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

Overview

Correct evaluation of uncertainty during inspections is necessary to avoid wrong decisions such as accepting nonconforming parts. The most popular technique for dimensional inspection in industry is coordinate measurement. The project aims to deliver two methods for evaluating the uncertainty of coordinate measurements. These will be suitable for inclusion in international standards and applicable to common cases in industry. Their progress will be reported to the relevant standardisation body ISO/TC213 on Dimensional and geometrical product specifications and verification WG10 on Coordinate measuring machines for possible inclusion in future standards. Thus, the project's methods for uncertainty evaluation will help to improve quality assurance and positively impact European manufacturing.

Need

In the last decade, 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. The key to staying competitive with low-wage developing countries is advanced manufacturing of high-quality products. This is impossible without high standards for intermediate and final inspections, primarily on dimensional and geometrical quantities (GPS – Geometrical Product Specification). Even a tiny improvement in this area would 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: Generalized decision rules for the acceptance and rejection of instruments and workpieces*, currently 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 currently technically very difficult and little guidance is available in international standards, which results in industry often overlooking it.

New viable and standardised methods for evaluating the uncertainty in coordinate measurement will 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/TC213/WG10 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).
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.

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

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

Currently, most manufacturing companies overlook the uncertainty of coordinate measurement in their routine inspections of products. This results in the requirements of EN ISO 14253-1 being unfulfilled, and subsequent decisions being based on unreliable measurements. This is particularly dangerous for safety-critical parts (e.g. in aeronautics) and has a large economic impact as it may induce designers to over-specify tolerances to ensure product functionality. The existing ISO 15530 series of standards (i.e. *GPS - Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement*) deals with this problem but it is currently incomplete and does not cover most practical scenarios. EN ISO 14253-2 provides guidance in dimensional measurements at large, however it does not currently focus on coordinate measurements. The EN ISO 14253-5, ISO/TS 17865 and ISO/TS 23165 cover uncertainty but specialise on acceptance and reverification testing of indicating measuring instruments – and CMMs in particular – rather than on part inspection.

This project will go beyond the state of the art and provide methods for the evaluation of coordinate measurement uncertainty, in a form suitable for direct integration into international standards. When designing the ISO 15530 series, the ISO/TC213/WG10 included two more parts, which were abandoned due to a lack of resources (at the time). This project will support the development of these missing parts; specifically, the project’s Objective 1 tackles an experimental method based on repetitions and reversals, which is intended to be a future Part 2 for ISO 15530. The project’s Objective 2 develops a method based on prior information suitable for predicting the uncertainty (as opposed to evaluating it a posteriori), which is intended to be a future Part 5 for ISO 15530. Finally, the project’s Objective 3 undertakes the experimental validation of these methods, which is an essential requirement for any standard.

Results

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

A method for evaluating the uncertainty a posteriori was developed. The method makes use of the workpiece under inspection only, thus removing the similarity limitation of the a posteriori method in EN ISO 15530-3 (where an almost identical calibrated working standard is required). The only additional standards required are a calibrated sphere and a calibrated gauge block, cheap and easily available. It also requires some additional experimental effort, as the measurement has to be repeated with four different workpiece orientations. 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. The complicated issue of the CMM geometry errors is resolved by ANOVA analysis of the measurement data. The complex effect of the probing system is resolved by measurement of a calibrated sphere (in line with EN ISO 10360-5). The traceability to the SI unit, the metre, is resolved by measurement of a calibrated gauge block. Very little prior information is needed.

The method 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 form and profile characteristics when the access to raw data is limited (by some software interfaces), by developing suitable approximations. This was extended to freeform measurements, with discrete point probing and scanning modes; the latter is addressed with a long and dense series of discrete points.

Data sheets were prepared to implement the necessary calculations, in an effort to make the method easier to implement in practice.

The main limit of the method is the requirement of reorienting the workpiece three times (four measurements in total), with 90° rotations about each coordinate axis. This may not be feasible for large workpieces, due to their weight (for massive workpieces), potential difficulties in fixturing (which may require additional equipment) or limitations of the CMM measuring volume (for high aspect ratios).

Preliminary investigations were carried out by measuring calibrated artefacts and comparing the measured and calibrated values, taking into account the calibration and the evaluated measurement uncertainty. The results were encouraging, showing that the method is fit for purpose. The method is now being validated through a systematic measurement campaign (see Objective 3). This will allow refinements of the method, such as the selection of the most suitable coverage factor. This is particularly true for the approximations imposed by CMM software interfaces granting limited access to raw data.

Further to the project's original aim, a slight adaptation of the method was tested with computer tomography (CT) yielding encouraging results. At this stage there is no claim of suitability of the method for CT; if this is demonstrated in future, it will give even wider breadth to the project's method for evaluating the 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).

A method for evaluating the uncertainty a priori was developed. It uses type B evaluation and is based on two steps. The first step considers the cloud of probed points, looking at the uncertainty and mutual correlation of their coordinates. The second step derives the final uncertainty from the cloud, based on sensitivity analyses. The second step is a mathematical problem, which (even if complex) is solvable in software. The first step is where prior information is needed.

