The Language of Tolerances†

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Abstract
Dimensional tolerancing is a language used to communicate product quality specifications. Effective communication using this language relies on there being a common, shared meaning for tolerances. By this measure, the language of tolerances defined in modern standards does not support good communication. Some reasons for this are: the evolution of technology; the lack of research on tolerances prior to the last two decades; and a greater need for rigorous product specifications in a computer environment. I discuss the weaknesses of the language of tolerances and suggest a three-part program of research and standards development to improve it.

1. INTRODUCTION

This paper is concerned with geometric variability in manufacturing. Designers have always had to deal with the sad fact that parts cannot be made perfectly; or that, if they could, they would not remain perfect for long during use. So defining the ideal part is only half of a designer's job. The designer must also work out how different an acceptable part can be from the ideal. A part can vary from the ideal in many ways: in its shape, its material strength, surface finish, electrical properties—a virtually unlimited list [1]. Of these, I will be discussing the ways in which variability of shape is handled in manufacturing. I will discuss some of the weakness of the language of tolerances and what we might do to make the language more effective.

Over the last century or so, the practice of engineering design has evolved from a variant of aesthetic design into a disciplined, formal method of communication [2]. Today, designers use a highly structured language of engineering drawings to communicate design intent. Various dialects of this language have been defined in national and international standards [3,4]. To date, the language of tolerances has been primarily a graphical symbology; tolerance requirements are expressed as symbols arranged in particular ways on blueprints.

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There continues to be considerable energy invested in developing better drawing conventions. Recently there has also been great effort to develop formal computer languages for communicating designs [5]. The first U.S. national standard for digital communication of technical product data was the Initial Graphics Exchange Specification (IGES),[1] developed in 1981 and now in its fifth version [6]. It provided a standardized means of exchanging drawing information between computer-aided design systems. A new standard for product data exchange is being developed by the Technical Committee on Industrial Automation of the International Organization for Standardization (ISO). This new standard, called the Standard for the Exchange of Product Model Data, or STEP [7], goes far beyond defining a computer representation of blueprints. It is a new language for product specification, as different from drawings as Chinese is different from English.

I have chosen the metaphor of language for more than its evocative power. I would like to analyze the current standards in language-theoretic terms. Language theory tells us that any language has (at least) three constituents: the vocabulary, the grammar, and the semantics. The vocabulary is the set of basic terms or elements of the language. The grammar defines the rules for composition—how the vocabulary terms can be assembled into larger constructs (e.g., sentences). The semantics defines the rules for understanding the meaning of sentences. Applying these definitions to drawings and to STEP, the following comparison can be made:

	Drawings	**STEP**
Vocabulary	Drawing symbols; call-outs; lines; arrows; and text	Type definitions; entity/relationship models; entity values
Grammar	Drawing conventions as defined in standards such as USA/ANSI Y14.5	The computer language EXPRESS and the mapping to physical file format
Semantics	As defined by illustrations; as explained in various standards; as interpreted by people in the manufacturing enterprise	As defined by the language semantics of EXPRESS; as explained in STEP documents; as interpreted by application software

We will soon have in our standards two fundamentally different languages for specifying tolerances: a language based on drawings (here I include IGES) and a language based on computer models of products. This situation can and will create great confusion unless

[1]Throughout this paper, I will use as examples, U.S. or ISO standards, being most familiar with them. Standards in other countries similar to IGES are SET (AFNOR Z68-300) in France and VDFS (DIN 66 301) in Germany.

the two languages share common semantics [8]. It is imperative that tolerances specified in drawings have the same meaning as tolerances specified in computer data structures.

In the next section, I will discuss how semantics can be developed for drawing tolerances. This material is based on work in the United States on developing standard mathematics for tolerances. I will also discuss several weaknesses of current tolerance semantics. In the third section, I will propose how the research and standards communities might cooperate to address these weaknesses.

2. WHY IMPROVE THE LANGUAGE OF TOLERANCES?

The meaning of a tolerance lies in how it is interpreted. Generally, standards provide explanations of how this should be done for specific tolerance call-outs. By the norms of formal language theory, these descriptions are somewhat casual. The explanations were written to convey the intent of the standards developers, and they strike a balance between the need to be precise and the need to be comprehensible to the average user of the standard.

Increasingly, tolerance information is directly used in computer systems. Computer applications that use tolerance information include computer-aided design, assembly simulation, generative process planning, and coordinate measuring machine inspection. Software writers are faced with the problem of converting the informal definition of tolerances found in standards into computer codes that carry out very specific actions, with no allowance possible for case-by-case interpretation. The result is that tolerances are interpreted in inconsistent ways by different application systems. This can have serious repercussions, as evidenced by a 1988 advisory published by the U.S. Department of Defense on discrepancies between the requirements of tolerances and the results of coordinate measuring machine software [9].

