NURBS-Based Variational Modeling as a Tool for the Analysis of Geometric Tolerances

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ABSTRACT
The purpose of this research is to investigate a computer-aided approach to tolerance analysis for assemblies and mechanisms. A CAD system which can generate NURBS surfaces is used to produce imperfect-form, variant models. A method is developed for simulating the mating of these imperfect-form components by formulating surface mating relationships as a nonlinear programming problem. Using this approach, tolerance analysis can be performed by generating a series of typical component variants, simulating the positioning of these imperfect-form components then measuring geometric attributes of the assembly or mechanism which correspond to functionality.

1 INTRODUCTION
Traditionally, the design of mechanical components has been carried out under the assumption that a manufactured component has exactly the form and dimension specified by the design engineer. Manufacturing processes are, however, inherently imperfect and produce parts which vary from the nominal design model. In order to control these variations, mechanical tolerances are appended to the model. In general, the design of a highly reliable product calls for tight tolerances, so that manufactured parts are as close as possible to perfect dimension and form. Unfortunately, the cost of producing such near perfect parts can be quite high, as manufacturing costs usually increase with a decrease in allowable tolerance. Tolerance specification can serve as a common ground between the need to design reliable products and the need to produce these products at a competitive cost.

An important step in tolerance selection is tolerance analysis. Tolerance analysis is concerned with defining the relationships between tolerances and product performance. If the product is an assembly or mechanism which has several attributes which are critical to functionality, tolerance analysis can become a complex problem. As an example, consider the mechanism shown in Figure 1. The components shown in this drawing comprise part of a high-speed stapling mechanism which is being used as a motivating example in this research. The mechanism consists of four prismatic components which, when assembled, form three prismatic sliding joints. A good measure of functionality of the mechanism is how well the driver, bender and bonnet components are aligned as the mechanism moves through the bottom of its stroke.

Suppose that the designers of this product know from experience with their manufacturing processes that there is typically some curvature in the (nominally straight) bonnet and that the (nominally parallel) side faces of the driver are typically not quite parallel. How can this information be incorporated into the design process and used to specify tolerances which insure that misalignment between components stays within acceptable limits? This tolerance analysis problem requires the designer to determine mating conditions between several different faces. Furthermore, this analysis must be repeated over a range of variant magnitudes, for a number of different sets of variants, and at a series of positions through the stapling cycle. Clearly, this analysis is too complex to be performed manually.

This paper describes the development of computer-aided tolerance analysis capabilities in the CODA system. CODA (COnfiguration Design of Assemblies) is a feature-based design and virtual prototyping environment which is being developed in the Systems Realization Laboratory at Georgia Tech (Rosen, 1994). Tolerance analysis capabilities which are being incorporated into CODA are intended to allow a designer to: 1) Model components of imperfect form and size (component variants) which might occur as the result of manufacturing errors, 2) Simulate positioning of different combinations of component variants (assembly variants), 3) Assess geometric measures of functionality of assembly variants (Pierce and Rosen, 1996).

The remainder of this paper is organized as follows: A brief review of relevant work in the fields of variational modeling and simulation of component mating is provided in Section 2. Section 3 describes the Variational Modeling Module which is being developed to allow simulation of
positioning of imperfect form components in CODA. Our approach to the generation of variant models and the simulated mating of these models is described in detail. In Section 4, the work to date is summarized and the direction of future work is discussed.

2 BACKGROUND AND LITERATURE REVIEW

2.1 Variational Solid Modeling

Variational modeling is the process of applying variations in form or dimension to a solid model of a part. Research in this field has focused on two areas: 1) The mathematically rigorous definition of geometric tolerances (Turner, 1990a, Rossignac and Requicha, 1986, Requicha, 1983), 2) Methods which can be used to manipulate the data base of a solid modeler in order to permit variational modeling (Aldefeld, 1988, Light and Gossard, 1982, Guilford and Turner, 1993). Work in the first area has lead to a formal mathematical definition of the geometric tolerancing standards (Walker and Srinivasan, 1994). Most of the research in the second area concentrates on methods for allowing variations in model variables. Relatively little research has been done on the problem of generating solid models of particular geometric variants.

