An Integrated View of Geometrical Product Specification and Verification

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Abstract: ISO/TC 213 is a technical committee that standardizes tolerancing and related metrological practices. During the past five years it has focused its attention on harmonizing and integrating these two areas. In that process it recognized the need for linking these two areas to product functionality and has published a vision for directing its future efforts towards it. This paper presents an integrated view of tolerancing and metrology, and describes the new vision of ISO/TC 213.

Keywords: ISO, Standards, GPS, Specification, Verification

1. INTRODUCTION

Since the summer of 1996, ISO/TC 213 on “Dimensional and Geometrical Product Specifications and Verification” [ISOTC213] has been working towards harmonizing previously standardized practices in tolerancing (specification) and related metrology (verification). Initial impetus for this work came from perceived gaps and contradictions in the “chain” of standards that dealt with dimensional and geometric tolerance specifications and their verifications using metrological instruments, systems and procedures [Bennich, 1994]. It was also reinforced by the needs of rapidly expanding CAD/CAM/CAQ marketplace that placed a high premium on mathematical formalism so that reliable and compact software can be developed to support computerized applications in these areas.

In the course of its work ISO/TC 213 recognized that a GPS (Geometrical Product Specification) language can be developed using an elegant classification of symmetry groups and that this could impact a functional feature taxonomy, datum definition and, as an added benefit, parameterization [Srinivasan, 1999b]. It also uncovered sets of dual operations in the specification and verification procedures. These dual operations include partitioning, sampling, filtering and fitting. It is thus possible to harmonize the (previously unspoken) set of operations involved in tolerance specifications with those employed during inspection of a workpiece. Finally, ISO/TC 213 began to espouse and expand the notion of uncertainty beyond just measurements.

Armed with the experience gained thus far, ISO/TC 213 recently published its vision for the next generation of the GPS language (see Annex at the end of the paper for a reproduction of this “vision document”). The objective of the improved GPS system is to provide engineering tools for economic management of variability in products and processes. ISO/TC 213 envisions an enriched, math-based GPS language that will allow expression of requirements relating to a wide range of workpiece function. It will use “uncertainty” as an economic tool to enable optimum allocation of resources amongst specification, manufacturing and verification. To ease the burden of inevitable verbosity of the resulting GPS language, it will strive towards a simplification using consistent logic and a “default” concept. This paper presents an integrated view of geometrical product specification and verification, and describes the new vision of ISO/TC 213.

Using a scientific structure borrowed from physics, the rest of the paper is organized as follows. In section 2 we start with a definition of tolerancing semantics as a *gedanken experiment*. This is followed in section 3 by a description of a *duality principle* that provides a one-to-one mapping between specification and verification. Then in section 4 product functionality is linked to specification and verification thorough a *generalized uncertainty principle*. Section 5 summarizes and concludes the paper.

2. A GEDANKEN EXPERIMENT

The works of ISO committees responsible for tolerancing (specification) and related metrology (verification) were combined in mid-1990s to form the mission of ISO/TC 213. One may wonder why these were united and why others, such as those dealing with manufacturing, were left out of this unification. The decision was not arbitrary, and it has to do with the fact that specification and verification are strongly related to each other both in theory and in practice. This section will be devoted to explaining one aspect of this strong relationship.

The GPS language has a syntax whose graphical representation is indicated on a view of a nominal model of a part; this nominal model consists of ideal surfaces. The semantics of the GPS language is, however, based on an abstract geometric model of a workpiece; this model consists of non-ideal surfaces. In his original work Requicha [Requicha, 1983] defined the semantics of the GPS language as a “theoretical inspection procedure”. In his scheme

> *“A (model of a) part P satisfies a tolerance specification T if and only if there exists a decomposition of ∂P (boundary of P) into subsets G_i, called actual surface features, such that*
>
> - $\cup G_i = \partial P$.
> - *There exists a one-to-one correspondence between G_i and the nominal surface features F_i of S.*
> - *Each G_i satisfies the assertion A_{ij} associated with its corresponding F_i.”*

Requicha's work provided the first formalism for defining the semantics of tolerancing - that is, the GPS language - as a gedanken experiment. It was an important intellectual milestone in the theoretical evolution of the GPS language in the pre-TC 213 era. What is impressive is that even today we depend on this formalism to define tolerancing semantics, with some additional operations defined to elaborate what Requicha termed “actual surface features”.

