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Measurement Traceability and Uncertainty in Machine Vision Applications

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Abstract

During the past decades increasing use of machine vision in dimensional measurements has been seen. From a metrological view every serious measurement should be traceable to SI units and have a stated measurement uncertainty. The first step to ensure this is the calibration of the measurement instruments. Quality systems in manufacturing industry require traceable calibrations and measurements. This has led to a good knowledge of measurement accuracy for traditional manual hand-held measurement instruments. The entrance of rather complex computerised machine vision instruments and optical coordinate measuring machines, at the production lines and measurement rooms, is a threat or at least a challenge, to the understanding of the accuracy of the measurement. Accuracies of algorithms for edge detection and camera calibration are studied in the field of machine vision, but uncertainty evaluations of complete systems are seldom seen. In real applications the final measurement uncertainty is affected by many factors such as illumination, edge effects, the operator, and non-idealities of the object to be measured.

In this thesis the use of the GUM (Guide to the Expression of Uncertainty in Measurement) method is applied for the estimation of measurement uncertainty in two machine vision applications. The work is mainly limited to two-dimensional applications where a gray-scale camera is used. The described equipment for calibration of micrometers using machine vision is unique. The full evaluation of measurement uncertainty in aperture diameter measurements using an optical coordinate measuring machine is presented for the first time.

In the presented applications the uncertainty budgets are very different. This confirms the conclusion, that a detailed uncertainty budget is the only way to achieve an understanding of the reliability of dimensional measurements in machine vision. Uncertainty budgets for the type of the two described machine vision applications have never previously been published.

Tiivistelmä

Viime vuosikymmenien aikana konenäkö on yleistynyt yhä enemmän geometrisissä mittauksissa. Metrologisesta näkökulmasta jokaisen mittauksen olisi oltava jäljitettävissä SI-yksikköjärjestelmään ja jokaisella mittauksella tulisi olla tunnettu mittausepävarmuus. Kaupallisesta näkökulmasta on tärkeää, että tavaran mitattavista ominaisuuksista ei synny mittausvirheistä johtuvia kiistoja ostajan ja myyjän välillä. Jos mittausepävarmuus on tunnettu, niin kalibroinnilla saadaan aikaan jäljitettävyys perussuureeseen. Jäljitettävyys konenäkösovelluksissa pituuden SI-yksikköön metriin saadaan aikaan pitkällä katkeamattomalla jäljitettävyysketjulla. Konepajoissa laatu järjestelmät ovat jo pitkään edellyttäneet, että mittalaitteet ovat jäljitettävästi kalibroitu. Jokaiseen kalibrointiin liittyy myös mittausepävarmuuslaskelma, jossa tärkeimmät epävarmuuslähteet ovat mallinnettu. Optisten koordinaattimittauskoneiden sekä muiden konenäköön perustuvien mittausjärjestelmien mutkikkuus on suuri haaste mittausepävarmuuslaskelman laatimiselle. Konenäkö sekä tarkkuuskysymykset konenäössä ovat paljon tutkittuja aiheita, mutta kokonaisten mittausjärjestelmien epävarmuuslaskelmia laaditaan edelleenkin erittäin harvoin. Epävarmuustekijöitä, jotka olisi otettava huomioon, ovat valaistuksen, reunojen ja käyttäjän valintojen vaikutus yhdessä mitattavan kappaleen mahdollisten puutteellisuuksien kanssa.

Tässä työssä tutkitaan GUM-menetelmän (Guide to the Expression of Uncertainty in Measurement) käyttöä kolmessa konenäkösovelluksessa, joille esitetään epävarmuuslaskelma. Neljäs esitettävä sovellus on apertuurien halkaisijan mittaaminen optisella koordinaattimittauskoneella. Ensimmäistä kertaa tällaiselle sovellukselle esitetään mittausepävarmuuslaskelma. Työn johtopäätöksenä on, että yksityiskohtaisen epävarmuuslaskelman laatiminen on ainut keino saada käsitys mittauksen virhelähteistä. Työ on rajattu kaksidimensionaalisiin mittauksiin, joissa käytetään yhtä harmaasävykameraa.

Preface

The research work behind this thesis is done at MIKES (Centre for Metrology and Accreditation) as several research and development projects. A part of work described in this thesis began when the author worked at VTT (Technical Research Centre of Finland) during 1989 to 2000. The dimensional measurement group at VTT moved to MIKES in 2000, due to a re-organization and strengthening of metrology in Finland.

The author is in gratitude to Prof. Timo Hirvi and Prof. Ulla Lähteenmäki for offering research possibilities to the author. The author also wants to thank Dr Heikki Isotalo for giving the initial inspiration to write this thesis. The author also greatly indebted to his supervisor Prof. Erkki Ikonen for encouragement and inspiration. I thank the Academy of Finland for financial support for this project.

The author wishes to thank Lic.Sc (Tech) Heikki Lehto for ideas and advice. The author wishes also to thank Dr Antti Lassila for ideas and support. The author is grateful to Mrs Jenni Kuva for proofreading this thesis. The author is grateful to M.Sc. (Tech.) Ilkka Palosuo, Mr Asko Rantanen, M.Sc. Anu Fagerholm (former Tanninen) and Mr Hannu Sainio at VTT for substantial co-work in projects related to this dissertation. In the last phase of this work the author received spiritual support and many helpful hints from M.Sc. Virpi Korpelainen, Dr Kaj Nyholm and Dr Mikko Merimaa. The author thanks Mrs. Kirsi Tuomisto and M.Sc. (Tech.) Milla Kaukonen for help with the final editing of the thesis. The author also thanks Prof. Henrik Haggrén at the laboratory of Photogrammetry at TKK (Helsinki University of Technology) for views and ideas

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Last but not least I thank my wife Marja-Riitta and daughters Ella and Malin.

Björn Hemming

List of Publications

This thesis consists of an overview and the following selection of the author's publications.

Publ. I

B. Hemming, I. Palosuo, and A. Lassila, "Design of Calibration Machine for Optical Two-Dimensional Length Standards", in Proc. SPIE, Optomechatronical Systems III, Vol. 4902, pp. 670-678 (2002).

Publ. II

B. Hemming, E. Ikonen, and M. Noorma, "Measurement of Aperture Diameters using an Optical Coordinate Measuring Machine", *International Journal of Optomechatronics*, **1**, 297–311 (2007).

Publ. III

B. Hemming and H. Lehto, "Calibration of Dial Indicators using Machine Vision," *Meas. Sci. Technol.* **13**, 45-49 (2002).

Publ. IV

B. Hemming, A. Fagerholm, and A. Lassila, "High-accuracy Automatic Machine Vision Based Calibration of Micrometers", *Meas. Sci. Technol.* **18**, 1655-1660 (2007).

Authors Contribution

The development of the equipment described in Publ. I was a team project, where the responsibility of the author was the machine vision hardware and software development. The software was written with the assistance of M.Sc. (Tech.) Ilkka Palosuo. The role of M.Sc. (Tech.) Ilkka Palosuo was the design of the mechanics of the instrument. For Publ. I the author prepared the manuscript and the uncertainty budget.

For Publ. II the author performed all measurements and analyses alone with the exception of the verification with probing CMM (Coordinate Measuring Machine), which was carried out together with M.Sc. (Tech.) Ilkka Palosuo. For Publ. II the author prepared the manuscript.

For Publ. III the author designed and built the instrument and wrote the software. The author also carried out all of the measurements and the uncertainty analysis. For Publ. III the author prepared the manuscript.

For Publ. IV the author designed and built the instrument. The software was written with the assistance of M.Sc. Anu Fagerholm. The author made all of the measurements and all of the research work including the uncertainty analysis. For Publ. IV the author prepared the manuscript.

The spread of the years of publication was partly due to the moving process to the new MIKES building in 2005.

List of abbreviations

1D	One dimensional
2D	Two dimensional
3D	Three dimensional
BIPM	International Bureau of Weights and Measures/ Bureau International des Poids et Mesures
CCD	Charged coupled device
CCIR	Comité International des Radiocommunications
CMC	Calibration and Measurement Capability
CMM	Coordinate Measuring Machine
EAL	European Cooperation for Accreditation of Laboratories
GUM	Guide to the Expression of Uncertainty in Measurement
LED	Light-emitting diode
METAS	Bundesamt für Metrologie
MIKES	Centre for Metrology and Accreditation/ Mittatekniikan keskus
NIST	National Institute of Standards and Technology
NMI	National Measurement Institute
NPL	National Physical Laboratory
PTB	Physikalisch Technische Bundesanstalt
SPIE	The International Society for Optical Engineering
TKK	Helsinki University of Technology (formerly abbreviated HUT)
VDI/VDE	Verein Deutscher Ingenieure/Verband der Elektrotechnik,
VTT	Technical Research Centre of Finland

List of symbols

dx	Distortion in x-axis
dy	Distortion in y-axis
k	Coverage factor
k_1	Coefficient for 2 nd order radial distortion
k_2	Coefficient for 4 th order radial distortion
ρ	Distance from image centre
S_x	Scale factor for x-axis
S_y	Scale factor for y-axis
$u(x)$	Standard uncertainty for the input estimate
$u_c(y)$	Combined standard uncertainty
x	Input estimate
X	Input quantity
X_p	Undistorted x-coordinate of a point in the image
y	Estimate of measurand
Y	Measurand
Y_p	Undistorted y-coordinate of a point in the image

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1. Introduction

In the manufacturing industry the tradition of systematic measurements is long. At the time of the first industrial revolution, James Watt invented the screw micrometer in 1772 [1]. One important step was the invention of gauge blocks in 1896 by C. E. Johansson in Sweden [2]. For the manufacturing industry the gauge blocks have been the basic reference in the calibration of simple handheld instruments such as callipers and micrometers. The first coordinate measuring machine (CMM) with three axes was manufactured by the Swiss company SIP already in 1930. An important invention for machine vision was the CCD camera, developed in the 1960s.

Systematic measurement with known uncertainty is one of the foundations of science and technology. Measurements are central in industrial quality control and in most modern industries the costs bound up in taking measurements constitute 10-15 % of production costs [3]. Quality management is important in any industry where the product is assembled from hundreds of parts, which have to fit together. Therefore, the measuring instruments are calibrated and the users must have knowledge of the measuring uncertainties when they verify that the products are within specified tolerances. If the product is not within specified tolerances, it is useless to send it to the customer. If the product seems to be within specifications, but rejected by the customer, the economic loss is even bigger. Therefore, there is a clear connection between understanding of measurement errors and economics.

In addition to the aforementioned requirements, another challenge is the demand for more accurate measurements. In figure 1 this demand, as seen by the National Physical laboratory (NPL) is illustrated. This increasing demand of accuracy is not narrowed to special cases or small volume production. An example from mass production where high accuracy is needed is the manufacturing of hard disk components and fuel injection systems [4].

During the last 20 years many advances in measurement instruments have also caused new challenges for uncertainty evaluation. First digital data processing made it possible to develop programmable CMM's. Then machine vision [5, 6] was developed and used for inspection and measuring tasks in industry.

