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FEATURE-BASED TOLERANCING FOR ADVANCED MANUFACTURING APPLICATIONS

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ABSTRACT

A primary requirement for the successful deployment of advanced manufacturing applications is the need for a complete and accessible definition of the product. This product definition must not only provide an unambiguous description of a product's nominal shape but must also contain complete tolerance specification and general property attributes. Likewise, the product definition's geometry, topology, tolerance data, and modeler manipulative routines must be fully accessible through a robust application programmer interface.

This paper describes a tolerancing capability using features that complements a geometric solid model with a representation of conventional and geometric tolerances and non-shape property attributes. This capability guarantees a complete and unambiguous definition of tolerances for manufacturing applications. An object-oriented analysis and design of the feature-based tolerance domain was performed. The design represents and relates tolerance features, tolerances, and datum reference frames. The design also incorporates operations that verify correctness and check for the completeness of the overall tolerance definition. The checking algorithm is based upon the notion of satisfying all of a feature's toleranceable aspects. Benefits from the feature-based tolerance modeler include: advancing complete product definition initiatives, incorporating tolerances in product data exchange, and supplying computer-integrated manufacturing applications with tolerance information.

1. TECHNOLOGY CHALLENGES

Industry today faces new challenges as it pursues precision manufacturing, distributed enterprises, higher quality products, and greater competitiveness. Many industries strive toward achieving these goals by implementing technologies that enable computer-integrated manufacturing. Efforts toward addressing these challenges have produced such technological advances as computer-aided design (CAD) systems and computer-controlled manufacturing systems. Unfortunately, these advances have created islands of automation, in which integration and exchange of data among these areas are still a time-consuming and labor-intensive task.

AlliedSignal Inc., Kansas City Division (KCD) has devoted significant efforts toward both establishing and demonstrating product data exchange and progressing and developing advanced manufacturing process definition applications. These shared experiences have resulted in the recognition of performance issues and underlying technological voids. Primarily there are three critical components that present significant challenges for a distributed agile manufacturing enterprise. The first is obtaining a complete representation of product definition. The second involves exchanging product data between sites. The third involves developing a rapid process definition capability. Solutions to these areas will provide key components for rapid response manufacturing that are critical to agility. We believe a common root cause for these problems is the lack of a tolerance definition that is both complete and accessible.

1.1 Product Definition Modeling

A major requirement for rapid product realization is the need for a complete and unambiguous product definition. This product definition must not only provide a description of a product's nominal shape but must also contain configuration control data, feature representations, and non-shape attributes, such as tolerance specifications, and general property attributes. Figure 1 illustrates pieces that make up a complete production definition. This information is necessary to completely define a product and successfully support advanced fabrication applications throughout the product life-cycle.

Modeler developers have succeeded in representing the shape of an object accurately and reliably using solid modeling technology. Unfortunately, tolerances and other pieces of the pie are not fully understood; therefore, most modeling systems do not implement tolerances. Few modeling systems associate and make

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accessible conventional and geometrical tolerances to the topological entities they control. None represent tolerances as a complete and unambiguous definition. As a result, many computer-integrated manufacturing applications must augment their geometry model with tolerances or not consider tolerances at all.

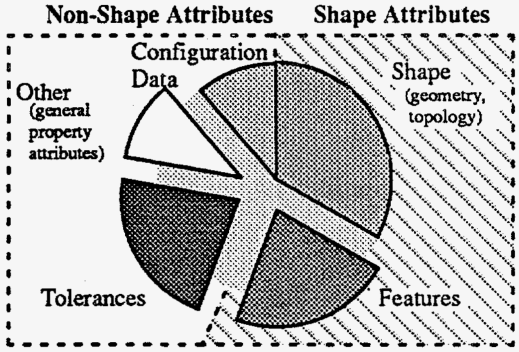

Figure 1. Complete Product Definition.

1.2 Product Data Exchange

To communicate design information from site to site, industry must transfer the product definition between different CAD systems. Product data exchange is the bi-directional communication of product information between dissimilar product definition systems (i.e., CAD). Today, through the implementation of solid modeling and STEP AP203 [1], industry is experiencing the successful exchange of nominal shapes as well as configuration control data. This is represented in Figure 1 as the pieces of the pie filling the circle.

The STEP international committee is developing a product definition exchange standard. In principle, STEP does not create new knowledge; it merely codifies existing technology into an unambiguous framework. In practice, when gaps were found, STEP would demand that they be filled with something. Unfortunately, knowledge of several pieces of the product definition pie is still evolving. In the area of tolerancing, there is a significant gap of knowledge where STEP has formulated some assumption and drafted STEP Part 47 - Shape Tolerances.[2] Many perceive that Part 47 suffers from the lack of a complete and unambiguous tolerance definition implementation.

