Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 75 (2018) 11–18

www.elsevier.com/locate/procedia

15th CIRP Conference on Computer Aided Tolerancing – CIRP CAT 2018

A Brief Analysis of Recent ISO Tolerancing Standards and Their Potential Impact on Digitization of Manufacturing

Edward P. Morse[a], Craig M. Shakarji[b], Vijay Srinivasan[b]*

[a]University of North Carolina, Charlotte, NC, U.S.A.
[b]National Institute of Standards and Technology, Gaithersburg, MD, U.S.A.

* Corresponding author. Tel.: +01-301-975-3508; fax: +01-301-258-9749. *E-mail address:* vijay.srinivasan@nist.gov

Abstract

The publication of the latest edition of ISO 1101 in 2017 is a landmark event in the development of ISO tolerancing standards. It represents an important milestone in the evolution of ISO tolerancing standards powered by a synergy between technological developments in tolerancing (for specification) and metrology (for verification). The external forces that caused this synergistic evolution stem from digitization of manufacturing (also variously called Smart Manufacturing, Cyber-Manufacturing, Cyber-Physical Production Systems, and Industrie 4.0). This paper provides a brief analysis of a new set of customer-facing ISO tolerancing standards which, along with their promises and challenges, will have a significant impact on digitization of manufacturing.

Peer-review under responsibility of the Scientific Committee of the 15th CIRP Conference on Computer Aided Tolerancing - CIRP CAT 2018.

Keywords: ISO; GPS; tolerancing; metrology; digitization; manufacturing

1. Introduction

After several years of intense development, the fourth edition of ISO 1101 was published in 2017, cancelling and replacing all previous editions of this standard [1]. Arguably, ISO 1101 – which deals with geometric tolerancing of form, orientation, location, and run-out – has been the most important of all ISO geometric tolerancing standards that practicing engineers have used for nearly five decades. It is also the ISO standard that most Computer-Aided Design (CAD) systems have implemented in the past to enable engineers in industry to create two-dimensional (2D) drawings and three-dimensional (3D) CAD models that incorporate geometrical tolerance specifications. Therefore, any change in ISO 1101 will have a dramatic impact on manufacturing industry.

ISO 1101:2017 has a brand-new look and feel. It now defines rules more by mathematical principles and less by cartoon-like graphics and prose that imply definitions by examples. It has also introduced many new symbols that have enhanced the tolerancing language by nearly an order of magnitude.

ISO 1101:2017 is just one of a comprehensive set of ISO standards produced by ISO Technical Committee (TC) 213 on Dimensional and Geometrical Product Specifications and Verification, which is abbreviated and branded as GPS. Some of the ISO GPS standards deal with fundamental concepts that provide guidance for developers of the ISO GPS standards themselves; these can be described as *developer-facing* standards. But there are other standards that define symbols and their meanings to guide designers and manufacturers on the use of the ISO GPS language in 2D drawings and 3D CAD models; these can be described as *customer-facing* standards.

As an example, ISO 17450-1:2011 [2] defines the fundamental concepts of ISO GPS and their mathematical bases; these concepts are used in the development of all other ISO GPS standards, and therefore it is a developer-facing standard. ISO 14405-1:2016 [3], on the other hand, defines 16 new symbols to specify linear size tolerances; this standard can be used by engineers to indicate several linear size tolerance

2212-8271
Peer-review under responsibility of the Scientific Committee of the 15th CIRP Conference on Computer Aided Tolerancing - CIRP CAT 2018.
10.1016/j.procir.2018.04.080

symbols in their drawings and 3D CAD models, and therefore it is a customer-facing standard. In fact, the first edition of ISO 14405-1 was introduced in 2010, making it one of the first in a new generation of customer-facing ISO GPS standards issued by ISO/TC 213.

A major driver behind the dramatic expansion in the richness of the ISO GPS language, as seen in the likes of ISO 14405-1:2016 and ISO 1101:2017, is the digitization of manufacturing. This trend in manufacturing is also referred to variously as Smart Manufacturing, Cyber-Manufacturing, Cyber-Physical Production Systems, and Industrie 4.0. Thanks to the recent proliferation of Coordinate Measuring Systems (CMS) and various sensors that are part of Industrial Internet-of-Things (IIOT), there is an increasing pressure on organizations such as ISO to support emerging digital technologies in addition to traditional metrology based on physical devices. To put it simply, there is a strong industrial pressure to make ISO GPS standards 'CMS-friendly' and not just 'gauge-friendly.' This also requires an injection of greater mathematical rigor in the definition of ISO GPS standards.

A second driver to expand the ISO GPS language is the variety of specifications needed by industry to convey functional intent that were not previously available. For example, a conventional, peak-to-valley flatness tolerance is often not sufficient to capture design intent. A designer of countertops using certain types of granite may allow some pits or fissures in the material but will have much more stringent requirements on any protrusion outside of the material. Or a designer of an optical surface may need to include a limit on the root-mean-square of the deviation from a perfect plane in addition to a looser peak-to-valley tolerance.