Tolerancing is, by definition, concerned with variations in the boundaries of a solid. Thus, a boundary representation (B-rep) is a natural choice for the modeling core of a tolerance analysis system. Ideally, a B-rep which is to be used for variational modeling should be capable of representing a broad spectrum of surfaces, including free-form surfaces and surfaces where the variation from nominal form is localized to only part of the surface. In many cases, a variant surface will be of higher order than the nominal surface. There are two approaches which can be used to handle this problem: 1) The nominal surface representation can be replaced by a higher-order surface, 2) The nominal surface can be divided into a mesh of smaller surfaces.

Pandit and Starkey (1988) develop a variational modeling scheme in which variant surfaces are modeled by meshing a nominal surface into planar facets. In order to generate variant surfaces, each planar facet is divided into a series of planar, triangular patches. Variant surfaces are then generated by perturbing the vertices of the patches in a direction normal to the nominal surface.

Gupta and Turner (1993) extend this “triangularization” approach to use non-planar patches to generate particular surface variants. First, the nominal surface is triangulized into planar patches in the manner described above. The edges of each triangle are then bisected and mid-edge vertices are defined. Each triangular face is then used to form a triangular, quadratic Bezier patch. For each patch, six control vertices are defined (the three corners and three mid-edge vertices). Interior vertices are moved only in the direction normal to the nominal surface. Moving a particular vertex changes only the patches which are defined using that vertex. Thus, this approach can be used to model localized surface variations. The minimum size of the variation which can be modeled is determined by the mesh density.

2.2 Modeling the Mating of Imperfect-Form Components

While commercially available CAD software has been developed which allows modeling of a limited set of mating relations, very little work has been done in modeling the mating of actual components which do not have perfect form. For such components there may be several sets of positions which are feasible. The final set of positions will depend on the form of component errors, the sequence in which contacts are established and on the forces transmitted between components. A system for modeling the positioning of component variants must provide some mechanism for choosing from amongst the set of feasible final positions.

Early work in modeling the assembly process focused on the definition of mating relations as constraints on possible component coordinate transformations. Lee and Andrews (1985) and Rochelleau (1987) describe a strategy for generating coordinate transformations directly from component geometry and mating conditions. In this work the mating conditions “against” and “fits” are formulated as a set of vector equalities. Use of equality relations means that only perfect-form components which mate exactly can be modeled. Mullineux (1987) proposes a modeling strategy which is a combination of
equality and inequality constraints. He points out that the existence of clearances between mating parts means that there is often a range of positions over which mating conditions can be satisfied. Thus, inequality constraints often provide a more accurate model of the requirements which must be satisfied in order for parts to assemble. Kim and Lee (1989) propose that components in an assembly can be broken into groups and that each group can be formulated as a separate mathematical programming problem. They point out that solving the positioning problem for each group in sequence is more computationally efficient than positioning the entire assembly simultaneously.

Turner (1990b) asserts that this sequential positioning approach best represents the manner in which assemblies are usually built. The author models the construction of an assembly as a series of linear programming problems. Each mate between a pair of elements is formulated as a separate problem. The convex hulls of mating surfaces are identified and these convex hulls are substituted for the (possibly non-convex) variant geometry. The mating relations between these convex surfaces are then linearized and solved using a linear programming algorithm. When the mating position is found between a pair of surfaces they are fixed by expressing their relative position as an equality constraint in subsequent positioning operations. An important aspect of Turner’s work is the manner in which the positioning problem is formulated. The objective function is always formulated as “minimize the maximum distance from ideal fit.” The requirement of non-interference is then embodied as a set of inequality constraints. By posing the problem in this fashion, there does not have to be an exact fit between mating surfaces in order for a feasible solution to exist. Thus, this formulation can be used to model the mating of parts which have imperfect form.

