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Geometrical Product Specification and Verification as toolbox to meet up-to-date technical requirements

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KEYWORDS : Geometrical Product Specification, vocational training, e-learning

Abstract:
The ISO standards for the Geometrical Product Specification and Verification (GPS) define an internationally uniform description language, that allows expressing unambiguously and completely all requirements for the geometry of a product with the corresponding requirements for the inspection process in technical drawings, taking into account current possibilities of measurement and testing technology. The practice shows that the university curricula of the mechanical engineering faculties often include only limited classes on the GPS, mostly as part of curriculum of subjects like Metrology or Fundamentals of Machine Design. This does not allow students to gain enough knowledge on the subject. Currently there is no coherent EU-wide provision for vocational training (VET) in this area. Consortium, members of which are the authors of this paper, is preparing a proposal of an EU project aiming to develop appropriate course.

1. Introduction

The ISO standards for the Geometrical Product Specification and Verification (GPS) define an internationally uniform description language, that allows expressing unambiguously and completely all requirements for the micro and macro geometry of a product with the corresponding requirements for the inspection process in technical drawings, taking into account current possibilities of measurement and testing technology. This avoids ambiguities and inconsistencies during the planning of manufacturing and inspection processes and in addition costs through time-consuming arrangements between the client and suppliers. GPS is a subject that is relevant to a growing number of sectors of industry throughout the EU. The standardization works are very intensive in the scope of GPS. Currently there are 60 standards under development, for which the total number of pages is ca. 2500.

Well trained staff in this subject is necessary for effective and wide implementation of new GPS tools. Currently there is no coherent EU-wide provision for vocational training (VET) in this area. A consortium of partners, members of which are the authors of this paper, prepares a proposal of an EU project aiming to develop appropriate course. It is of vital importance that this dearth of knowledge at a vocational level is addressed to ensure EU industry competitive advantage in a global marketplace. Due to accessibility of the course though the internet it's easy to use in any place and suitable time. Duration of the learning is controlled by the user. Learner can also control the level of the gained knowledge through the comprehension tests provided. A significant number of real life examples and illustrations makes the understanding of the material much easier. The final version of the prepared didactic material and curriculum can be a base for an EU wide course in the proposed subject that leads to skills that are relevant and timely for industry.

2. Importance of the subject

Engineering drawings without geometrical tolerances and datums or datum systems are in most cases incomplete and ambiguous and therefore not unambiguously interpretable. The incomplete, ambiguous tolerancing of components in engineering drawings causes not only increased production and inspection costs but also makes impossible reasoned complaints of shortcomings and ultimately lead to an incalculable liability risk in the case of legal disputes. Therefore the designers and metrology engineers must have good knowledge on the Geometrical Product Specifications (GPS) and verification methodology which ought to be given during studies or refreshed and supplemented by specialized training courses on the new standards. The practice shows that the university curricula of the mechanical engineering faculties often include only limited classes on the GPS, mostly as part of curriculum of subjects like Metrology or Fundamentals of Machine Design. This does not allow students to gain enough knowledge on the subject.

The problem of ambiguous specification of product geometry requirements relates primarily to distances. Examples can be the distance between two integral features facing opposite directions (Fig. 1a), linear step dimensions (Fig. 1b) and distance between an integral and a derived feature (Fig. 1c) which are specified on the drawing as toleranced dimensions. This problem is raised in ISO 14405-2 [1].

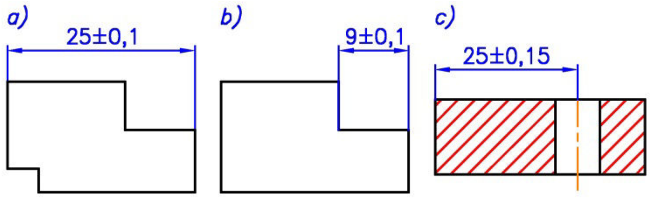

Fig. 1. Example of ambiguous specification of manufacturing accuracy by means of linear distance: a) distance between two integral features facing opposite directions, b) linear step dimension, c) distance between axis and plane [1]

Another example of ambiguous geometry specification is dimensioning of radii (Fig. 2) and chamfers (Fig. 3) [1].

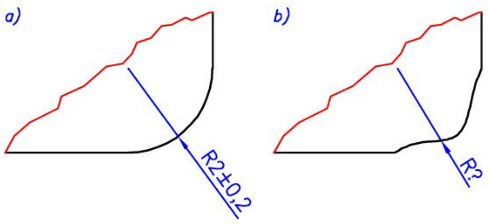

Fig. 2. Example of ambiguous specification of radius [1]

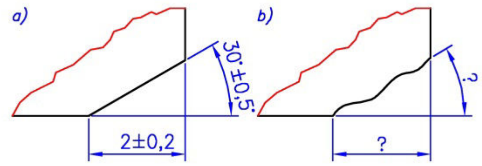

Fig. 3. Example of ambiguous specification of chamfer [1]

3. Most important GPS standards concerning macro-geometry of products

The most important GPS standards concerning macro-geometry of products are definitely ISO 1101 [2], ISO 5459 [3], ISO 14405-1 [4], ISO 14405-2, ISO 2768-1 [5], ISO 2768-2 [6], ISO 5458 [7], ISO 13715 [8], ISO 10579 [9] and ISO 2692 [10]. The standards include many tools for proper (unambiguous) requirements' specification – one just needs to use them. Geometrical tolerances, and especially tolerance of position [1, 2], give possibility of unambiguous definition of requirements. Fig. 4a presents three examples for replacing toleranced linear dimension from Fig. 1 with position tolerance. It's worth to mention that the ways of specification are directly connected with the possible measurement strategies (Fig. 4b).