Prior to the emergence of ISO GPS standards, industry had to handle such situations either by using existing tools or by annotating drawings with customized notes to convey design requirements. The problem with using the few existing tools is that tolerances may have to be needlessly tightened to meet the design requirements, which can vastly increase costs. And the problem with custom annotations is that it is very easy to be unintentionally ambiguous – even by a skilled engineer, and they are often written in the native language of the engineer, preventing universal understanding. Standards developers go to great lengths over many iterations to create symbols and definitions that unambiguously convey design intent.

The main purpose of this paper is to present a brief analysis of recent customer-facing ISO GPS standards, and examine their potential to impact the ever-increasing digitization of manufacturing. It starts with the example of linear and angular size tolerancing, which can now be specified in a great variety of ways using special modifiers.

2. Size

Size is a ubiquitous engineering concept, and it has received special attention from ISO/TC 213 [4]. There are two recent ISO GPS standards on size tolerancing; one on *linear* sizes [3] and the other on *angular* sizes [5]. These standards are prepared in working group WG 12 of TC 213. Traditional metrological means of verifying size tolerances employ measuring equipment such as micrometers, Vernier calipers and height gauges to measure *local* sizes. They also use 'go' and 'no-go' hard gauges (also known as functional gauges) to check for conformance to *global* size tolerances. The recent ISO GPS standards for size tolerancing support these traditional practices. But they also go much further to support engineering requirements whose verification can only be implemented using a CMS, as described below.

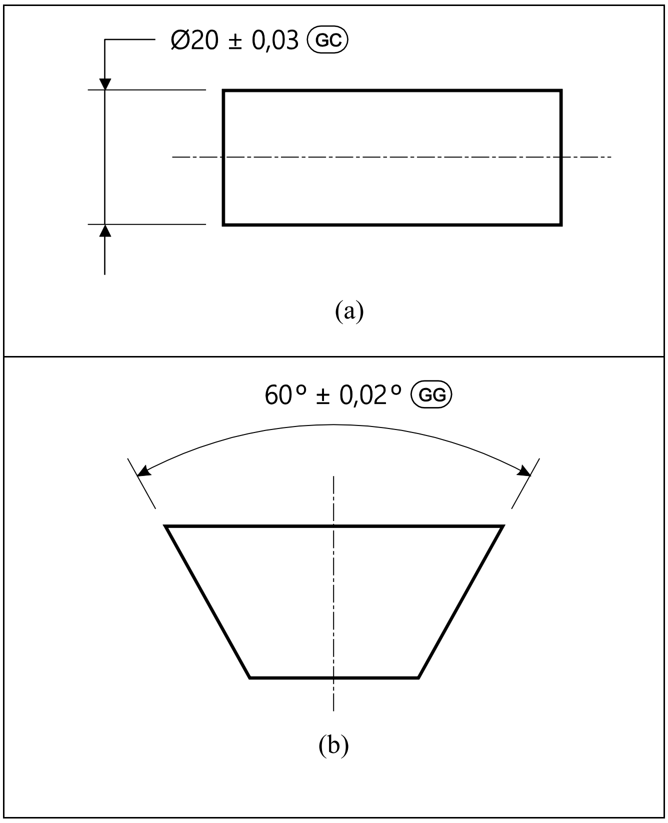

Fig. 1. Use of special modifiers for (a) linear size tolerancing of a cylindrical feature, and (b) angular size tolerancing of a conical feature.

Figure 1(a) shows a linear size tolerancing of a cylindrical feature, with a GC modifier. When a GC (which may be read as Global Chebyshev) modifier is used, it means that a mathematically perfect-form cylinder is fitted to an extracted cloud of points on a cylindrical feature of a work-piece using the minimax (Chebyshev) association criterion. Then, the diameter of this associated cylinder is checked to see if it is within the indicated tolerance limits.

Figure 1(b) illustrates the application of another modifier, in this case a GG modifier, to control the angular size of a conical feature. When a GG (which may be read as Global Gaussian) modifier is used, it means that a mathematically perfect-form cone is fitted to an extracted cloud of points on a conical feature of a work-piece using the least-squares (Gaussian) association criterion. Then, the apex angle of the associated cone is checked to see if it is within the indicated tolerance limits.

It is clear from these descriptions that the GC and GG modifiers require collecting points on a work-piece, most probably using a CMS or a similar scanning device, and processing this 'point cloud' data using sophisticated software that employs Chebyshev and Gaussian fitting algorithms. GC and GG are not the only new ISO GPS symbols for size tolerancing. Table 1 enumerates all the current 16 modifiers for linear size tolerancing [3]. Likewise, Table 2 enumerates all the current 11 modifiers for angular size tolerancing [5].

Table 1. ISO GPS modifiers for linear size tolerancing [3].