While better education can address some of the problems of inconsistent tolerance interpretations, there also are serious technical difficulties in precisely defining the meaning of tolerances. At a 1988 workshop sponsored by the U.S. National Science Foundation [10], the most frequently mentioned need was to provide a sound theoretical basis for mechanical tolerances. As demand increases for tighter tolerances on manufactured goods, the economic impact of misunderstood or misapplied tolerances becomes ever greater [11]. The development of a sound theoretical foundation for tolerances is not only an intellectually demanding challenge. It is rapidly becoming an economic necessity.

2.1. Existing Tolerance Theories

Most theories of tolerance semantics are based on providing a mathematical or logical formulation of tolerance specifications. (For a survey of tolerance theories, see Juster [12] or Feng and Hopp [13].) For instance, a flatness tolerance applied to a nominally planar feature specifies that the actual feature must lie within some pair of parallel planes separated by the tolerance value. The differences between many of the theories have to do with the rules by which bounding geometries (such as the parallel planes) are derived from nominal geometries and tolerance call-outs. Early theories were based on concepts of varying parameters of the nominal geometry: for instance, a position tolerance allowed a variation in the location of the axis of a hole. Researchers found that such theories did not allow consistent geometries or topologies to be maintained. Other researchers struggled to find consistent theories that did not rely on a plethora of special cases. Unfortunately, these theories, of which that of Requicha [14] is perhaps the most widely cited example, did not produce interpretations that corresponded to practical applications of tolerances [15]. A recent proposal by Jayaraman and Srinivasan [16,17] to address this issue is to base tolerance semantics on the notion of *virtual boundaries*. A virtual boundary is a surface that, in essence, corresponds to the worst-case mating part in an assembly. It is very similar to the concept of *virtual condition* found in tolerancing standards. In their approach, Jayaraman and Srinivasan develop methods based on virtual boundaries that closely match practical uses of tolerances and that do not require special, case-by-case rules for interpretation of call-outs.

Virtual boundaries appear to hold much promise as a basis for formalizing the semantics of our current tolerancing standards. Work under way in the United States to develop a standard tolerance semantics is based, in part, on virtual boundary concepts. However, much is left to be done. The standards development work has made clear that despite considerable advances in tolerance theory, there remain significant gaps in our ability to formalize the language of tolerances in a way that matches engineering common sense.

One can identify at least two approaches to developing a theory of tolerances. The first is to treat a tolerance as a constraint on the surface of the part. Under this approach, one may sensibly ask whether a part conforms to a tolerance. The second approach is to associate a measurable quantity—a deviation from ideal—with a tolerance. Under this second approach, one may sensibly deal with the actual value of deviation—actual out-of-flatness, actual position deviation, etc. These two meanings are not of necessity equivalent. We might define conformance and actual value in ways such that both definitions are reasonable, but comparing the actual value to the tolerance does not produce the same decision as the definition of conformance. We have no tolerance theory that provides consistent definitions for both views of product tolerances.

In the remainder of this section, I will discuss two kinds of weaknesses of our current language of tolerances. The weaknesses are at both the semantic level (what the tolerances mean) and at the level of vocabulary and grammar (what can be represented). I first consider some of the semantic weaknesses.

2.2. Tolerance Semantics

Tolerances grew out of the concepts of geometry. For instance, we freely discuss tolerances on the size and position of features. But what is meant by the size of a manufactured hole, which is not cylindrical? Where does the hole end and the surfaces of the adjacent features start? How do we assign a coordinate system to the part in order to verify a position tolerance for the hole? These questions, some of which have been noted before [12,18], are at the heart of the major weaknesses of modern tolerance semantics. I will consider examples of challenges in three areas: boundary, size, and datum reference.

Boundary

The notion of boundary seems fairly simple. If I say that a table top must be parallel to the floor within some tolerance, then I expect the table top to lie within a pair of planes, separated by the tolerance and parallel to the plane of the floor. When we try to formalize this, however, we immediately run into the problem of defining the table top. All tolerance theories, being geometric in nature, require that we abstract the table top as a set of points in space. So the question becomes, what are all the points on the part feature called "table top"? Put another way, what separates the top of the table from the sides, and what is meant by a point on the top? Neither question has been answered adequately by existing theories.

The question of identifying features has been studied in terms of models of ideal parts [19]. There has been little attention given to identifying the extent of features on physical parts. The problem can be seen in Figure 1. There is no clear demarcation of the top of the table from the side. How much of the rounded corner should be allocated to the side

