Publishable Summary for 17NRM03 EUCoM
Standards for the evaluation of the uncertainty of coordinate measurements in industry

Overview

Evaluating measurement uncertainty during inspections is key for verifying the conformity of parts with sufficient confidence. However, the evaluation is known to be difficult in practice for coordinate measurements, which is the most popular technique for dimensional inspection in industry. This project developed three viable methods (i.e. A, B1 and B2) which are suitable for common industrial cases and inclusion in international standards. The methods were reported to the relevant standards body; ISO/TC 213 on Dimensional and geometrical product specifications and verification WG 10 on Coordinate Measuring Machines. The *a posteriori* type method A has been accepted as input to ISO/TC 213/WG 10's and the WG's project on ISO 15530-2 has already started. The project's other two *a priori* type methods B1 and B2 are still under scrutiny but it is hoped that they will be included in a possible future project ISO 15530-5. Thus, the project's methods will help to improve quality assurance and positively impact European manufacturing.

Need

In the decade prior to the start of this project, the GDP due to manufacturing grew in Europe less than the accumulated inflation (11.7 % vs. 15.7 %), with a net contraction of the European manufacturing. Key to staying competitive with low-wage developing countries is advanced manufacturing of high-quality products. However, this is impossible without high standards for intermediate and final inspections, primarily on dimensional and geometrical quantities (GPS – Geometrical Product Specification). Hence even a tiny improvement in this area should result in a very large economic impact due to the large GDP fraction of manufacturing in Europe.

Inspections provide factual evidence for decision-making. Current standards such as EN ISO 14253-1 on *GPS - Inspection by measurement of workpieces and measuring equipment - Part 1: Decision rules for verifying conformity or nonconformity with specifications*, and ISO/TR 14253-6, *Part 6: Generalised decision rules for the acceptance and rejection of instruments and workpieces*, help end users decide upon part conformity or nonconformity with specifications (tolerances) taking account of the inevitable uncertainty incurred in measurement. However, the evaluation of the uncertainty in coordinate measurement is technically very difficult and little guidance is available in international standards, which often results in industry overlooking it. This can result in the wrong decisions being made, such as (i) accepting nonconforming parts with consequences ranging from production downtime to catastrophic failures for safety-critical parts, and (ii) rejecting conforming parts causing economic loss.

The new viable and standardisable methods for evaluating the uncertainty in coordinate measurement delivered by this project will help to make inspections in manufacturing more reliable, support better quality control of products, and help maintain and strengthen the competitiveness of manufacturing in Europe.

Objectives

The goal of this project is to develop viable methods for evaluating the measurement uncertainty in coordinate measurements in industry, in order to support ISO/TC 213/WG 10 in further development of related standards (i.e. the ISO 15530 series). The specific objectives of the project are:

1. To develop traceable and standardised methods for evaluating the uncertainty of coordinate measurement a posteriori using type A evaluation.
2. To develop a simplified and validated method for predicting the uncertainty of coordinate measurements a priori using type B evaluation (i.e. expert judgement).

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3. To demonstrate the validity of existing methods and those from objectives 1 & 2 in industrial conditions and evaluate their consistency and accuracy against the Guide to the Expression of Uncertainty in Measurement (GUM) and its supplements.
4. To contribute to revisions of the EN ISO 15530 and the EN ISO 14253-2 by providing the necessary data, methods, guidelines and recommendations, in a form that can be incorporated into the standards at the earliest opportunity. In addition, to collaborate with the technical committees CEN/TC290 and ISO/TC213/WG10 and the users of the standards they develop to ensure that the outputs of the project are aligned with their needs and recommendations for incorporation of this information into future standards at the earliest opportunity. To promote early dissemination of the developed methods to industry.