Modifier	Description
(LP)	Two-point size
(LS)	Local size defined by a sphere
(GG)	Least-squares association criterion
(GX)	Maximum inscribed association criterion
(GN)	Minimum circumscribed association criterion
(GC)	Minimax (Chebyshev) association criterion
(CC)	Circumference diameter (calculated size)
(CA)	Area diameter (calculated size)
(CV)	Volume diameter (calculated size)
(SX)	Maximum size
(SN)	Minimum size
(SA)	Average size
(SM)	Median size
(SD)	Mid-range size
(SR)	Range of sizes
(SQ)	Standard deviation of sizes

If no such modifier is specified for linear size tolerance, then the 'two-point size' (LP) is invoked as the default; so, using traditional measurement equipment, such as a micrometer, will suffice for the verification of such specification, provided a sufficient subset of all of the two-point sizes are evaluated. If no modifier is specified for angular size tolerance, then the default is a 'two-line angular size' with minimax association criterion (LC); this requires employing a CMS and some serious computational effort.

Table 2. ISO GPS modifiers for angular size tolerancing [5].

Modifier	Description
(LC)	Two-line angular size with minimax association criterion
(LG)	Two-line angular size with least-squares association criterion
(GG)	Least-squares association criterion
(GC)	Minimax association criterion
(SX)	Maximum angular size
(SN)	Minimum angular size
(SA)	Average angular size
(SM)	Median angular size
(SD)	Mid-range angular size
(SR)	Range of angular sizes
(SQ)	Standard deviation

The modifiers shown in Tables 1 and 2 try to remove ambiguities that exist in the traditional size tolerance specifications. Moreover, they provide new capabilities to address needs that arise from industrial applications such as rolling bearings and plastics. For example, the circumference diameter modifier (CC) is more appropriate in the specification of plastic caps – which can flex but don't stretch – that serve as tight lids on more rigid cups. If only the inscribed diameter could be specified (GX in the new symbology), the verification of this tolerance would cause many functional parts to be rejected, where a cap with the correct circumference was out-of-round, resulting in a non-conforming inscribed diameter.

3. ISO GPS Operations and Measures of Dispersion

In the above description of size tolerancing, several concepts were mentioned without any elaboration. These include the notions such as 'extracted cloud of points,' 'feature of a work-piece,' and 'association criterion.' These and other notions are defined in the developer-facing ISO GPS standards using four major ISO GPS operations, which are now described in Section 3.1.

3.1. ISO GPS operations

ISO GPS specifications are based on the nominal product geometry but include the concept of a *skin model*, which is a computable representation of the boundary of an imperfect form model. The operations of specification (design phase) and verification (metrology phase) can both be described in terms of the following four ISO GPS feature operations:

1. *Extraction*. In this operation, a finite subset of points is taken from the infinite point set that comprises the skin model. In modeling verification, these are the points obtained by the CMS.

2. *Partitioning*. In this operation, the model of a work-piece is divided into pieces, each of which corresponds to a surface feature. Features extracted from the skin model correspond to features on the boundary of a nominal model of ideal form. (The boundary of a nominal model of ideal form may be subjected to the same partitioning operations to define features of interest for specifications.)

3. *Filtration*. In this operation, a scale-dependent computable representation of (potentially a portion of) a skin model is created. This may precede or succeed the extraction operation.

4. *Association*. In this operation, a mathematically perfect-form surface (or curve) is fitted to an extracted and filtered set (which may be discrete or continuous) of points, using an optimization process.

Two other operations, collection and construction, are also addressed, but are not necessary for this discussion. The four operations listed above are applicable for specifications as well as verification. The major differences are that (1) the specification operations work with the continuous sets of points, which form the non-ideal 'skin model,' and (2) the verification operations will have measurement uncertainties – including those introduced by discrete sampling to create discrete sets of points – that should be carefully accounted for. ISO/TC 213 is actively engaged in producing a series of documents on these ISO GPS operations. Most of these documents may come under the category of developer-facing standards, even though the customer community should have a good understanding of these operations to properly use the new ISO GPS language, such as in Fig. 1.

3.2. Measures of central tendency and dispersion

Statistical measures of variability are typically characterized by their lower order moments. In this section, two measures of variability are addressed:

- *Measures of central tendency*: Under central tendency, measures such as mean (also known as average) and median have found popular use in science and engineering. Among the size tolerance modifiers in Tables 1 and 2, the presence of average size and median size attest to this popularity. So, limits can be specified for these measures of central tendency to indicate the allowable variability of acceptable features.

- *Measures of dispersion*: Under dispersion, measures such as standard deviation and range can be used for the specification of allowable variability about the measures of central tendency. The presence of standard deviation and range in Tables 1 and 2 is a clear evidence of the use of such measures of dispersion to specify the allowable variability in size.

Table 3. Dispersion parameters introduced in recent ISO GPS standards.