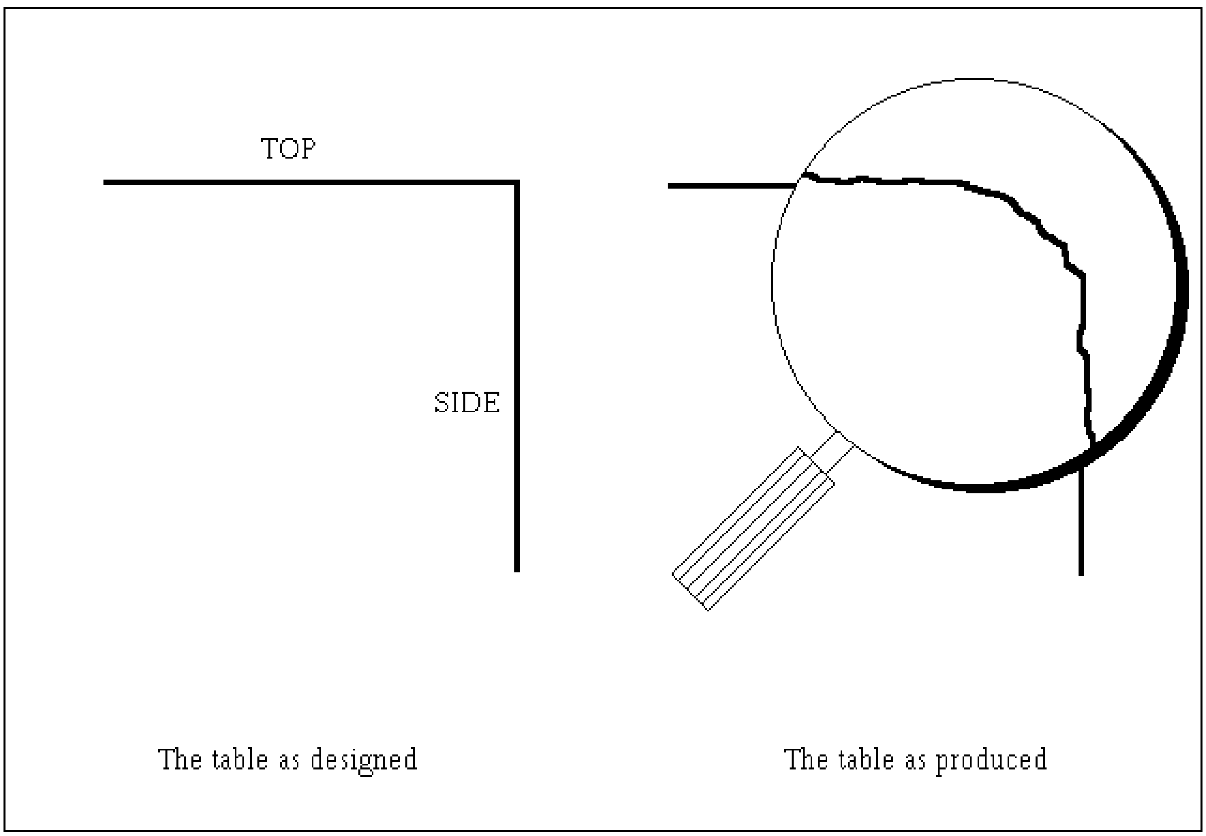

Figure 1 Ideal geometry versus physical feature

and how much to the top? For that matter, should the entire surface of the part be allocated to features controlled by tolerances, or might there be an area of the edge exempt from both the top and side tolerance controls? If the latter, what controls the transition area? One proposal is to claim that a part conforms to its tolerances if there exists some partition of the surface into features such that each feature conforms to its controlling tolerances [20]. This proposal fails to provide a definition for the actual feature: it only resolves the issue of conformance for a part in its entirety. It may be that any definition of actual value of, say, flatness of the top and side of the table illustrated in Figure 1, must rely on information external to the part definition.

A second issue of boundary is to define the surface of the part. Clearly we do not mean a surface in the mathematical sense: at sufficiently small scale, there is no surface, but only subatomic particles thinly spread out in a void. In the physical sense, a definition of the surface must involve some kind of smoothing. The difficulty is in providing enough smoothing to provide a basis for defining geometric constraints and actual values, while not smoothing over surface characteristics that we may want to control.

Some guidance to this issue can be found in existing standards. The U.S. standard on surface texture [21] uses a spatial filter that, in principle, is applied before assessing the part. A low-pass filter is used for shape variation, while various band-pass filters are used for roughness, surface texture, and waviness. Each filter has a specific response curve as a function of the scale of the variation. A similar approach is found in the U.S. standard on roundness [22]. This standard recommends that a roundness specification include an instrument frequency response characteristic and a sensor tip radius—values which control the filtering of the surface.

We do not understand how surface smoothing operations interact with other tolerance semantics. In some cases the issue of smoothing is extremely important. For instance, the heat shield tiles on the NASA space shuttle are composed of a porous, glass foam. The tiles must fit together with no gaps that would allow hot gasses to penetrate to the shuttle skin. The form tolerances for the tiles are tighter than the surface roughness requirements. The tolerances are specified by including a specified measurement procedure for verification. In this case, the semantics of the tolerance is defined as the result of a particular inspection process. Such "process semantics" allow designs to push the limits of manufacturing technology. At the same time, tying a design to a specific manufacturing method can make it harder to introduce better manufacturing tools in the future.

