A Framework for a CAD-Integrated Tolerance Optimisation System

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Abstract: Current assembly modelling and tolerance analysis functionality offered by most CAD vendors extends to the evaluation of a design in terms of its form and fit. There is no evidence of these tolerance optimisation tools offering the designer an 'in-context' perspective of process capability: an assessment of whether the required tolerances are achievable from the available manufacturing process. There is also a lack of provision for the direct use of experimental design data, within the CAD system environment. The aim of this research is to enable these prototype and production test results to be used in conjunction with a manufacturing capability model to establish the best compromise between product performance and process capability. This research program is to establish a framework with which process capability data can be captured, interpreted and subsequently used in a CAD system, making it readily available for the designer to use in the pursuit of a more robust product. The framework will be demonstrable in the context of vacuum pump design and manufacture in BOCE (BOC Edwards), the company hosting the research activity.

The framework will have the potential to reduce the level of first time test failures that are attributed to products containing parts that are not made to specification. It will also eliminate the time and resource overhead incurred in redesigning parts, which cannot be manufactured due to the specification of unachievable tolerances. As a result, machining scrap will also be reduced. In addition, the designer will be more confident that a 'robust' product has been produced, with reduced sensitivity to normal variations in the manufacturing process. Where a 'close' tolerance is absolutely vital, and the current manufacturing process is not capable, the framework will highlight this early in the design phase and allow the purchase of additional (and possibly long lead time) tooling or fixturing, thereby providing effective support to the new product introduction process.

Keywords: Process capability, CAD, PDM, SPC, tolerances

The original version of this chapter was revised: The copyright line was incorrect. This has been corrected. The Erratum to this chapter is available at DOI: 10.1007/978-0-387-35492-7_50

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CHALLENGES OF TOLERANCE SPECIFICATION

Manufactured parts are rarely made to exact specifications: variation exists in the size of parts and their constituent features because of variations in the chosen manufacturing process. The amount of variation is a function of the cost and the quantity of the finished product. The purchase price of the product will dictate its prime cost, which in turn, dictates the available manufacturing processes with which it can be economically made. Selection of an appropriate manufacturing process is therefore critical to the commercial success of the product in the market, and to the profitability of the manufacturer. Of equal importance is an appropriate tolerance specification to satisfy a product's functional requirements, and to gain an understanding of how the dimensional variation of critical components in an assembly will affect overall product performance. Once a functional envelope has been established, this can be compared with the available manufacturing technology and processes, which are economically suitable to the product quantities and price of the product.

Often, the performance envelope of a product is determined by knowledge of the manufacturing capacity, particularly where it is desirable to have tight dimensional control on critical components that directly influence product performance and reliability. It is vital to understand manufacturing capability here because over-tight tolerances are often relied upon to guarantee performance, but with the penalty of high manufacturing rejects and first-time test failures. Effectively, the tolerances are being used to control the process, rather the process being inherently capable of achieving the desired tolerances. The product designers therefore must know at the development stage the required part tolerances to satisfy its specification, and must also understand the *capability* of the available manufacturing technology to deliver these tolerances.

Most manufacturing companies, particularly with an established quality department, collect data on the dimensional accuracy of their manufacturing processes. This can be achieved during the pre-production sample approval stage where a batch of production representative parts is 100% inspected. For production parts, statistical process control (SPC) is used, where only critical features on each part are measured. These data are displayed as control charts showing the measurement trend over time and are used to detect whether the parts are within tolerance and whether the mean values of the features measured are centrally disposed about the mid-value in the tolerance range. Along with other data held on product performance and reliability, the objectives of the framework are too:

- Provide a generic process capability model applicable to the available manufacturing resource.
- Produce a method to link this process capability model with the latest statistical process (SPC) data.
- Produce a method of comparing the process capability available with the tolerance specification sought within the CAD environment.
- Advise the designer as to whether the component tolerance specification will enable the product to deliver the desired performance, given that it is manufactured with a capable process.
- Introduce product data management (PDM) and other enabling technologies to dynamically link departmentally maintained design, manufacturing and inspection databases.