1.3 Advanced Process Definition Systems

The link that bridges product design systems with computer controlled machines is automated process definition systems. Advanced process definition is seen as the critical flowtime reduction component required to obtain rapid response manufacturing. KCD has developed significant process definition prototypes for both the material removal [3] and the coordinate metrology [4] domains. Process definition typically involves the generation of process plans, machine part programs, and support documentation such as work instructions and illustrations. Recent KCD efforts have been devoted toward integrating these capabilities into a common system entitled IRIM (Integrated Rapid Intelligent Manufacturing). IRIM is a data-integrated standards-based manufacturing system to support the rapid generation of production process definition functions for mechanical products. As illustrated in Figure 2, the IRIM architecture consists of multiple components, such as product definition, database management system, knowledge based system, graphical user interface, persistent object storage, object-oriented process definition environment, and manufacturing verification and simulation. The system will generate process plans, part programs, and operator instructions with illustrations.

These experiences in developing automated process definition prototypes have identified a number of technology voids. Again, one of the major gaps is the representation of tolerances, particularly as an integrated part of the product definition. This information is of paramount importance to dimensional measurement, because tolerances dictate what must be measured and how. The requirement for tolerance representations is not unique to inspection applications. Tolerances are needed to support the definition of manufacturing features and to influence the determination of processes for material removal applications.

1.4 Proposed Solution

A review of the above domains reveals a critical need to augment shapes with tolerances. The proposed solution defines and implements a complete and unambiguous representation of tolerances and other non-shape attributes. This paper furthers the understanding of representing tolerances. Tolerance Features are used to bridge tolerances with solid model entities. The feature-based tolerance solution will migrate tolerances and some general property attributes "pieces" as part of the unambiguous product definition "pie". This is illustrated in Figure 3. The feature-based tolerance model design is consistent with ANSI Y14.5M. It supports STEP shape entities, integrates with the ACIS® geometric kernel, and follows general tolerance abstractions.

2. TOLERANCE MODELING

Today, manufacturing and metrology engineers, numerical control analysts, and part programmers perform their job functions by extracting implicit information through their interpretation of the

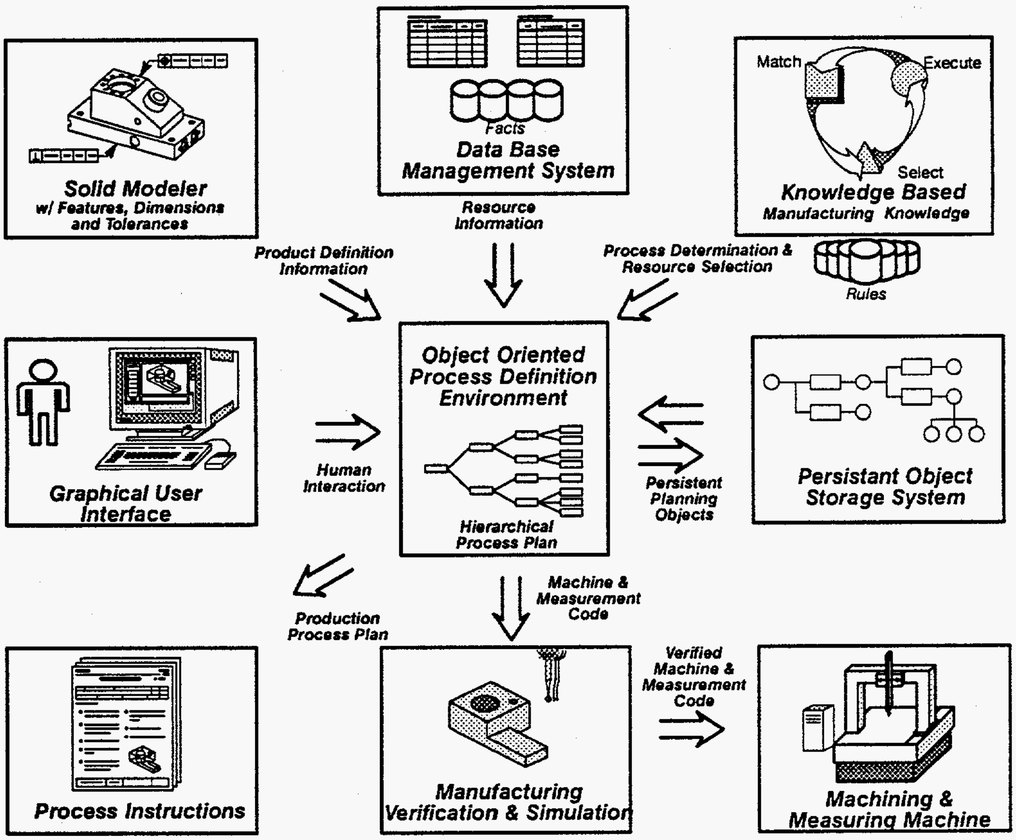

Figure 2. IRIM Architecture.