Fig. 5 presents three examples for replacing linear dimension used on Fig. 1c. In this case position tolerance with single datum can be used (Fig. 5a and b) or datum system (Fig. 5c) [2, 3].

Possible way of requirement specification for radius using profile any line/surface and chamfer is depicted on Fig. 6 (a – for radius, b – for chamfer).

In order to connect geometrical product specification with appropriate measurement procedures, the standard ISO 14405-1 [4] introduces possibility of specification of type of dimension (Fig. 7). The term "type of dimension" is directly connected with the possible way of performing the measurement.

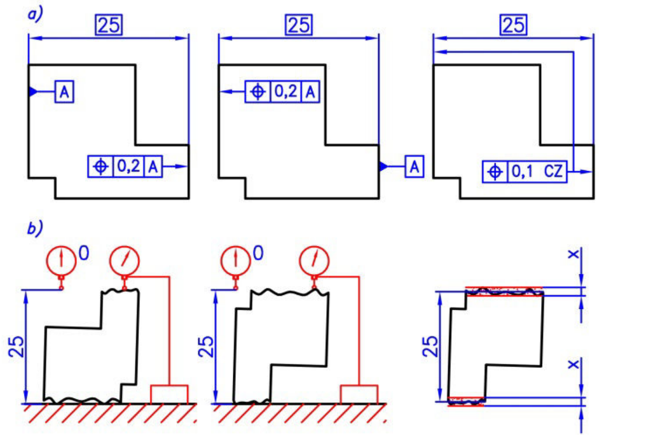

Fig. 4. Three examples of possible unambiguous specification using position tolerance (a) and associated ways of measurement (b)

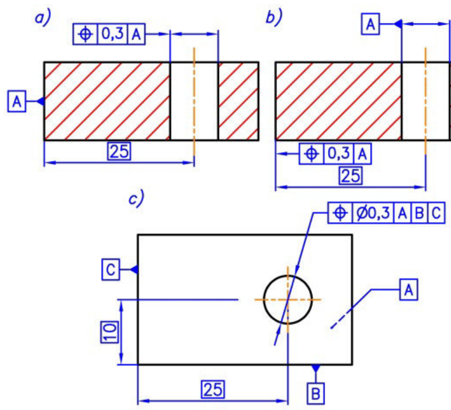

Fig. 5. Three examples of possible unambiguous specification of distance between hole axis and a plane using position tolerance: a) datum is plane, b) datum is axis of the hole, c) the hole position is defined in respect to 2 datum system

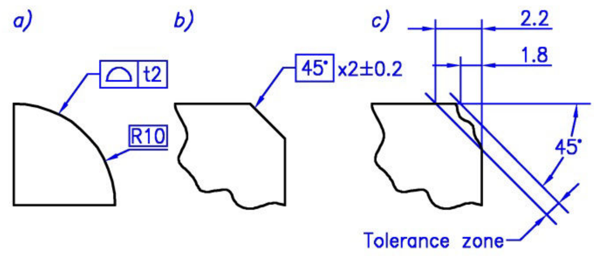

Fig. 6. Examples of unambiguous specification of: a) radius, b) chamfer, c) interpretation of chamfer tolerance

Some types of dimensions received their designation:

- two-point size – LP,
- local size defined by a sphere (ball size, spherical size) – LS,
- least-squares association criterion (least-squares size) – GG,
- maximum inscribed association criterion (maximum inscribed size) – GX,
- minimum circumscribed association criterion (minimum circumscribed size) – GN,
- circumference diameter – CC,
- area diameter – CA,
- volume diameter – CV.

Further types of dimensions like section size and portion size are pointed out on the drawing by other tools like e.g. symbol "ACS" which stands for "any cross section".

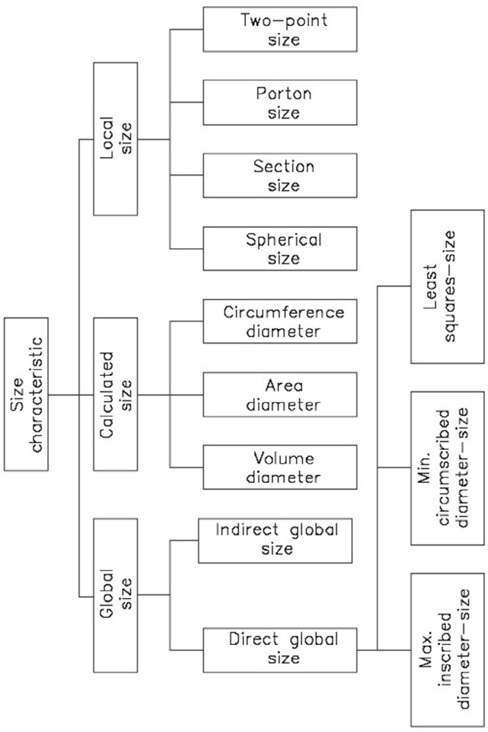

Fig. 7. Classification of dimensions taking into account different measurement techniques [4]

Moreover, for local two-point size it's possible to specify so called rank-order sizes including 5 types of dimensions:

- maximum size (maximum measured value) - SX,
- minimum size (minimum measured value) - SN,
- average size (average of measured values) - SA,
- median size (median of measured values) - SM,
- mid-range size (mean of maximum and minimum measured values) - SD

and 1 characteristic describing dispersion of dimension:

- size range (difference between maximum and minimum value) – SR.

Examples of use of the designation of dimension type are depicted on Fig. 7.