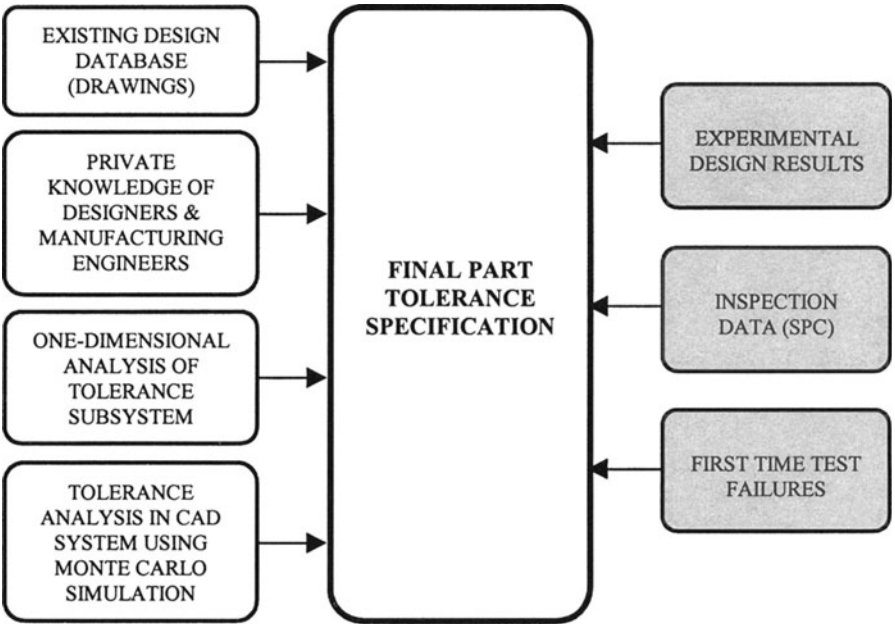

Figure 1: Process Inputs for Part Tolerance Definition

Figure 1 illustrates the key inputs in the tolerance specification process. The left-hand side lists the inputs that the designer traditionally establishes prior to deciding a final tolerance specification. Designers may refer to examples of similar solutions (from a drawing database for example) as a reference for tolerancing, using a solution already in production, or from their own personal experience or that of others. The danger here is that a 'legacy' tolerance may not functionally suit the part as used in its *new* assembly. In addition, by referencing a drawing in isolation, there is little understanding of how capable the current manufacturing technology is at achieving this tolerance, and whether as a consequence, there would be a high scrap or rework rate. A potentially unsuitable tolerance would then be perpetuated into the new design. A more sophisticated approach is to use worst-case (arithmetic) tolerancing, performed as a one-dimensional tolerance stack-up either by manual calculation or in a spreadsheet package. The success of this approach relies on an understanding of the tolerance chain and the correct use of the component feature minimum or maximum condition [1]. However, this analysis is external to the CAD modelling environment. At a higher level of sophistication, there are CAD-based tolerance analyses tools available using Monte Carlo statistical simulations to evaluate clearance conditions in 3D digital assemblies (such those from Tecnomatix or VSA). Figure 1 also highlights three additional inputs (on the right-hand side) that, in contrast, are not formally used in the tolerance assignment process within the CAD system, probably since there are currently few ways to explicitly link current manufacturing capability or product performance with the final tolerance specification:

- Experimental design results: During the product development process, prototypes are built and tested, with critical components deliberately made at upper and lower tolerance limits to test the possible range in performance. If pre-production prototypes are manufactured, these may be built in a statistically significant batch number to accrue product performance data that could be used in a series of experimental designs to test the sensitivity of critical components to dimensional variation.
- First-time test failures: Manufactured products usually undergo some form of quality testing before shipment, usually expressed as a series of metrics. This information is reviewed in isolation as trend data, but is often not explicitly correlated on a continuous basis with other available data such as machine tool life and component inspection results.
- Component inspection data: statistical process control is often used to monitor the manufactured output at the component level, expressed in various indices such as C_p (potential capability), C_{pk} (process capability) and C_{pm} (a modified process capability, emphasising 'on target' performance) – with the proviso of a stable process [2]. But this process data is rarely fed back to the design stage of a new or modified product, where the selection of a particular tolerance may exceed the capability of the manufacturing facility.