Symbol	Parameter
P	Reference-to-peak
V	Reference-to-valley
T	Peak-to-valley
Q	Root mean square (RMS)

Traditionally, the definition of specifications using geometrical tolerancing has depended heavily on tolerance zones. This has led to the *range* as the only measure of dispersion available to engineers for handling geometric variations. The recent ISO GPS standards have enlarged the toolset available to engineers by defining several measures of dispersion. In addition to the traditional tolerance zones, dispersion parameters shown in Table 3 are now allowed [1].

Table 4. Objective functions and constraints for association operations in recent ISO GPS standards.

Symbol	Association Operation (Objective functions and constraints)	
C	Minimax (Chebyshev) criterion	Objective function
G	Least-squares (Gaussian) criterion	
X	Maximum inscribed criterion	Objective function and constraint
N	Minimum circumscribed criterion	
E	Constrained external to the material	Constraint
I	Constrained internal to the material	

The parameters of Table 3 are defined from a reference surface, which is obtained by an association operation that can be specified using the symbols shown in Table 4 [1]. The symbols of Tables 3 and 4 can be combined in several ways, one of which is shown in Fig. 2 for flatness specification.

4. Form and Filtration

Form tolerancing controls straightness, flatness, roundness, cylindricity, line profile and surface profile. One distinguishing aspect of form tolerancing is that it may not need datums. Traditionally, form tolerances involved tolerance zones. In addition to such zones, recent ISO GPS standards allow the use of other measures of dispersion described in Section 3.2 to control geometric variation. Figure 2 shows one of the new ways to specify flatness tolerance, which also invokes a long-wave pass filter.

In Fig. 2, the top face that has a form tolerance specification is first subjected to filtration by a closing ball (indicated by CB) filter using a 0,5mm diameter (also known as the 'nesting index') ball. The dash following the number 0,5 indicates that it is a long-pass filter that removes some of the short-wave details from the surface. ISO/TC 213 has standardized symbols for Gaussian, morphological, and spline filters [1]. Symbols and definitions for more filters are being developed.

After filtration, the trailing symbols G and Q in Fig. 2 indicate that a plane is fitted to the filtered surface using the least-squares (as indicated by G in Table 4) association criterion, and the root mean square (RMS as indicated by Q in Table 3) deviation from the associated plane should be within the indicated tolerance value of 0,01. In this case, the RMS parameter is also the standard deviation, since the deviations are taken from the unconstrained least-squares plane. More filter symbols and the associated nesting indices can be found in [1].

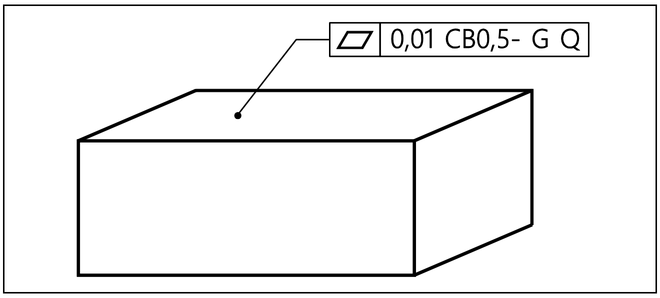

Fig. 2. Specification of flatness tolerance using Gaussian association, RMS parameter, and with a closing ball filter.

If none of the new symbols appear in the geometrical specification indication in Fig. 2, then the default is the traditional zone-based specification. It is interesting to note that if C and T had been used in Fig. 2, instead of G and Q, it would have had the same effect as the default zone-based specification. This brings up an interesting question about the *syntactic correctness* and the *semantic soundness* in the new ISO GPS specifications. For example, using C and Q in Fig. 2, instead of G and Q, will not violate any syntactic rule. But mixing Chebyshev association criterion with an RMS parameter requires some careful design justification.

Profile tolerancing is an important part of form tolerancing, and it can also be used with datums to control orientation and location. The latest edition of ISO GPS standard for profile tolerancing provides a richer set of tools to the designers [6]. With the rise of additive manufacturing (also known as 3D printing), profile tolerancing is gaining greater importance and is likely to be used quite extensively in the age of digitization of manufacturing. Even though the recent profile tolerancing standard [6] describes mainly zone-based specifications in greater detail, it can be used with symbols from Tables 3 and 4 to specify other measures of dispersion.

5. Datums and Toleranced Features

Datums are needed for all tolerance specifications other than size and some form tolerances. As mentioned earlier, they can be used with profile tolerancing to great effect in controlling intricate geometries. The current version of the ISO datum standard [7] is undergoing revision, and a new edition is expected in the near future.