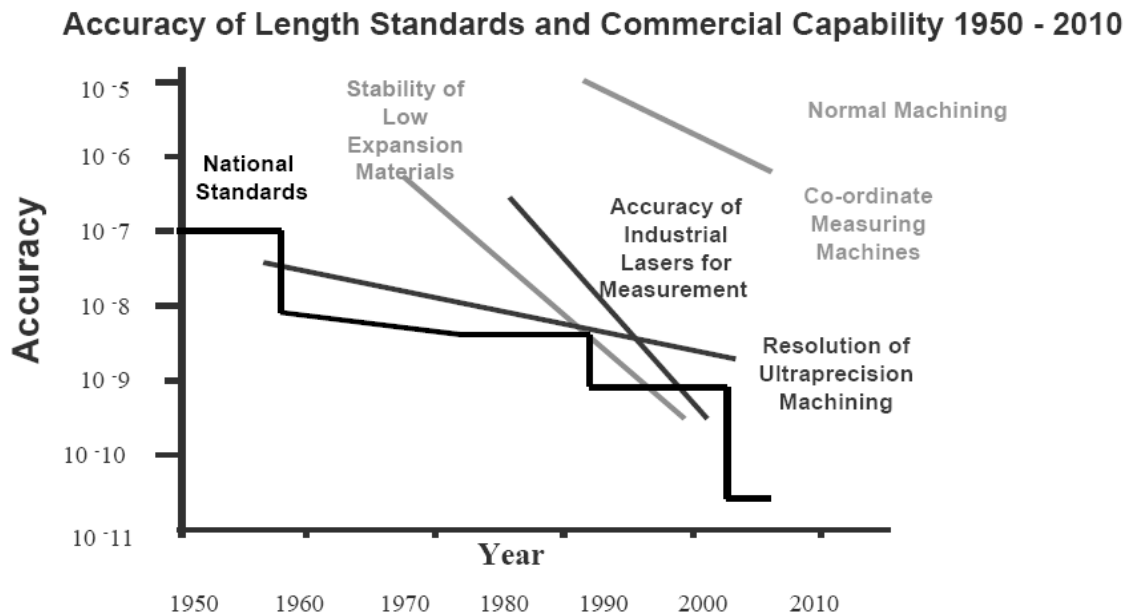


Figure 1. The demand for lower measurement uncertainty in dimensional measurements [7]

Finally, during the last ten years machine vision capabilities were installed to some CMM's and the Video Measuring Machine or optical CMM was developed. However, some new problems have emerged. According to Ref. [8] the uncertainty for CMM measurements is in many cases simply a guess from an experienced operator. Moreover, there are situations where intuition and experience may fail dramatically [9]. In machine vision, which is a younger technology than CMM, the situation is roughly the same or even worse. Machine vision has, during the recent years, gained from the cheaper computing costs. This means that more and more machine vision applications are developed all the time.

The amount of work and complexity in a measurement uncertainty calculation corresponds to the complexity of the measurement. If a part was previously measured

using a mechanical vernier or micrometer calliper and is now measured by machine vision, a lot of work would be needed to find the error sources of the new system. It seems that the measurement uncertainty and traceability chain is no longer as well known as it was before. In this thesis it is shown how traceability and measurement uncertainty are achievable in machine vision applications using the GUM method [10].

2. Measurement Traceability and Uncertainty

In 1799 in Paris, the Metric System was established by the deposition of two platinum standards representing the metre and the kilogram. This was the first beginning of the present International System of Units, the SI system [11]. From year 1983 the definition of the metre is given as the length of the path traveled by light in vacuum during a time interval of $1/299\,792\,458$ of a second. Some concepts in the practical realisation work of the SI-unit metre are described in the following.

2.1. Measurement Traceability

A traceability chain is an unbroken chain of comparisons, all having stated uncertainties. This ensures that a measurement result or the value of a standard is related to references at the higher levels, ending at the realisation of the definition of the unit.

The definition of calibration according to Ref. [12] is the following: “Set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material and the corresponding values realised by standards.” The most important measuring instruments in length and dimensional metrology are the laser interferometers, line scales, gauge blocks, ring gauges and form standards. Important reference standards used in coordinate metrology are step gauges and ball plates. All instruments and reference standards have to be calibrated regularly [13]. The result of the calibration is a certificate usually containing a table where instrument readings can be compared to reference values. It is then up to the end user how he will use the certificate and its results.

Sometimes the procedure, when a scale factor between a transducer output and a physical unit is established, is also called calibration. In machine vision literature there are many articles about camera calibration. Usually the purpose is to define the relation between the captured image and world coordinates.

Every measurement intended to be reliable should have a traceability chain to the corresponding definition of the SI-unit (figure 2). At MIKES there are six iodine-stabilized lasers. Thanks to advances in laser technology the traceability for these secondary frequency standards was recently achieved from a femtosecond frequency comb [14, 15]. The traceability to the frequency comb comes from a primary frequency standard, a Cs atomic clock. The wavelengths of the lasers of the primary interferometers are calibrated against the wavelengths of the iodine-stabilized lasers. These primary interferometers are then used to calibrate other reference instruments, such as gauge blocks, step gauges, line-scales and other laser interferometers [16]. Interferometrically calibrated gauge blocks are used to calibrate other gauge blocks using a gauge block comparator [17].

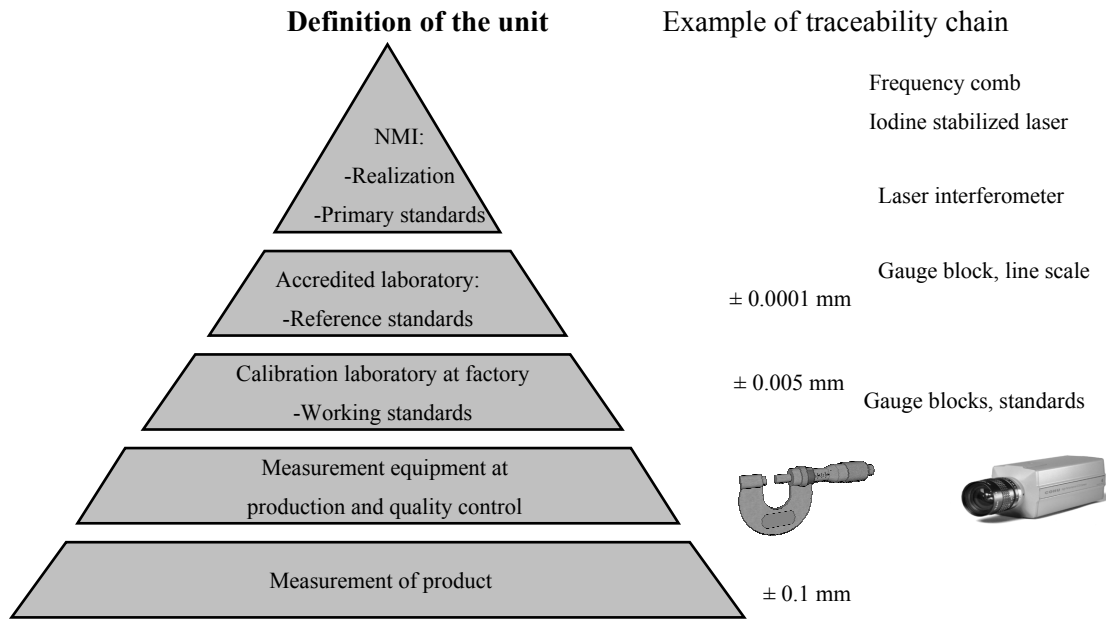


Figure 2. Traceability chain from national standard to product.

For example, a micrometer calliper may be used at factory floor to measure a product. The calibration of a micrometer calliper using calibrated gauge blocks [18] is simple and straightforward and the user has an understanding of both the calibration and the measuring process. It is also an advantage that the calibration using gauge blocks is quite similar to the measurement of the products. If the manual measurement of products is replaced by a machine vision based inspection system the benefits, such as speed, are obvious but the measuring process, and error sources too, get more complex.

In trade comparability and reliability of measurements are important, between buyer and seller. This gives a requirement of reliability and traceability, which cannot be neglected, when mechanical measurement is replaced by machine vision in industry.

2.2. Measurement Uncertainty

In a measuring process, there are several factors that influence the measuring results and measuring uncertainty. The most important factors are properties of the used measuring instrument and calibration and how well they are suited for measuring the object (figure 3).

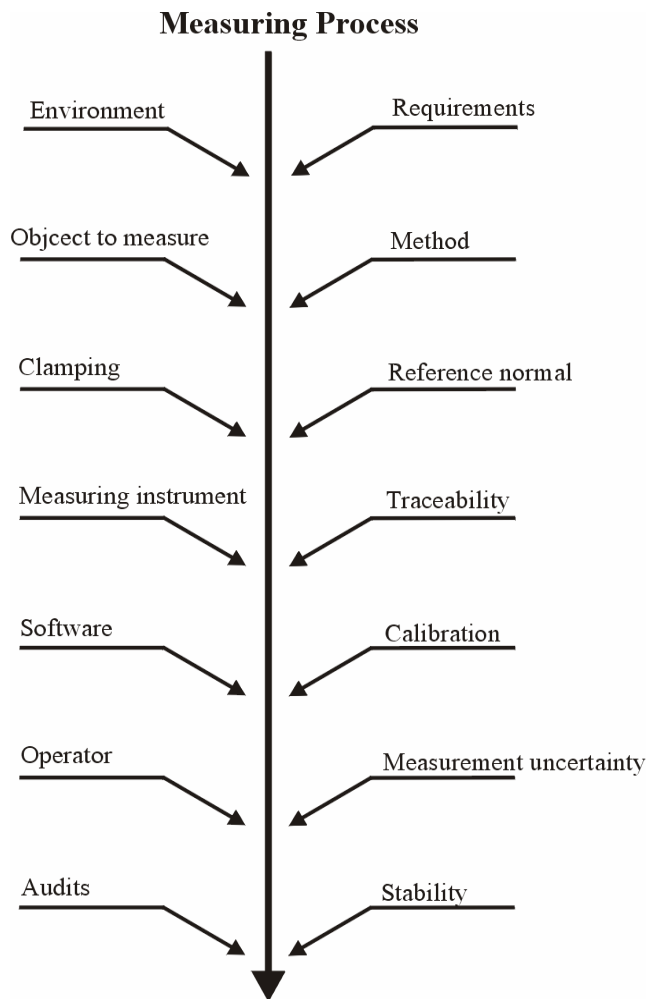


Figure 3. Factors affecting a measuring process (after [19]).

In the documentation of GUM [10] general rules for evaluating and expressing measurement uncertainty are described. In the GUM the estimate of the measurand Y , denoted by y , is obtained from input quantities x_1, x_2, \dots, x_n representing N quantities X_1, X_2, \dots, X_N . The output estimate y , which is the result of the measurement, is given by:

$$y = f(x_1, x_2, \dots, x_n) \quad (1)$$

The standard uncertainties for the input estimates are noted as $u(x_i)$. If the input quantities are independent, the combined standard uncertainty $u_c(y)$ is obtained from:

$$u_c^2(y) = \sum_{i=1}^N \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) \quad (2)$$

Usually the combined standard uncertainty is multiplied by the coverage factor $k=2$, to express the expanded uncertainty at a 95% confidence level.

Equation 1 represents the measurement model. In a simple measurement using a handheld instrument like a vernier calliper, the measurement model is trivial with only three or four input estimates. However, in a machine vision system containing hundreds of program lines in its software, the measurement model is quite complex. An example of this is seen in Publ. IV.

A lot of work has been done on accuracy problems in photogrammetry and accuracy questions in camera calibration in machine vision. However, measurement uncertainty for a whole system and the concepts of GUM are rare in these fields. There are some exceptions, which should be mentioned. In metrology institutes, machine vision has for some time been used for interferometric gauge block calibration [20], flatness measurements with Fizeau interferometers [21], line scale measurements [22] and photomask measurements [23]. For these applications a detailed analysis of measurement uncertainty is normally found.

2.3. Research Question

The area of interest in this thesis is measurement traceability and uncertainty in dimensional machine vision applications. This thesis is limited to two-dimensional applications where one gray-scale camera is used. It might be argued that the principles of GUM are well known and that also accuracy has been studied in the vast literature of machine vision. However, the principles of GUM have been applied only in very few machine vision applications, and there are gaps which should be filled. In this thesis the research question is:

what is the role and benefit of an uncertainty evaluation during the development of a measurement application where machine vision is used for a dimensional measurement?