Most of this information remains isolated, and is often never visible to designers responsible for specifying tolerances. At the very least, the data is not available in a timely, seamless fashion to expedite its use. Deciding the tolerances for a part is traditionally a consultation process between departments or organisations. It is a time consuming, iterative task, which is conducted by review and may require several drawing up-issues. Furthermore, the time-honoured activity of drawing production (now usually generated from a geometric CAD model) does not interactively call for the use of process capability data. Yet this is the stage at which tolerance decisions are made, and where SPC data should be transparently available to support tolerance assignment. The tolerance framework aims to address this requirement, and this paper introduces the fundamental concepts of its architecture, and the direction of the research programme. The research will establish how this data can be captured, stored and interactively used in a CAD system, in the pursuit of a more robust product. The framework will also support the *association* of data pertaining to the part, including tolerance analyses contained, for example on spreadsheets stored separately from the CAD model.

OVERVIEW OF THE PROPOSED FRAMEWORK

Architecture of the Framework

The bedrock of the entire framework is the integration of the PDM and CAD systems. Figure 2 illustrates the underlying software environment

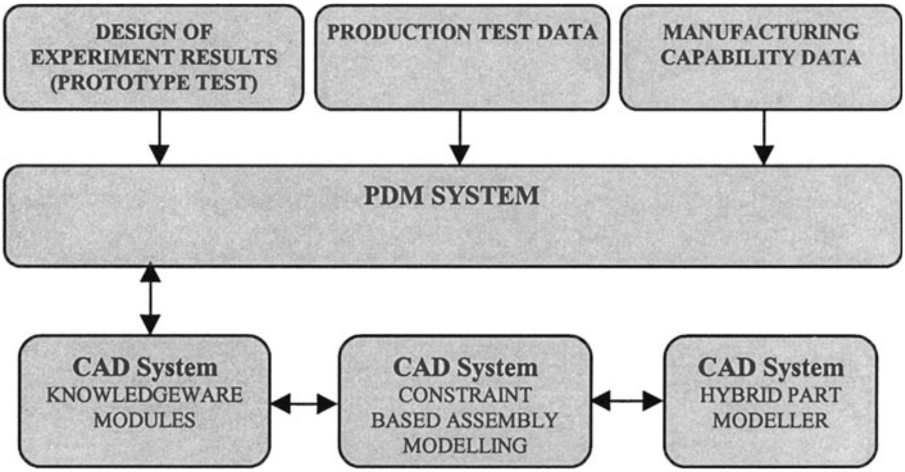

Figure 2: Software Environment of the Framework

of the framework. The PDM system manages, stores and shares the data pertaining to production and prototype testing, together with process capability. The data relating to these activities may not actually reside in the database shipped with the PDM system: they may actually exist on a remote part of an organisation's network possibly in a variety of database or application formats (for example, an Excel spreadsheet or an Oracle database).

The CAD system is used to create, modify and store constraint-based geometric models and assemblies. These part models should be built on a feature-based approach, enabling a logical decomposition of the part for subsequent analysis and for ease of modification [3]. The CAD system also exploits the growing knowledgeware functionality from vendors. The PDM system is essentially used as a medium to centralise and format the required data for the CAD system's knowledgeware front-end.

Definition of A General Process Capability Model

At the heart of the framework is a generalised model to represent the available manufacturing capability (Figure 3). This is the main logic 'engine' of the framework, which (with user interaction) will consider the function of the part, its feature composition and its position in the context its parent assembly within the CAD environment. The model is intended to address the commercial needs of a variety of manufacturing industries including fabrication, metal machining, plastics moulding and printed circuit board manufacture. It would therefore undertake to support the common denominators from these activities, which could include data from the manufacturing process tools (such as machining centres), component inspection data, and test data at a component or product level. In addition to

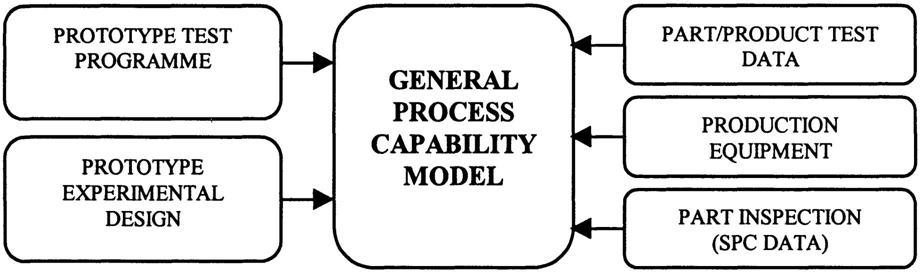

Figure 3: General Process Capability Model

data relating to production, it should also be able to consider prototype design and testing. Before actually using the framework, the functional subassembly will be constructed using the logical constraints available in the CAD system. Typically, these might include adjacency, concentricity and co-axiality conditions, depending upon the richness of functionality in the CAD system. This step enables the designer to view the part in context, and helps to define the primary and any secondary functional datums on the part. Once the assembly definition is complete, the next step is to identify