Size

Size is an attribute of certain types of geometry. These include cylinders, spheres, and parallel, opposed planes. Cones and non-opposed parallel planes do *not* have a size. For a physical part, the concept of size, like the concept of feature boundary, is surprisingly complex. The current U.S. standard on dimensioning and tolerancing defines the actual size of a feature as, simply, the measured size. Unfortunately, there is no standard definition of the measured size of a feature. What is worse, the essence of a measurement is comparing a physical phenomenon to a reference. If we are going to insist on using size as an attribute of actual features, we need a theoretical definition of actual size to use as the reference model. It is useless to define the reference in terms of the measurement.

Consider the pin shown in Figure 2. It has two sizes, a diameter and a length, each with a tolerance. What are the semantics of the diameter size specification? In the United States, where the envelope principle applies, the size specification also limits form deviation. The effect of this is that the physical pin must fit entirely within a cylinder that is of diameter 25.1 mm and at least as long as the pin. But what of the ISO interpretation, and what of the lower limit of size? The standards state that the part must be

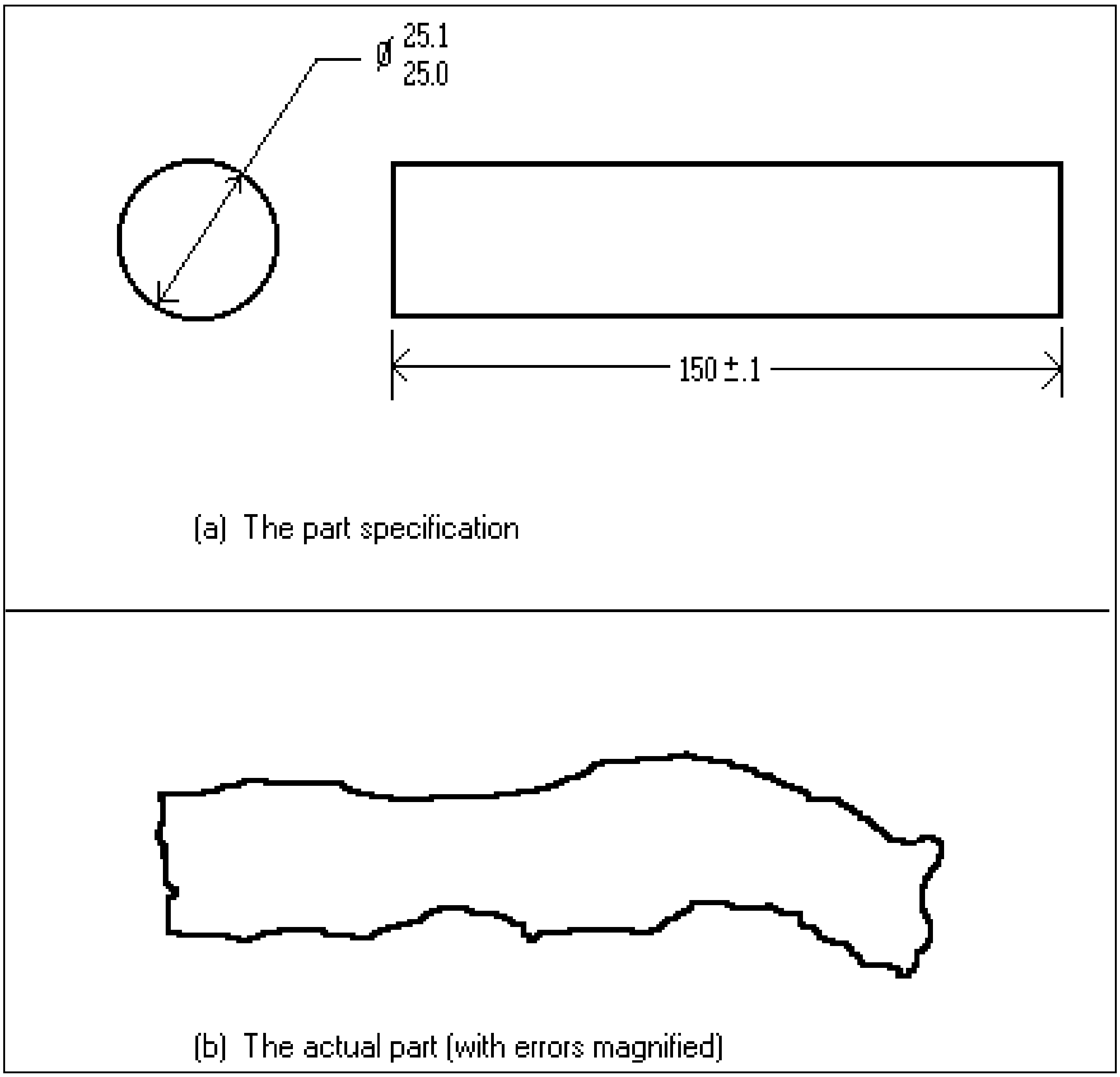

Figure 2 Typical part with sizes

within the limits of size measured at each cross section. There is no guidance as to how the cross sections should be oriented on the actual part (that has no clear axis), or how size is measured at a cross section. We would like answers that generalize from the pin of Figure 2 to all applications of size.