Inoue and Okano (1996) demonstrate the use of the linear programming approach to the mating of components which have randomly generated form errors. Deviation from nominal fit is defined by measuring the differences in position and orientation between points on mating components which are coincident in a perfect assembly. Forces and moments at each point are calculated using pre-specified loading conditions. These values are then used to calculate the potential energy associated with a particular set of component positions. The objective of the positioning algorithm is then to minimize the potential energy of the system.

3 VARIATIONAL MODELING FOR TOLERANCE ANALYSIS IN CODA

3.1 The “Generate and Test” Approach

As discussed in Section 1, the goal of tolerance analysis is to establish relationships between a proposed set of tolerances and measures of product functionality. In order to determine whether a proposed tolerance set is sufficient to ensure functionality, a designer must consider the form and magnitude of variations which are allowed (the variational class). The designer must analyze the manner in which component variants will mate and assess the functionality of different groupings of component variants. In order to perform such an analysis the designer must: 1) specify variations from nominal size and form which are likely to occur for each component, 2) generate models of imperfect form component variants, 3) analyze the mating relationships between variants, 4) assess the functionality of different sets of component variants. We refer to this approach to tolerance analysis as the “generate and test” method (a term first used by Pandit and Starkey, 1988).

Figure 2 is a schematic diagram of a CODA module which will allow a designer to perform the tasks listed above using a boundary-representation solid modeler. The “Variational Modeling Module” (VMM) uses the CODA front-end running on top of the ACIS geometry engine. Using the CODA interface, a designer can generate nominal solid models of the components of an assembly or mechanism. The VMM then allows the generation of “as manufactured” component models by specifying sets of points which lie on the surfaces of
The reasoning behind this approach is that information about probable manufacturing errors for a particular class of component often exists in the form of discrete point measurements. Such a point set might be the result of measuring similar or prototype components using a coordinate measuring machine (CMM).

Point measurements which define component variants are used to fit freeform surfaces. These freeform surfaces are then used to replace the corresponding nominal surfaces in the component solid model. Once a set of variant components has been constructed in this manner, mating between components can be simulated by formulating mating relations as a nonlinear programming problem. Geometric attributes of the assembly or mechanism which correspond to functionality can then be measured using this model. In the case of a mechanism, each set of variant components can be tested in a series of different points in the mechanism cycle. By repeatedly generating and testing variants which are allowed under a proposed set of tolerances, a designer can test the effect of particular tolerances on the overall function of the assembly or mechanism.

Figure 3 illustrates the advantage of applying the “generate and test” approach to a two-dimensional simplification of parts of the high-speed stapling head (note that for illustrative purposes, the size of clearances and form errors have been greatly exaggerated). Figure 3a shows the nominal design near the bottom of the stapling stroke. Angular misalignment of the driver during this part of the stroke is taken as a measurement of functionality. Figure 3b shows tolerance boundaries at least-material condition (LMC) and most-material condition (MMC) which would be generated by applying tolerances of size, flatness and parallelism to the components. Currently, computer-aided tolerance analysis is limited to evaluating the mating conditions between these perfect-form, tolerance zone boundaries. Figure 3c shows the result of such an analysis for this example. The maximum angular misalignment of the driver is found to occur when all components are at LMC. Figure 3d shows the maximum error which would result for one possible “as-manufactured” variant of the mechanism. Note that the maximum misalignment which would occur for this as-manufactured mechanism is significantly less than that predicted using the LMC component boundaries (indeed, any in-tolerance set of components will have less error than that predicted using the LMC boundaries). Thus, tolerance analysis which is performed using only the boundaries of the tolerance zones will lead to tolerances which are overly conservative and expensive to meet.