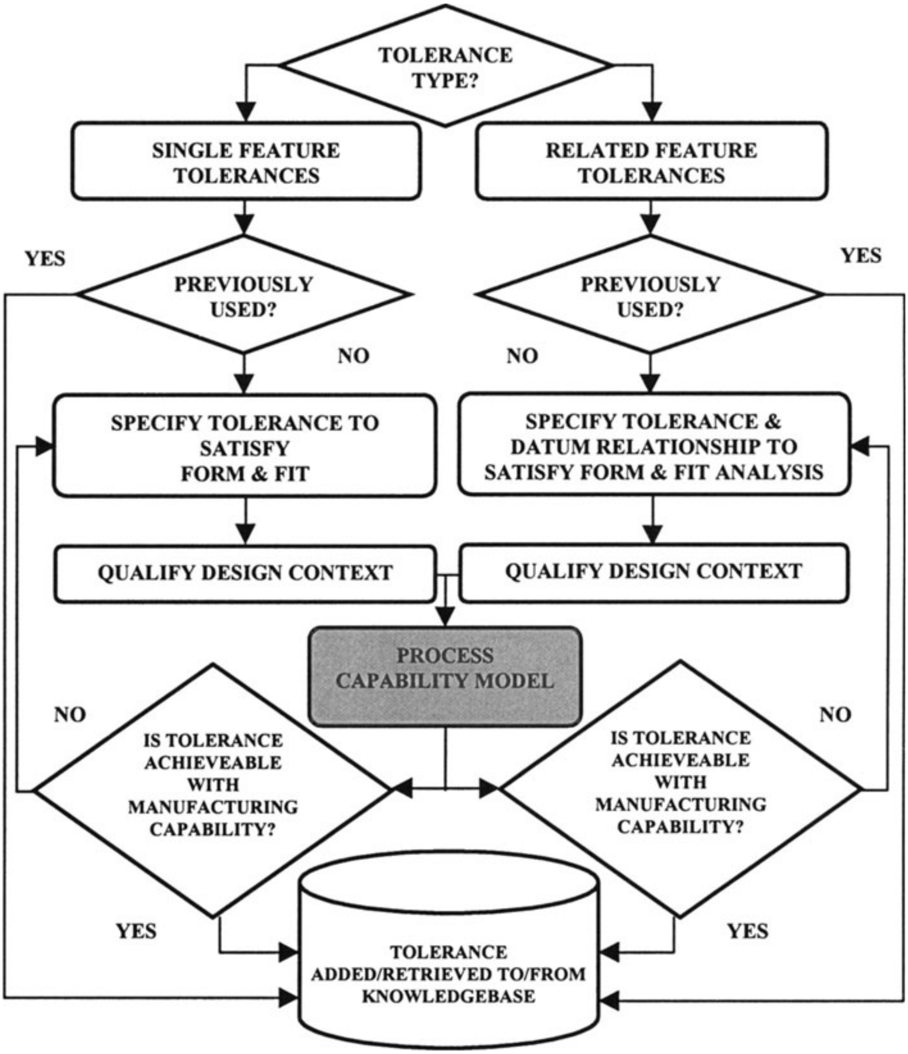

Figure 4: The Concept Framework

the geometric and linear tolerances for dimensional control. As previously discussed, there are tools available both internally (for example the Valysis product) and externally (such as an Excel spreadsheet) to the CAD environment to support functional tolerance allocation.

