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 false 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 two methods will be suitable for inclusion in international standards and applicable to common cases in industry. In addition, 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 so that they can be disseminated to end users. 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.

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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, but also the resultant decisions being made 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 cases. The EN ISO 14253-2 provides guidance in dimensional measurements at large, however it does not currently focus on coordinate measurements. The present 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. Therefore, 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 uptake 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 that is intended to be a future Part 2 for ISO 15530. The project's Objective 2 tackles a method based on prior information suitable for predicting the uncertainty (as opposed to evaluating a posteriori) which is intended to be a future Part 5 for ISO 15530. Finally, the project's Objective 3 tackles the experimental validation of such 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.

The EN ISO 15530-3 provides an a posteriori method based on measurements of a calibrated workpiece. This calibrated workpiece is required to be identical to the actual workpieces. Effectively, the burden of the uncertainty evaluation is down to the person who calibrates the calibrated workpiece. The project will remove this limitation by restricting the experimental investigation to the workpiece under inspection. This will be applicable to a broad range of measurands (sizes, angles and geometrical features - related to datums and not related to datums, and freeform) and probing conditions (discrete points and scanning).

A method for evaluating the uncertainty a posteriori has been developed. The method does require additional experimental effort, as the measurement has to be repeated with different workpiece orientations. However, the evaluation is all experimental, and very little external 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 a parallelism or a coaxiality) or without (such as a flatness or a roundness).

The project has also dealt with the issue of limited access to raw data (as imposed by some software interfaces) by developing approximated alternatives for such cases. The approximated alternatives also cover freeform measurements, on the same footing as for profile characteristics with discrete point probing and scanning modes; the latter is addressed with a long and dense series of discrete points.

Preliminary investigation were carried out by measuring calibrated artefacts and comparing the measured and calibrations values, taking into account both the calibration and the measurement uncertainty. The results were encouraging, showing that the method for evaluating the uncertainty a posteriori is fit for purpose. Some refinement is still required and will be investigated by the project in the coming months, in particular for approximated uncertainty evaluation of geometrical characteristics when the CMM software interface grants a limited data access to data.

Further to the project's original aim a slightly adaptation of the method for evaluating the uncertainty a posteriori was tested with computer tomography (CT) measurements, and demonstrated encouraging results. At this stage it cannot be stated that the method is applicable to CT too, but if it can be used with CT it will give an even wider breath 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).

The current relevant ISO standards offers no guidance on uncertainty prediction. Instead, experts must use their knowledge while ordinary CMM users are unable to predict the uncertainty on their own. The project will address this problem by providing guidance to practitioners so that they can predict the coordinate measurement uncertainty.

The project's developed method for predicting the uncertainty of coordinate measurements a priori using type B evaluation 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 by the project for predicting the uncertainty of coordinate measurements a priori using type B evaluation. The first approach is based on simplified error models of the CMMs, deemed to capture most of the errors with a small set of descriptive parameters. 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 have so far supported both approaches.

In addition, an alternative method was developed, based on the fact that any measurand can be ultimately 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 ISO 10360-2 specification and are usually tested according to this. The project's alternative method combines the actual test values with the ISO 10360-2 specification values and sensitivity analysis, in order to derive the uncertainty. The advantages of this alternative method are (i) that it requires no complex software programmes, (ii) it relies on available ISO information, and (iii) is powered by a table of taxonomical sensitivity coefficients, which can be easily made available in a standard. This method was additional to those original planned in the project and will be tested along with the other methods as a part of objective 3.

Evidence provided by dedicated experiments made in the project contributed to make the ISO/TC213/WG10 pass a resolution that future standards on CMM testing (ISO 10360 series) will be based on a triple 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 will be 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 project's validation campaign will involve two sets of standards: prismatic geometries and freeform. A total of 7 artefacts were selected to be representative of real measurements in industry and they include 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, an involute gear standard 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 by the project and circulated amongst the partners to make the validation exercise more consistent. The data types required by the methods developed in Objectives 1 & 2 and to be under test were documented to ensure that the measurements taken during the validation exercise will provide the required data.

A twelve-month timetable was prepared for the measurement validation exercise, which contains 38 time slots. In the timetable each of the seven artefacts will be measured by 4 to 6 different CMMs and partners.

Impact

The main dissemination goal of the project is toward standardisation. The target body for this is the ISO/TC213/WG10 (CMM), which is regularly attended by three partners.