Progress beyond the state of the art

Evaluating the uncertainty of coordinate measurement is difficult and hence many manufacturing companies simply overlook it. In product inspections, this results in the requirements of EN ISO 14253-1 being unfulfilled, and decisions being made based on unreliable measurements. This is particularly dangerous for safety-critical parts (e.g. in aeronautics) and has a large economic impact as designers may over-specify tolerances to ensure product functionality. The ISO 15530 series of standards (*GPS - Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement*) does not cover most practical scenarios. EN ISO 14253-2 provides general guidance in dimensional measurements but does not focus on coordinate measurements. Further to this, EN ISO 14253-5, ISO/TS 17865 and ISO/TS 23165 cover uncertainty in coordinate measurement but only specialise on acceptance and reverification testing of indicating measuring instruments and CMMs rather than on part inspection.

This project went beyond the state of the art by developing viable methods for the evaluation of coordinate measurement uncertainty, in a form suitable for input to international standards. Prior to the start of this project the ISO/TC 213/WG 10 had planned two more parts of ISO 15530 series but then abandoned this work due to a lack of resources. However, the results from this project can be used to support the development of these missing parts of the ISO 15530 series. The project's Objective 1 resulted in an experimental method A based on analysis of variance (ANOVA), which has become the ISO/TC 213/WG 10 project ISO 15530-2. The project's Objective 2 resulted in two methods B1 and B2, based on prior information and sensitivity analysis suitable for predicting the uncertainty, which were submitted to the ISO/TC 213/WG 10 and are currently under scrutiny. The project hopes that they will become a future ISO 15530-5. Finally, the project's Objective 3 went beyond the state of the art and resulted in the experimental validation of these methods with an extensive measurement campaign throughout Europe and Japan on several industrial workpieces and measurement artefacts.

Results

Objective 1: To develop traceable and standardised methods for evaluating the uncertainty of coordinate measurement a posteriori using type A evaluation.

An experimental method for evaluating uncertainty *a posteriori* was developed, based on the analysis of variance (ANOVA). The project's method A removes the limitation of EN ISO 15530-3 i.e. that a working standard almost identical to the workpiece under inspection is needed and independently calibrated, as in this new method A the workpiece alone suffices. The only additional standards required are a calibrated sphere and few calibrated gauge blocks, which are cheap and easily available.

The method A also requires some additional experimental effort: the measurement is repeated with four different workpiece orientations, and the calibrated sphere and gauge blocks are measured. However, this extra effort is needed only once when the measurement is repeated for several identical workpieces, i.e. for serial inspections of a lot.

The evaluation is entirely experimental and hence the complicated issue of the CMM geometry errors is resolved by ANOVA of the measurement data. The complex effect of the probing system is also resolved by method A by the measurement of the calibrated sphere (in line with EN ISO 10360-5). In addition, the traceability to the SI unit, the metre, is resolved by measurement of the calibrated gauge blocks. Very little prior information is needed for method A.

The method A covers both size characteristics (such as a pin diameter or a keyseat width) and geometrical characteristics, either with reference to a datum (such as parallelism or coaxiality) or without (such as flatness or roundness). It also covers the case of geometrical characteristics when the access to raw data is limited (by some software interfaces), resolved by suitable approximations based on the maximum entropy principle. This was further extended to freeform measurements, either in discrete-point probing or scanning modes; the latter is dealt with as long and dense series of discrete points.

Spreadsheets were prepared to implement the calculations and are available to end users via Zenodo (https://doi.org/10.5281/zenodo.6563175) and the project website (www.eucom-empir.eu), to make method A easier to implement in practice.

There is only one main limitation of method A, which is the requirement to reorientate the workpiece three times (four measurements in total), with 90° rotations for each coordinate axis. This means that method A may not be feasible for large workpieces, due to their weight, or potential difficulties in fixturing (which may require additional equipment) or limitations of the CMM measuring volume (for high aspect ratios workpieces and CMMs).

Further to the project's original aim, a slight adaptation of method A was tested with computer tomography (CT) and yielded encouraging results, that could in future give even wider breadth to the project's method for evaluating uncertainty *a posteriori*.

Objective 2: To develop a simplified and validated method for predicting the uncertainty of coordinate measurements a priori using type B evaluation (i.e. expert judgement).