Practical measurement procedures might be used as a guide, but there are significant differences between measurement practice with different instruments. Another approach might be to look at the design objectives represented by each size limit. The upper (maximum material) limit of size is usually intended to control fit and interference. The lower limit is often used to maintain material for strength. Of course, other objectives may apply. There is no way of knowing what was intended by examining the call-out alone.

Datum Reference

Datum referencing[2] is a means of assigning a coordinate system to a physical part. Semantic rules of datum referencing define how to associate datums—ideal geometric elements such as points, lines, and planes—to physical surfaces. Tolerances that require coordinate systems (position, orientation, profile, runout, etc.) are interpreted in coordinate systems established by datum references. The challenge of this scheme is in establishing the rules for assigning datums to datum features. The major difficulty in establishing sensible rules is in defining when a datum feature wobbles or rocks. There are two difficulties, one a question of principle and one a technical problem [23].

The question of principle is illustrated in Figure 3, which shows three variations of quality of a primary datum feature (the base of the part). If the feature is manufactured as shown in the top sketch, with only a small chamfer at each edge, most people would agree that the part does not wobble on the datum. As the surface form degrades, however, a definite wobble eventually appears, as shown in the bottom sketch. There is a transition state, shown in the middle sketch, which is highly ambiguous. There are absolutely no guidelines—in standards, the technical literature, or common engineering practice—for resolving this ambiguity.

Putting aside the question of what wobble is, we are still faced with the technical problem of developing a mathematical definition of "all rocked positions" that allows only those datums that make engineering sense. In other words, suppose we were agreed on when the progression illustrated in Figure 3 changed from a stable to a rocking datum. How would we describe this in a general way, that would apply when the actual datum feature was domed, when it was shaped like the top of a bread loaf, when it was concave, etc. All formulations proposed to date, when tested against a large number of problems, have either excluded datum assignments that one would want to use in practical applications or

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[2]In the "standards English" of tolerancing standards, a *datum feature* is a physical part surface and a *datum* (plural: *datums*) is a geometric element assigned to a datum feature.