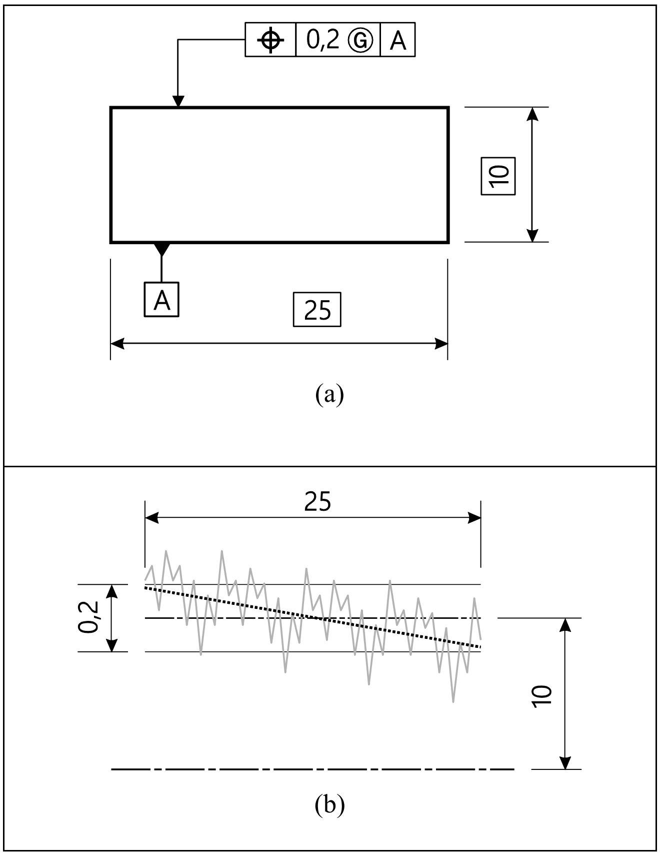

Fig. 3. (a) Indication and (b) interpretation of a location tolerance. The illustrations are not to scale.

ISO/TC 213 has been actively seeking a new mathematical definition of datums that will address all datum types, and will also achieve a good compromise between the use of traditional measurement tools (such as surface plates, angle blocks, opening and closing vises, expanding mandrels, and contracting chucks) and modern digital techniques (such as CMS). A promising candidate that has emerged is a definition of datums based on constrained least-squares criterion, which can be composed with the symbols G (for Gaussian objective function criterion) and E (constrained to be external to the material) from Table 4 [8]. Some of the current deliberations in ISO/TC 213 are leaning towards making this as the default association operation for all datums that are not subjected to maximum or least material conditions.

Relative to such datums, other features can be located and oriented using geometric tolerances. Here again, recent ISO GPS standards provide greater freedom and clarity. Until recently, standards did not explain how centres, axes, and median planes of toleranced features can be derived for orientation and location tolerances. But now ISO 1101:2017 provides some tools in the form of symbols, as illustrated in an example in Fig. 3. Even though it is a 3D problem, Fig. 3 shows the entities in 2D for simplicity. The modifier Ⓖ in Fig. 3(a) is interpreted in Fig. 3(b) to mean a least-squares (Gaussian) association of a plane, indicated in dots, that is fitted to an extracted top surface on a work-piece. Then a limited portion of the fitted plane (determined by the extent of the toleranced surface) should be contained within a tolerance zone of 0,2 units thick, positioned parallel to datum A with a central distance from A of 10, as shown in Fig. 3(b). Table 5 summarizes the symbols that can be used for association operations on toleranced features. For example, the Ⓖ symbol used in Fig. 3(a) can be found in Table 5. These symbols can be applied only for a selected set of feature types [1]. For example, Ⓝ and Ⓧ cannot be applied to a single planar feature or a conical feature.

Table 5. Symbols for association operation on toleranced features.

Symbol	Association Operation
Ⓒ	Chebyshev (minimax)
Ⓖ	Gaussian (least-squares)
Ⓝ	Minimum circumscribed
Ⓣ	Tangent: Constrained least-squares
Ⓧ	Maximum inscribed

6. Challenges Ahead

Even the brief analysis provided thus far shows the power of the new tolerance specification tools that are now placed at the disposal of engineers. Verifications of these specifications will often require digital technologies such as CMS supported by sophisticated software. So, the recent ISO GPS tolerancing standards are well positioned to advance as well as exploit digitization of manufacturing. However, many industrial customers may be concerned about the need for sophisticated verification tools such as CMS. It is important to reassure those customers that simplified verification techniques employing relatively inexpensive measurement tools can be used, with proper accounting for the accompanying measurement uncertainties.

The recent ISO tolerancing standards also pose some additional challenges, which are discussed in the following subsections.

6.1. Education and training

The new look and feel, and the emphasis on rules rather than examples, of the new ISO GPS standards place a heavier responsibility on education and training. New teaching materials have to be developed. New training programs have to be designed to train even the educators. Initial reaction from the industrial users of ISO GPS standards indicates that the education and training material may have to be split into modules that vary in complexity from the simplest to the more advanced.

Simpler modules can cater to beginners and relatively simple applications need only a subset of the symbols, which have been described only briefly in this paper and are being developed by ISO/TC 213. But the users should be cautioned about potential ambiguities that may arise from the use of such simple symbol sets, and their consequences. The users should also be made aware of the default rules that apply if some of the symbols are omitted. It is quite possible that many users are willing to assume the risk, and opt for the simpler set of symbols.