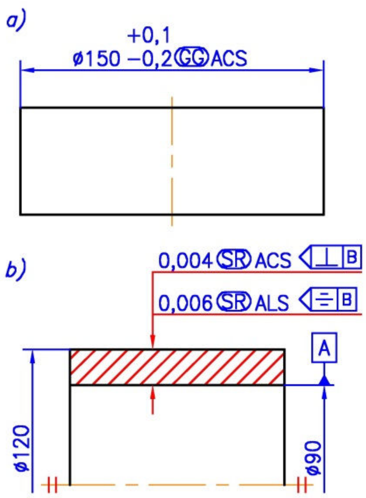

Fig. 7. Examples of use of different types of dimensions: a) dimension of 150 mm understood as diameter of Gaussian associated circle; b) difference in wall thickness in any cross section perpendicular to the axis must not exceed 4 µm, and in any axial section 6 µm

Introduction of modifier CZ (common zone) enables specification of requirements for common axis (Fig. 8) or common plane.

Additionally, in ISO 5459 new tools for datum specification are included. Of particular note is the possibility of specifying moveable datum target (Fig. 9).

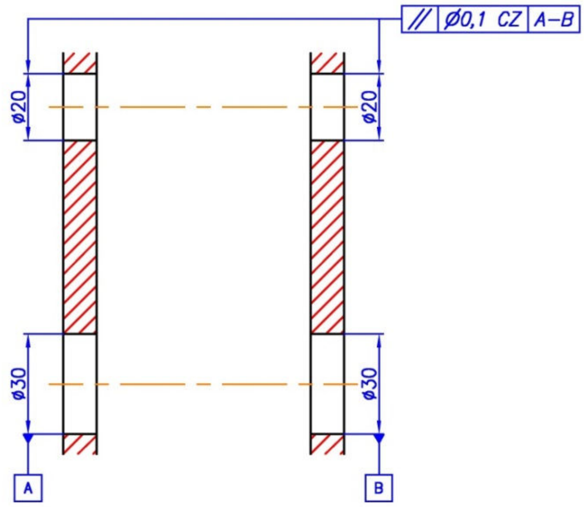

Fig. 8. Symbol CZ used for specification of requirement of coaxiality of common axis of two holes (in regards to common datum)

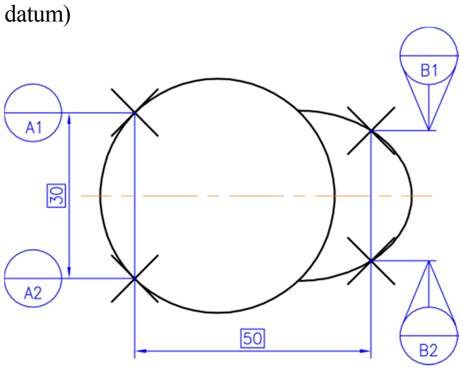

Fig. 9. Example of use of moveable datum target frame (the motion of moveable datum target which is given by the direction of the modifier „moveable" is parallel to a line going through the datum targets A1 and A2)

ISO 5459 [3] introduces also other new modifiers, e.g.:

- [CF] - contacting feature,
- [DV] - variable distance (for common datum),
- [PT] - situation feature of type point,
- [SL] - situation feature of type straight line,
- [PL] - situation feature of type plane,
- >< – modifier „for orientation constraint only" (Fig. 10),
- direction feature (Fig. 11),
- collection plane (Fig. 12),
- intersection plane (Fig. 13),
- orientation plane (Fig. 14),

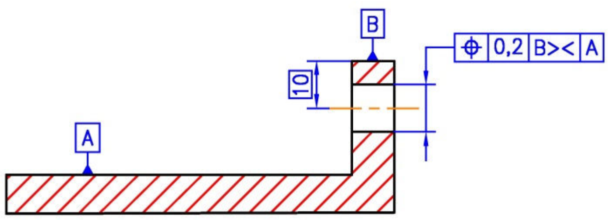

Fig. 10. Example of use of modifier „for orientation constraint only"

Fig. 11. Direction feature indicator

Fig. 12. Collection plane indicator

Fig. 13. Intersection plane indicators

Fig.14. Orientation plane indicators

Significant financial savings are achievable through the use of maximum material requirement, least material requirement and reciprocity requirement [10]. This is due to the fact that the "savings" resulting in incomplete use of the tolerance of dimension can be used to expand the geometrical tolerance zone, and in some cases the "savings" resulting in incomplete use of the geometrical tolerance zone can be used to expand the tolerance of size dimension.

4. Standards concerning surface roughness

The most important standards for surface roughness include:

- for 2D measurements: ISO 1302 [11], ISO 4287 [12], ISO 4288 [13], ISO 13565-1 [14], -2 [15] and -3 [16], ISO 16610-21 [17], ISO 16610-71 [18], ISO 16610-85 [19],
- for 3D measurements: ISO 25178 (a few parts) [20-25].

It may be noticed that the attention is brought to the precise requirements specification – standard surface structure designation may include many important details (Fig. 15), especially information on filtering parameters.