At this point the new framework is used, and is illustrated in Figure 4. The designer selects whether the tolerance is a single feature tolerance (for example flatness, straightness or cylindricity), or a related feature tolerance (for example parallelism, position or concentricity). The initial tolerance from the functional form and fit analysis is called up. The framework also considers the context in which the tolerance assignment is being made – if there is additional demand from other factors such as deep bore machining or limitations with the position of the fixture for example. The proposed values are then passed into the process capability model for evaluation, providing feedback to the designer as to whether the chosen tolerances are suitable for the available manufacturing process technology and resources. Where relevant, the process capability model can also be used to evaluate if the product is likely to meet performance requirements, which can be disseminated from Experimental Design (for example Taguchi results). If there are anticipated capability issues, the designer can re-specify a new tolerance value, or, if the value is acceptable, the feature and its tolerance may be stored via the CAD system's knowledgebase for future reuse. As mentioned earlier, the interface should be integral with the CAD system, which centralises both the decision-making process and the justification for the tolerance selection. The framework will implement Open Database Connectivity (ODBC) to enable the CAD/PDM system to link into the most commonly used relational database systems such as Access, SQL Server, Oracle and Visual FoxPro [4]. It is worth noting that it would be commercially desirable to enable the framework to use the Object Linking and Embedding Database (OLE DB) specification, which defines interfaces for gaining access and manipulating all types of data. In short, it enables the use of both relational *and* non-relational databases and will ensure the greatest flexibility of implementation [5].

An Industrial Case Study

BOC Edwards designs and manufactures vacuum pumps and accessories for the Scientific, Chemical and Semiconductor manufacturing industries. The company employs a cellular manufacturing strategy, and is currently installing shop floor co-ordinate measuring machines (CMMs) in each machining cell. The intention is to build a manufacturing database, primarily displayed in terms of control charts deriving C_p and C_{pk} indices. At present the structure of the database is driven by the requirements of the Quality Department - a somewhat limited audience. There are no plans at present to externalise this data to other departments within the company, and certainly no means of feeding the raw data back into the product design. The research program undertaken at BOC Edwards will review the range and depth of the currently available SPC data, and investigate data on pump first-time test failure. It will also review data on tool life, stored in the controller memory on each machining centre, and investigate characteristics of different machine tools: for example accuracies of position and circular interpolation. A Correlation of the data for machining centre tool life, SPC data and pump first time test failure can be made.

The first step is to develop a process capability model specifically for BOC Edwards. The task here is to define the constituent elements of the model to represent the particular processes of the company, encompassing manufacturing capability (manifested as SPC data), prototype performance test results (from experimental design), machining-centre characteristics, tool life data and production first-time test results (Figure 5).

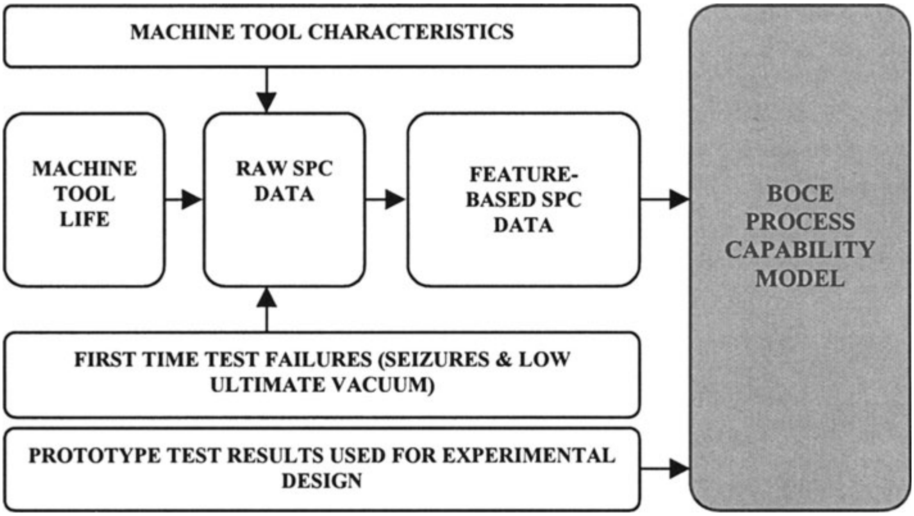

Figure 5: Relationship of Key Elements in the BOCE Process Capability Model

SPC data will be the main element of the capability model. In BOC Edwards, SPC data will be available for all critical part tolerance evaluations. However, this data has to be presented in a useful way to the designer, on a feature basis, which is how the design data is organised and stored in the CAD system. The process capability model should cater for the available manufacturing resource, (i.e., machining centres) since each available machine tool will have a set of physical machining characteristics (such as machining envelope and available accuracy), which can be stored as attributes. The tool life trend on these machines will also be considered, particularly in the context of machining critical component features. This will help establish the worst-case process capability, where worn tooling will allow the process mean to drift off the tolerance mid value. These SPC results can also be correlated with the first time test results database, illustrating the effect on product performance of critical parts, which are not made to nominal size. In addition, the process capability model is designed to allow the use of experimental design test data (to determine 'robust' design). The model should consider the relationship and weighting of these factors in the context of a feature-based tolerance definition. The model will be devised in a way consistent with its intended implementation as a CAD system integrated program.