Two methods for evaluating the uncertainty a priori were developed (method B1 and B2). Method B2 was developed in addition to the original project's plan and provided added value to the project. Methods B1 and B2 are based on prior information available at no or little extra cost. It is the information provided by EN ISO 10360 *Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring systems (CMS)* series of standards, and specifically its Part 2 *CMMs used for measuring linear dimensions* and Part 5 *Coordinate measuring machines (CMMs) using single and multiple stylus contacting probing systems using discrete point and/or scanning measuring mode*. EN ISO 10360 is widely accepted in industry and most CMMs are routinely tested accordingly. EN ISO 10360 defines a set of standardised performance parameters on which MPEs (*Maximum Permissible Errors*) are set. When available, the detailed testing results for a specific CMM can be used to apply the project's methods B1 and B2; when not, similar information is derived from the MPEs. The latter is the case where no specific CMM has yet been identified.

The purpose of methods B1 and B2 was primarily to *predict* the uncertainty before any measurement is taken, and thus they are necessarily coarser than the method A, which instead is fed with actual measurement results. Approximations were taken, to keep the project's methods practically viable and the two methods differ primarily in their type of approximation.

The method B1 is based on two steps: (i) the first step considers the cloud of probed points and evaluates the joint uncertainty of their coordinates; (ii) the second step derives the uncertainty of the final measurement from that of the cloud.

Step 1. is where the approximation occurs. Experience had shown that the CMM geometry errors are dominated by only a few parameters such as the axes' scale errors and the squarenesses between axes. Therefore, a simplified geometry model was developed by the project based on seven parameters. Experience also had shown that points close in space are more likely to exhibit similar geometry errors than points far in space: a correlation exists with the mutual distance of point pairs. This spatial correlation was captured by the project in a simple model based on two parameters only. The EN ISO 10360 values are then used to derive the few parameters involved and the joint uncertainty of all probed points (point cloud) is derived with no further approximation.

Step 2. the final measurement uncertainty is derived from the point cloud through sensitivity analysis. This was achieved by the project using suitable (Jacobian) matrices, which make the entire calculation linear. A comprehensive set of cases were analysed by the project and the relevant matrices were evaluated.

The main limitation of the method B1 is that it requires mathematically complex software, whose development is generally not available to average CMM users (but is within the capabilities of CMM manufacturers). Therefore, the method relies on the availability of a software suite for implementing it, which the project has helped to provide.

The method B2 is based on an approximation upon the probed points. In actual measurements, many measurements are taken, as the more there are the better accuracy. Essential sets of points were considered instead by method B2, which enables a dramatic simplification of the subsequent calculations.

The numerosity of any essential set depends on the degrees of freedom of the geometry at hand. For instance, the flatness of a nominally flat surface is defined as the shortest separation between two parallel planes that encompass the surface and possesses four degrees of freedom. Therefore four points are taken as representative for flatness, three on a plane and one on the surface point farthest off-plane. The locations of such points cannot be predicted and are then approximated by method B2 to the most logical locations for the workpiece under measurement. In the project's case example, the three points on the plane were taken at its external boundaries on the workpiece and the fourth at the central point among them. Once the points are selected, the measurand is derived with a simple closed-form function (which is possible as the number of points matches the unknowns). The input quantities are point-to-point distances and their input uncertainties are evaluated based on values known via EN ISO 10360-2. The propagation to the final uncertainty is made through sensitivity analysis. A comprehensive study by the project, identified the essential point sets that should be able to cover a large majority of practical cases, including complex geometrical tolerances. These cases and their sensitivity coefficient equations were suitable to be summarised in tables, and hence input to international standards. The main limitation of method B2 is that it does not account for detailed sampling strategies and cannot compare competing ones. However, method B2 is able to capture the macro-geometry constraints (e.g. a portion only of a feature, such as a sphere patch, available to measurement) by proper localisation of the essential points.

Objective 3: To demonstrate the validity of existing methods and those from objectives 1 & 2 in industrial conditions and evaluate their consistency and accuracy against the GUM and its supplements.

The methods from Objectives 1 & 2 were validated with different CMMs and by partners in order to provide robust evidence and ascertain the validity limits of the methods.