One approach which has been used in commercial software to make tolerance-zone based analysis less conservative is to use Monte Carlo simulation to generate a series of (perfect-form) components whose faces are positioned randomly within the tolerance zone. As discussed in Section 2.1, previous research work has extended this Monte Carlo based analysis to the generation of random form errors by randomly perturbing the control vertices which define component faces. The approach to tolerance analysis which is incorporated into the VMM is a significant departure from either of these methods. Rather than generating random variations from nominal, our method allows the designer to use existing manufacturing process information to generate and test models of those component variants which are most likely to occur. We feel that this approach can lead to a more realistic analysis of the relationship between tolerances and functionality.

Figure 3: Tolerance analysis using zone boundaries vs. the “generate and test” approach. (a) Nominal design of a simplification of the high-speed stapling head. (b) LMC and MMC boundaries. (c) Maximum possible misalignment error calculated by considering only zone boundaries. (d) Maximum misalignment error which would occur for one as-manufactured” instance of the mechanism.
Development of the VMM is an ongoing project. Currently, the capabilities to generate variant solid models have been implemented in the modeling system. The methods which are to be used for assembly simulation have been developed and we are in the process of implementing the positioning algorithms as the next step in the development of the tolerance analysis system.

3.2 Generation of Variant Component Models

As discussed above, the ACIS geometric modeler is being used as the modeling engine for the CODA system. ACIS is a b-rep solid modeler which incorporates non-uniform, rational, b-spline surfaces (NURBS). A bicubic NURBS surface is defined by a quotient of rational polynomials as follows (Piegl, 1991):

\[ Q_{i,j}(u) = \frac{\sum_{i=0}^{n-1} \sum_{j=0}^{m-1} P_{i,j} w_{i,j} N_{i,k}(u) N_{j,l}(v)}{\sum_{i=0}^{n-1} \sum_{j=0}^{m-1} w_{i,j} N_{i,k}(u) N_{j,l}(v)} \]

where \( w_{i,j} \) are weights which can be assigned to each point, \( P_{i,j} \) are the control vertices and \( N_{i,k}(u) \), \( N_{j,l}(v) \) are the b-spline blending functions of order \( k \) and \( l \) respectively. These blending functions are defined recursively as:

\[ N_{i,0}(u) = \begin{cases} 1 & \text{if } u_i \leq u < u_{i+1} \\ 0 & \text{otherwise} \end{cases} \]

\[ N_{i,k}(u) = \frac{u - u_i}{u_{i+k} - u_i} N_{i,k-1}(u) + \frac{u_{i+k+1} - u}{u_{i+k+1} - u_{i+1}} N_{i+1,k-1}(u) \]

over knot vectors:

\[ U = (0, 0, 0, 0, u_4, ..., u_n, 1, 1, 1, 1) \]

\[ V = (0, 0, 0, 0, v_4, ..., v_n, 1, 1, 1, 1) \]

Note that defining weights, knot vectors and a set of control vertices completely defines a NURBS surface. The goal of a surface fitting algorithm is to generate best-fit values for these parameters. In this work, a bicubic surface is used for fitting and, since there is no reason to weight one data point more heavily than another, all points are assigned a weight of 1. A two-step least-squares fitting algorithm is used to calculate the control vertices. Isoparametric curves are fit to each row of data points in one parameter direction using a least-squares fit. The resulting control vertices are then fit in the other parameter direction in order to calculate the complete set of control vertices.

The NURBS surface representation was chosen for this work for the following reasons: 1) NURBS provide broad variational coverage. The relatively large number of parameters used to define the surface make it possible to model a wide range of variant shapes. This flexibility eliminates the need to mesh a nominal surface into many smaller surfaces in order to model a variant. Using a NURBS representation it is possible to model a variant surface by replacing a nominal surface with a single, higher order surface. 2) The effects of moving a NURBS control vertex are localized to a selected area of the surface around the vertex. This property of NURBS makes them suitable for modeling components which have localized form errors.