dimensions and tolerances on the part drawing. Likewise, any robust computer-aided applications assisting these job functions must have dimension and tolerance semantics explicitly represented in a computer understandable form.

Many researchers have recognized the technological void in the representation of tolerances and have suggested various approaches.[5][6] These approaches vary as to how much they attempt to use traditional tolerancing approaches, suggest new tolerancing approaches, depend on related solid modeling systems, their geometric coverage, and whether they emphasize tolerance analysis, user interaction, or manufacturing.

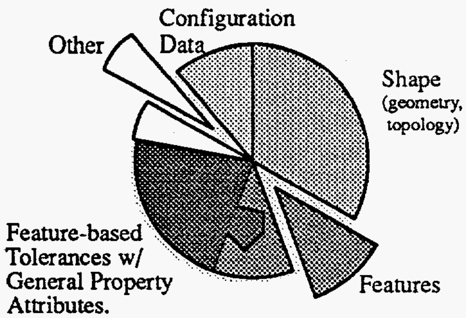

Figure 3. Feature-based Tolerances.

Of significant importance, Burkett [7] defined the principle information necessary to communicate ANSI Y14.5M tolerances using a boundary representation (BREP) solid model. Assumptions for his conceptual model were the following:

1) The connectivity of the dimensions and tolerances must correspond to the topology (faces, edges, and vertices) of a boundary representation geometric model.

2) The geometric model defines the theoretically exact or nominal shape of the object.

3) The ability to reference functional geometry that is not referenced to topological entities. This occurs with:
   a) adjunct geometry that contributes to the definition of something (e.g., hole center-lines);
   b) surface geometry on surfaces (e.g., point, curve, or sub-region);
   c) derivation geometry that is not intimately related to the shape (e.g., planar offsets);
   d) loose geometry used as information only (e.g., major reference plane of a mating object).

4) A feature capability makes it possible to address a collection of entities to which a tolerance applies as if it were a single entity.

Additional significant work involves the Consortium for Advanced Manufacturing - International (CAM-I) contracting Johnson [8] to define data structures for a Dimension and Tolerance (D&T) model. These data structures represent the dimensional and tolerance data for a part in association with a BREP geometric model. This study was significant because the data structures could be created, modified, and interrogated through an application programmer interface. It also progressed the support of tolerances to the feature classes identified in ANSI Y14.5M.

Ranyak and Fridshal [9] furthered Johnson's preliminary design by demonstrating a Dimension and Tolerance modeler [10]. The D&T modeler unambiguously represented the variational model of a part, thereby complementing the nominal solid model.

The basic foundation of the D&T model is illustrated in the Information Analysis diagram in Figure 4. The modeler is based upon the interrelationship among three high-level entity node types: features, tolerances, and datum reference frames (DRFs). Reading counterclockwise from the bottom right, a tolerance controls one or many tolerance features, where a tolerance feature defines zero or many datum reference frames via a datum designation, and each DRF is referenced by one or many tolerances. In the clockwise direction, a tolerance references zero or one DRF, a DRF is defined by one or many features, and each feature is controlled by one or many tolerances. Finally, the connectivity of the feature to the geometric model is through one or more solid model entities. Furthermore, the CAM-I D&T model had its own application programmatic interface, written in Pascal. This interface provides the modeler with the functionality of creating, deleting, and interrogating dimensional and tolerance information. Application programs requiring both tolerance data and geometric data in a computer-intelligible form can interface both the solid geometric and tolerance modelers through their respective subroutine calls.