Figure 6 illustrates the key components of the prototype system. The PDM system underpins the entire implementation, which will be used to manage, store and share information relating to this engineering research project. The product selected is SmarTeam (from Smart Solutions Ltd), which when shipped with CATIA V5 from Dassault Systemes, is equipped with an Oracle database. Process capability data will be accessed from the company QS-STAT database. The PDM system will enable access to the

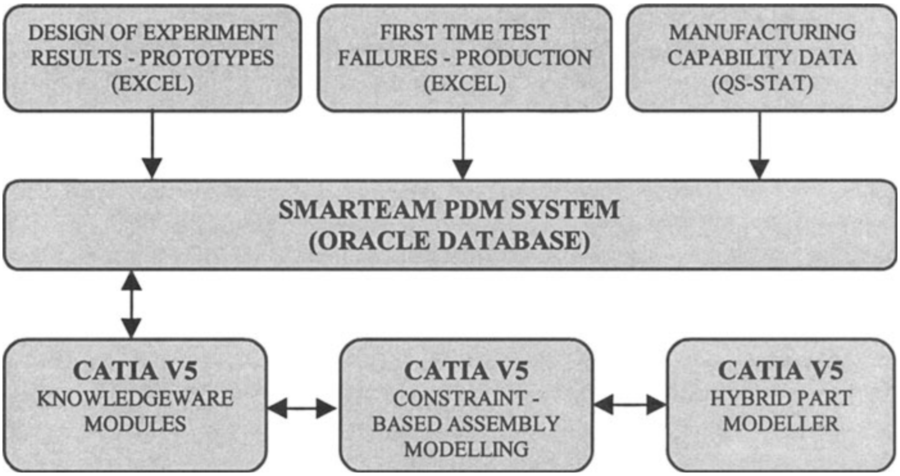

Figure 6: Components of the Prototype Tolerance System

experimental design results used for prototype testing, held in Excel spreadsheet format. CATIA V5 will be the primary part and assembly-modelling engine for the system. Dassault Systems have a suite of Knowledgeware modules for CATIA, which facilitate the creation of dedicated applications, completely integrated within the CAD environment.

INDUSTRIAL BENEFITS

The key benefits of the research will be to pioneer a system to reduce first time product test failures, reduce the scrap and rework rate, and to reduce the time and human resource absorbed in redesign due to unachievable manufacturing tolerances. The overall objective is a more robust product, insensitive to normal variations in the manufacturing process. The framework also supports the new product introduction process by identifying any shortfall in available manufacturing capability: the project management team can then plan to make new capital investment or identify a suitable subcontract source.

CONCLUSIONS

This CAD-integrated optimisation system addresses the shortfall of current tolerance analysis systems which do not provide an 'in-context' perspective of process capability or make provision for the direct use of experimental design data, within the CAD system environment. The aim of this research is to enable these prototype test results to be used in conjunction with the manufacturing capability model to establish the best compromise between product performance and process capability. The research therefore aims to endow the designer and the manufacturing resource planner with a complete vision of how the tolerance chosen for form and fit, compares with the capability available from the manufacturing process to achieve the target tolerance. It therefore complements existing functionality in CAD/CAM systems, in particular the ability to create constrained assemblies; to apply tolerances to geometric models; and the use of these tolerances in statistical analysis. In the research company, the overall impact of the project will be to reduce the level of first-time test failures that are attributed to pumps containing parts that are not made to specification. It will also eliminate the need to rework and redesign parts that cannot be manufactured due to originally specifying unachievable tolerances and reduce machining scrap. In addition, the designer will be confident that a 'robust' product has been produced, which is not subject to normal variations in the manufacturing process.

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