On one hand, the development of a measurement application might be design, building and testing of new measurement equipment. On the other hand, in industry, where machine vision is used for quality control, there is a need for reliable measurements. Therefore the research question is divided into two subquestions:

how can uncertainty sources be evaluated during design of a measurement instrument based on machine vision ?

how is it possible to achieve traceability and reliability in a measurement based on machine vision ?

In this thesis applications using four different measurement systems are described; optical CMM, measurement of two-dimensional (2D) standards and two calibrations systems for micrometers and dial indicators. The original motivation for these applications was not only to answer the abovementioned research questions. Still the second subquestion is addressed in Publ. II and section 4 where the use of a commercial optical CMM is analysed. The other publications describe uncertainty budgeting during design of instruments.

The applications look quite different but on the other hand the 2D standard measuring instrument is in principle an optical CMM. Also, it should be noted that the border between optical CMM and machine vision will fade away in the future [24]. The requirement of traceability for production measurements where machine vision is used, causes a need of calibration standards such as line scales or 2D standards. These standards are in turn also calibrated using machine vision. Examples of traceability chains are also presented and discussed in this thesis. The hypothesis of this thesis is that a thorough uncertainty evaluation is crucial during the development of a measurement application where machine vision is used.

2.4. Progress in this work

Publ. I.

In dimensional metrology the traceability comes from lasers with stable and well-known wavelengths. An example is the calibration of line-scales using laser-interferometers. Using line-scales, measurement machines can be calibrated one axis at a time. One quick method to check and calibrate optical coordinate measuring machines is to use 2D standards.

A design and development project aiming at a new calibration service for two-dimensional length standards was started in 2000 at MIKES. In the developed measurement equipment the expanded ($k=2$) measurement uncertainty is $Q[0.094; 0.142 L]^1 \mu\text{m}$, where L is the position in metres. This result is obtained by applying error compensation methods to the pitch error of the movements and to flatness errors of the mirror block. The achievable measurement uncertainty of $0.1 \mu\text{m}$ ($k=2$) for a position at 150 mm is sufficient for most calibrations.

¹ Expression for combination of non-length dependent and length (L) dependent uncertainty components: $Q[A; B L] = (A^2 + (B L)^2)^{1/2}$

Publ. II

Apertures are used in photometry and radiometry to limit a precisely known area of the incoming radiation field in front of a detector. The known area is needed to determine such quantities as illuminance or irradiance.

An optical CMM or video measurement machine is used for the measurement of mean diameters of apertures. It is obvious that the measurement uncertainty, even of a high accuracy optical CMM, cannot be as good as that of a dedicated aperture measurement facility in a National Measurement Institute. However, if the required standard uncertainty for the mean diameter is not less than 1 μm , the optical CMM is both useful and easy to use for aperture area measurements. In a comparison with probing CMM excellent agreement was found. This report presents the first full uncertainty analysis of the aperture area measurement by optical CMM, including confirmation of the results by Monte-Carlo method.

Publ. III

With machine vision it is possible to check hundreds of points on the scale of a dial indicator, giving new insight into error sources of the dial indicator. The article describes a machine vision based system for the calibration of dial indicators developed at MIKES. With the developed machine vision system the uncertainty of the reading and interpretation of the pointer is of the same order as when a dial indicator is calibrated manually. In the article the calculation of the measurement uncertainty is described in detail. Uncertainty evaluation according to GUM has not previously been published for an automatic measurement system for dial indicators.

Publ. IV

The manual calibration of a micrometer calliper according to ISO 3611 is done by using ten gauge blocks. This gives only a rough figure for the accuracy of the instrument and is not a complete check of the scale. Using automatic machine vision based systems; the calibration of measurement instruments can be extended.

Equipment for the automatic calibration of micrometers is presented. The purpose of the study is to show the feasibility of traceable calibration of micrometers using machine vision. Another similar system is not known to the author and therefore it is probably the first of its kind. Detailed uncertainty analysis following the recommendations of GUM is given.

3. Calibration of Reference Standards for Machine vision

3.1. Calibration of 2D standards

One important reference standard in high accuracy machine vision applications is a line-scale. In Finland line scales of length less than 1160 mm can be calibrated using a line-scale interferometer at MIKES [22, 25]. The uncertainty of the calibration of line-scales is $Q[62; 82L]$ nm ($k=2$), where L is the length of the scale in metres. Longer line-scales and measurement tapes up to 30 m can be calibrated interferometrically at the 30 m measurement rail in MIKES.

Although traceability for a machine vision measurement can be achieved by a line-scale, a two dimensional standard or calibration grid is a very useful tool in camera calibration. The advantage is that a large measurement area and orthogonality error is covered in a single measurement. A practical disadvantage is that the correction of the misalignment of the two-dimensional standard depends on the selected alignment criteria or selected reference points. This makes it difficult to compare different calibration certificates for a two-dimensional standard. For a line scale it is much easier to compare the results and to document the stability.

Several instruments for measurements of 2D standards and photomasks with high accuracy have been developed during the recent ten years [26, 27, 28, 29, 30]. Error separation is also used in many applications [31, 32, 33]. In the manufacturing of integrated circuits, lithographic processes are used where accurate 2D positioning is needed. Therefore, the needs of these applications has led to a field called mask metrology. State of the art systems used in this industry achieve positional repeatabilities of the order of 10 nm [34].

The most accurate measurements systems for 2D measurements are equipped with interferometers and orthogonal two-plane mirror reflectors. The optical detection of the features and structures on the mask or 2D standard is done using a microscope, usually equipped with a camera. Such instruments are nowadays found in large national measurement institutes such as NPL in Britain, Physikalisch Technische Bundesanstalt (PTB) in Germany, Bundesamt für Metrologie (METAS) in Switzerland and National Institute of Standards and Technology (NIST) in the United States. Usually the 2D standard is measured in four different positions, each turned by 90° . The measurement uncertainty for the instrument at NPL is $0.06 \mu\text{m}$ ($k=2$) [26]. In another paper the instrument is verified to achieve the uncertainty of $0.08 \mu\text{m}$ ($k=2$), for an 80 mm x 80 mm grid [34].

The measurement range of the instrument developed in METAS is 300 mm x 400 mm. The equipment in METAS is especially developed for photomask measurements, but it can also be used for various calibration tasks for line scales and 2D standards. An important property of the instrument in METAS is that the Abbe error of the measurement beams is negligible [27]. In calibration measurements for the equipment using a 400 mm quartz line scale mirror, corrections of 40 nm and 140 nm were derived [27]. The final measurement uncertainty is not reported in Ref. [27] but according to the CMC database of BIPM it is about $0.04 \mu\text{m}$ ($k=2$) for a 100 mm x 100 mm grid. In a comparison between NPL and PTB for a 120 mm x 120 mm 2D standard the agreement between the results was within $\pm 0.1 \mu\text{m}$ [23]. The dominating uncertainty source of the instrument in NPL is Abbe error [23]. Other uncertainty sources; discussed in the literature, are the flatness and orthogonality deviations of the two-plane mirrors and temperature effects, such as thermal expansion and refractive index of air.

3.2. Development of equipment for calibration of 2D standards

A design and development project aiming at a new calibration service for two-dimensional length standards was started in 2000 at MIKES. The technical requirement for the new calibration machine was an expanded uncertainty in calibrations of $0.1 \mu\text{m}$ ($k=2$) over the measuring range of 150 mm x 150 mm.

The operating principle of the device is based on use of a moveable xy-stage on air bearings. The mechanics of the equipment consist of two linear granite rails, two linear stepping motor actuators, and ten air bearings (figure 4). The two-dimensional standard under calibration is fastened to the Zerodur mirror block using three suction pads. A three-axis plane-mirror heterodyne interferometer system measures the position of the mirror block. The optical components of an old lithography machine were used. Unfortunately the use of this old hardware lead to an Abbe offset of 15 mm between the laser beams and the two-dimensional standard under calibration. Using online compensation, based on measured data on pitch angle, the Abbe error can be reduced but not completely eliminated.

The position of the feature in the standard is detected with a $\frac{1}{2}$ " CCD camera, equipped with a telecentric lens. The scale factor is from $0.3 \mu\text{m}/\text{pixel}$ to $6 \mu\text{m}/\text{pixel}$, depending on the selected lens. The achieved expanded ($k=2$) uncertainty for a position measurement is $Q[0.094; 0.142 L] \mu\text{m}$, where L is the position in metres. For a length of 100 mm this equals $0.095 \mu\text{m}$.

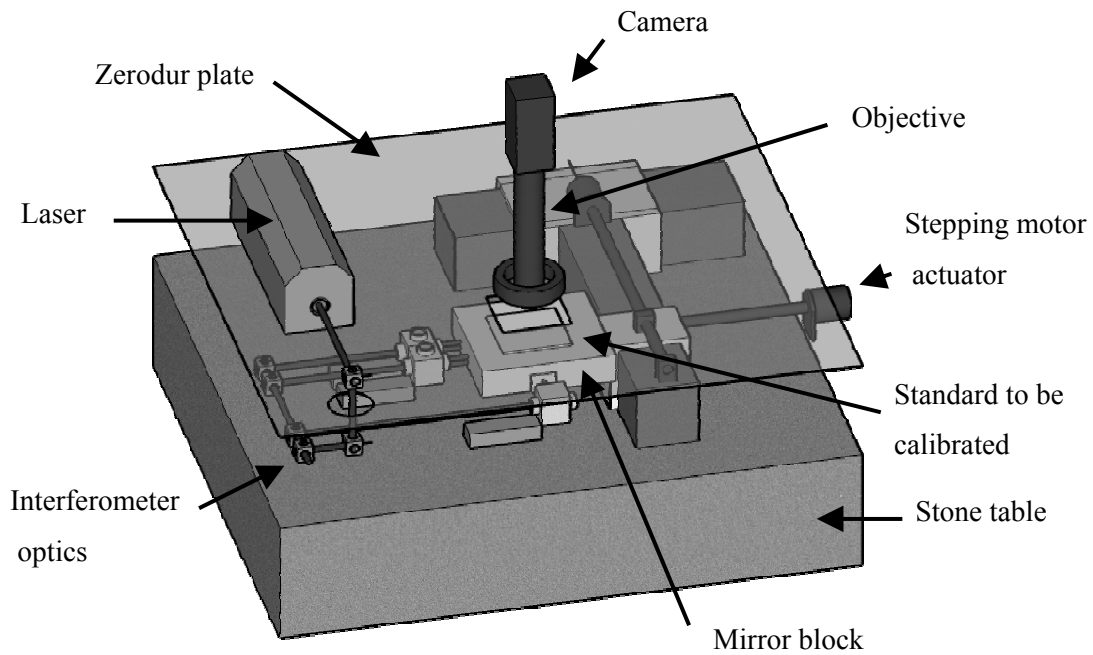


Figure 4. Calibration instrument for two-dimensional standards.

The graduation marks of the standard are positioned in turn at the centre of the image. The position of the graduation mark is measured using template matching or gray-scale correlation [35]. An alternative method to measure the position of the feature would be to use subpixel detector and minimization [36], or fitting of lines on the grid mark edges [37]. In some cases the Hough transform is a robust method to find lines in an image [38, 39, 40]. In this application gray-scale correlation was selected because it gives a good combination of accuracy and speed [41].

In order to test performance of the device, a 50 mm glass line scale was measured using the equipment. A line was used as a template and results were averaged from five measurements (figure 5). The differences of the results compared to measurements of MIKES' line scale interferometer were typically below 60 nm. The expanded uncertainty of the reference results for the particular scale were 90 nm ($k=2$). The line scale was too short to reveal errors due to temperature and mechanics, but the good result is a verification of the chosen image processing and machine vision parts of the developed system.