3. FEATURE-BASED TOLERANCING

The Feature-Based Tolerance Modeler is an object-oriented system using C++ for the representation of conventional and geometric tolerances compatible with ANSI Y14.5M. It extends past work [11] and expands the foundation provided by the CAM-I D&T model. Using Booch's [12] object-oriented methodology, the top-level object-oriented domain analysis diagram is illustrated in Figure 5. The modeler is based upon the interrelationship among five class objects: tolerance features, toleranceable aspect

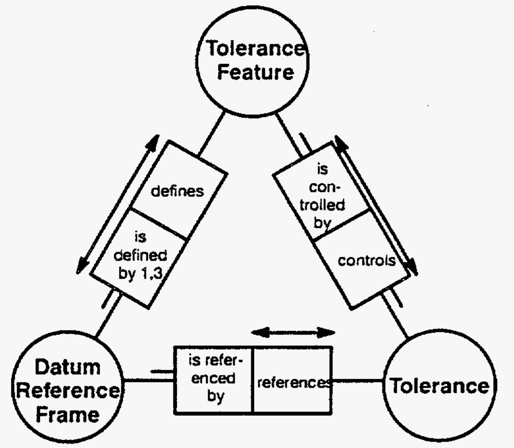

Figure 4. Tolerance Definition Interrelationship.

constraints, tolerances, datums, datum reference frames (DRFs), and an additional relationship to a solid model entity class object

3.1 Tolerance Features

The Tolerance Feature class taxonomy contained in the Feature-Based Tolerance Modeler is illustrated in Figure 6. Tolerance features are classified as either simple, feature-of-size (FOS), or compound. FOS tolerance features include internal or external cylindrical features typified as a hole or circular boss, respectively. Another FOS feature is an opposite parallel plane feature. Typical inner opposite parallel plane features are slots, while external opposite parallel plane features are sometimes described as blocks or tabs. Additional FOS features include internal and external spheres. Simple tolerance features are non-FOS such as planar faces and

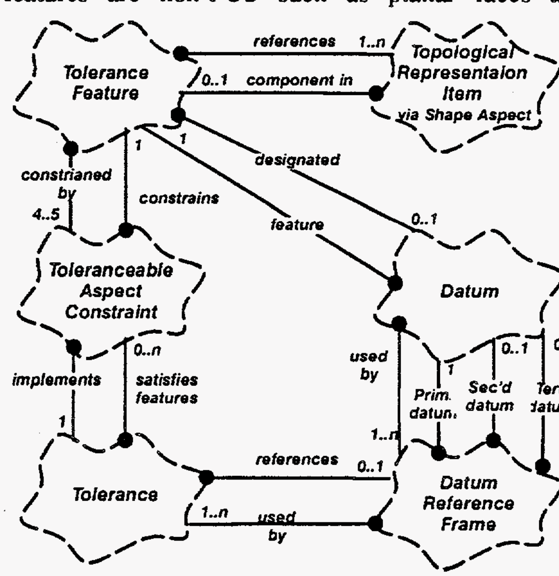

Figure 5. Feature-based Tolerance Top level Object Model.

cylindrical arc segments. These arc segments consist of less than 180° of the circumferential surface. Compound features consist of simple feature patterns, compound simple features, profile groups, revolute and linear swept features, and complex sculpture features. Simple feature patterns consist of two or many identical types of FOS features that as a group can resolve to a center-line. Examples of simple feature patterns include bolt hole patterns and patterns of tabs. Compound simple features consist of two or more geometrically identical entities or features. Examples of compound simple features are two planar faces divided by a slot that together must represent a datum or have a common tolerance constraint. A profile group feature consists of one or more arc-wise connected simple tolerance components. A profile group is usually associated with the profile tolerance. The revolute swept feature corresponds to a surface of revolution. The linear swept tolerance feature consists of a surface of linear extrusion. The complex sculpture tolerance feature consists of a bounded b-spline surface.

The Feature-Based Tolerance Modeler is implemented by referencing tolerance features with the solid model entities in the ACIS geometric model.