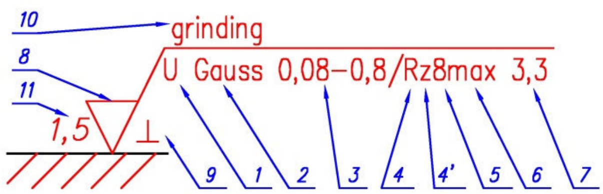

Fig. 15. Example surface roughness designation: 1 – upper (U) or/and lower (L) specification limit, 2 – filter type: default filter is Gaussian, 3 – transmission band λs – λs, , 4 — roughness (R), waviness (W) or profile (P) parameter, 4' – parameter type, 5 – number of sampling lengths, 6 – comparison rule (16% or max), 7 – value limit in µm, 8 – material removal, 9 – surface lay and orientation, 10 – manufacturing method. 11 – machining allowance in mm

5. Standards concerning coordinate measuring technique

Coordinate measurements are commonly used measuring technique. Together with its introduction a new philosophy of measurements and terminology are introduced. Many aspects of this technique are presented in standards ISO 14660-2 [26], ISO 17450-1 [27], ISO 17450-2 [28], ISO 22432 [29], ISO 25378 [30], ISO 12180-1 [31], ISO 12180-2 [32], ISO 12181-1 [33], ISO 12181-2 [34], ISO 12780-1 [35], ISO 12780-2 [36], ISO 12781-1 [37], ISO 12781-2 [38].

The standards dealing with coordinate measurements include such new terms as skin model, geometrical feature, situation feature, integral feature, derived feature, feature of size, etc. There are concepts associated with operations on geometric elements such as partition, extraction, filtration, association, collection, construction, reconstruction, reduction, evaluation, transformation. There is term characteristic (single property defined from one or more geometrical feature(s)) of different type like intrinsic or situation (Fig. 16).

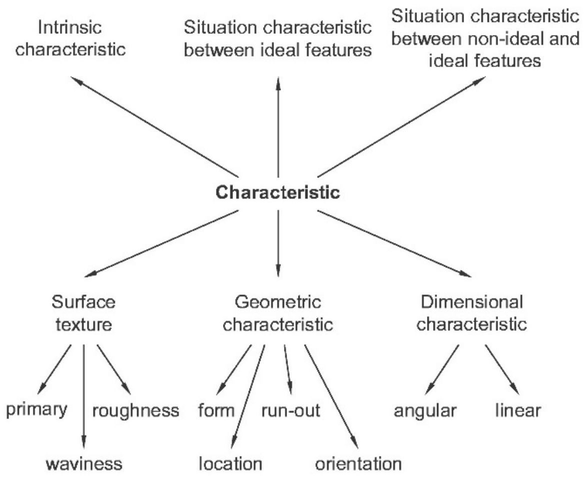

Fig. 16. Concept of GPS characteristic [27]

It's important to underline close connection between the requirements in the range of manufacturing accuracy (geometrical product specification) and possibilities of coordinate metrology in the range of geometrical product verification.

6. ISO 14638

The standard ISO 14638 [39] systematizes the work in the range of GPS by introducing classification of the GPS standards into 3 groups (fundamental, general, complementary), and its scope includes nine types of geometrical property (size, distance, form, orientation, location, run-out, profile surface texture, areal surface texture, surface imperfections). The former edition of the standard distinguished fourth group (global) and more types of geometrical property (size, distance, radius, Angle, form of a line independent of datum, form of a line dependent on datum, form of a surface independent of datum, form of a surface dependent on datum, orientation, location, circular run-out, total run-out, datums, roughness profile, waviness profile, primary profile, surface imperfections and edges).

Particular standards are assigned to so called chain links, designated with letters A to G (previously with numbers 1 to 6):

A. Symbols and indications (this consists of ISO GPS standards defining the form and proportions of symbols, indications and modifiers and the rules governing their use).

B. Tolerance characteristics and specification limits (this consists of ISO GPS standards defining tolerance characteristics, tolerance zones, constraints and parameters; this would include standards defining geometrical characteristics, size properties, surface texture parameters, the shape, size, orientation and location of tolerance zones, and the definitions of parameters).

C. Feature properties (this consists of ISO GPS standards defining the characteristics and conditions of features on a workpiece; this would include standards defining operations of partitioning, extraction, filtration, association, collection and construction).

D. Conformance and non-conformance (this consists of ISO GPS standards defining the requirements for comparison between specification requirements and verification results; this includes standards defining default values, rules for conformance and non-conformance and standards dealing with uncertainty).

E. Measurement (this consists of ISO GPS standards defining the requirements for measuring feature characteristics and conditions).

F. Measurement equipment (this consists of ISO GPS standards defining the requirements for equipment used for measurement).

G. Calibration (this consists of ISO GPS standards defining the requirements for calibration and calibration procedures for measurement equipment).

7. ISO 8015

The standard ISO 8015 [40] is of key importance. Many years ago it introduced concept of independency principle – currently it sets out general principles binding in GPS, namely:

- invocation principle,
- principle of GPS standard hierarchy,
- definitive drawing principle,
- feature principle,
- independency principle,
- decimal principle,
- default principle,
- reference condition principle,
- rigid workpiece principle,
- duality principle,
- functional control principle,
- general specification principle,
- responsibility principle.

With this standard, there is, among others, legal basis for resolving conflicts between supplier and customer.

8. Standards concerning measurement uncertainty

The problems of measurement uncertainty in GPS are considered in: ISO 14253-2 [41], ISO 16015 [42] in relation to conventional measurements and in ISO 15530-3 [43] and ISO 15530-4 [44] in relation to coordinate measurements. ISO 14253-2 provides a classification and detailed list of error sources. It references the parent documents concerned with uncertainty evaluation, namely JCGM 100 [45] and JCGM 101 [46], distinguishes black and transparent box model of uncertainty estimation and provides comprehensive examples of uncertainty evaluation. ISO 16015 is completely devoted to the temperature errors evaluation.

ISO 15530-3 [43] deals with uncertainty evaluation of coordinate measurements according to the procedure using calibrated workpiece. This method can be easily implemented in automotive industry (Fig. 17).