More advanced users will require more education and training in the use of the new symbols. The major challenge facing them is 'making the business case' for justifying the additional cost of education and training. This requires the development of carefully chosen case studies that show the superior benefits (and the avoidance of costly mistakes) that result from the use of the more advanced features of ISO GPS standards. More efforts should be spent in making such a business case.

6.2. Implementation in CAD systems

All major CAD systems support ISO 1101 prior to the 2017 edition. They must now provide support for the new ISO 1101:2017 and other customer-facing ISO GPS standards because, officially speaking, these new editions cancel and replace the older editions. The CAD systems may provide initial support for 2D drawings before they can support presentation and representation of ISO GPS tolerances in 3D models. General availability of the new ISO GPS tolerancing standards in CAD systems will be a major determining factor in their adoption by the engineering community.

The CAD vendors also need the 'business case' mentioned above to justify significant investment in software development to support the new ISO GPS standards. This can come only from customer demand, which depends on education and training as discussed earlier. The interdependency of customer use/demand and CAD implementation, and the cost associated with both, pose a major challenge that requires some urgent attention from industry.

Some of the emerging manufacturing technologies may provide part of the business case. The first tolerancing standard for additively manufactured (that is, by 3D printing) parts is the recently issued ASME Y14.46 draft standard for trial use [9]. It uses profile tolerancing quite extensively, for example, as shown in Fig. 4. The popularity of profile tolerancing in additive manufacturing comes at an opportune moment for the new ISO GPS standard on profile tolerancing [6] discussed briefly in Section 4.

The ISO 1660:2017 standard [6] on profile tolerancing has added several important capabilities that may be useful for additive manufacturing industry. These include tools for defining specifications (1) for restricted features and compound features, (2) using unequally disposed or offset tolerance zones, and (3) using tolerance zones of variable width. In addition, as mentioned in Section 4, the new ISO GPS profile tolerancing can be used with symbols from Tables 3, 4, and 5 to specify other measures of dispersion. These new capabilities may find innovative use in additive manufacturing applications.

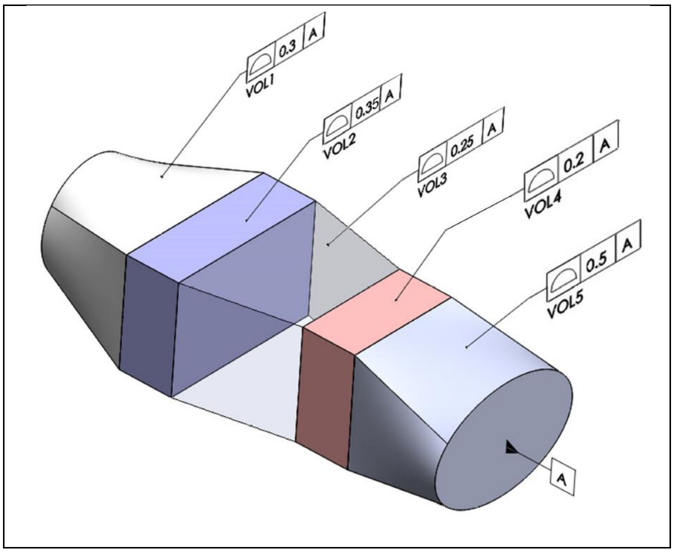

Fig. 4. An example of the use of profile tolerancing for an additively manufactured part [9].

6.3. Implementation in CMS and other inspection systems

New features in ISO GPS tolerancing standards depend on digital measurement tools, technologies, and software for verification purposes. Developing and implementing reliable algorithms in CMS, for example, will take some time because there are several research issues that need to be solved before reliable software can be developed.

All four of the ISO GPS operations described in Section 3.1 require further research for effective implementation in CMS software. A brief description of some of the research issues are outlined below:

- Extraction: The extraction operation usually collects a set of discrete points on a work-piece during the verification phase. Here, sampling strategy plays an important role. The sampling strategy should be tied to the partitioning, filtration, and association operations discussed below.

  In some verification operations, such as tactile probing, it is possible to obtain information about the normal to the surface at a contact point in addition to the coordinates of that point. Such (point, normal) tuple information could be very useful for subsequent operations. This opportunity has not been fully explored.

  Another important problem is the construction of a surrogate geometric model based on discrete measurement data. This may require surface reconstruction by some interpolation techniques, such as a simple triangular tessellation, from the discrete point (and potentially normal) data. Although these techniques are popular in computer graphics literature, their application to ISO GPS verification in CMS is still in its infancy.