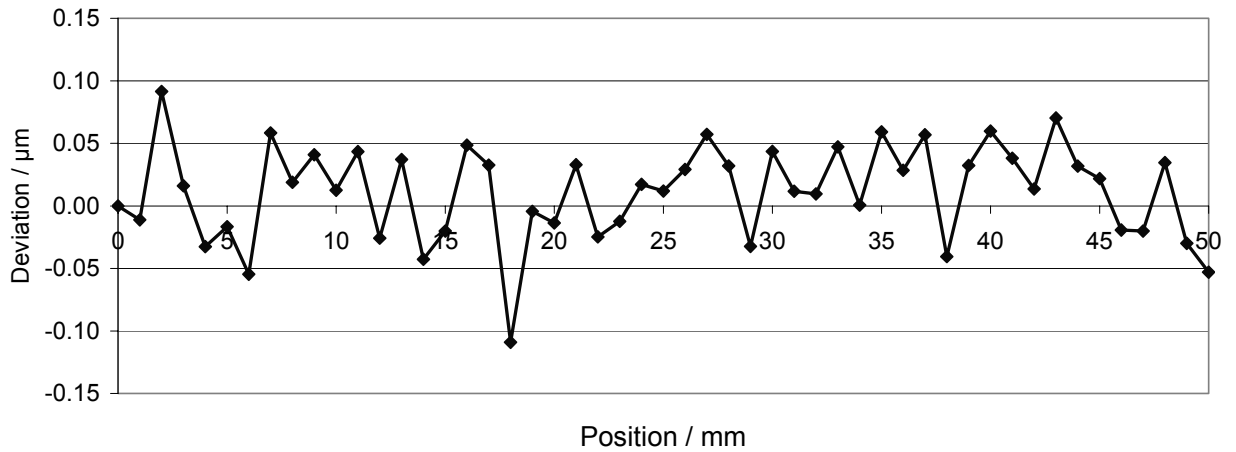


Figure 5. Deviation between results from the developed instrument and MIKES line-scale interferometer for a 50 mm line-scale [41].

Shown in figure 6 is an example of a standard of the size 100 mm x 100 mm calibrated with the instrument. In figure 7, the result of the calibration is shown. The user of a small optical CMM may use this kind of standard to measure the scale and orthogonality errors of the CMM. In Publ. I the uncertainty budget is presented, and it was found that the largest uncertainty source in the equipment is the uncompensated part of the previously mentioned Abbe error.

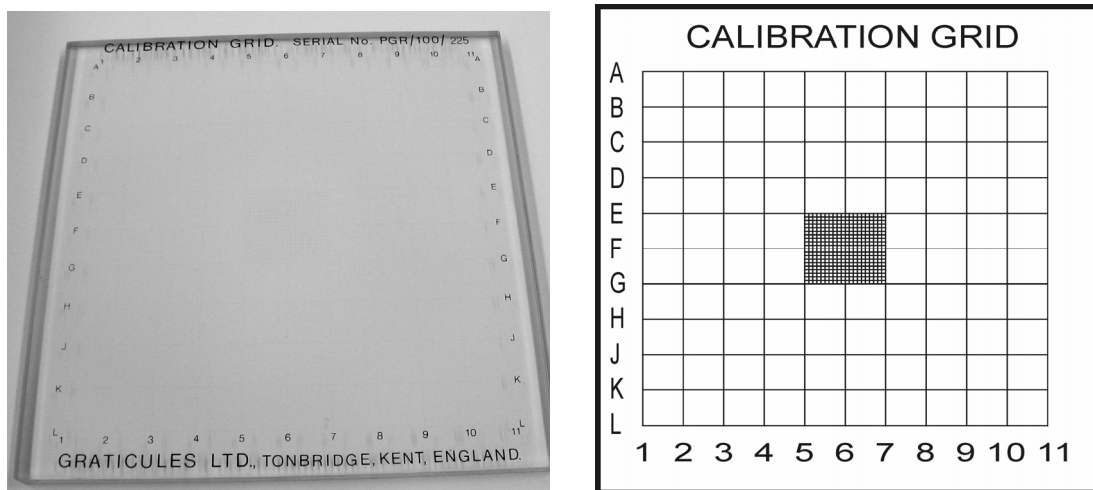


Figure 6. A photograph of the standard (left) and a drawing of the same standard (right). The larger grid has 10 mm intervals and in the middle there is a denser grid with 1 mm intervals.

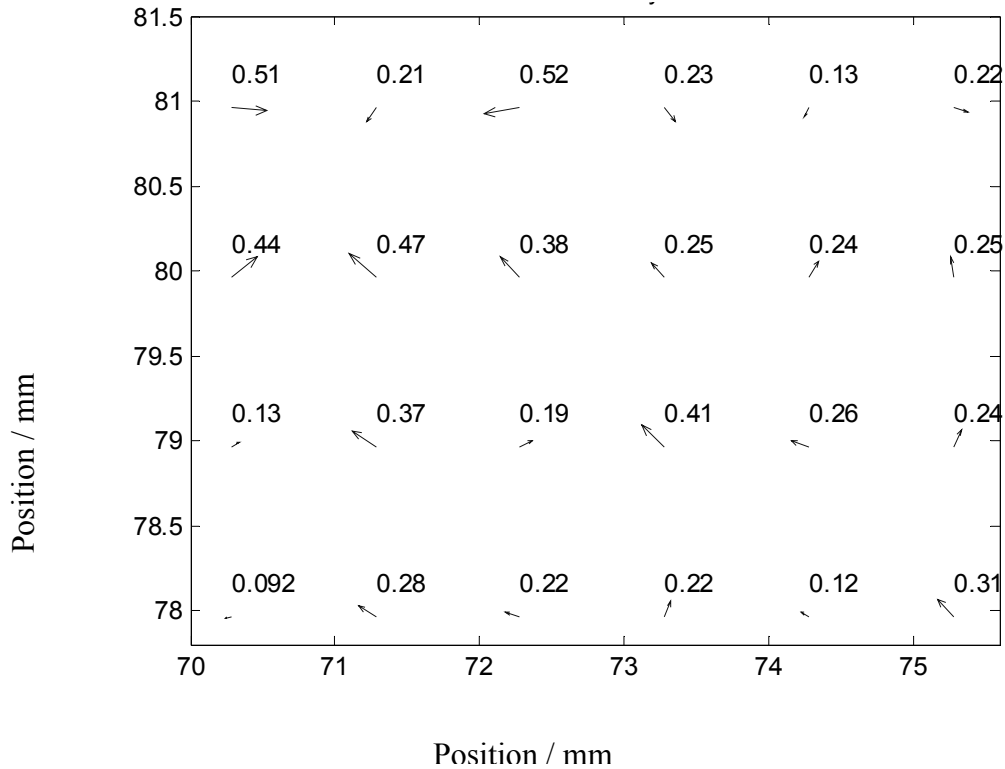


Figure 7. Detail of the results of the error vectors of a grid (unit of axes in mm, unit of error vectors in μm).

3.3. Discussion

The developed equipment is in many aspects similar to those developed in leading national measurement institutes. The accuracy is of the same order as the accuracies in these laboratories. The motivation for building the instrument was the estimated demand for more accurate 2D measurements (see figure 1), and now the demand from Finnish industry can be met. The traceability chain to the definition of metre is evident, as the lasers of the instrument are directly traceable to the frequency comb at MIKES. The equipment is verified to fulfil the required accuracy. However, due to the use of components from another instrument, there exists an Abbe error which is unfortunate. However, it should be noted that instruments of submicrometre precision cannot always be built at any cost, and that the technical compromise to achieve the budget is satisfying. The benefit of the uncertainty evaluation was ensuring that

traceable measurements of the required accuracy can be made. This conclusion is a partial, although not a complete answer to the research question.

As for any new measurement instrument in a NMI (National Measurement Institute), the participation in an interlaboratory comparison would be desirable, to finally prove the measurement capability and to give ideas for improvements to the instrument.

4. The Use of Optical Coordinate Measuring Machines

4.1. Introduction to CMM

The coordinate measuring machine is a universal measurement machine in dimensional metrology [42]. With these machines complex structures, for example, parts of engines and pumps, can be measured. The size or measurement volume of a CMM does vary a lot. A big CMM in the car industry may have axes of a length of several metres and a CMM for the measurement of microsystem components has an axis length of some centimetres [43, 44]. A complete description of the CMM and the measurement uncertainty of CMM is beyond the scope of this dissertation [45, 46, 47,48]. In some studies laser interferometers are used to get traceability and achieve a small measurement uncertainty [49]. Also error compensation methods are applied [50]. In one specific work error compensation is applied for a cylinder [51]. Measurement comparisons between laboratories using error separation methods have also been done [52].

The measurement uncertainty depends not only on the errors of the CMM but also on fitting algorithms of the measured feature and sampling. There are only few guidelines for the calibration of a CMM. One example can be found in Ref. [53].

One type of CMM is an optical CMM, which is a CMM equipped with a camera instead of a contacting probe. Typical lens magnifications provide a resolution of 0.5 $\mu\text{m}/\text{pixel}$ to 2 $\mu\text{m}/\text{pixel}$ [4]. The optical CMM is ideal for non contact 3D measurements of small elastic parts and features. Typical claimed measurement uncertainties for commercial optical CMM's range from 0.8 μm to 6 μm [54, 55].

A third type of CMM is equipped with an opto tactile sensor. Here an optical fibre is used for probing and the position of the fibre is measured by a camera [56].

The measurement uncertainty of a specific CMM measurement task is a widely studied subject and in figure 8 one approach is shown. A similarity between optical CMM's and machine vision is the importance of the illumination. Different operators may perform different illumination selections and the results of the dimensional measurements may therefore be different. Also the selected measurement strategy may affect the results [57]. Therefore it can be said that the skill of the user is critical for successful CMM measurements and figure 8 is a somewhat idealized presentation because it hides the human factor.



Figure 8. Factors affecting a CMM measurement [9].

In table 1, the relative distribution of uncertainty components for measurements using a CMM and an optical CMM are presented. The effect of the operator is very high for instruments operated in the industry. Especially for the case of the optical CMM the operator is responsible for the selection of illumination, measurement strategy and alignment compensation.

Table 1. Fractional distribution of uncertainty components for measurements using a CMM and an optical CMM [58].

	Operator	Instrument	Environment	Object
Probing CMM	30-50 %	5-20 %	5-20 %	10-30 %
Optical CMM	50-70 %	5-20 %	2-5 %	20-40 %

In metrology it is customary to test the claimed measurement capabilities by arranging comparisons where the same artifact is circulated and measured by different participants. As pointed out by a national comparison in Finnish industry [59], many

users do not know the real measurement uncertainties. In an other comparison for 11 optical and 12 mechanical CMM's, the results showed agreement with the reference values within the reference uncertainty, and also showed that optical CMM measurements can be as good as mechanical CMM measurements [60].

4.2. Task specified uncertainty for CMM

Although the question of measurement uncertainty for a specific measurement made with a CMM, has been intensively studied, there is still no single clear solution to this problem. In a survey [61] published in 2001 the following possibilities are classified as:

- Sensitivity analysis
- Expert judgement
- Experimental method using calibrated objects (Substitution method)
- Computer simulation (Virtual CMM)
- Simulation by constraints
- The expert CMM
- Statistical estimations from measurement history
- Hybrid methods

In [24] the possibilities are classified and presented as:

- Expert judgement
- Uncertainty evaluation based on step gauge results
- Simplified substitution without corrections
- Substitution according to ISO15330-3
- Uncertainty evaluation based on geometric errors together with simulation (PTB software Kalkom Megakal and VCMMtool)
- Virtual CMM (OVCMM)

In the following, three of the above approaches are discussed: sensitivity analysis, substitution method and virtual CMM. One conclusion of the survey was that there are large classes of coordinate measuring systems that have only been partially addressed in the literature such as photogrammetry systems and vision based CMM's [61]. Another conclusion was that none of the methods for task specific uncertainty appear to successfully address the interaction between sampling strategy and possible part form error. During the preparation of this thesis the new ISO 15530 series of standards "GPS- Coordinate measuring machines – Techniques for determining the uncertainty of measurements" was not yet completely published with the exception of ISO 15530:3 describing the substitution method. In the future, the remaining parts describing expert judgement, virtual CMM and methods using statistics from measurement history and methods using uncalibrated workpieces are expected to be published.