The technical specification ISO/TS 15530-4 [44] deals with evaluation of uncertainty of coordinate measurements by analytical methods, and especially with use of Monte Carlo simulation. These methods are now-a-days used mainly by calibration laboratories.

9. Standards concerning calibration of measuring equipment

Following standards concern requirements and calibration of conventional measuring equipment:

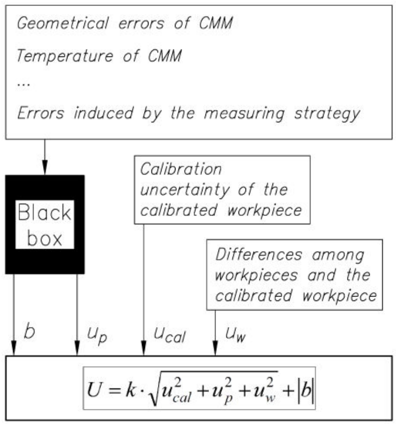

Fig. 17. Black box model for uncertainty evaluation according to ISO 15530-3 [78]

- general issues – ISO 14978:2006 [47],
- dial indicators – ISO 463:2006 [48], ISO 13102:2012 [49],
- gauges – ISO/DIS 1938-1 [50],
- micrometres – ISO 3611:2010 [51],
- gauge blocks – ISO 3650:1998 [52],
- height gauges – ISO 13225:2012 [53],
- callipers – ISO 13385-1:2011 [54], ISO 13385-2:2011 [55].

The standard ISO 10360 [56-64] is especially large and deals with coordinate measuring machines CMM. It includes 10 parts (additional are under development), in which the acceptance, verification and reverification tests are described for different types of CMM:

- ISO 10360-2 [57] – classical CMMs,
- ISO 10360-3 [58] – CMMs with the axis of a rotary table as the fourth axis,
- ISO 10360-4 [59] – CMMs used in scanning measuring mode,
- ISO 10360-5 [60] – CMMs using single and multiple stylus contacting probing systems,
- ISO 10360-6 [61] – Estimation of errors in computing Gaussian associated features,
- ISO 10360-7 [62] – CMMs equipped with imaging probing systems,
- ISO 10360-8 [63] –CMMs with optical distance sensors,
- ISO 10360-9 [64] – CMMs with multiple probing systems.

Moreover, a lot of valuable information can be found in technical specification ISO/TS 23165 [65].

10. Standards concerning specific machine parts

Rules for specification requirements as well as verification of products geometry for specific machine parts like threads, gears, splines, cones, etc. can be found in following standards:

- threads – ISO 965-2 [66], ISO 1502 [67],
- gears – ISO 1328-1 [68], ISO 1328-2 [69] and ISO 1340 [70],
- splines – ISO 4156-3 [71],
- cones – ISO 3040 [72],
- wedges – ISO 2538-2 [73].

11. Proposal of EU project

In 1999-2001 some of the consortium members participated in the project carried out under Leonardo da Vinci programme, which output was the book "Geometrical Product Specification - course for Technical Universities" which was published in English [74], German

[75], Polish [76]. In Poland, because of strong demand from the engineers this book got 2nd edition in 2004 [77]. Nevertheless, due to huge innovation in the GPS standards area since that time, those books are outdated. Current project aims to develop interactive electronic resources, use of which is very convenient since the material can be accesses at any place and time over the Internet.

The importance of the GPS as well as e-learning with use of the Internet is underlined in many publications [78-90].

The authors propose to develop and implement a coherent learning system for higher-level vocational training concerning the GPS, which can also be a supplement for existing curricula of engineering studies bridging a gap in the education of engineers. The courses are delivered by means of basic and specialized continuing e-training systems offering on-demand e-learning modules, as well as assistance systems that incorporate permanent participation in a ubiquitous e-learning community of experts. Necessity of transnational cooperation for the realization of the project justifies the fact that relationships for delivering parts and products in manufacturing industry are involving nowadays very often customers and suppliers from different countries. Large and even medium-sized companies have production sites in several European countries, using the advantages of a united Europe. As especially customer-client-relationships depend strongly on the quality and reliability of performed measurements, employees and employers would profit from a unique and innovative European training standard in the area of manufacturing metrology. Therefore, in a European perspective it is very valuable to provide a training offer that can be used in many countries and is accredited and accepted there on a comparable and commonly acknowledged level. Nevertheless, integration into national systems for vocational education has to be considered in order to allow for a high impact of the training offer. With the intended consortium and learning platform learning offer on Geometrical Product Specification and Verification by means of manufacturing metrology will be provided, which is adaptable to the diversity of learning and teaching constraints in different countries as well as to the equipment of specific training providers.

The intended approach combines eLearning materials defining a uniform standard of generally available information with individually designed presence-based offers. The teaching material will be implemented by an international cooperation of universities and metrological institutes and assessed in a pilot implementation in all participating countries, thus assuring the European dimension of the training offer and taking provisions for the later on transfer to further countries. During the further use, it will be possible to enhance the cooperation and communication of learners from different countries, unified by a basic standard learning offer, but still profiting from the diversity and individual strength of each specific learning environment.

The learning resources of the project will also be accessible at the workplace. It will include attractive links, small training tasks and self-assessment questions that should encourage users to broaden their learning, to go into greater depth and to take a more systematic learning path that, originating from a problem of practical relevance - will automatically retain its orientation towards application.

As those e-learning resources are constantly available, and as users are always able and encouraged to customize the direction and profoundness of their competence acquisition process, also those who were less active in a continuous process of work-related retraining in the past may be motivated towards entering a real lifelong learning path. These aims - towards application orientation and lifelong learning - require all learning resources, including instructional media, access to source material, all elements of the learner support and tutoring system, and the peer-learner virtual learning community have to be strictly available over the Internet and configurable for intranets, utilizing standard browser functionalities. Consortium also plans to enable offline use of the material, however in this case some interactive functionality may be lost, but still useful and required by some users.