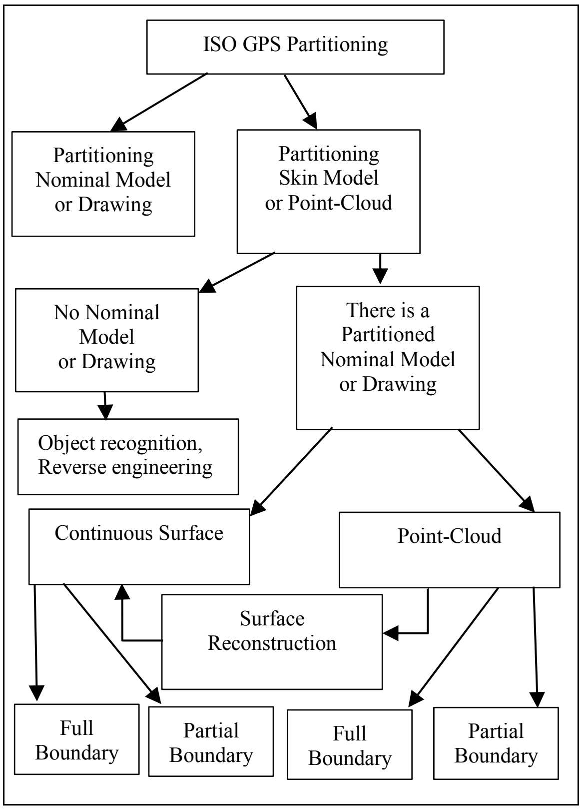

Fig. 5. A classification diagram for ISO GPS partitioning operations [10].

- *Partitioning*: The topic of the partitioning operation has been subjected to a science-based classification to support standardization only recently [10]. Figure 5 shows a proposed classification diagram for ISO GPS partitioning. A key differentiator between the general surface 'segmentation' problem discussed in literature (that deals with object recognition and reverse engineering) and the ISO GPS partitioning problem is the availability of a nominal model and its partitioning. This *a priori* knowledge is important in establishing a one-to-one correspondence between the partitioning of a nominal model and the partitioning of a skin model. Some surface features – such as threads, counter bores/sinks, chamfers, fillets, and rounds – may be represented only symbolically (rather than as surface patches in an explicit boundary representation) on a nominal model. These symbolic features should be considered in partitioning a skin model.

  Recent advances in machine learning and image processing have produced some impressive results in edge detection, feature recognition, and object classification. These results can be exploited in CMS, with possible hardware and software assistance from Graphics Processing Units (GPUs).

- *Filtration*: Historically, the filtration operation consisted of two major types of filters: mean-line filters and envelope filters. These filters (each applied for profile as well as areal filters) have been used extensively in controlling surface texture. The new ISO GPS standards have expanded the role of filtration operation beyond surface texture.

  Consider, for example, Fig. 2 in which a closing ball filter (CB) is used to specify the filtration operation as part of the flatness specification. For verification of such flatness specification, a CMS needs to implement a closing ball filtration operation. ISO/TC 213 has issued several standards in the ISO 16610 series of filtration standards, and is working on more. Algorithms for efficient filtration operations and their robust implementation are topics for further research, especially for surfaces embedded in 3D.

- *Association*: Although the topic of the association operation has been well studied, the emergence of constrained least-squares fitting as a default association criterion for establishing datums has inspired some recent research [8]. Initial results from these research efforts include the combinatorial characterization of the optimality conditions for constrained least-squares fitting of some linear and non-linear geometrical elements [11, 12].

  Application of association operations under various criteria listed in Tables 1 through 5 open more research problems that need to be solved for implementation in CMS. These are optimization problems with a variety of constraints. While they serve as a rich source of research problems, timely implementation of their solutions in commercial-grade software – where a balance is always sought between absolute correctness of algorithms and adequacy for the proposed use – remains a challenge.

6.4. Implementation in data exchange standards

Supply chains in manufacturing industry depend on standardized data, such as STEP, to exchange complete product information. Major CAD vendors have implemented and tested dimensional and geometrical tolerancing specifications that are currently used in industry [13]. Figure 6 shows an example of a test case in which a 3D model with geometrical tolerancing information is represented in a neutral STEP format for exchange. But similar support of new ISO GPS tolerancing standards must await the native CAD implementations of these new standards as discussed in Section 6.2.

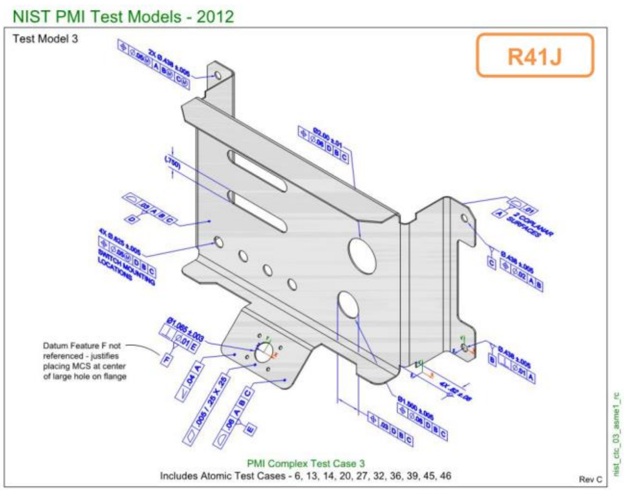

Fig. 6. Example of a test case for model exchange [13].