Figure 1 is a reproduction of an illustration from a recent document ISO/TS 17450-1 [ISO17450-1]. Under the heading “NOMINAL DESIGN” it describes how the syntax of the GPS language is presented. Using Requicha's terminology, we would say that the nominal model S is decomposed into nominal features F_i (these are the ideal features in Figure 1 obtained by operations such as partition, collection and construction). Then each F_i is tagged with a set of assertions A_{ij} that, when expressed using graphical or other symbology, will form the tolerancing syntax.

Tolerancing semantics is illustrated in Figure 1 under the heading “DESIGN INTENT (specification procedure)”. This is Requicha's “theoretical inspection procedure” - the gedanken experiment - but with more details added on how his "actual surface features" (termed “non-ideal features” in Figure 1) are to be defined. These details are grouped under a specification operator, which consists of several feature operations. Needless to say, the specification operator resides strictly in the imagination of the designer.

Why, we may well ask, do we have to define the specification operator in such detail and how do we know that these are the feature operations we need in a specification operator? To answer the first question, we observe that the gedanken experiment is not merely an intellectual exercise; a workpiece will be actually inspected to see if it conforms to the tolerance specification. This actual inspection procedure should imitate the theoretical inspection procedure as closely as possible to preserve the integrity of the design intent. In fact, the designer demands it. A careful examination of actual inspection procedures, described under the heading “VERIFICATION OF MANUFACTURED WORKPIECES FOR COMPLIANCE WITH DESIGN INTENT (measurement procedure)” in Figure 1, reveals that metrologists use several feature operations listed in the verification operator. We can now answer the second question - the feature operations in the specification operator simply mirror those in the verification operator.

This one-to-one mapping between the feature operations in the specification operator and the verification operator provides the technical basis for an integrated view of geometrical product specification and verification. It also explains why the tolerancing and related metrology standards groups were merged to form ISO/TC 213.

3. A DUALITY PRINCIPLE

The dual sets of feature operations (grouped under specification operator and verification operator) shown in Figure 1 deserve some explanation. As admitted earlier, these operations are more familiar to metrologists. A designer responsible for expressing his design intent usually does not explicitly think or document the details embodied in the specification operator. This is highlighted by a simple reference to just “actual surface features” in Requicha's theoretical inspection procedure. Let's first look at the problem from a verification perspective.

3.1. Verification Perspective

We start by considering how a metrologist perceives a manufactured workpiece, that is, a physical object. This is addressed under “REAL SURFACE” in Figure 1. Intuitively, a *real* surface is the set of infinite number of points that separate a workpiece from its surrounding. Given any physical workpiece, it is, of course, impossible to come up with a mathematical representation of this set; we need some additional information about the resolution at which the real surface is perceived. ISO/TC 213 defines at least two ways to