Although, the university students are not the target group of this project they also can benefit from the outputs as the partners from different European Universities plan to use the developed material also in their lectures where GPS subject is included.

This course aims to bridge the gap in understanding that exists in the area of GPS, a vital component of manufacturing and quality management, such that knowledge in this area is accessible and immediate at the front line of industry. The contents of the course will be high quality product covering the up-to-date state of knowledge in the area of GPS. Transfer and implementation of this knowledge by the learners in the industry should lead to increasing the quality their products and rising the competitiveness of the enterprises.

The draft curriculum content is divided among partners according to their competences in particular field and necessary resources for preparation of the learning material. It's planned to develop following modules of the course:

1 Geometrical characteristics and ISO system of limits and fits

2 Tolerances of form

3 Datums

4 Tolerances of orientation

5 Tolerances of location

6 Tolerances of any line/surface

7 Tolerances of runout

8 Principle of independency and other requirements

9 General tolerances

10 Complex geometrical features

11 Roughness, waviness, primary profile 2D/3D

12 Measurements with use of conventional measuring devices

13 Measurements with use of measuring machines

14 Measurements with use of coordinate measuring systems

15 Measurements of form deviations

16. Measurements in micro- and nanoscale

17 Measurements of surface roughness

18 Inspection by gauges and decision rules for proving conformance or non-conformance with specifications

19 Measurement uncertainty

20 Tolerancing of assemblies, dimensional chains

21 Calibration of measuring equipment

12. Conclusions

Globalization and the ensuing dissipation of the production of machine parts require precise formulation of requirements for geometrical accuracy products. From the side of standardization problem is to a large extent solved. However, there is a significant gap in the education of engineers, which - if the problem is not solved - may be a barrier in the development of new, finer design. According to the authors problem can be solved by developing and widely providing high-quality teaching materials. Due to the widespread use of English in enterprises materials do not need to be translated into other languages in most cases.

13. References

1. ISO 14405-2:2011 Geometrical product specifications (GPS). Dimensional tolerancing. Part 2: Dimensions other than linear sizes
2. ISO 1101:2012 Geometrical product specifications (GPS). Geometrical tolerancing. Tolerances of form, orientation, location and run-out
3. ISO 5459:2011 Geometrical product specifications (GPS). Geometrical tolerancing. Datums and datum systems
4. ISO 14405-1:2010 Geometrical product specifications (GPS). Dimensional tolerancing. Part 1: Linear sizes
5. ISO 2768-1:1989 General tolerances. Part 1: Tolerances for linear and angular dimensions without individual tolerance indications
6. ISO 2768-2:1989 General tolerances. Part 2: Geometrical tolerances for features without individual tolerance indications
7. ISO 5458:1998 Geometrical Product Specifications (GPS). Geometrical tolerancing. Positional tolerancing
8. ISO 13715:2000 Technical drawings. Edges of undefined shape. Vocabulary and indications
9. ISO 10579:2010 Geometrical product specifications. (GPS). Dimensioning and tolerancing. Non-rigid parts
10. ISO 2692:2014 Geometrical product specifications (GPS). Geometrical tolerancing. Maximum material requirement (MMR), least material requirement (LMR) and reciprocity requirement (RPR)
11. ISO 1302:2002 Geometrical Product Specifications (GPS). Indication of surface texture in technical product documentation
12. ISO 4287:1997 Geometrical Product Specifications (GPS). Surface texture: Profile method. Terms, definitions and surface texture parameters
13. ISO 4288:1996 Geometrical Product Specifications (GPS). Surface texture: Profile method. Rules and procedures for the assessment of surface texture
14. ISO 13565-1:1996 Geometrical Product Specifications (GPS). Surface texture: Profile method; Surfaces having stratified functional properties. Part 1: Filtering and general measurement conditions
15. ISO 13565-2:1996 Geometrical Product Specifications (GPS). Surface texture: Profile method; Surfaces having stratified functional properties. Part 2: Height characterization using the linear material ratio curve
16. ISO 13565-3:1998 Geometrical Product Specifications (GPS). Surface texture: Profile method; Surfaces having stratified functional properties. Part 3: Height characterization using the material probability curve
17. ISO 16610-21:2011 Geometrical product specifications (GPS). Filtration. Part 21: Linear profile filters: Gaussian filters
18. ISO 16610-71:2014 Geometrical product specifications (GPS). Filtration. Part 71: Robust areal filters: Gaussian regression filters
19. ISO 16610-85:2013 Geometrical product specifications (GPS). Filtration. Part 85: Morphological areal filters: Segmentation
20. ISO 25178-2:2012 Geometrical product specifications (GPS). Surface texture: Areal. Part 2: Terms, definitions and surface texture parameters
21. ISO 25178-3:2012 Geometrical product specifications (GPS). Surface texture: Areal. Part 3: Specification operators
22. ISO 25178-6:2010 Geometrical product specifications (GPS). Surface texture: Areal. Part 6: Classification of methods for measuring surface texture
23. ISO 25178-601:2010 Geometrical product specifications (GPS). Surface texture: Areal. Part 601: Nominal characteristics of contact (stylus) instruments
24. ISO 25178-602:2010 Geometrical product specifications (GPS). Surface texture: Areal. Part 602: Nominal characteristics of non-contact (confocal chromatic probe) instruments
25. ISO 25178-701:2010 Geometrical product specifications (GPS). Surface texture: Areal. Part 701: Calibration and measurement standards for contact (stylus) instruments
26. ISO 14660-2:1999 Geometrical Product Specifications (GPS). Geometrical features. Part 2: Extracted median line of a cylinder and a cone, extracted median surface, local size of an extracted feature
27. ISO 17450-1:2011 Geometrical product specifications (GPS). General concepts. Part 1: Model for geometrical specification and verification
28. ISO 17450-2:2012 Geometrical product specifications (GPS). General concepts. Part 2: Basic tenets, specifications, operators, uncertainties and ambiguities
29. ISO 22432:2011 Geometrical product specifications (GPS). Features utilized in specification and verification
30. ISO 25378:2011 Geometrical product specifications (GPS). Characteristics and conditions. Definitions
31. ISO 12180-1:2011 Geometrical product specifications (GPS). Cylindricity. Part 1: Vocabulary and parameters of cylindrical form
32. ISO 12180-2:2011 Geometrical product specifications (GPS). Cylindricity. Part 2: Specification operators
33. ISO 12181-1:2011 Geometrical product specifications (GPS). Roundness Part 1: Vocabulary and parameters of roundness
34. ISO 12181-2:2011 Geometrical product specifications (GPS. Roundness Part 2: Specification operators
35. ISO 12780-1:2011 Geometrical product specifications (GPS. Straightness- Part 1: Vocabulary and parameters of straightness
36. ISO 12780-2:2011 Geometrical product specifications (GPS). Straightness. Part 2: Specification operators