Two approaches were investigated for the first step. The first approach is based on simplified (low-order) geometry error models of the CMMs, deemed to capture most of the errors. The second approach is based on the assumption that the CMM volumetric error is a smooth function of the position in space, i.e. close points in space are likely to be affected by very similar geometry errors. Preliminary simulations supported both approaches. MATLAB software was developed to implement the necessary calculation and determine the variance-covariance matrix of a point cloud. A small set of descriptive parameters are required, which can be derived from an expert judgement and/or an evidence of standardised performance testing (EN ISO 10360), likely to be available. Adjustments based on a posteriori evidence are being studied, in a Bayesian perspective.

The second step is entirely based on sensitivity analysis. Its theory is fully understood and implemented in software for a limited number of types of features. More are being added, to include as many of those measured in the validation campaign (see Objective 3) as possible. Whether or not all will be covered in the project will depend on the progress to be made within the last part of the project. In any case, extending this approach to other missing features should not pose any difficulties, although it would be labour-intensive.

The main limitation of the method is that it requires mathematically complex software, whose development is generally not in reach of average CMM users (but within the capabilities of CMM manufacturers). The method then relies on the availability of a software suite implementing it, which the project is providing.

An alternative method was developed, additional to those originally planned in the project. It is based on the observation that any measurand – even those controlled by the most complex geometrical tolerances such as coaxiality – can ultimately be reduced to a limited set of distances (point to point, point to plane, etc.) involving a limited number of probed points. The distances, as such, are subject to the EN ISO 10360-2 testing and prior information is therefore (usually) available. This method combines the actual test values with the EN ISO 10360-2 specification values and propagates them by sensitivity analysis for each toleranced feature.

The advantages of this method are that it (i) requires no complex software programmes, (ii) relies on available ISO information, and (iii) is powered by a table of taxonomical sensitivity coefficients, which can easily be published in a standard. The main limitation is that this table is large, with an entry for every possible toleranced feature (17 classes with subclasses of geometrical tolerances defined in EN ISO 1101 plus dimensional tolerances). However, the sensitivity coefficient tables for particular cases include many components with null value, which can be omitted. So far there were about 20 models developed and many of them are suitable for analysis of a few different geometrical characteristics.

Evidence provided by experiments carried out in the project contributed to the decision of ISO/TC213/WG10 to ratify a resolution that future standards on CMM testing (ISO 10360 series) will be based on a triplet of descriptive parameters rather than on a single comprehensive one. This will provide better and more detailed prior information for uncertainty evaluation.

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 are being validated with different CMMs and by different partners in order to provide robust evidence and ascertain the validity limits. The validation results will be made available to end users via an open source data repository, and ISO/CEN standards.

The validation campaign involves two sets of standards: prismatic geometries and freeforms. A total of 7 artefacts were selected to be representative of real measurements in industry: a connecting rod, two multi-feature checks (high and low quality) and a steering knuckle (constituting the prismatic geometry set of standards); a hyperbolic paraboloid, two involute gear standards and an NPL freeform artefact (constituting the freeform set of standards). For each artefact, their measurands were documented in detail. As most partners use either Calypso or Quindos software 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 provide the required data.

A detailed measurement plan had been prepared, but the unfortunate COVID-19 outbreak and consequent repeated lockdowns have disrupted it. Nevertheless the campaign is progressing well on a day-by-day basis, coordination being based on the availability of standards and laboratories at any given time. So far, nine measurements of prismatic artefacts and four measurements of freeforms were carried out. The updated aim of the campaign is to achieve at least one measurement per partner, either prismatic or freeform, with an aspiration of more, if possible.

The prismatic artefacts were calibrated and the freeform given reference values prior to the circulation. An exception is made for the steering knuckle, which was calibrated later and should enter circulation soon. The intention for these reference values is to be compared with the individual measured values. The normalised error E_n is then derived based on the uncertainties of the reference values and derived from the methods being validated. Values $|E_n| \leq 1$ would indicate that the uncertainty estimation is reliable, $|E_n| > 1$ that the uncertainty is underestimated and the methods should be revised, $|E_n| << 1$ in most cases that the uncertainty is overestimated and the methods can be relaxed. This approach is in line with EN ISO 15530-4.

The validation campaign will also be useful for fine tuning of the methods. Specific values such as the coverage factor were defined as a first trial with the intention of a possible revision based on results. Preliminary data analysis showed encouraging outcomes, with only a small fraction of cases needing adjustments. This is particularly valuable for freeforms and scanning, by their nature more complex than prismatic and discrete point probing.

Impact

The main dissemination goal of the project is standardisation related. The target body for this is the ISO/TC213/WG10 (CMM), which is regularly attended (twice a year) by three partners (four experts). The method from Objective 1 is already in the ISO/TC213/WG10 portfolio as a preliminary project to deliver the ISO 15530-2. The WG10 is regularly updated on the EUCoM progress and ready to convert the preliminary project into a formal normative one as soon as supporting experimental evidence is made available by EUCoM. The methods from Objective 2 are also shared with the WG10, but are not yet included in its project portfolio.