The validation campaign involved two sets of artefacts: (i) prismatic geometries and (ii) freeforms. A total of 6 workpieces were measured, representative of real measurements in industry: (1) a connecting rod and (2 & 3) two multi-feature checks (high and low quality), which were the prismatic geometry set of standards; and (4) a hyperbolic paraboloid and (5 & 6) two involute gear standards (with and without a sinusoidal wave superimposed onto the involute profile), which were the freeform set of standards.

For each artefact, their measurands were documented in detail. As most partners used two major CMM programming languages with their CMMs, part programmes in these two languages were developed and circulated amongst the partners to make the validation exercise more consistent. The data types required by the methods developed in Objectives 1 & 2 were documented to ensure that the measurements taken during the validation exercise provided the required data.

A detailed measurement plan was prepared, but the COVID-19 pandemic resulted in repeated revision and delays to the plan. However, the campaign progressed well on a day-by-day basis, coordination being based on the availability of standards and laboratories at any given time. Twenty-two measurements of prismatic artefacts and twenty-four measurements of freeforms were carried out.

The prismatic geometry artefacts were calibrated and the freeform artefacts were given reference values prior to the circulation. These reference values were compared with individual measured values. The normalised error E_n was then evaluated based on the uncertainties of the reference values and those derived from the project's methods. Values $|E_n| \leq 1$ indicated that the uncertainty estimation was reliable, $|E_n| > 1$ that the uncertainty was underestimated and the methods should be revised, $|E_n| << 1$ that the uncertainty was likely overestimated and the methods could be relaxed. This approach was in line with EN ISO 15530-4. For method B2, a chi-squared test was also carried out to validate the null hypothesis that the predicted uncertainty was the same as the experimental one.

Overall, the results were very promising and good. More specifically, the type A method proved to be very effective for all but the connecting rod workpiece, for which a relevant number of underestimations occurred. But detailed analysis showed that the choice of the connecting rod artefact had been unfortunate, as its big eye was not monolithic and its two halves drifted during measurement. To try and address this, the denominator in the normalised error E_n (the uncertainty) was scrutinised, but discrepancies occurred in the nominator instead. The big eye was also the primary datum feature, and its drift affected most of the measurands even when not related to the big eye. Furthermore, the eyes were assumed cylindrical ignoring that they were far from that *by design*; this introduced additional cross-talk with the datum system shift and with differences in probing strategies. In contrast method A performed well for other measurands on the same connecting rod workpiece (those not affected by the primary datum) and for all other artefacts, whether prismatic or freeform.

The type B methods are about prediction of the uncertainty and hence subject to approximations. Thus a more variable uncertainty estimation was expected. The results supported the successful validity of methods B1 and B2, even though the fraction of underestimations was slightly higher than desired 5 %.

Impact

The project website http://eucom-empir.eu was created and contains relevant information and updates on the project.

The project has disseminated it results to stakeholders via 9 open access publications in journals such as Metrology and Measurement Systems, Measurement: Sensors and euspen. The project was also presented 11 times at conferences such as IMEKO 2021, Mathematical and Statistical Modelling in Metrology and Virtual 3DMC 2020.

Furthermore the project has produced 3 press releases in Italy (i) CronacaTorino entitled EUCoM project, INRIM wants to help European manufacturing production (http://www.cronacatorino.it/scienza-tecnologia/progetto-eucom-inrim-vuole-aiutare-produzione-manifatturiera-europea.html), (ii) Sole24Ore-Scenari entitled The value of the uncertainties of the measures and (iii) MeteoWeb entitled The uncertainty that helps the manufacturing industry (http://www.meteoweb.eu/2018/08/lincertezza-che-aiuta-lindustria-manifatturiera/1143064/) as well as a fourth press release (iv) in metrology.news entitled EUCoM Project – Evaluating Uncertainty In Coordinate Measurement (https://metrology.news/eucom-project-evaluating-uncertainty-in-coordinate-measurement/)

Impact on industrial and other user communities

The results of the project will benefit companies performing inspections. The project has provided them with viable methods (Objectives 1 & 2) for evaluating uncertainty, that companies can use to make more reliable inspection-based decisions e.g. the acceptance or rejection of parts.