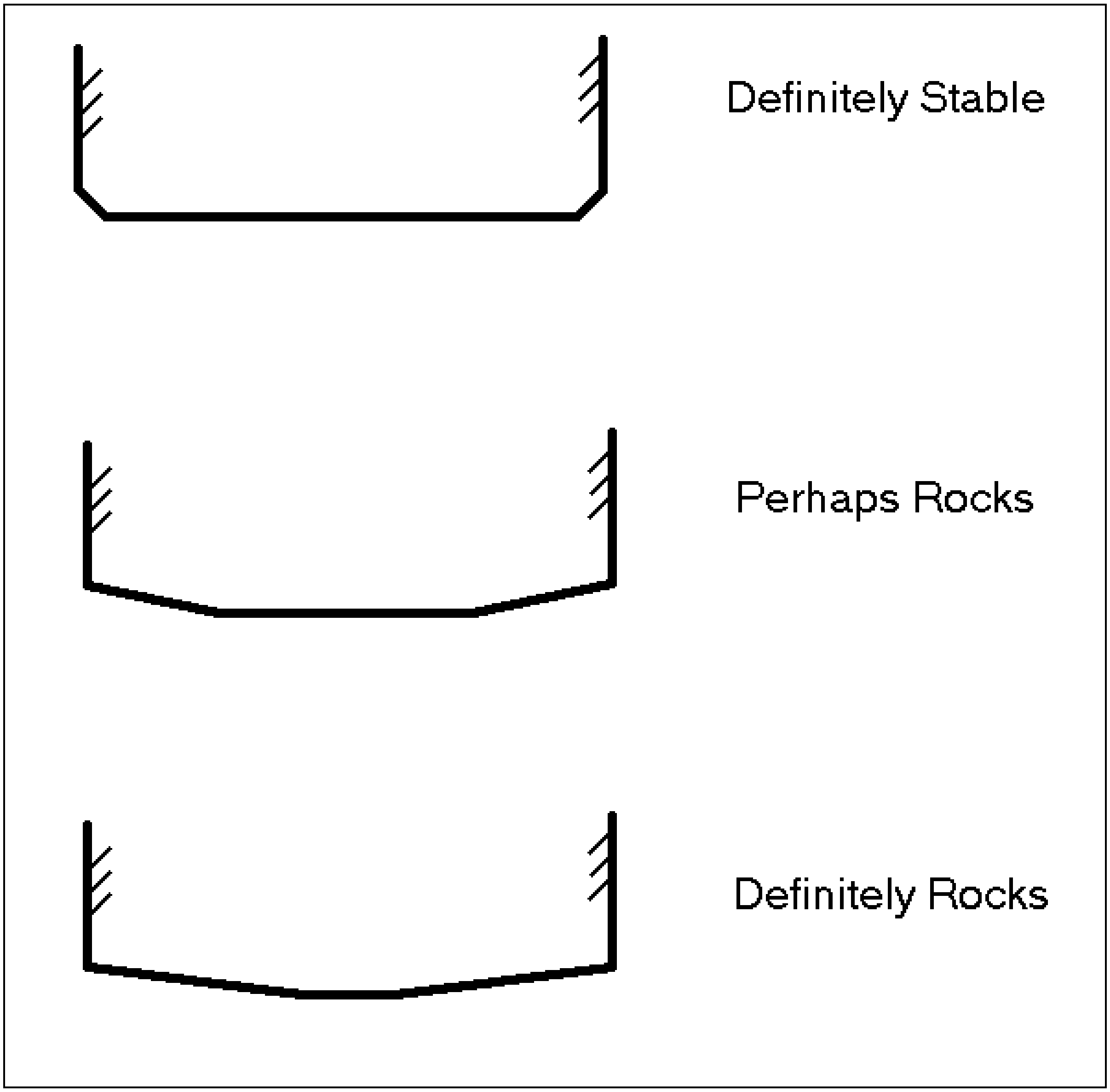

Figure 3 The difficulty of defining a rocking datum

have allowed datum assignments that are patently nonsensical.

I believe that the question of when a datum rocks is inherently unanswerable. (We will never reach consensus on just when the transition occurs in Figure 3.) We should concentrate on developing a technical definition of limits of rock that resolves the problems known for the existing proposals. The technical definition of rocked positions will then provide a *de facto* definition of when a datum rocks.

2.3. The Vocabulary of Tolerances

The previous section focused on weaknesses in the semantics of our tolerancing language, that is, the challenges facing us in defining what tolerances mean when they appear on a drawing. There are, however, also weaknesses in the vocabulary and grammar of tolerances—what kind of tolerancing information can be placed on the drawing in the first place. The main difficulty is that while our tolerancing language captures the results of the design process—the end decisions—designers often need to communicate something about how those decisions were reached. We will consider three examples of this.

Statistical Tolerancing

Suppose I want to build a wall 10 m high out of blocks each 10 cm thick. If the tolerance for the height of the wall is 1 cm, then each block must be manufactured with a size tolerance of 0.1 mm for thickness. This is an example of worst-case tolerancing, a common practice in industry. If I were to relax my requirement for full interchangeability of blocks—that is, if I allow myself to pick and choose blocks from a large selection—then I can relax the tolerance requirement for each block. In fact, I may never have to swap blocks, because variations in block thickness are usually going to average out, not accumulate in a worst-case way. The amount by which I can relax the tolerance on each block depends on what risk I am willing to accept for having to try different block combinations during assembly and what I expect by way of distribution of block thicknesses. This technique of using statistical analysis instead of worst-case analysis is called statistical tolerancing. It is gaining in popularity as designers recognize the savings in manufacturing cost that it provides.

There is a difficulty, however. Use of statistical tolerancing requires the designer to use information about the capability of the manufacturing process—the expected distribution of shape variation. Unfortunately, there is no formal way for the designer to record, as part of the tolerance, the process capability information that makes the tolerance a faithful representation of design intent. Leaving out this information can have as much impact as not placing tolerances on the drawing in the first place [24]. A typical problem occurs when a manufacturing process is improved, such as occurs when a new machine tool is installed or better process control techniques are introduced. The process distributions used for setting tolerances are no longer valid and parts no longer assemble as expected. The problem becomes acute when processes for one component are improved without a corresponding change in the processes used for mating parts.

One suggestion being considered by the standards community is to provide a notation whereby the designer can document the assumed process characteristics on the drawing. While this would help communication, it has the danger of *requiring* certain process variability. Manufacturing would not be able to use a better (or worse) process than what was assumed by the designer. A more difficult approach, but one with perhaps fewer economic side effects, is to develop new tolerance notation for describing assembly tolerances. This would generalize the work on standard notation for limits and fits [25]. Either approach will require expanding the vocabulary of tolerances.

Tolerance Analysis

Tolerance analysis is the process of studying how the shape variations allowed by the part tolerances affect part function. Tolerance analysis distinguishes between the *design function* of a product and its *model variables* [26,27]. The design function is the property of the product that the designer wishes to study. The model variables are the parameters of the product design that define its shape. Shape tolerances are a way, albeit indirect, for the designer to control the design function. Tolerance analysis involves simulating changes to the shape of the part, as allowed by the tolerances, and studying the effect of those changes on the design function.

Tolerance analysis is used by product designers to develop part designs: to allocate tolerances, to develop more robust shapes, and in general help to optimize the design. Tolerance analysis is also used by production engineers to help define the manufacturing process—to allocate a tolerance budget to each process, to study the effects of process variability on production yield, and to minimize manufacturing costs.