37. ISO 12781-1:2011 Geometrical product specifications (GPS). Flatness. Part 1: Vocabulary and parameters of flatness
38. ISO 12781-2:2011 Geometrical product specifications (GPS). Flatness. Part 2: Specification operators
39. ISO 14638:2015 Geometrical product specifications (GPS). Matrix model
40. ISO 8015:2011 Geometrical product specifications (GPS). Fundamentals. Concepts, principles and rules
41. ISO 14253-2:2011 Geometrical product specifications (GPS). Inspection by measurement of workpieces and measuring equipment. Part 2: Guidance for the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification
42. ISO/TR 16015:2003 Geometrical product specifications (GPS). Systematic errors and contributions to measurement uncertainty of length measurement due to thermal influences
43. ISO 15530-3:2011 Geometrical product specifications (GPS). Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement. Part 3: Use of calibrated workpieces or measurement standards
44. ISO/TS 15530-4:2008: Geometrical Product Specifications (GPS). Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement. Part 4: Evaluating task-specific measurement uncertainty using simulation
45. JCGM 100:2008 (GUM 1995 with minor corrections) Evaluation of measurement data. Guide to the expression of uncertainty in measurement
46. JCGM 101:2008 Evaluation of measurement data. Supplement 1 to the "Guide to the expression of uncertainty in measurement". Propagation of distributions using a Monte Carlo method
47. ISO 14978:2006 Geometrical product specifications (GPS). General concepts and requirements for GPS measuring equipment
48. ISO 463:2006 Geometrical Product Specifications (GPS). Dimensional measuring equipment. Design and metrological characteristics of mechanical dial gauges
49. ISO 13102:2012 Geometrical product specifications (GPS). Dimensional measuring equipment: Electronic digital-indicator gauge. Design and metrological characteristics
50. ISO/DIS 1938-1 Geometrical product specifications (GPS). Dimensional measuring equipment. Part 1: Plain limit gauges of linear size
51. ISO 3611:2010 Geometrical product specifications (GPS). Dimensional measuring equipment: Micrometers for external measurements. Design and metrological characteristics
52. ISO 3650:1998 Geometrical Product Specifications (GPS). Length standards. Gauge blocks
53. ISO 13225:2012 Geometrical product specifications (GPS). Dimensional measuring equipment; Height gauges. Design and metrological characteristics
54. ISO 13385-1:2011 Geometrical product specifications (GPS). Dimensional measuring equipment. Part 1: Callipers; Design and metrological characteristics
55. ISO 13385-2:2011 Geometrical product specifications (GPS). Dimensional measuring equipment. Part 2: Calliper depth gauges; Design and metrological characteristics
56. ISO 10360-1:2000 Geometrical Product Specifications (GPS). Acceptance and reverification tests for coordinate measuring machines (CMM). Part 1: Vocabulary
57. ISO 10360-2:2009 Geometrical product specifications (GPS). Acceptance and reverification tests for coordinate measuring machines (CMM). Part 2: CMMs used for measuring linear dimensions
58. ISO 10360-3:2000 Geometrical Product Specifications (GPS). Acceptance and reverification tests for coordinate measuring machines (CMM). Part 3: CMMs with the axis of a rotary table as the fourth axis
59. ISO 10360-4:2000 Geometrical Product Specifications (GPS). Acceptance and reverification tests for coordinate measuring machines (CMM). Part 4: CMMs used in scanning measuring mode
60. ISO 10360-5:2010 Geometrical product specifications (GPS). Acceptance and reverification tests for coordinate measuring machines (CMM). Part 5: CMMs using single and multiple stylus contacting probing systems
61. ISO 10360-6:2001 Geometrical Product Specifications (GPS). Acceptance and reverification tests for coordinate measuring machines (CMM). Part 6: Estimation of errors in computing Gaussian associated features
62. ISO 10360-7:2011 Geometrical product specifications (GPS). Acceptance and reverification tests for coordinate measuring machines (CMM). Part 7: CMMs equipped with imaging probing systems
63. ISO 10360-8:2013 Geometrical product specifications (GPS). Acceptance and reverification tests for coordinate measuring systems (CMS). Part 8: CMMs with optical distance sensors
64. ISO 10360-9:2013 Geometrical product specifications (GPS). Acceptance and reverification tests for coordinate measuring systems (CMS). Part 9: CMMs with multiple probing systems
65. ISO/TS 23165:2006 Geometrical product specifications (GPS). Guidelines for the evaluation of coordinate measuring machine (CMM) test uncertainty
66. ISO 965-2:1998 ISO general purpose metric screw threads. Tolerances. Part 2: Limits of sizes for general purpose external and internal screw threads. Medium quality
67. ISO 1502:1996 ISO general-purpose metric screw threads. Gauges and gauging
68. ISO 1328-1:2013 Cylindrical gears. ISO system of flank tolerance classification. Part 1: Definitions and allowable values of deviations relevant to flanks of gear teeth