The project website http://eucom-empir.eu/ has been created and is maintained regularly. Up to now, the project gave 6 presentations at 5 conferences (2 international and 3 national) and disseminated its outputs via 1 international and 5 national workshops/seminars (mainly for industry). In addition, 1 international and 5 national training courses were organised on related topics, and 4 national press releases were published.

Ten EUCoM seminars are in preparation; each country participating in the project will organise one of them. To overcome any language barriers, widen the project's scope across the Europe and adapt to specific national needs, they will be held partly in English and partly in the national language of the organiser. The seminars represent a unique opportunity – likely unprecedented in Europe – for widespread, simultaneous and coordinated training for industry on a specific topic of great relevance to them. A blend of introductory topics, details of the EUCoM methods and results from validation data will be presented.

Impact on industrial and other user communities

The early impact of the project is focused on companies performing inspections. The project is providing them with viable methods for evaluating the uncertainty. This will enable them to make more reliable inspection-based decisions – such as acceptance or rejection of parts.

A stakeholder committee consisting of members from 8 companies from 6 European countries was established. This includes the Chief Stakeholder Škoda Auto a.s. (CZ). Two of the stakeholders have become also project collaborators and have contributed in particular to the validation campaign of Objective 3.

Impact on the metrology and scientific communities

Evaluating and predicting the uncertainty of coordinate measurements is a recognised and long-standing scientific issue. The EUCoM methods are significant and complementary contributions to its solution.

The a posteriori method (Objective 1) is very practical but without an underpinning theory. All experts from the field recognise the potential of reversals but no detailed modelling of the actual capability has been attempted (not even within the project). Hence, the scientific contribution is in demonstrating that the method works in practice (Objective 3), however the investigations as to why are left for future scientific projects. On the other hand, sound theory underpins the a priori method (Objective 2) but results in a far too complex procedure than viable for practitioners, and simplifying approximations are necessary. Hence, the scientific contribution is in demonstrating that such approximations are correct, i.e. what is retained in the models captures most of the effects compared with what is disregarded (Objective 3).

Coordinate measurements are instrumental for research in a variety of scientific fields. The project's methods will provide scientists with guidance on how to make their coordinate measurements metrologically sound.

Impact on relevant standards

The ISO/TC213/WG10 resolution described above (triplet of descriptive parameters in future ISO 10360 standards, see Results section) will provide better and more useful prior information for uncertainty evaluation for end users.

Two different contributions to standardisation result from the two EUCoM methods (Objectives 1 and 2). The a posteriori method (from Objective 1) requires an experimental procedure easily describable in a written standard. The calculations are simple enough to be also describable in a standard and left to the user to implement. Once the validation campaign (Objective 3) confirms the method's validity, the possible intake to an international standard would be relatively straightforward. On the other hand, the a priori methods (Objective 2) are mathematically complex, even though implementable in software. An equivalent mathematical complexity is found with the method based on Monte Carlo simulations. In that case, the ISO/TC213/WG10 resolved to focus the ISO 15530-4 on standardised ways for *testing* such software rather than on the method itself – fully left to software developers. A similar solution is unlikely to be applied for the EUCoM's a priori methods, for two reasons: (1) the ISO 15530-4 originated from Monte Carlo but the testing scheme therein is in fact valid for *any* method for evaluating the uncertainty, including EUCoM's; and (2) Monte Carlo software for CMMs is usually embedded in the programming software – which is prominent competitive feature of any CMM – and is thus undisclosed. On the contrary to that, the methods developed in EUCoM and the related software are disclosed and made available to end users. This provides a possibility for its adoption in an international standard.

ISO/TC213/WG4 on Uncertainty of measurement and decision rules has started the revision of the ISO 14253-2 and the project is willing to provide examples taken from coordinate measurement. However, due to limited time left, the examples are likely to be addressed beyond the project.

National standardisation bodies were regularly kept informed of the project progress including the VDI/VDE-GMA FA 3.31 / DIN/NA 152-03-02-12 GUA KMT (DE) and the 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 control on the uncertainty evaluation will reduce conservative overestimation and result in more profit margin for industry.

More reliable uncertainty evaluations will also improve risk management. The use of nonconforming parts presents 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.

Decisions are made according to decision rules, which account for the measurement uncertainty. A better evaluation of the uncertainty – or even a simple evaluation in today's many cases when none is done at all – according to the EUCoM's methods will support more reliable decisions. A systematic and wide-spread reduction of false decisions in product acceptance/rejection will lead to reduced waste. In false rejections, the conforming parts are wasted, often resulting in extra transportation to withdraw and then reinstate the product, which is a particular problem for heavy items. In false acceptance, faults in the assembly line results in a waste of energy (and time) to recover the items or to resolve the issue. Furthermore, the wasting of final products is always worse than wasting simpler parts.

List of publications

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

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

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 June 2018, 42 months</td></tr>
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<tr><td>Internal Funded Partners:
1 INRIM. Italy
2 CMI, Czech Republic
3 DTI, Denmark
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