Sensitivity analysis

For simple measurements where a well defined mathematical model of the measurements can be formulated, the GUM method is easy to use and this is called sensitivity analysis in [61]. For example, when a CMM is used for a simple length measurement, the measurement model is also relatively simple and the sensitivity coefficients can be determined. For a 2D measurement task the measurement model is already of considerable complexity.

Experimental method using calibrated objects

This method, also called the substitution method, is based on the comparator principle. If a reference work piece, almost identical to the object to be measured is available, repeated measurements on both are performed. This means that it would be good to have quite a large number of different calibrated references available. One advantage with this straightforward method is that it is simple and can be brought and communicated to the user. On the other hand, any differences (for example thermal expansion coefficient) between the reference part and the object to be measured can lead to unwanted uncertainties [61].

Although the substitution method is valuable, it is not the complete solution to the task specific uncertainty problem [61]. Because the full substitution method is regarded as tedious a simplified substitution method is suggested in [24].

Computer simulation and virtual CMM

A straightforward application of GUM becomes very difficult or perhaps impossible in complex measurement processes such as form measurement and 2D or 3D coordinate measurements. In these measurements, digital filtering of measurement points is used, and at the points geometric elements are fitted. The question is how to formulate a measurement model with sensitivity coefficients. If for example a hole is measured by fitting a circle on say 100 measured (x, y) points, what is the contribution to diameter from the uncertainty of x-ordinate of one specific point ? And what if 4 points are used for the measurement, instead of 100 ? Here is a problem of interaction between sampling strategy, form error of the object to be measured and the geometric fit algorithm.

The concept of virtual CMM or VCMM, based on Monte Carlo simulations, has been presented by researchers at PTB during the last decade. Examples of Monte-Carlo simulations for uncertainty evaluation for CMM's are given in Refs. [62, 63, 64] and for other fields in metrology they are given in Refs. [65, 66]. There is also an ISO document [67] where this technique is documented. The amount of work needed for the Monte-Carlo analysis is a problem, but software packages have been developed at PTB [68]. The first commercial software packages aimed at non-academic users, was launched by the corporations Zeiss and Leitz in 2003 [24, 69]. One challenge when using virtual CMM is how to estimate the effect of form and roughness of the object to be measured.

4.3. Measurement of apertures using an optical CMM

Since 2002 an optical CMM [70] of high precision has been used in MIKES for several measurements tasks especially for the electronics industry and customers in the field of medicine (figure 9).



Figure 9. The optical CMM at MIKES.

The optical CMM is well suited for repeated measurement tasks and in 2005 a measurement series of apertures was initiated (Publ. II). Apertures are used in photometry and radiometry to limit a precisely known area of the incoming radiation field in front of a detector with calibrated power responsivity. The known area then gives access to quantities such as illuminance or irradiance which describe suitably weighted optical power density. Several contact [71] and non-contact [72, 73, 74, 75, 76, 77, 78] methods have been used for measurement of aperture areas. Non-contact methods are of special interest in radiometric applications because they do not damage the sharp edge of apertures which is essential to produce a well-defined area. The reported relative standard uncertainties are typically 10^{-4} or less. However, for many practical applications in photometry and radiometry an aperture area uncertainty

of 10^{-3} would be sufficient, provided that it can be achieved in a straightforward way. Apertures and diameters of apertures are also of interest in other applications than photometry and radiometry [79].

The purpose of the measurements was to study the stability of newly machined apertures. Ten conventionally machined aluminium apertures were measured eight times. The effects of illumination and amount of measured points along the circumference were found to be quite large. The effect of deviation from roundness (figures 10-11) can be decreased by increasing the number of measured points. In this work most measurements were made using 120 points, and this number can be considered as an acceptable minimum.

As pointed out in Ref. [55], the selection of the illumination is very critical. In Publ. II the effect of different illumination selections was studied. The resulting variation in diameter was taken to the uncertainty budget as an error source. The result of the uncertainty evaluation was an uncertainty of $2.3 \mu\text{m}$ ($k=2$) for diameter.

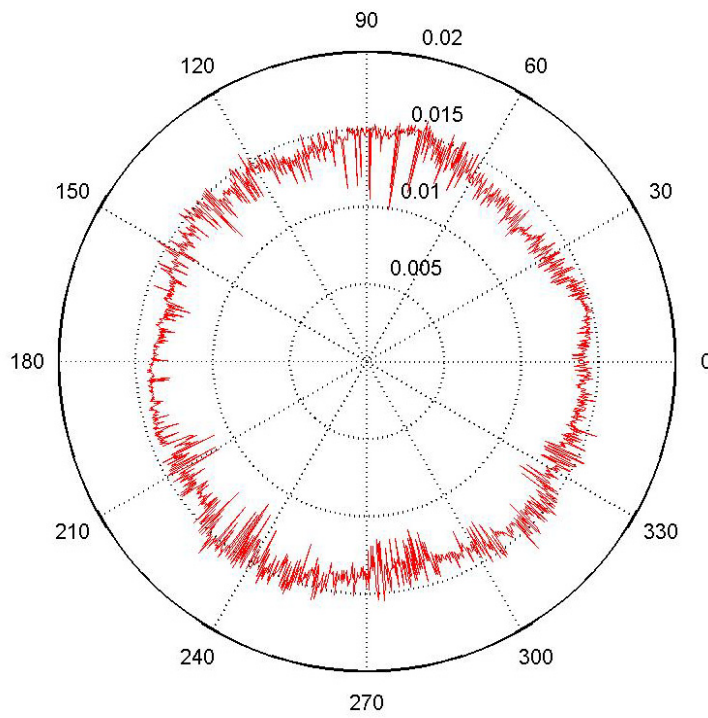


Figure 10. Roundness polar plot of aperture HUT-9 with 2000 points. Dashed circles indicate 5 μm scale grid in the polar plot (Publ. II).

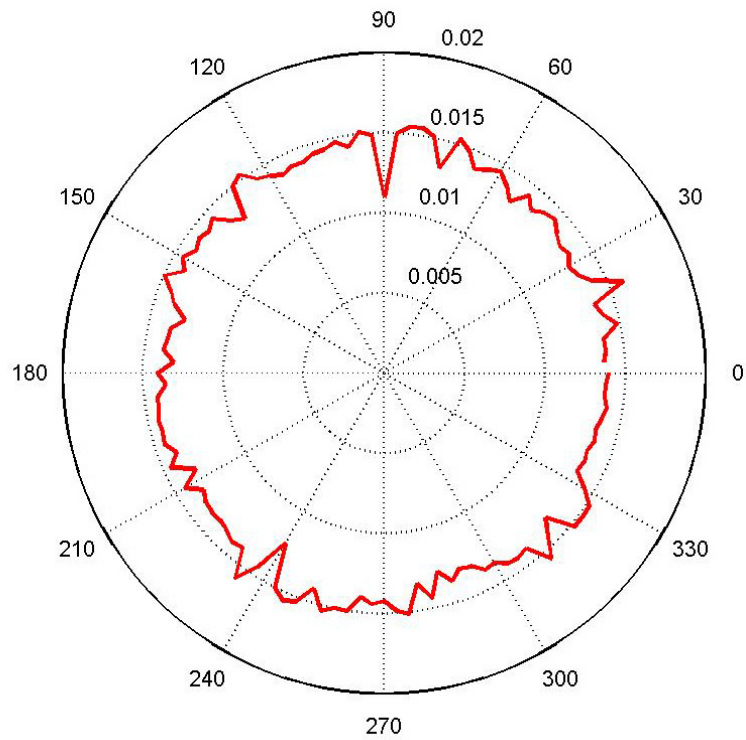


Figure 11. Roundness plot of HUT-9 with 120 points. (Publ. II).

Verification measurements

Verification measurements for one aperture were made on a high-accuracy CMM using a contact probe. Because the probe is large compared to the roughness of the aperture, the measured diameter is decreased by a contact error (figure 12). The contact between probe and aperture was simulated and this effect was corrected from the diameter result, together with the effect of measuring force [80]. The result of this simulation was an estimate of the contact error of $1.1\ \mu\text{m}$ and a force correction of $0.06\ \mu\text{m}$. The difference in diameter between the contact probe CMM and the optical CMM, after these corrections were applied, was only $0.1\ \mu\text{m}$.

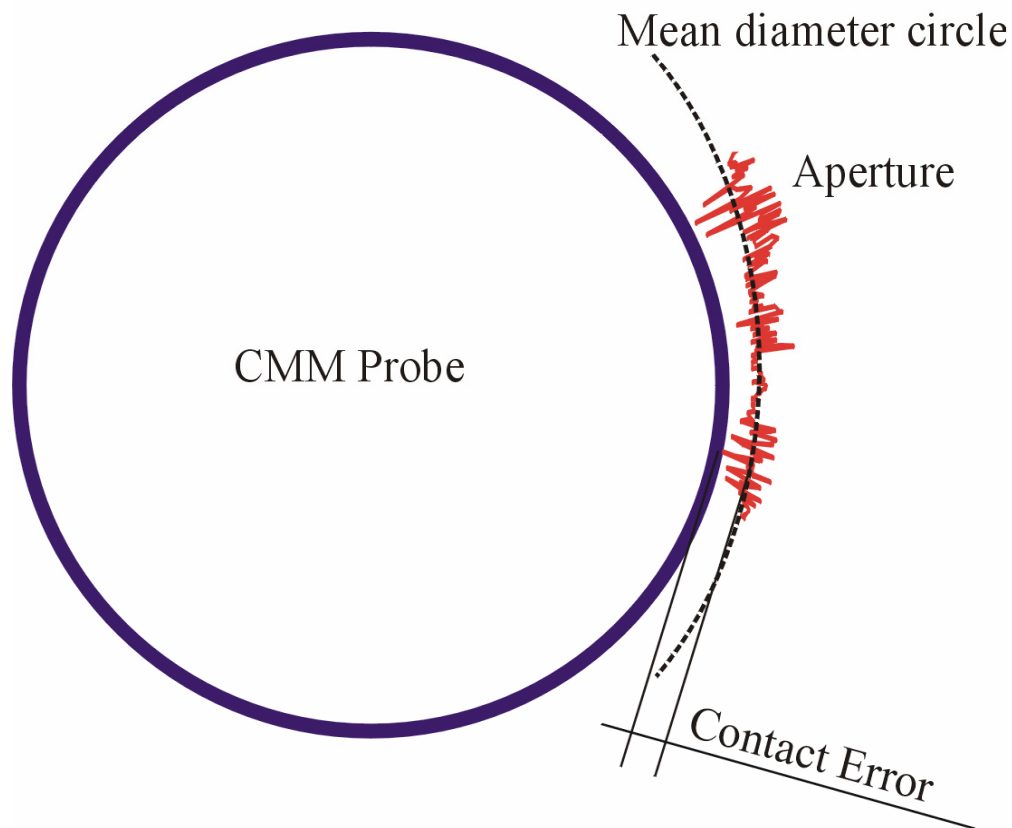


Figure 12. The roughness of the aperture results in an apparent diameter smaller than the mean diameter of the aperture.