69. ISO 1328-2:1997 Cylindrical gears. ISO system of accuracy. Part 2: Definitions and allowable values of deviations relevant to radial composite deviations and runout information

70. ISO 1340:1976 Cylindrical gears. Information to be given to the manufacturer by the purchaser in order to obtain the gear required

71. ISO 4156-3:2005 Straight cylindrical involute splines. Metric module, side fit. Part 3: Inspection

72. ISO 3040:2009 Geometrical product specifications (GPS). Dimensioning and tolerancing. Cones

73. ISO 2538-2:2014 Geometrical product specifications (GPS). Wedges. Part 2: Dimensioning and tolerancing

74. Humienny, Z. (ed.), Osanna, P.H., Tamre, M., Weckenmann, A., Blunt, L., Jakubiec, W., "Geometrical Product Specifications. Course for Technical Universities", Warsaw University of Technology Printing House. Warszawa 2001

75. Humienny, Z., Białas, S., Osanna, P.H., Tamre, M., Weckenmann, A. [ed.], Blunt, L., Jakubiec, W., Geometrische Produkt-spezifikation (GPS), Kurs fuer Technische Universitaeten. Erlangen 2001

76. Humienny Z. [ed.], Białas S., Osanna P.H., Tamre M, Weckenmann A., Blunt L., Jakubiec W.: Specyfikacje geometrii wyrobów (GPS). Wykład dla uczelni technicznych. Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2001 (in Polish)

77. Humienny, Z., Osanna, P.H., Tamre, M., Weckenmann, A., Blunt, L., Jakubiec, W., "Specyfikacje geometrii wyrobów (GPS), Podręcznik europejski" Wydawnictwa Naukowo-Techniczne, Warszawa 2004 (in Polish)

78. Jakubiec,W., Płowucha, W., „Coordinate measurement uncertainty: Models and standards", tm - Technisches Messen, 82 (1), pp. 1-6, 2015

79. Płowucha, W., Werner, T., Savio, E., Blunt, L., Jakubiec, W., A new didactic approach to statistical analysis of measurement data for the evaluation of measurement uncertainty - "SAM-EMU". Measurement 45 (2012) 2359–2367

80. Weckenmann, A., Werner, T., "Reducing operator influences on results in coordinate metrology via a holistic qualification concept". 9th ISMQC, Madras 2007

81. Humienny, Z., Turek, P., "Animated visualization of the maximum material requirement", Measurement, vol. 45, nr 10, 2012, pp. 2283-2287

82. Jakubiec, W., Płowucha, W., Starczak, M., "Analytical estimation of coordinate measurement uncertainty". Measurement, 45, pp. 2299–2308, 2012

83. Płowucha, W., Jakubiec, W., "Theory and practice of uncertainty evaluation of coordinate measurements". Key Engineering Materials, Vol. 613, pp. 344-353, 2014

84. Jakubiec, W., Płowucha, W., "First coordinate measurements uncertainty evaluation software fully consistent with the GPS philosophy". Procedia CIRP, vol. 10, pp. 317-322, 2013

85. Weckenmann, A., Werner, T., "Introducing Engineering Students to Open Distance Learning – a case study on the acceptance of a virtual course as compulsory subject", in: F. K. Fink (Ed.), SEFI 2008 – 36th Annual Conference 2–5 July 2008 Aalborg Denmark: Book of Abstracts, Sense Publishers, Rotterdam, 2008, p. 50 and CD-ROM.

86. Wen, X.-L., Zhu, X.-Ch., Zhao Y.-B., Wang, D.-X., Wang, F.-L., "Flatness error evaluation and verification based on new generation geometrical product specification (GPS)". Precision Engineering. Volume 36, Issue 1, January 2012, Pages 70–76

87. Werner, T., Płowucha, W., Jakubiec, W., Weckenmann, A.„ "Creating a web-based course on measurement uncertainty in international cooperation", in: K. Resetova (ed.), Proceedings of the Joint International IGIP- SEFI Annual Conference 2010. Diversity unifies – Diversity in Engineering Education. Abstracts, SEFI, Bruxelles, 2010, pp. 84–85 and CD-ROM.

88. Neamtu, C., Hurgoiu, D., Popescu, S., Dragomir, M., Osanna, P.H., "Training in coordinate measurement using 3D virtual instruments". Measurement 45 (2012) 2346–2358

89. Marxer, M., Keferstein, C.P., Weckenmann A., "Sustainable Manufacturing Using a Global Education Concept for Coordinate Metrology with a Blended Learning Approach". Advances in Sustainable Manufacturing 2011, pp 31-35

90. Keferstein, C., Marxer, M., Jakubiec, W.; Weckenmann, A.; Beetz, S., "EUKOM – European Training for Coordinate Metrology. At: 8th ISMQC, October 12th-15th, 2004, Erlangen