In addition, the project website has been created http://eucom-empir.eu/ and the project has been presented at 4 conferences including the Zeiss User Association and a Focus-variation microscopy (FVM) Special Interest Meeting in Denmark.

Furthermore, the project has produced 3 press releases in 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), Sole24Ore – Scenari entitled '*The value of measurement uncertainties'* and MeteoWeb entitled *'The uncertainty that helps the manufacturing industry'* (http://www.meteoweb.eu/2018/08/lincertezza-che-aiuta-lindustria-manifatturiera/1143064/).

Impact on industrial and other user communities

The early impact of the project is focused on companies performing inspections. The project will provide 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.

The project will facilitate training between companies and itself. Seminars in different countries will be organised and two workshops have been organised in Denmark to advertise the project to the industrial community. The first workshop was a metrology workshop at DTI (September 2018) and was attended by approximately 35 participants. The second workshop was on CMM uncertainty (June 2019) was attended by approximately 40 participants. In addition, five training seminars were organised: one in the Czech Republic (March 2019, 10 attendees), two to Polish companies (February and April 2019, 10 attendees each), one to the Saudi Arabia NMI (October 2019, 5 attendees) and one for the a CMM user association (Italy, November 2019, 65 attendees).

The industrial collaborator Carl Zeiss Industrial Metrology (DE) has joined the project. In addition, a stakeholder committee with seven members from SMEs and large industries including the project's Chief Stakeholder Škoda Auto a.s. and Hexagon Metrology SpA, Deltamu, ANGA, Capvidia, Kirchhof Automotive and AWE plc from five different European countries has been established.

Impact on the metrology and scientific communities

The metrology community will benefit from the scientific contribution of the project's two developed methods for evaluating experimentally and for predicting the uncertainty of coordinate measurements, which are long-standing scientific problems in coordinate metrology.

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. The dissemination of first results is on-going. Six presentations were given in conferences or scientific-technical meetings including a presentation to the International Academy For Production Engineering, Scientific Technical Committee on Precision Engineering and Metrology (CIRP STC "P") meeting in Paris (FR) February 2019 and to the Mathematical And Statistical Methods For Metrology meeting MSMM 2019 in Turin (IT) May 2019.

In addition, the Cracow University of Technology has joined the project as a collaborator and is particularly interested in the validation of the project's developed type A and type B evaluation methods.

Impact on relevant standards

The ISO/TC213/WG10 has received three reports of the project's progress. The a posteriori method is already part of a registered project in the WG, namely the ISO 15530-2. The ISO/TC213/WG10 has welcomed the project's outcomes and is waiting for the successful validation of the project's methods. In principle, the WG is also open to an a priori method for predicting the uncertainty of coordinate measurements, but no formal project has been started yet.

Evidence provided by the project has contributed to ISO/TC213/WG10 passing a resolution that future standards on CMM testing (ISO 10360 series) will be based on a triple of descriptive parameters rather than on a single comprehensive one. This will provide better and more detailed prior information for uncertainty evaluation for end users.

ISO/TC213/WG4 on Uncertainty of measurement and decision rules has started the revision of the standard ISO 14253-2 and the project is willing to use this opportunity to provide examples taken from coordinate measurement.

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 reduce the risks. The end-users risks are the use of nonconforming parts, with potential negative consequences such as faults in the assembly line, final rejection and waste of complete products, commercial loss in acceptance, and loss of reputation to customers or to the market at large, disputes and even court cases. The producer's risks are waste of conforming parts, with potential consequences of direct loss of the production cost, delays in the subsequent manufacturing operations, and disputes with suppliers.

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 even worse than wasting simpler parts.

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 June 2018, 36 months</td></tr>
<tr><td colspan="3">Coordinator:
Alessandro Balsamo, INRIM Tel: +39 011 3919-970 E-mail: a.balsamo@inrim.it
Project website address: eucom-empir.eu</td></tr>
<tr><td colspan="3">Chief Stakeholder:
ŠKODA AUTO a.s. Tel: +420 604 292 120 E-mail: David.Macoun@skoda-auto.cz</td></tr>
<tr><td>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</td><td>External Funded Partners:
9 ATH, Poland
10 IK4-TEKNIKER, Spain
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12 AIST, Japan</td></tr>
<tr><td colspan="3">RMG -</td></tr>
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