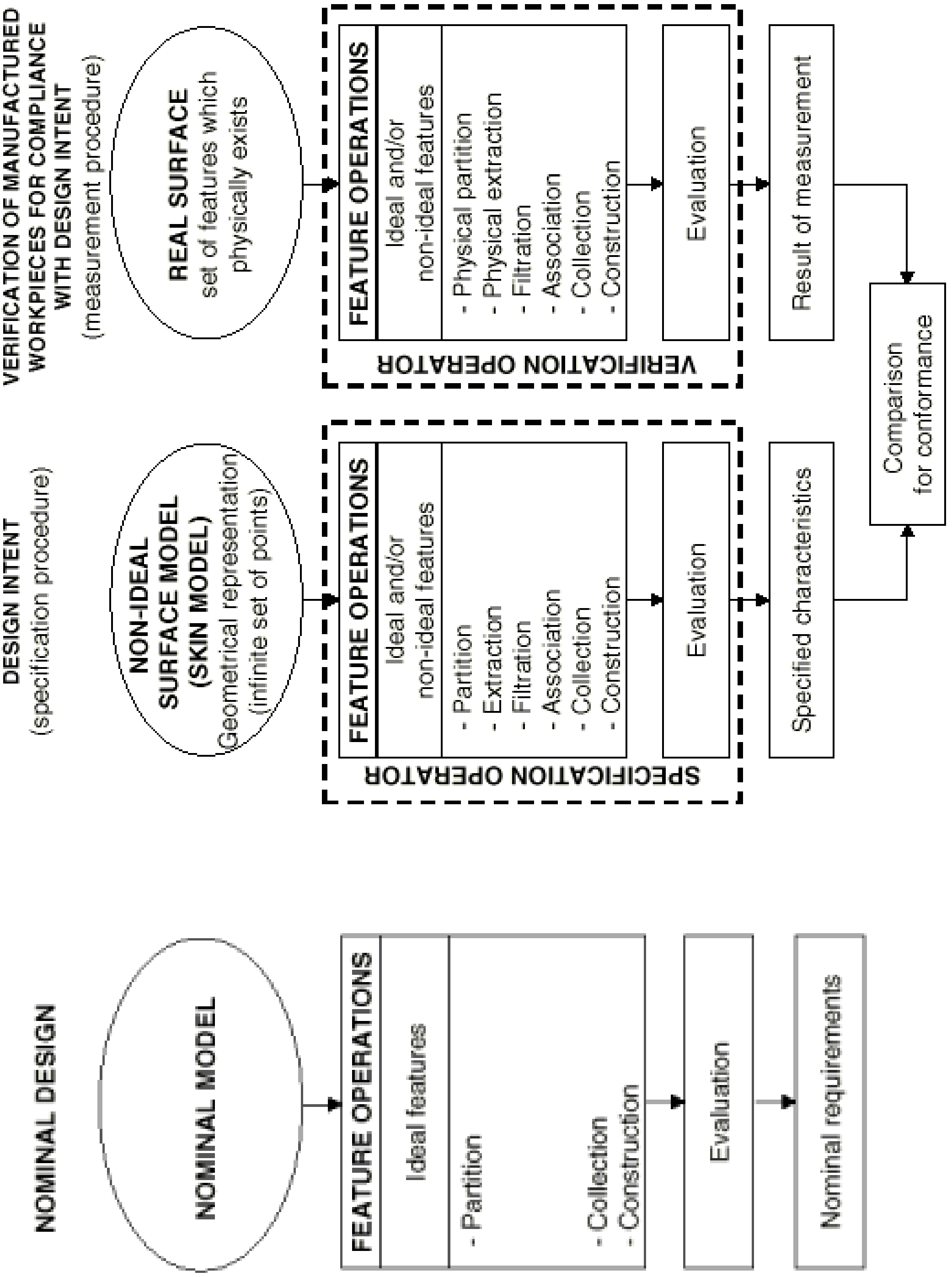

Figure 1. ISO/TC 213's comparison between tolerancing and metrology.

characterize this resolution - one is a *mechanical* real surface and the other is an *electro-magnetic* real surface.

Roughly speaking, a mechanical real surface is the set of all points on a real surface that a spherical probe of finite radius r can touch; an electro-magnetic real surface is the set of all reflection points on a real surface by electro-magnetic radiation with a specified wavelength λ. In both cases, we have a *nesting parameter* - radius r in the case of mechanical real surface and wavelength λ in the case of electro-magnetic real surface. The nesting arises from the fact that a real surface obtained with a smaller value for the nesting parameter contains more information than the one obtained with a larger value for the parameter.

Theoretically, a mathematical model that approximates the real surface can be obtained within any measure of closeness by choosing the nesting parameter very close to zero.

We can now describe various feature operations listed under the verification operator in Figure 1. No ordering of operations is implied in this list. In Figure 2 the results of various feature operations are illustrated. A real surface corresponding to a specified nesting parameter is *partitioned* into *real integral features*. These features still contain infinite number of points. During actual inspection, however, we sample only a finite number of points on these features. These are called *extracted* integral features. It turns out that sampling alone is insufficient to extract a feature; it should be accompanied by some smoothing to remove noise and unwanted details from the measured data. Therefore, techniques for extracting information on real integral features involve both sampling and some *filtration*. Ideal surfaces are then fitted to the extracted and filtered data points - this fitting process is called *association*. Results of most of these feature operations are illustrated in Figure 2.

Sometimes the geometric objects are combined together using a *collection* operation; for example, two cylindrical features may be collected together to form a pattern of two cylindrical features. Features may also be subjected to a *construction* operation; for example, two planar faces may be intersected to obtain a straight edge feature.

3.2. Specification Perspective

The rationale for spelling out the details of feature operations in the verification operator is clear - the metrologist needs them to do his job. In the course of implementing these operations several decisions - the nesting parameter, sampling density, filtering scheme, etc - are made by the metrologist. Can the designer remain an uninterested bystander while these decisions are being made? The answer seems to be clearly no, because these decisions may impact the ultimate functionality of the workpiece.