Figure 4 illustrates the process of generating a variant component using point measurements. In this case, the variant component is the slider component of a slider-crank mechanism (which is a simplification of the high-speed stapling head). Figure 4b shows a pointset which represents a manufacturing error which can occur in end milling operations as a result of cutter deflection combined with a chucking error. The sample data set was generated by sampling an analytical approximation to the cutter deflection data presented by Kline, DaVor, and Shareef (1982). This approximation has the form of an offset sinusoidal surface, as the cutter deflection error is approximately sinusoidal in form. In order to simulate the effects of surface roughness and measurement error, each data point was randomly perturbed by multiplying it by a scaled, normally distributed random number. Note that the error magnitude has been multiplied by a factor of 10 in this figure so that the error is visible.

Figure 4c shows the bicubic NURBS surface which is fitted to this pointset. In order to account for the possibility that the width of the slider may be larger than the nominal dimension, extra points are generated outside of the nominal surface by extrapolating the form of the original, measured points. The surface is then fit to the dataset and incorporated into the solid model of the slider by first extending the nominal face of the model so that the interior of the surface is embedded within the slider, then slicing the model into two pieces with the surface and discarding the extraneous piece (figure 4d). Figure 4e shows the slider after the same set of operations has been performed on a second face using a pointset which represents a milling error caused by spindle tilt.

3.3 Simulation of Mechanism Component Mating

As discussed in Section 2, previous research has utilized a linear programming algorithm in order to solve for the mating positions between surfaces. While such an approach is computationally efficient, it requires excessive simplification of the part model. In particular, these approaches consider only the convex hull of a surface or positions of extreme points on
mating surfaces. However, as-manufactured components may have several maximum and minimum points across their

Figure 4: Constructing an “as manufactured” variant of a slider. (a) Nominal slider/guideway. (b) Pointset which defines a manufacturing error on the side face of the slider due to cutter deflection during milling. (c) NURBS surface fitted to the pointset with the face of the slider extended to cover the surface. (d) Slider with the variant face replacing the nominal side face. (e) Slider with both the top and side faces replaced with variant surfaces. The top face reflects an error due to spindle tilt during milling.
surfaces. Consideration of only the extreme points of a surface ignores the interaction between these local surface variations. The existence of these local extrema may cause a traditional linear programming algorithm to get stuck in a local minimum which is not the global minimum solution. This possibility is particularly likely when simultaneous mating between multiple faces is considered.

A major goal of this research is to solve the component mating relationship problem without simplifying the shape of the variant surfaces. Towards this end, a nonlinear programming algorithm is used to solve the positioning problem. The problem will be formulated as:

Minimize: \( Z = \text{Total Distance Between Mating Surfaces} \)

Subject To: Non-Interference Between Components

This problem will be implemented by incorporating the non-interference constraint into the objective function as a weighted penalty term. There are two major reasons that the penalty formulation is used instead of formulating non-interference as a “hard” constraint: 1) If the nominal component positions do not yield a non-interfering initial position, the optimization algorithm (which is discussed at the end of this section) can be used to search for such a position by minimizing the interference term. If no non-interfering position exists the algorithm will at least find the position of minimum interference.

2) The penalty method allows the optimization algorithm to move the search through a position where there is slight interference in order to find the optimum position.

For the positioning of a single component within an assembly, the problem is formulated mathematically as:

\[
\text{Minimize } Z(x,y,z,\alpha,\beta,\gamma) = \left( \sum_{j=1}^{p} \sum_{i=1}^{q} \sum_{r=1}^{s} d_{ij} \right) + W \sum_{m=1}^{s} \left( \frac{B_k \cap B_m}{B_k} \right)
\]

where:

\( x,y,z,\alpha,\beta,\gamma \) = position and orientation variables of the component

\( p \) = number of component faces involved in the mating operation

\( q, r \) = number of grid points in \( u,v \) directions for a particular face

\( d_{ij} \) = distance from the \( i,j \)th grid point to the mating face (see Figure 5c)