A stakeholder committee consisting of members from 10 companies from 6 European countries was established by the project. This included the Chief Stakeholder Škoda Auto a.s. (CZ), Hexagon Metrology SpA, Deltamu, ANGA, Capvidia, Kirchhof Automotive and AWE plc. Three stakeholders also became project collaborators and contributed to the validation campaign of Objective 3, these were Carl Zeiss, MG Spa and Cracow University of Technology.

A major method of disseminating the project's results was via the EUCoM seminars. An international plenary session in English was held as a webinar in June 2021 with 250+ attendees. Following this, ten national sessions were held from June to November 2021, one session for each country participating in the project. To overcome language barriers and widen the project's scope across Europe, sessions in specific countries were held in the national language. The plenary session focussed on the general project's findings, including the methods (Objectives 1& 2) and the validation campaign (Objective 3). The national sessions were devoted to Q&A and to sharing the host partner's practical experience in applying the project's methods and attracted between 15-100 participants to each session. The EUCoM seminars were a unique opportunity for widespread, coordinated training for industry and nearly all of the sessions were recorded and are available through the project website and via Zenodo (see the EUCoM Community page, https://zenodo.org/communities/17nrm-03/).

Further to this, five courses/workshops were hosted by the project for training for industrial stakeholders on

1. "Measurement uncertainty evaluation" in February 2019
2. "Measurement uncertainty" in April 2019
3. "Thread Gauge measurements and Uncertainy Calculation by using CMM" in October 2019
4. InTeRSeC 38 - Criteri di Massimo/Minimo Materiale (UNI EN ISO 2692) e regole decisionali per la verifica di conformità (UNI EN ISO 14253-1) in November 2019
5. "Unified system of limits and fits, dimensions tolerance" in November 2020.

Impact on the metrology and scientific communities

Evaluating and predicting the uncertainty of coordinate measurements is a recognised and long-standing scientific issue. The project's newly developed methods are a significant contribution to its solution and hence of benefit to the metrology and scientific communities.

The posteriori method A (Objective 1) is very practical but without a complete underpinning theory. Experts in the field recognise the potential of reversals but no detailed modelling of the actual capability has been attempted. Hence, the demonstration of the viability of method A in practice was a significant step forward (Objective 3).

The project's a priori methods B1 and B2 (Objective 2) have a sound theory that underpins them but require procedures that are unlikely to be accessible for average practitioners, thus simplifying approximations were developed by the project. Hence, the major scientific contribution from the project was the successful demonstration of such approximations being correct (Objective 3). Aside a simplification of the geometry error model, the method B1 introduced a novel spatial correlation scheme among points based on their mutual distances. Method, B2, pioneered the approach of disregarding the specific locations of the probed points in favour of an essential set with as many points as intrinsic degrees of freedom.

The validation campaign (Objective 3) was a unique opportunity for collecting data according to a plane deliberately intended for uncertainty evaluation purposes. The resulting raw data are an extremely valuable asset to the scientific community and are available for possible further developments on Zenodo at https://doi.org/10.5281/zenodo.6563144.

Coordinate measurements are instrumental for research in a variety of scientific fields. Thus, the project's methods (as published in open access journals) can provide scientists with guidance on how to make their coordinate measurements metrologically sound. The published papers (see list below) describe the method in detail.

Impact on relevant standards

The project has provided significant input and regular dissemination of its results to ISO/TC 213/WG 10. This has led to the initiation of the project ISO 15530-2, which will implement the project's method A (Objective 1). The WG 10 has also passed a resolution for future EN ISO 10360 standards to describe the performance of CMSs (*Coordinate Measuring Systems*) consistently based on a triple of unified metrological characteristics. This followed experimental evidence from the project and provides more suitable input values for the posteriori (type B) methods. The priori methods (Objective 2) are still under scrutiny by the WG 10, but the project hopes that they will become a future ISO 15530-5

Further to this, national standardisation bodies were also regularly informed of the project's results including the VDI/VDE-GMA FA 3.31 / DIN/NA 152-03-02-12 UA (DE), UNI/CT047 (IT) and its Working Groups GL1 and GL6, and the JSA ISO TC213 domestic response committee group B2 (JP).