A solution to this problem proposed by ISO/TC 213 is to postulate a principle of duality. Under this principle the specification operator and verification operator are duals of each other - one imagined by the designer and the other implemented by the metrologist. These operators contain identical sets of feature operations as shown in Figure 1. By explicitly defining these feature operations many of the previously unspoken details have been brought out into the open. ISO/TC 213 believes that this openness greatly reduces the possibility for unpleasant surprises for the designer when the metrologist implements the feature operations.

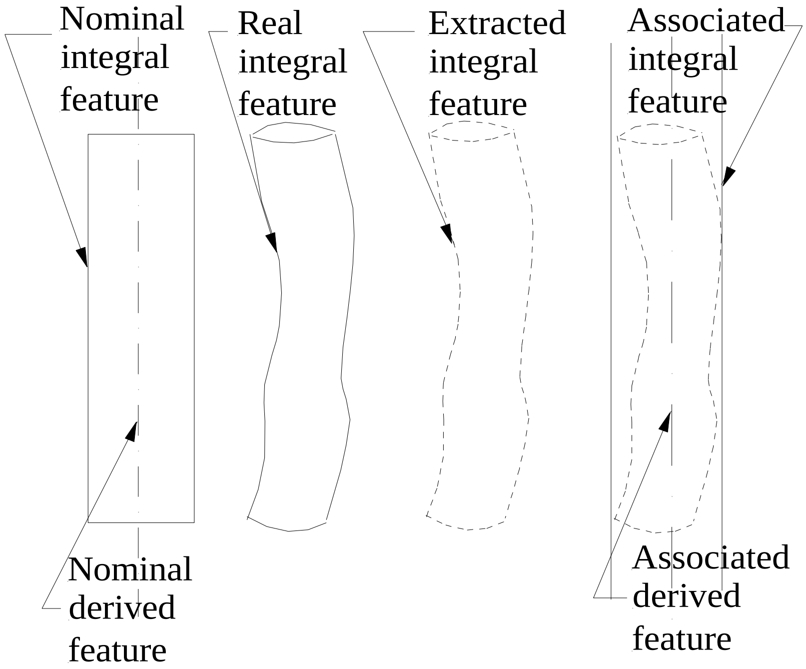

Figure 2. Results of various feature operations. This example is for a cylindrical feature.

But does this *principle of duality* violate the time-honored *principle of verification independence*, that is, the designer specifies only what is required of a part and not how to check it? To answer this question we need to look at the specification operator in some detail. Partition, collection and construction operations are not controversial. They are clearly needed in the specification operator. That leaves extraction, filtration and association for further scrutiny.

Association is a geometrical fitting operation. It can be defined mathematically as a constrained optimization problem. We need it, and this a crucial argument, to define datums and position tolerances. Datum specification implies a substitution of ideal geometrical elements in place of non-ideal features. Position tolerance, in particular RFS (Regardless of Feature Size) position tolerance, specification defines allowable variations in the relative position of axis, center, or median plane of a feature. This implies a fitting of an ideal surface to a non-ideal surface feature even at the gedanken experiment stage.

Having established the need for an association operation in a specification operator we then observe that we will also need extraction and filtration operations to prepare the input for the optimization algorithms. One may argue that all these three operations can be dispensed with if a physical operation is substituted - for example, a surface plate to establish a planar datum - in the verification operator in the place of a “datum” operation in the specification operator. A flaw in this argument is that it makes the physical apparatus as the primary definition of a verification process whereas ISO/TC 213 strives to give primacy to mathematical definitions. As a fundamental rule ISO/TC 213 has decided to base all its definitions on mathematics - as opposed to definitions by examples - so that product functions can be simulated using physical and mathematical models.

It therefore seems possible to observe the principle of duality without compromising the principle of verification independence. Note that we allow the verification operator to be implemented in multiple ways - for example, a datum by a fitting algorithm or by a surface plate - and these are distinguished, as we will see in the next section, by the amount of uncertainty. In fact, the guiding philosophy of ISO/TC 213 is to standardize only the specification operator. The verification operator will implement the standardized feature operations in the specification operator with careful accounting of the amount of uncertainty in each step of the implementation.