6.5. Future direction of ISO GPS standards

The long list of challenges described in Sections 6.1 to 6.4 has prompted ISO/TC 213 to reexamine ISO GPS standards that have been issued already [1-3,5,6] and those under development (such as the revision of [7]). In a recent meeting of ISO/TC 213, experts who interface with industrial customers discussed some of the issues related to the ISO GPS system of standards with respect to their use, acceptance, and implementation by industry. They expressed their concern that the complexity of the ISO GPS system is leading to fragmentation in its use, at both national and industrial levels, and is hampering its uptake and implementation.

To address these concerns and to facilitate the use of the ISO GPS system, ISO/TC 213 has initiated a proposal to (1) improve the organizational structure of the ISO GPS system, (2) split its standards into smaller units, having regard to 'customer-facing' and 'developer-facing' sections, and functionally self-contained units, and (3) address contradictions among its standards.

7. Summary and Concluding Remarks

This paper has presented only a brief analysis of a major new development in ISO tolerancing standards. A more detailed study, which may involve several people and several publications, is needed to guide the standardization process and to aid the manufacturing industry that is getting increasingly digitized at an impressive rate.

While there are promising opportunities offered by these new tolerancing standards, several challenges remain. Therefore, this keynote paper issues a call for action. In addition to more detailed study of these new standards, it calls for

- Better education and training (Section 6.1)
- Implementation in CAD systems (Section 6.2)
- Implementation in CMS and other inspection systems (Section 6.3)
- Implementation in data exchange standards (Section 6.4)
- Better packaging of standards and more customer focus in standards development (Section 6.5)

The CIRP CAT community is well positioned to answer this call and contribute to overcoming many of these challenges.

Acknowledgements

The authors thank ISO and ASME standards experts whose advice and suggestions were invaluable in initiating and sustaining this research investigation. Any mention of commercial products or systems in this article is for information only; it does not imply recommendation or endorsement by NIST. This work has been supported in part by a cooperative research agreement (NIST grant number 70NANB14H254) between UNC Charlotte and NIST.

References

[1] ISO 1101:2017. Geometrical product specifications (GPS) – Geometrical tolerancing – Tolerances of form, orientation, location and run-out. International Organization for Standardization, Geneva, 2017.

[2] ISO 17450-1:2011. Geometrical product specifications (GPS) – General concepts – Part 1: Model for geometrical specifications and verification. International Organization for Standardization, Geneva, 2011.

[3] ISO 14405-1:2016. Geometrical product specifications (GPS) – Dimensional tolerancing – Part 1: Linear sizes. International Organization for Standardization, Geneva, 2016.

[4] Morse EP, Srinivasan V. Size tolerancing revisited – A basic notion and its evolution in standards. Proc Inst Mech Eng Part B - J Eng Manuf 227(5):662-71, 2013.

[5] ISO 14405-3:2016. Geometrical product specifications (GPS) – Dimensional tolerancing – Part 3: Angular sizes. International Organization for Standardization, Geneva, 2016.

[6] ISO 1660:2017. Geometrical product specifications (GPS) – Geometrical tolerancing – Profile tolerancing. International Organization for Standardization, Geneva, 2017.

[7] ISO 5459:2011. Geoemtrical product specifiaitons (GPS) – Geoemtrical tolerancing – Datums and datum systems. International Organization for Standardization, Geneva, 2011.

[8] Shakarji CM, Srinivasan V. Toward a new mathematical defintion of datums in standards to support advanced manufacturing. In: Proceedings of the ASME 2018 Manufacturing Science and Engineering Conference, MSEC2018, College Station, Texas, June 18-22, 2018.

[9] ASME Y14.46-2017, Product Definition for Additive Manufacturing, The Americal Society of Mechanical Engineers, New York, NY, 2017.

[10] Anwer N, Scott PJ, Srinivasan V. Toward a classification of partitioning operations for standardization of geometrical product specifications and verification. In: 15th CIRP Conference on Computer Aided Tolerancing, CIRP CAT 2018, Milano, Italy, June 11-13, 2018.

[11] Shakarji CM and Srinivasan V. Convexity and optimality conditions for constrained least-squares fitting of planes and parallel planes to establish datums. In: Proc. ASME 2017 Int Mech Engg Conf and Exp, Tampa, FL, Nov. 3-9, 2017.

[12] Shakarji CM and Srinivasan V. Optimality conditions for constrained least-squares fitting of circles, cylinders, and spheres to establish datums, to appear in ASME J of Computing and Inf Sci in Engg., 2018.

[13] CAx Implementor Forum. www.cax-if.org