4.4. Discussion

It is clear that the accuracies of dedicated aperture measurement instruments are better than the accuracy of a general purpose optical CMM. As pointed out by [56] one of the difficulties in using an optical CMM is edge detection which depends on illumination and algorithms (see also figure 13 in following section) and also, among others, distinct detection of edges distorted by material faults [56]. These problems were experienced in this study where an optical CMM was used for aperture measurements. Fortunately the errors sources can be quantified and estimated in an uncertainty budget. This is the first time an uncertainty budget for optical CMM has been presented for aperture diameter measurements. This uncertainty evaluation may serve as an example of how to achieve traceability and reliability in a measurement based on machine vision, giving an answer to the second research subquestion.

Although the roundness effects are believed to be reduced by averaging, it would be desirable to put more effort to the quality of drilling of the apertures. In the future diamond drilling could be considered. In future work the effects of illumination on the diameter measured by an optical CMM should be examined also analytically and not only empirically. The excellent agreement between contact probe CMM and optical CMM is regarded as a coincidence and not as an indication of an excessively pessimistic uncertainty evaluation.

The conclusion of Publ. II is that if the required uncertainty is not very low, the optical CMM used in this study is useful for aperture diameter measurements. A line-scale was used to evaluate the errors of the optical CMM.

A new type of CMM equipped with an opto tactile sensor appears to be an attractive alternative to an optical CMM, provided that the measurement force is very low. Similarly the probing CMM seemed to give an accurate diameter result. However, non-contact measurements are demanded or at least preferred by the end-users of the apertures in the photometric and radiometric laboratories.

5. Machine Vision Based Calibration Equipment

5.1. Introduction to Machine Vision

Machine vision is a vast field of science and engineering, where the image can be anything from a continent to a nanoparticle. However, in the industry many machine vision applications are inspection tasks where the position, orientation or dimension of a feature is measured [81, 82].

Sometimes the systems consist of two or more cameras as in the Finnish product Mapvision [83]. A more recent example of the use of two cameras in patient radiotherapy is given in [84]. Although there is a profound understanding of machine vision in universities and research institutes [85, 86] and the competence of machine vision vendors is high, measurement uncertainty statements are seldom seen.

The situation is that for most machine vision systems intended for dimensional measurements only results from performance test are given. Typically only repeatability tests are performed. If the performance tests are sufficiently extensive, the collected data may be enough for an adequate uncertainty evaluation. An example of this can be found in [87]. Sometimes accuracy statements according to procedures of VDI/VDE 2363 guidelines are given [88], which of course gives confidence in the reliability of the instrument. Hence the situation is similar to that of many CMM's. A verification is made but the measurement uncertainty is still unknown.

In figure 13 the error sources in a simple machine vision system intended for dimensional measurements are presented. Similarly to the presentation in figure 3, there might be errors from the setup and errors coming from environment such as temperature.

Illumination together with roughness and edge effects may affect the appearance of the object to be measured. Errors in the instrument, such as camera and lens error, may distort the image. Moreover, the selected measurement method, measurement strategy and simplifying assumptions affect the result. For example; how should the angle between two lines be measured when the lines are not straight ? Errors in edge finding may be the result of errors in software, but more probably due to non optimal parameter selection or just mistakes done by the operator. If the calibration of the scale factor is not properly done using a good reference standard, scale errors may occur, also.

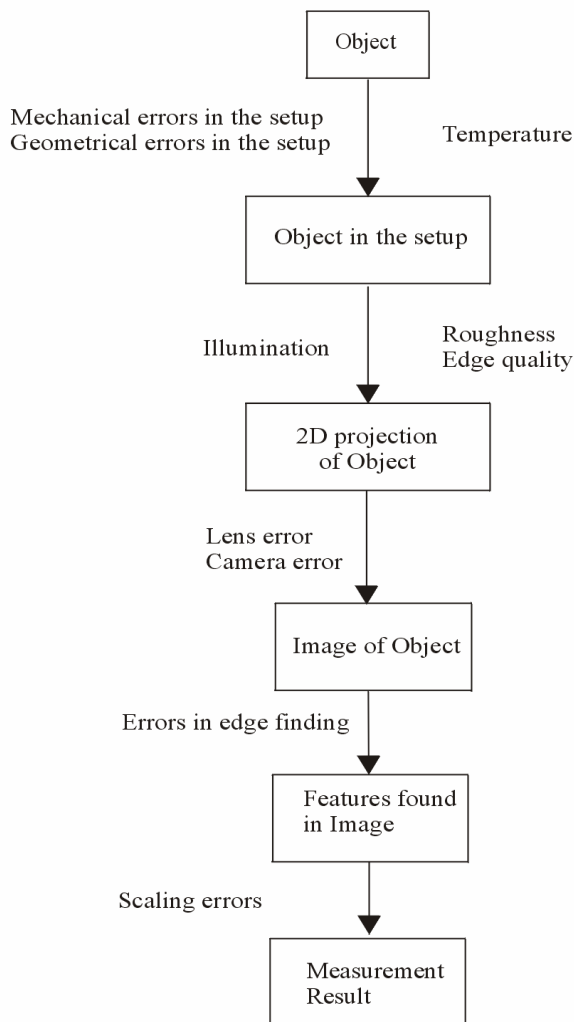


Figure 13. The dimensional error sources in a machine vision system

One important detail which is depending on the measurement task is shown in figure 14. Difficulties in edge detection are not critical, when the centre position of symmetrical features is measured. Therefore, the measurement of diameters of holes is very difficult, but the measurement of distances between holes is not so critical to the edge detection.

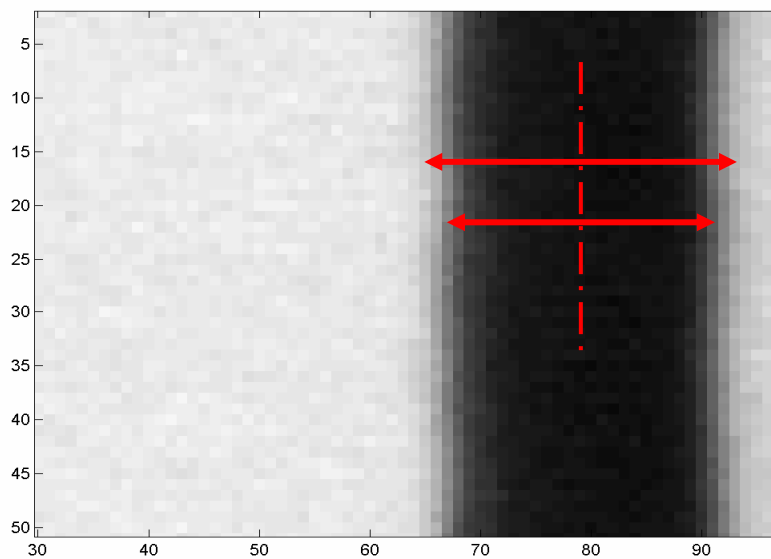


Figure 14. Illustration of the difference between measurement of the size of a feature and measurement of the centre position of a feature

It should be noted that any of the error sources shown in figure 3 may be a dominating error source. Stability is not included in the presentation of figure 3, but it might be the most important feature in many machine vision systems. When machine vision is used in the processing industry, the measurement result may be used as an input for the process control. Although traceability to the SI units is not crucial in process control, a drift in the measurement device can result in problems.

One way to address these problems has been the definition of acceptance tests, such as the VDI/VDE 2634 guidelines. The purpose of an acceptance test is to verify that the measurement errors lie within the limits specified by the manufacturer or the user. In the acceptance test, calibrated artefacts are measured. Acceptance tests for optical 3D

measuring systems are defined in Refs. [89] and [90]. The methods are similar to the methods of acceptance tests for coordinate measuring machines. Performance tests are very useful, but the measurement uncertainty for real measurements of real parts or products is probably not as good as the outcome or result of an acceptance test, where well defined artefacts of good quality are used.

5.2. Camera Calibration in Machine Vision

Camera calibration usually means setting the relation between world coordinates and camera coordinates at the captured image [91, 92, 93]. Camera calibration in machine vision is a widely studied subject [94, 95, 96, 97, 98, 99, 100]. The most well known camera calibration method presented by Tsai [101] and some basic ideas are briefly described. The camera model consists of extrinsic and intrinsic parameters. The extrinsic parameters are related to the position and angle of the camera in relation to the world coordinates. The intrinsic parameters may contain radial or tangential lens distortion. According to Tsai radial lens distortion should be evaluated and corrected (figure 15). The calculation of tangential lens distortion may result in numerical instabilities when the distortion parameters are searched [101].

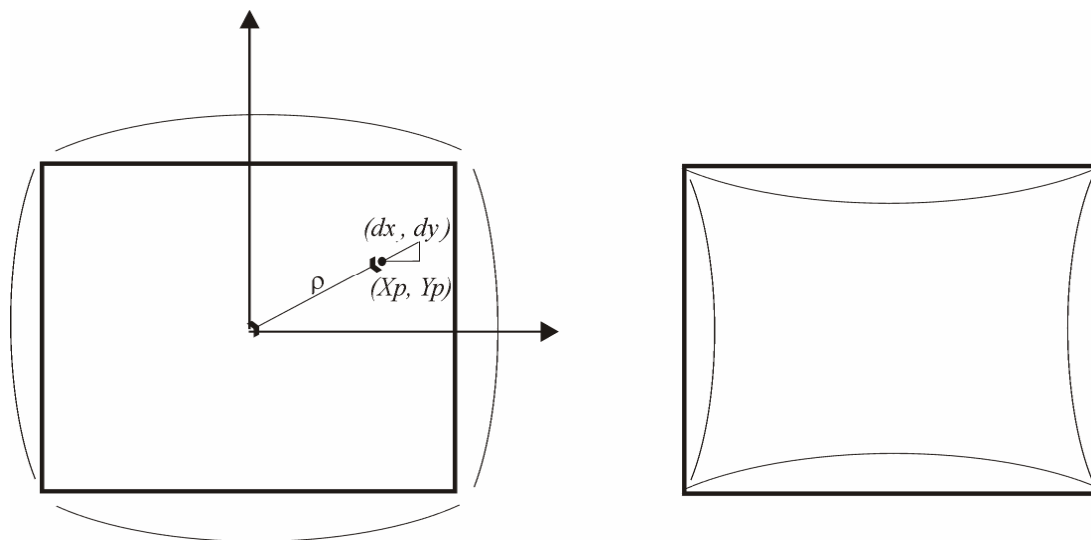


Figure 15. Barrel (left) and pin-cushion (right) types of radial distortion.

Radial distortion dx, dy in x- and y- direction is modelled by the polynoms:

$$dx = Xp (k_1 \rho^2 + k_2 \rho^4) \quad (3)$$

$$dy = Yp (k_1 \rho^2 + k_2 \rho^4) \quad (4)$$

where (Xp, Yp) is the undistorted position of a point in the image, k_1 and k_2 are coefficients for radial distortion and the distance from image centre (ρ) is:

$$\rho = \sqrt{Xp^2 + Yp^2} \quad (5)$$

According to Tsai the polynom of second order gives acceptable accuracy and the parameter k_2 can usually be neglected.

An example of camera calibration

The equipment used for the automatic calibration of micrometers (Publ. IV) was checked for lens errors using the afore-mentioned two-dimensional standard. In the equipment, the field of view is roughly 4 mm x 6 mm. Using gray-scale correlation the positions of the cross feature of the grid is retrieved. The coefficients of the camera models are solved using Matlab and Nelder-Mead minimization of the residuals which represent camera errors with respect to the standard.

Some results of camera calibration are presented in table 2. The average error found in the calibration is about 1 μm and equals 1/7 pixel. The average error becomes smaller when radial distortion is included in the camera calibration model. From table 2 it is seen that the horizontal scale factor S_x is in the range 7.22 $\mu\text{m}/\text{pixel}$ - 7.23 $\mu\text{m}/\text{pixel}$ depending on the chosen camera model. In Publ. IV, the value 7.24 $\mu\text{m}/\text{pixel}$ was used, based on calibration measurements using a line-scale. In the application where

machine vision was used for 1D measurements, the line scale provided satisfactory accuracy. For applications with 2D measurements the calibration grid is a better choice, especially because radial distortion may be modelled and compensated for.