4. A GENERALIZED UNCERTAINTY PRINCIPLE

The notion of uncertainty is by now well entrenched in metrology. It is based on a basic principle in metrology that all measurements have inherent uncertainty and therefore this uncertainty should be quantified and reported along with the result of any measurement. As ISO/TC 213 looked at the integrated picture of specification and verification it realized that the notion of uncertainty should be generalized beyond that of just measurement.

In successful product development processes one starts with customer requirements and breaks this down to product functional specifications and then to detailed design specifications. Broadly speaking the function of a product is dependent on its geometry, material properties and operating conditions. The supplier of the product may not have much control over its operating conditions but he does have control over its geometry and material properties. The scope of ISO/TC 213 is restricted to geometry. It is charged by ISO with developing a language for detailed specification of product geometry and methods for verifying whether manufactured workpieces meet these specifications. Therefore a major, though not all, responsibility for satisfying the intended function of the product rests with the geometric specification language and verification methodology standardized by ISO/TC 213.

When one looks at the integrated picture the natural question to ask is whether the finished workpieces when assembled will perform the intended function. Here ISO/TC 213 postulates a generalized uncertainty principle: there will always be some uncertainty as to whether the finished product will perform the intended function. This uncertainty has several components. At the geometric level the uncertainty has been divided into (1) correlation uncertainty (2) specification uncertainty and (3) measurement uncertainty [ISO17450-2]. Before we proceed further it should be pointed out that these terms and concepts are still evolving and are subject to modification and refinement as the work of ISO/TC 213 progresses. Never the less, some basic ideas have emerged as front runners.

4.1. Correlation Uncertainty

Correlation uncertainty arises from the fact that the intended functionality and the controlled geometric characteristics may not be perfectly correlated. A good designer tries to achieve a very high level of correlation but it may never reach 100%. There are several reasons for this. First, the chemical and physical phenomena governing a product's functionality may be quite complex and may only be partially understood. Second, mathematical modeling of the understood phenomena and solutions to resulting mathematical equations may be approximate. Third, all these may be confounded by interactions of geometry with material properties and operating conditions.

Thus far we have spoken only about correlation. But to control function we implicitly assume *causality*, a condition stronger than correlation. Although we speak of correlating a product's functionality to its geometry, we intend to control the function through geometry (and, by other standards, material properties and operating conditions). Function is deemed to be the effect - geometry, material properties and operating conditions are the causes. Engineers rely upon considerable prior knowledge - whether tacit or explicit - and some controlled experiments to establish causality. Statistically speaking all these are wrought with some uncertainties, however small they may be.

4.2. Specification Uncertainty

Specification uncertainty results from incorrect or incomplete application of geometric specifications. A diligent designer can reduce this uncertainty to an insignificant amount. This assumes that the GPS language defined by ISO/TC 213 is complete and correct. This assumption can be called into question. Our standards development process is in a continuous improvement mode and we may never claim perfection in these standards. Some allowance has to be made for this type of uncertainty as well.

4.3. Measurement Uncertainty

Measurement uncertainty [GUM, 1995] is the best known of the three types of uncertainties mentioned earlier. It is a statistical parameter associated with the result of a measurement and it characterizes the dispersion of the values that could be attributed to what is being measured. This parameter may be, for example, a standard deviation (or a given multiple thereof) or the half-width of an interval having a stated level of confidence. It has several components, too numerous to discuss here.

In a verification process the measurement uncertainty may be further compounded by poor or intentionally different interpretation of the specifications. Because of this, ISO/TC 213 has proposed a further classification of measurement uncertainty into method uncertainty and implementation uncertainty. Method uncertainty arises from the difference between the actual application of the specification operator and its mapping into a verification operator. Implementation uncertainty arises from physical deviations in applying a verification operator.

4.4. Relative Importance of Uncertainties

What is the benefit of the generalized uncertainty principle? We argue that for optimal allocation of resources in an engineering enterprise one should take an integrated view of various processes employed and should ascertain their relative importance from the overall business perspective. This is enabled in part by applying the generalized uncertainty principle. The overall uncertainty can be broken down into its component factors and their relative magnitudes can be compared. For example, if we know that correlation uncertainty is the dominant uncertainty affecting a product's quality then more resources should be applied to correct this as opposed to buying more precise coordinate measuring machines.

Before leaving this section, let's make a few general observations. Uncertainty may be viewed as an annoyance but it is a reality we have to live with. The vision of ISO/TC 213 is to turn this unpleasant fact into an economic tool. It believes that by openly acknowledging the prevalence of uncertainty better decisions can be made in allocating resources in an engineering enterprise.