Longer-term economic, social and environmental impacts

When a part or product is being inspected for acceptance, the uncertainty effectively competes with the manufacturing: given a certain tolerance, the larger the uncertainty, the larger the guard bands, and the narrower the acceptance zone left for production. Better uncertainty evaluations reduce conservative overestimation and result in more profit margin for industry.

More reliable uncertainty evaluations according to the EUCoM's methods–or even a simple evaluation in today's many cases when none is done at all–also improves risk management. The use of nonconforming parts is a risk for the consumer, with potential negative consequences such as faults in assembly lines, rejection and waste of complete products, loss of reputation to customers or to the market at large, disputes and even court cases. The producer's risk lies in the waste of conforming parts, with potential negative consequences such as loss of the production costs and of future sales, delays in further operation, and disputes with suppliers.

The reduction of false decisions leads to reduced waste too. In false rejections, conforming parts are wasted, including their raw materials and production energy, often resulting in extra transportation to withdraw and then reinstate the product, which is particularly problematic for heavy items. In false acceptances, faults in the assembly line results in a waste of energy (and time) to recover the items or to resolve the issue. Furthermore, wasting final products is always worse than wasting simpler constituting parts.

List of publications

[1]. W. Płowucha, *Point-plane distance as model for uncertainty evaluation of coordinate measurement*, Metrol. Meas. Syst., Vol. 27 (2020) No. 4, pp. 625-639, https://doi.org/10.24425/mms.2020.134843

[2]. F. Zanini, M. Sorgato, E. Savio, S. Carmignato, *Uncertainty of CT dimensional measurements performed on metal additively manufactured lattice structures*, 10th Conf. on Industrial Computed Tomography, Wels, AT (iCT 2020), https://www.ndt.net/article/ctc2020/papers/ICT2020_paper_id104.pdf

[3]. O. Sato, T. Takatsuji, Y.Miura, S. Nakanishi, *GD&T task specific measurement uncertainty evaluation for manufacturing floor*, Measurement: Sensors 18, 100141, (2021), https://doi.org/10.1016/j.measen.2021.100141

[4]. A. Forbes, *Approximate models of CMM behaviour and point cloud uncertainties*, Measurement: Sensors 18, 100304, (2021), https://doi.org/10.1016/j.measen.2021.100304

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[6]. P. Rosner, M. Wojtyła, E. Gomez-Acedo, A. Balsamo, *Uncertainty evaluation for complex GPS characteristics*, Measurement: Sensors 18, 100323, (2021), https://doi.org/10.1016/j.measen.2021.100323

[7]. M. Wojtyła, P. Rosner, A. Forbes, E. Savio, A. Balsamo, *Verification of sensitivity analysis method of measurement uncertainty evaluation*, Measurement: Sensors 18, 100274, (2021), https://doi.org/10.1016/j.measen.2021.100274

[8]. F. Zanini, E. Savio, S. Carmignato, *Uncertainty determination of X-ray computed tomography dimensional measurements of additively manufactured metal lattice structures*, euspen's 21st International Conference & Exhibition, Copenhagen, DK, June 2021, https://www.euspen.eu/knowledge-base/ICE21150.pdf

[9]. A. Arscovic, M. Menoncin, E. Savio, *An approach to improve accuracy and productivity of industrial CMM measurements at high speed scanning*, euspen's 21st International Conference & Exhibition, Copenhagen, DK, 2021, https://www.euspen.eu/knowledge-base/ICE21306.pdf

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	01 June 2018, 42 months	
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Internal Funded Partners: 1 INRIM. Italy 2 CMI, Czech Republic 3 DTI, Denmark 4 GUM, Poland 5 Metrosert, Estonia 6 NPL, United Kingdom 7 PTB, Germany 8 TUBITAK, Turkey	External Funded Partners: 9 ATH, Poland 10 TEKNIKER, Spain 11 UNIPD, Italy	Unfunded Partners: 12 AIST, Japan
RMG: -		