The language of tolerances is incomplete because it does not give designers a way of communicating the relationship between tolerances and the design function. That relationship must be communicated by some means other than the formal product specification. The alternative is having to infer the design function on the basis of design data and "common sense" about what the designer meant. We will need to find a better way of communicating tolerance analysis information as tolerance analysis tools become more widely accepted and used in the production life cycle.

Economic Models

The previous two examples, process characteristics for statistical tolerancing and design function for tolerance analysis, can be seen as special cases of a more general shortcoming of the language of tolerances. The design process can be viewed as an effort to maximize (or at least to achieve a threshold for) the value of a product while satisfying a number of constraints—functional requirements, limitations of material properties, manufacturing capability, etc. Many factors considered during the development of a design are of value to later processes. Similarly, much of the information used by the designer is culled from processes occurring later in the life cycle. Much of the interest in concurrent engineering, product data sharing, and enterprise integration is based on the recognition that design decision data must be shared throughout a manufacturing enterprise.

Many design decisions are based on economic factors. For instance, Taguchi frames the entire task of product and process design as an economic problem of minimizing the loss to society due to purchase and use of the product [28,29]. Tolerance design is one of three key components of Taguchi's method, the others being experimental design and parameter design. Tolerance design influences the loss to society due to the combined effects of manufacturing costs and deviations by the product from ideal performance. As with statistical tolerancing and tolerance analysis, tolerance design relies on information—

in this case, models of process distributions and loss functions—that should be communicated between design and other life cycle functions.

The Taguchi method (also called off-line quality control) is only one technique of tolerance design. Another aspect of tolerance design is the intent of the designer in specifying a particular tolerance value. For instance, a tolerance may represent a functional limit, or it may include the anticipated effects of measurement uncertainty in product acceptance [30].

Any systematic tolerance design practice, however, relies on information that must be part of the design data for effective communication of product definition. The language of tolerances must be expanded if we are to communicate economic models, tolerance goals, and other design decision data effectively.

3. IMPROVING THE LANGUAGE OF TOLERANCES

I have discussed several weaknesses of our language of tolerances. This is far from a complete list. There are many other areas of active research related to tolerances. Ongoing research has led to many advances in tolerance theory and in the practical application of tolerances. I believe that much more progress can be made, much more effectively, if we develop better mechanisms for relating progress in one area to problems in another.

We can step back from the issues involving one or another standard and think of ourselves producing a single product—a language of tolerances. The language has many components: tolerance-related standards, technology, and practice. These components have traditionally evolved in a serial manner. We identify a needed change in standard tolerancing practice and write the change into the tolerancing standard. This change impacts other areas: metrology standards, computer software, training, etc. Eventually, after several years, the new practice permeates our entire system and the cycle repeats.

The practice of concurrent engineering is a method, within a manufacturing setting, of greatly shortening the cycle time of product development [31]. I believe we should apply concurrent engineering concepts to the development of a better tolerancing language. Concurrent engineering is primarily a management approach. It involves identifying the work needed to develop a product, who will do the work, and how the workers can be brought together to work as a team throughout the entire product life cycle. In this section I will discuss how these concepts might apply to the development of an improved tolerancing language. I will discuss a program of work to improve the language and then discuss the roles of various players in this program.

3.1. A Program for Improving Tolerances

In this section, I describe a three-part program: develop a framework for the use of tolerances; develop formal semantics for each use; and develop a coordinated set of standards that incorporate the formal semantics. Taken together, these efforts will be an effective way to improve our tolerancing language.

Develop a Framework for Tolerances in Manufacturing

The first area of work is to develop an overall framework for the application of tolerances in manufacturing. This framework should identify the manufacturing life cycle functions, the role of tolerances in each function, and the standards that codify the language of tolerances as used in each application area.

One can identify four broad areas of manufacturing in which tolerances are used: design, manufacturing, inspection, and product data sharing. In design, tolerances are used to study and specify the range of parts that will satisfy design objectives. Typical tolerance data include limits and fit, dimensions and tolerances, and process capacity models. In manufacturing, tolerances are used to develop error budgets for processes, characterize and measure process capacities, and control quality. Typical tolerance data include machine tool performance measures, manufacturing tolerances for individual parts, and process control limits. In inspection, tolerances are used to select inspection equipment, develop inspection programs, and assure product quality. Typical tolerance data include product tolerances, measurement uncertainties, and product acceptance limits. Shared product representations are used throughout the manufacturing enterprise to communicate product definitions and to correlate manufacturing data with product data. Tolerances are used for cost estimation, design retrieval, variant process planning, and group technology. Tolerances are typically expressed either in graphical form on drawings or electronically in product data bases.

Developing a framework for tolerance use in manufacturing will contribute to efforts to develop standard frameworks for the integration of manufacturing enterprises. Such efforts are underway in a number of countries, as well as within the international standards community [32-34].

Develop Formal Semantics

The second effort is to develop formal semantics for tolerances in each life cycle function. While tolerance semantics may differ among applications, the meanings should be compatible across the manufacturing enterprise. The tolerance framework will provide a blueprint for achieving this harmonization.