Table 2. Results of camera calibration using three different camera calibration models for the equipment in Publ. IV. The found scale factors S_x and S_y depend on the chosen camera model.

	No distortion included	2 nd distortion included	order 2 nd and 4 th distortion included
$S_x / (\text{mm/pixel})$	0.00722	0.00723	0.00723
$S_y / (\text{mm/pixel})$	0.00725	0.00726	0.00726
k_1 / mm^{-2}		-0.00026	-0.0003
k_2 / mm^{-4}			6.48×10^{-6}
Average error / μm	1.39	0.93	0.91

5.3. Calibration of Dial Indicators with Machine Vision

In Publ. III an automatic calibration system for the calibration of dial indicators is described. Dial indicators are widely used in industry for various measurement tasks [102]. In the industry and accredited calibration laboratories dial indicators are calibrated manually at an uncertainty level varying from $1\mu\text{m}$ to $3\mu\text{m}$ ($k=2$), mostly by comparing to either length transducers or mechanical micrometers.

The automatic system for the calibration of dial indicators is not unique. Two previous machine vision based systems for the calibration of dial indicators are known to the author. The Institute of Nuclear Energy in Bucharest has developed a laser interferometer based instrument [103]. In this instrument the linear displacement of the dial indicator rod is measured by a Michelson interferometer. Over the dial indicator face a specially designed angular transducer with phototransistors is placed.

A commercially available instrument is also offered by the Steinmeyer Feinmess corporation [104]. The measurement uncertainties of these systems are unknown or not given.

The system described in Publ. III consists of a motorised stage, a holder for the dial indicator and two length transducers, and a red LED ring light source together with a CCD camera [105]. The position of the stage was measured by the two length transducers and their average used as a position reference to eliminate the Abbe error (figure 16).

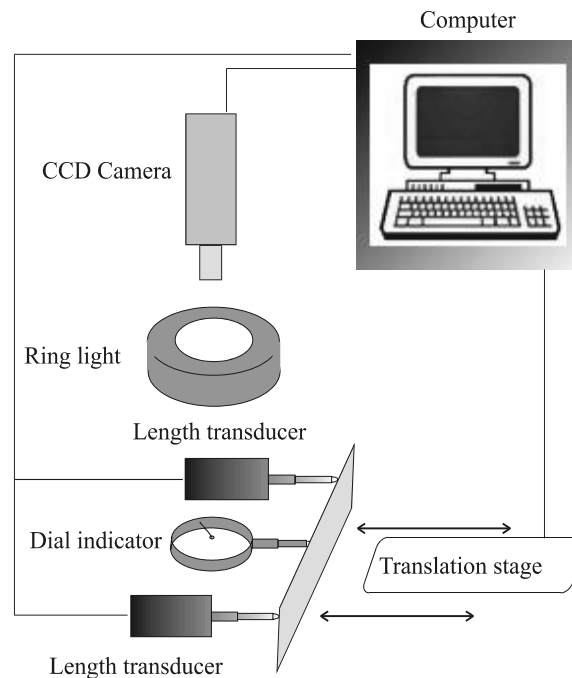


Figure 16. Operating principle of the equipment for calibration of dial indicators (Publ. III).

The image area is large and covers the whole face of the dial indicator to be calibrated. In order to exclude unwanted features from the image a simple method also used in Ref. [81] was implemented. Removal of the static background comprising the dial is done by subtracting the two images of the dial. Since the pointers are the only moving part of the dial, subtraction results in the removal of everything in the images except the pointers. It is assumed that the large pointer is on its right lap,

precluding the need to measure the position of the small pointer. The error in the camera and lens is about ± 0.3 pixel in the x and y directions measured with a two dimensional grid. The measurement uncertainty for the developed instrument is $1.57 \mu\text{m}$ ($k=2.01$). When a dial indicator is calibrated manually, the uncertainty of the reading and interpretation of the pointer is of the same order as with the developed machine vision system. Using machine vision in normal routine calibration makes it possible to check hundreds of points on the scale of a dial indicator (figure 17).

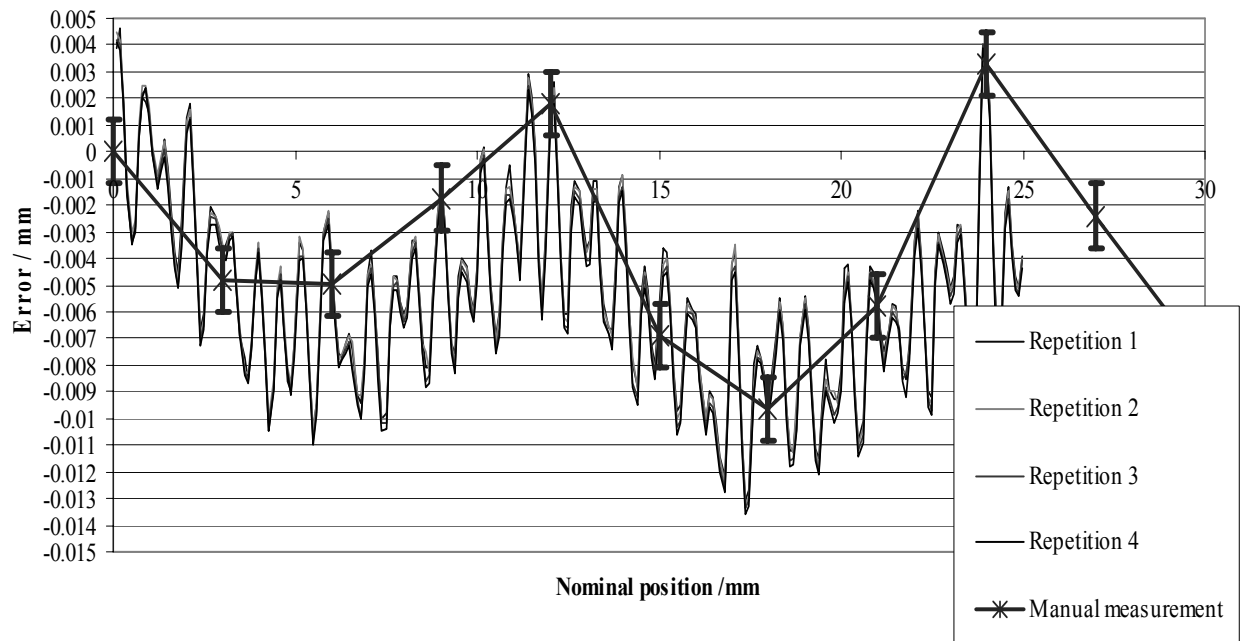


Figure 17. Error curve of a dial indicator measured manually (with uncertainty bars) and using the developed machine vision system with four repetitions (Publ. III).

5.4. Calibration of Micrometers with Machine Vision

The micrometer calliper is a simple but still accurate handheld mechanical instrument for measuring outside dimensions. For the measurement of inside dimensions there are also two-point micrometers and three-point micrometers. The scale of a micrometer is made from a screw usually with a pitch of 0.5 mm per revolution. According to requirements in ISO3611 the error of measurement to a typical micrometer calliper with a measurement range of 0 ... 25 mm, should be below $4 \mu\text{m}$ [18].

The cost of calibration of a hand-held measurement device such as a micrometer calliper or dial indicator is roughly equivalent to the price of a new instrument. Manual calibration therefore usually involves checking a mere 10 to 20 points. In some calibration laboratories a CCD camera together with a monitor are used as a magnification glass. Therefore, why not connect the camera to a computer and automate the reading of the micrometer or dial indicator? With automatic machine vision-based systems the calibration can be extended to several hundred points, giving a more complete picture of the errors.

The manual calibration of a micrometer according to ISO 3611 is done by using ten gauge blocks [18]. This gives only a rough figure of the accuracy of the instrument and is not a complete check of the scale. To reveal the error sources of a typical micrometer, many more points should be checked. Possible error sources are zero setting error, form error on the measuring faces, pitch error and nonlinearities in the screw, location errors or bad quality of graduation lines on the thimble and variations in the measuring force.

In Publ. IV an automatic calibration system developed for the calibration of micrometers is described. The instrument consists of two motorised stages, a length transducer, and a LED ring light together with a CCD camera. The rotation of the micrometer drum is motorised through a flexible coupling. A plate is fastened to a translation stage and the micrometer is run against this plate (figure 18). To keep the measuring force stable throughout a measurement, the motorized thimble of the micrometer is turned making two clicks at the ratchet drive of the thimble. A force transducer can also be placed between this plate and the measurement surface of the micrometer. A CCIR (Comité International des Radiocommunications) standard camera was installed to read the micrometer. The position of the stage was measured by a length transducer.

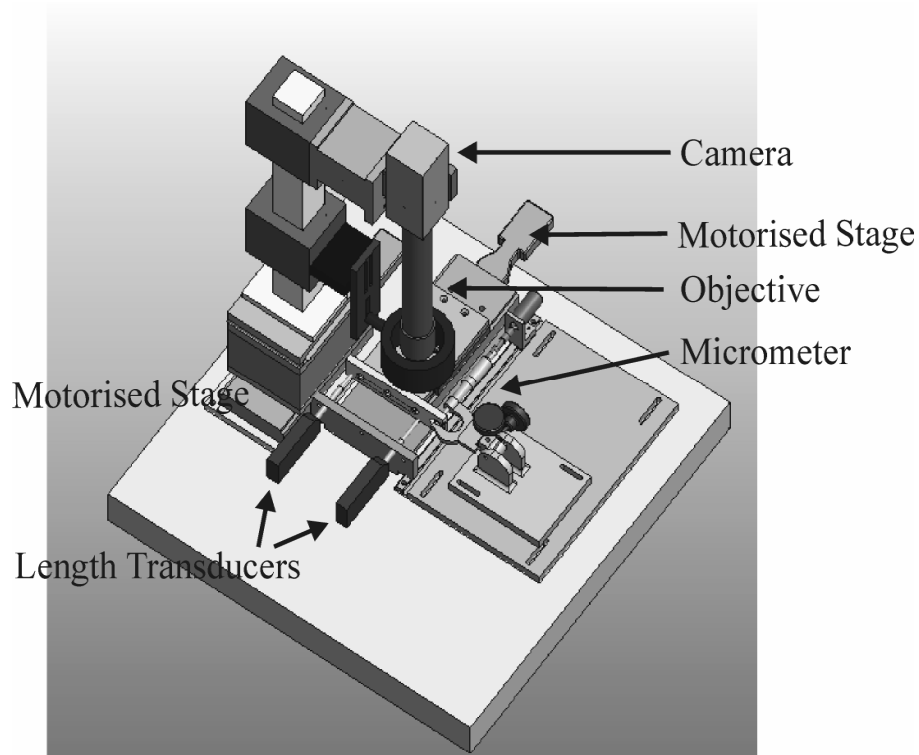


Figure 18. Instrument for automatic calibration of a micrometer.

The position of the division lines on the micrometer drum is found using the pattern-matching function in the Matrox Mil library. The pattern-matching algorithm is based on cross-correlation and the accuracy of about 1/8 pixel is verified by using Matlab. The field of view is only 4 mm x 6 mm. As indicated in figure 19, this field of view covers only the thimble. Before the measurement the angle and position of the fiducial line is separately and automatically measured.

Although both machine vision methods and mechanical design of the equipment could be improved, the main conclusion is that the presented new approach has the potential to produce more than ten times more calibration results at an uncertainty which is less than 10 % compared to the uncertainty of a manual calibration (figure 20). The large number of measurement points makes it possible to analyse the frequency spectrum of the error curve. The calibration result gives pitch error and nonlinearities in the screw at an uncertainty of $0.8 \mu\text{m}$ ($k=2$).