\( d_{ij_{\text{MAX}}} \) = the maximum allowable value for distance \( d_{ij} \)

\( B_k \cap B_m \) = the volume of intersection between the body which is being positioned (Body \( k \)) and the \( m \)th other body involved in the mate

\( B_k \) = the total volume of the body which is being positioned

\( s \) = the number of bodies other than \( B_k \) involved in the mate

\( W \) = the penalty term (a relatively large constant)

Figure 5 illustrates the simulation of component mating for the slider as it is being pushed into the corner of the guideway. To begin the simulation, a base component (in this case the guideway) is fixed in model space. The next component in the assembly is then “coarse positioned” so that there is no interference between components. Coarse positioning is accomplished using the ACIS bounding-box capabilities. Bounding boxes are generated for the mating faces of each component. The component being positioned is then moved so that the faces of the bounding boxes are coincident. Clearly, it is possible that coarse positioning in this manner may not yield a non-interfering position. In this case, positioning is started from the nominal configuration and the positioning algorithm is used to search for a feasible position.

Once the component is coarse positioned, the optimization algorithm begins generating candidate sets of position and orientation variables (Figure 5b). Evaluation of a candidate variable set begins by moving the component model into that position, then evaluating the interference terms:

\( B_k \cap B_m \quad m=1, \ldots \text{number of bodies other than } B_k \text{ involved in the mate} \)

For each body involved in the mate, a quick interference check is first performed using bounding boxes. If the bounding boxes interfere, a Boolean intersection between the two bodies is performed. If the Boolean intersection returns a non-NULL result, the interference volume is calculated. The interference volume is then normalized by dividing by the total volume of \( B_k \) so that the interference term is a dimensionless number between 0 and 1. This normalization makes it possible to add the two terms in the objective function and keeps the relative weights of the two terms constant when the size of the mating components changes. The total interference over all mating components is then multiplied by the penalty term, \( W \). This term is chosen to be large enough to overwhelm the other term in the objective function, so that a position with any significant interference has a high objective value.

The next step in the evaluation of the objective function is to measure the distance between mating faces. For each mating face, a grid of sampling points is generated on the component being positioned (Figure 5b). For a particular grid point (point \( i \)) on mating face \( j \), the closest point on the
The corresponding face of the stationary component is found and the distance between the points \( d_{ij} \) is measured (Figure 5c). If a negative distance is found (i.e., the parts interfere) \( d_{ij} \) is defined to be zero at that point. The sum of these distances over all of the component mating faces is calculated and this sum is normalized to a dimensionless value between 0 and 1 by dividing by the sum of the maximum possible values for each of the \( d_{ij} \). These maximum values may result directly from the assembly geometry and the proposed tolerance set or they may need to be specified directly. For example, in the case of the slider/guideway assembly the maximum distance between the side face of the slider from the side of the guideway is the maximum clearance generated when both the slider and guideway are at least material condition. However, the maximum distance between the bottom face of the slider and the guideway would need to be specified directly as there is no geometric constraint on this value.

Using the normalized intersection volume and normalized distances, the value of the objective function is calculated. This is then compared against a minimum value which is specified as a stopping criterion. If the stopping criterion is not met the optimization algorithm generates a new set of candidate position/orientation variables and a new iteration is started. If the stopping criterion is not met after a prescribed number of iterations the algorithm is stopped and the
position corresponding to the minimum value of the objective function is reported.

Referring back to figure 3, the steps involved in analyzing a proposed tolerance set for the simplified stapling head are:

1) Define sets of likely manufacturing variations for each of the three components. These variations are defined by sets of points which are used to fit freeform surfaces.

2) From the set of likely variations, generate a particular as-manufactured instance of each component which just satisfies the proposed tolerance set.

