked in detail about their assessment after completing the program. All groups confirmed that they had understood the usefulness of the course and its relation to real practice. Furthermore, it was confirmed that the students were neither overstrained nor understrained at any time. The first group, which had already conducted an experiment on a similar topic in a different form a long time ago, represented a special case. This group confirmed above all the increase in clarity and confirmed that they had become better familiar with the topic due to the many integrated qualitative graphical representations of the results. The third reason for the preliminary tests is to test the stability of the system. This means both the system stability of the hardware and the stability of the software. None of the groups experienced any problems in this regard. The hardware ran stably, did not cause any dropouts, and the software did not deliver any errors.

6. CONCLUSION

The present work represents a full methodological treatise on the development of a training concept of engineering students in the field of optical coordinate metrology and adjacent to the image processing. Current and relevant problems are integrated, basic problems of image processing are simulated, demonstrated and solved. Ensuring expert supervision, but intervening only when necessary, underlines the pedagogical concept. The clearly identified problems are solved using current tools. The focus is also always on creating a graphical picture between data, their evaluations and calculations, on the basis of which the results are easily discussed and the facts are easily memorized by the students through the graphical symbolization.

Special attention was paid to typical, recurring deficits and problems of the students during the creation of the program, which is why they were specifically included and problems are intentionally implied during the execution of the program.

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