5. SUMMARY AND CONCLUDING REMARKS

This paper described recent efforts of ISO/TC 213 in integrating product functionality, its geometric specification and verification. Starting with a definition of tolerancing semantics as a gedanken experiment, a tentative link between a theoretical inspection procedure and an actual inspection procedure was established. This link was strengthened by postulating a duality principle; it provided a one-to-one mapping between operations in a specification operator and a verification operator. It was then asserted that only the operations in the specification operator need to be standardized; the verification operator would then merely implement their dual operations in the specification operator - albeit with some inevitable uncertainty. This then led to a postulation of a generalized uncertainty principle that connected product functionality with its geometric specification and verification. It was a natural consequence of taking an integrated view of functionality, specification and verification.

It should be emphasized that we have just begun the task of integrating product functionality with its geometric specification and verification. As ISO/TC 213's vision statement reproduced at the end of the paper indicates, it is a challenge that would take considerable effort. Researchers in computer-aided tolerancing have several important roles to play in this effort.

First, they can strengthen the link between tolerancing and metrology. Geometric sampling, fitting and filtering, which form the bulk of computational metrology, have become even more important now and they are a source of several interesting problems.

Second, a language is beginning to emerge to convey the concept of generalized uncertainty. This opens up a wide area for research. Correlation uncertainty, in particular, is an unchartered territory. Standards don't tell us how to find this. They merely provide a language to describe it. This should be an area for some intense research.

Finally, pervasive use of uncertainty in geometric specification and verification will necessitate consistent use of statistics all through specification, production and verification, and in relating back to functionality. It is indeed a most welcome step [Srinivasan, 1999a].

6. ACKNOWLEDGMENT AND A DISCLAIMER

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Next generation of the Geometrical Product Specifications (GPS) language

The vision for an improved engineering tool

This integrated GPS system for specification and verification of workpiece geometry is an improved engineering tool for product development and manufacturing. This GPS system is necessary, as companies are rapidly moving ahead with new technologies, new manufacturing processes, new materials and visionary products in an environment of international outsourcing.

Objective

The objective of the improved GPS system is to provide tools for the economic management of variability in products and processes. This will be achived by the use of a more precise method of expressing workpiece functional requirements, complete and well defined specifications, and integrated verification approaches. This improved GPS system will clarify the current practices and be harmonized with the work of other relevant Technical Committees (TC) of the International Organization for Standardization (ISO). This harmonization will, for example, enable better integration with 3D CAD/CAM/CAQ-systems.

The improved GPS system will be based on the experience from the use of current practices and traditions. The legal and technical contents of existing drawings will be left intact, realizing that there is a vast domain of existing specifications, which cannot be changed without the explicit or implicit consent of those responsible.

Proper implementation of the improved GPS system will *reduce costs* by avoiding the manufacture of inadequate workpieces due to incompletely defined specifications.

Controlling function

The intended function of a product can be ensured by controlling the geometry and material properties of the workpiece(s) making up the product. GPS is the language for controlling geometry only and its evolution will be based on computable mathematics and correct, consistent logic using a generic set of rules, that can be applied to all types of specifications.

The challenge for the future is to enrich the GPS language to allow expression of requirements relating to a wide range of workpiece functions.

Proper implementation of the improved GPS system is a prerequisite for the continuous improvement of *product quality* and *time to market*.

Uncertainty - An economical tool

The improved GPS system will use “uncertainty” as the “currency” for quantifying:

a) how well the specification expresses the functional requirements;
b) what ambiguities exists in the specification itself;
c) the uncertainty of measurement.

Proper implementation of the improved GPS system will enable *optimum economical allocation* of resources amongst specification, manufacturing and verification.

Simplification

The improved GPS language will be richer, more precise and, therefore, more verbose. However, in most cases, the complexity of drawing indications will not increase due to the consistency of the logic and the “default” concept.

There will be a global default for each type of GPS specification, which is based on simplicity and minimization of total cost. In addition, there will be a number of shorthand indications covering commonly occurring workpiece functions, e.g. fits.

Proper implementation of the improved GPS system within a company is important for *surviving in global competition*.

International standardization

This effort is being spearheaded by ISO/TC 213 *“Dimensional and geometrical product specifications and verification”*.

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