3) Specify a base component (the bonnet) and the component mating hierarchy (e.g. bender mates against the bonnet guideway, driver mates against the bender guideway).

4) Starting with the first mating pair (the bender and bonnet), generate bounding boxes for all mating faces.

5) Use the bounding boxes to move the bender into a non-interfering initial position (if possible). If no position is found where bounding boxes do not interfere, start the positioning algorithm from the nominal position.

6) Use the optimization algorithm to generate a set of candidate position and orientation variables for the bender. Move the bender to the candidate position/orientation.

7) Generate bounding boxes for the bender and for all potentially interfering faces. Test for interference between these bounding boxes. If interference is detected between bounding boxes, perform a Boolean intersection between the potentially interfering components. Measure the total interference volume for all components and normalize this value.

8) Generate a sampling grid over each face of the bender which mates with the bonnet. For each sampling point measure the distance between the point and the closest point on the mating bonnet face. Normalize this distance and sum the normalized distances over all mating faces.

9) Calculate the value of the objective function.

10) Check the objective function value against the stopping criterion value. If the objective function value is less than or equal to the stopping criterion value, stop the algorithm and save the position/orientation of the bender. Otherwise, return to step 6 and iterate.

11) If the maximum number of iterations is reached, stop the algorithm and save the position/orientation which gave the minimum objective function value.

12) With the bender set in the position which minimized the objective function, repeat the positioning process (from step 4) for the mate between the driver and the bender.

13) Once both components have been positioned, measure the misalignment between the bender and the driver.

14) Repeat the process from step 2, generating and testing sets of as-manufactured instances using each of the likely component manufacturing errors. In each case, measure and store a misalignment value.

Using the measurements of misalignment, the efficacy of the proposed tolerance set can be evaluated. If misalignment is excessive for one or more variants, the combination of component errors which causes this misalignment can be determined and a new tolerance set can be proposed and evaluated. Conversely, the analysis may show that one or more tolerances do not greatly affect misalignment and can be loosened or eliminated.

As previously stated, development of the assembly simulation component of the VMM has not yet been completed. The algorithm which will initially be tested for generation of candidate positions will be based on the method of simulated annealing (Press, 1995). The reason for this choice is the ability of simulated annealing algorithms to find a global minimum in the presence of several local minima. As discussed above, when mating between multiple variant faces is considered there is a strong possibility that local minima in the objective function will exist. By occasionally making a search move in an “uphill” direction, the algorithm can avoid getting stuck in a local minimum and will search through the local minima until the global minimum is found. The main disadvantage of the simulated annealing approach is that it is computationally inefficient. Testing is needed to determine whether this method can be used to simulate positioning of multiple components in a reasonable amount of CPU time.

4 CONCLUSIONS AND FUTURE WORK

This paper has discussed progress toward the development of an environment for computer-aided tolerance analysis. This environment is intended to allow a designer to test the efficacy of a proposed set of geometric tolerances by generating models of as-manufactured component variants and simulating the positioning of these variants in an assembly or mechanism. The strengths of our approach to tolerance analysis are:

- Information about the probable form of manufacturing errors is included in the analysis.
• It is possible to model a broad range of dimensional and form variants.
• It is not necessary to simplify the shape of component variants in order to simulate positioning.

Limitations of our approach are:

• It does not take into account the transmission of forces and moments between mating components.
• It does not explicitly consider the statistical distribution of manufacturing errors.
• Evaluation of Boolean intersections in the objective function and use of the simulated annealing algorithm are computationally expensive.

Future work will focus on the implementation and evaluation of the positioning algorithm. Progressively more complex mechanisms will be simulated and mating conditions will be developed for non-planar contacts. In the long term, we plan to investigate the use of design optimization techniques along with the VMM in order to move towards computer-aided selection of geometric tolerances.

ACKNOWLEDGMENT

The authors would like to thank the National Science Foundation, which sponsors this work under NSF grants DMI-9420405 and DMI-9414715.

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