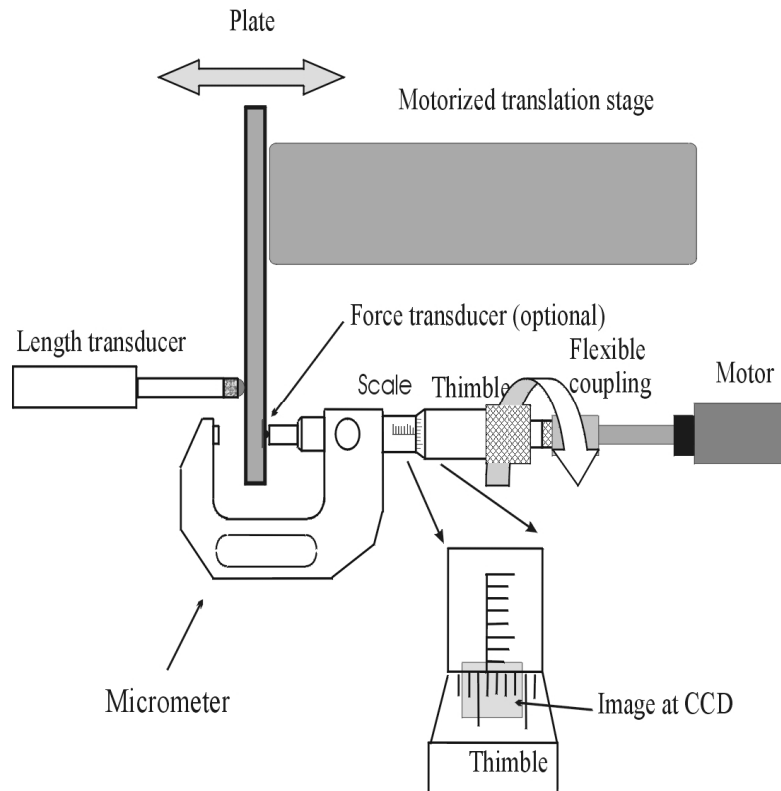


Figure 19. Setup for automatic calibration of a micrometer (Publ. IV).

The time needed for a detailed calibration with 0.05 mm intervals and 400 points is about two hours and, therefore; speed optimization should be made in the future. Limitations of the equipment are that flatness measurement of the measuring faces is not included and that force measurements require some extra setup. The deflection of a tested force transducer was large and therefore force cannot be measured during the dimensional calibration of the screw. Another limitation is that for a typical 25 mm micrometer only the range 5 mm – 25 mm can be calibrated. For larger micrometers such as 25 mm – 50 mm and 50 mm -75 mm, the whole 25 mm range can be calibrated. The instrument can also be operated in a semi-automatic mode, where gauge blocks are manually inserted between the measuring faces of the micrometer [106].

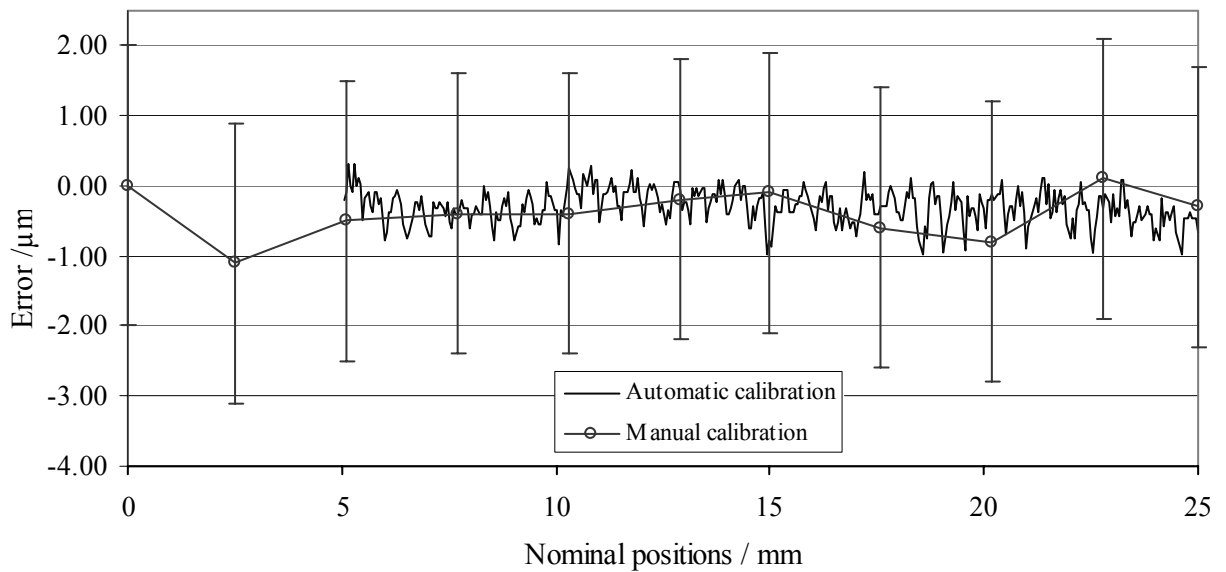


Figure 20. Calibration results using ten gauge blocks (with uncertainty bars for manual result) and using the automatic system (Publ. IV).

5.5. Discussion

The hardware of the equipment of Publ. III and Publ. IV are partly similar. The length transducers used as a reference are calibrated using a laser interferometer and the cameras and lenses are calibrated by traceable calibrated line scales. In both applications only centres of lines and features are measured, reducing the effects of illumination and problems in edge detection. A similar feature and benefit in both micrometer and dial indicator applications is that many points can easily be automatically measured. The large number of measurement points makes it possible to analyse the frequency contents of the error curve by Fourier transform. Another automatic system for the calibration of micrometers is not known to the author. The calibration of dial indicators by machine vision is not unique, still an uncertainty evaluation for such a system has not previously been published.

Some technical difficulties and marketing challenges were also noted. The equipment for calibration of micrometers in its first preliminary implementation requires too much time and effort for operation to be commercially profitable to its owner. Therefore a mechanical re-design should be considered in the future.

As both dial indicators and micrometers are cheap a meticulous calibration might sound as an exaggeration or bad cost-benefit. However, there are two things worth to note. If a micrometer is used for quality checking at a production line in a factory, measuring the same dimension thousands of times each year might cause wear, and errors at that single point of the scale of the micrometer. In a manual routine calibration, this wear would probably not be revealed. It can be concluded that the benefit of automation is an extensive calibration. And to be reliable, a detailed uncertainty budget is needed. The second thing worth to note is the nature of the error curve of the dial indicator in figure 16. The limited number of points in a manual calibration cannot give the complete picture of the errors.

For the equipment for calibration of dial indicators the largest uncertainty source comes from the machine vision sub-system (errors in camera and lens and edge finding algorithm for the pointer). On the other hand for the equipment for calibration of micrometers the uncertainty contribution from machine vision was very small compared to the contributions from mechanical errors and Abbe error. Hence, the dominating uncertainty source was quite different in each application. In one stage of the design process of the micrometer application cosine error of the micrometer appeared to be a dominating error source. The conclusion was that extra care is needed to align the micrometer.

These examples show that it is difficult to base uncertainty estimation on intuition, and that all mechanical, geometrical and optical uncertainty components should be separately estimated.

The hypothesis of this thesis was that a thorough uncertainty evaluation is crucial during the development of a measurement application where machine vision is used. The first subquestion of the research question was about uncertainty sources and design of a measurement instrument based on machine vision. The Publ. III and Publ. IV are considered to serve as two examples of how to evaluate the error sources, and a technically detailed answer to the subquestion is given in these publications.

6. Conclusions

Accurate dimensional measurements are needed in many fields, especially in the manufacturing industry. During the past decades the electronic industry, with the miniaturizing trend, has demanded precision measurements.

The benefits and dangers of machine vision in measurement are similar to the impact of computers in measurement. Many benefits are achieved through automation but the understanding and physical contact to the measurement is easily lost. One way to approach these problems has been the definition of acceptance tests such as the VDI/VDE 2363 guidelines. However, experiences with CMM's have shown that the operator is the largest uncertainty source. Therefore an acceptance test of a CMM performed by the supplier or a third party, does not completely give the accuracy of the production measurements of the CMM. The situation for optical CMM's and machine vision systems is the same or even worse, due to illumination effects. The best way to regain the understanding of the measurement is to make an uncertainty budget. In this budget the illumination contributions, selectable by the operator, are included.

The publications describe four different measurements or measurements systems, where the camera axis is perpendicular to a plane where the measured object is located. Another common feature is that the size of the objects is in the millimetre range and that the illumination is controlled.

There exist also more complex applications which are used in the industry, such as applications with two or more cameras and 3D measurement applications. The measurement uncertainty and traceability of these should be future research topics.

In this thesis, traceability and measurement uncertainty in machine vision applications are described. The most important reference standards are line-scales and two-

dimensional standards. The calibration and use of 2D standards is described. Together line-scales and 2D standards give traceability to the other applications described in this thesis. The largest uncertainty source in the presented equipment is the uncompensated part of the Abbe error, due to the offset between the laser beams and the calibrated standard.

The use of an optical CMM and its measurement uncertainty for the measurement of apertures is described. Here the largest uncertainty source is the selection of the illumination. Due to the complexity of the CMM measurement, a complete and strict uncertainty budget according to GUM was not made. However, a rough model of the measurement has been given together with a Monte-Carlo evaluation of uncertainty.

Measurement uncertainty and traceability for CMM's is widely studied in the literature. Still there is no easy single answer for how to obtain measurement uncertainty for a complex CMM measurement and especially not for a measurement performed with an optical CMM. In Publ. I the sensitivity analysis method is applied for the measurement of 2D standards. In Publ. II, the virtual CMM method is applied.

The use of machine vision in high accuracy measurements is described in one example concerning the calibration of dial indicators and in one example concerning the calibration of micrometers. In the equipment for calibration of dial indicators, the largest uncertainty source came from the machine vision, but in the equipment for calibration of micrometers, the uncertainty contribution from machine vision was very small compared to the contributions from mechanical errors and Abbe error. Hence, the dominating uncertainty source was quite different in each application. These examples show that it is difficult to base uncertainty estimation on intuition, and confirms the hypothesis of the importance of uncertainty budgeting already in the design process. The systems, especially the equipment for calibration of dial indicators, are quite simple but have no value in a metrological sense without an uncertainty budget. It is the view of the author that the uncertainty budget is part of the design of a measurement instrument, just like the drawings. The emphasis of both

Publ. III and IV is on the description on the uncertainty budget and the use of the GUM method.

A new scientific contribution of this work is the development of uncertainty analysis according to GUM method to machine vision applications. The obtained results clearly verify the hypothesis that a thorough uncertainty evaluation is crucial during the development of a measurement application where machine vision is used for a dimensional measurement. The author suggests that the GUM method should be more widely applied for machine vision based calibration and measurement equipment. In a situation where machine vision is used for calibration or measurements of products the measurement uncertainty and traceability should be understandable and believably documented. This is also an economical issue, because failure in measurement, at the end, means economic loss. For a manufacturer it is costly to reject a large production batch which is actually within the specifications. It is also bad practice to send products, which perhaps are within the specifications, to the customer to be rejected. If the measurement process is understood and measurement uncertainty is in correct proportion to the geometric tolerances, we get lower quality costs. Therefore potential economical benefits can be included to the answers to the research question.

Real confidence of a machine vision based measurement instrument is achieved only by systematic documentation and calculation of the uncertainties. When these uncertainties are studied during the design process of a measuring instrument or measuring application, the bottlenecks of metrological performance, can be corrected.

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