I have already discussed some of the issues in defining tolerance semantics. I have focused on semantics related to design. Tolerances may have quite different semantics for other applications. Consider, for instance, the selection of data analysis algorithms for coordinate measurement systems. One goal is to select an algorithm that minimizes uncertainty of the reported measurement results. This involves studying the relationship between the design semantics of the tolerances, the uncertainty of coordinate values acquired by the sensor, and the sensitivity of the data analysis algorithm to such errors. The semantics for actual value of tolerances for coordinate measurement may, when formally defined, be significantly different from actual value when measurement uncertainty is not an issue. Nevertheless, there should be a well-defined relationship between the two semantics.

Develop Coordinated Standards

The end goal of the program I am suggesting is the development of a coordinated set of standards that codify the tolerance languages used at each stage of the manufacturing life cycle. This will place the language of tolerances in a form in which it can be transferred to commercial manufacturing applications.

Many tolerance-related standards are already in use and others are under development. In design, standards exist for limits and fits and for dimensioning and tolerancing. In manufacturing, languages for numerical control, such as APT [35], define specialized representations for tolerances. Machine tool performance standards define tolerance capabilities of manufacturing equipment [36]. Similar roles are held in inspection applications, with inspection languages such as DMIS [37] and performance standards for coordinate measurement systems [38]. Shared product representation standards include drawing standards, IGES, and STEP.

3.2. Roles for Implementing the Program

The program I suggest involves increased interaction between four communities: manufacturers, standards developers, researchers, and technology vendors. Each sector has a role to play.

Manufacturers are the end users of standards and supporting technology. Standards are developed in response to perceived needs or opportunities in manufacturing. Standards are developed either by or with strong participation from industry. The role of manufacturing is to recognize and act on the need for an improved language of tolerances, to support standards efforts and to demand improved technology from vendors.

Standards development is sometimes pulled along by changing technology and it sometimes pushes new uses of technology. In the case of tolerances, we have both situations. Drawing standards are fairly mature and change only slowly, in response to introduction of new manufacturing technology (e.g., CAD/CAM) or new business practices (e.g., international trade). STEP, on the other hand, presages the introduction of new technology and is, in fact, viewed as a new technology itself that will enable new engineering practices [31,39]. It is easy to understand how standards efforts that push technology can identify substantial research issues. STEP, for example, has spawned research in data modeling, object-oriented data bases, and data-driven manufacturing. It is less obvious that evolution of mature standards can also be the source of a strong research agenda. This has, in fact, happened in the United States as a result of attempts to formalize the semantics of engineering drawings, to develop measurement methods based on these semantics, and to develop performance standards for software that inspects parts specified according to drawing standards. The close working relationship that has begun between some of the tolerance-related standards committees and several researchers from industry, government, and academia should be expanded. Standards committees should become much more proactive in recruiting the involvement of researchers, identifying barriers to improving standards, and using the results that researchers obtain.

In a similar vein, the research community is always interested in problems that are intellectually challenging, will attract support, produce useful results, and help develop better curricula. Researchers should seek support to become involved in standards efforts as one of the most effective ways to identify and gain support for substantive research topics. The products of research may, in some cases, be delivered directly to standards committees or, more often, be made available to developers of new manufacturing technology. That this has happened in several areas of tolerance standards shows that such involvement by researchers is both feasible and productive. Unfortunately, standards participation has, at least in the United States, been traditionally viewed as strictly an industry activity. We need to find ways to increase the career value to researchers of participating in standards work.

Technology vendors are the primary consumers of research results. Vendors, having long ago recognized the relationship of standards to manufacturing, are strong participants in standards efforts. They participate as full partners in understanding and analyzing industry needs and in developing appropriate standards. Technology vendors are in the best position to support participation by researchers. Vendors can transfer research results into practical commercial applications. It is my hope that future generations of CAD systems, machine tools, inspection software, shared product data bases, and other manufacturing technology will be based on a stronger, more unified language of tolerances.

4. CLOSING REMARKS

To date, there has been very little work on developing a common technical basis for tolerance semantics among the many tolerance-related standards we use. As a result, we spend an inordinate amount of effort, time, and money resolving disputes and disagreements about what tolerances mean. Tolerances established by designers are understood differently by manufacturing engineers. Suppliers believe they have shipped high-quality goods, only to find that the customer believes the parts do not comply with specifications. Inspection engineers develop plans to measure part attributes that are irrelevant to the needs of quality control or quality assurance.

Many of the problems we have in using tolerances effectively are, at root, caused by the weaknesses of our tolerancing language. These weaknesses, some of which I have discussed in this paper, need further research. Improvements will require contributions from all phases of manufacturing. I have suggested an integrated program of developing a framework, defining tolerance semantics within that framework, and coordinating development of standards to codify the definitions. Many of the components of the program are already in place, but we must recognize their proper role in relationship to one another.

This program will increase the effectiveness of our research efforts and will yield great benefits to manufacturing throughout the world.

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