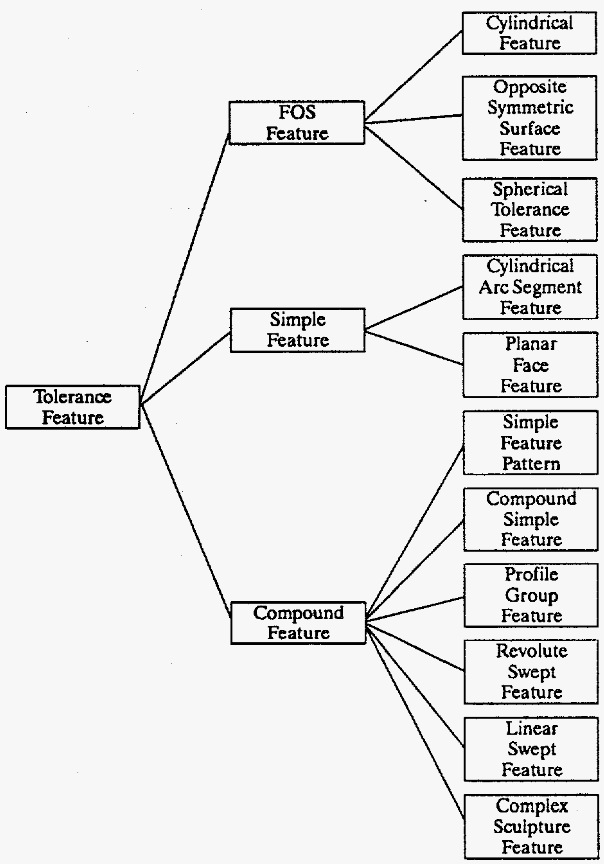

Figure 6. Tolerance Feature Hierarchy.

Each tolerance feature references one or more tolerance component entities. Tolerance component entities can be either another tolerance feature or a solid model entity consisting of either a BREP body, face, sub-face, edge, curve on surface, vertex, or point on surface. General property attributes, such as thread specifications, material type, edge breaks, or cosmetic attributes, are permitted to be assigned to a tolerance component entity. Furthermore, if a feature is designated as an explicit datum feature, the feature's resolvable is used for determining the datum reference frame's transformation matrix. This results in a mathematically explicit Cartesian coordinate system for every DRF.

3.2 Tolerances

Tolerances are created and assigned to formally constrain tolerance features. The model's tolerance classes are angle, distance, form, orientation, position, profile, radial, runout, size, and surface finish tolerances. Although these tolerances are not identical to those explicitly defined in ANSI Y14.5M, they are fully compatible. Since the ANSI Y14.5M standard is drawing-based, its tolerance classes must also convey geometric information. The Feature-Based Tolerance Modeler implements a more general approach for tolerance abstraction and permits the geometric modeler to provide the geometric information. As a result, the ANSI class for any tolerance-feature combination is derivable. For example, parallelism and perpendicularity are special cases of orientation that have a specific geometric angle relationship of 0° and 90°, respectively. Therefore, if the geometric relationship between two planar faces is 90° and they are related by an orientation tolerance, then we can easily deduce the ANSI perpendicularity tolerance. Figure 7 shows the tolerance aspects and the associated tolerance classes that may provide that constraint. The figure also shows the ANSI tolerances that can be mapped to our modeler's tolerance classes.

3.3 Tolerancable Aspect Constraints

As illustrated in Figure 7, the Feature-Based Tolerance Modeler is based upon the notion that each feature must be constrained by the toleranceable aspects of location, orientation, form, and surface finish. Furthermore, if the feature is a FOS, a size toleranceable aspect is also required. For example, a hole must have a set of tolerances that controls all five tolerance aspects. A location and a size tolerance are always given. This results in satisfying the location and size toleranceable aspects for the hole feature. Interestingly, the location tolerance provides a certain degree of orientation tolerance aspect. However, if more orientation control is required, then orientation tolerance may be added. Likewise, the size tolerance provides the feature with a default form tolerance aspect. However, if more form control is needed, a specific form tolerance may then be added. The surface finish aspect is usually applied by an overall part default unless specifically called out for a feature.

3.4 Datum Reference Frames

Each datum reference frame (DRF) may be defined by one, two, or three existing tolerance features that have been designated as explicit datum features. For dimensional measurement, each DRF actually represents an inspection set-up. As a result, the completed DRF must define a coordinate system with an explicit origin location and axis directions. The classifications of DRFs follow the CAM-I datum reference frame classes. The resolvables from a DRF's datum features explicitly define a Cartesian coordinate system. A datum feature of a DRF typically defines an axis direction and/or one or many origin coordinates. The determination of the direction and origin is influenced by the DRF's datum precedence. One DRF datum feature rule is that the primary datum's resolvable defines the Z-axis component of the resulting DRF.

3.5 Tolerance Modeler Functions

For a tolerance modeler to be complete and exact, the modeler must have functions for validation and verification of the tolerance model during creation and modification. Furthermore, upon completion of a tolerance model, the overall scheme of the model must be checked for completeness. The following are functions supported by the tolerance model design.

Feature Evaluation. The tolerance model evaluates each tolerance feature by checking the correctness of its associated solid model entities. For example, this capability allows planar face tolerance features to be assigned only to planar face solid model entities.

Feature-Tolerance Evaluation. The tolerance model validates the tolerance attributes, correctness of the tolerance's assigned feature, and correctness of each DRF. Furthermore, the tolerance model can

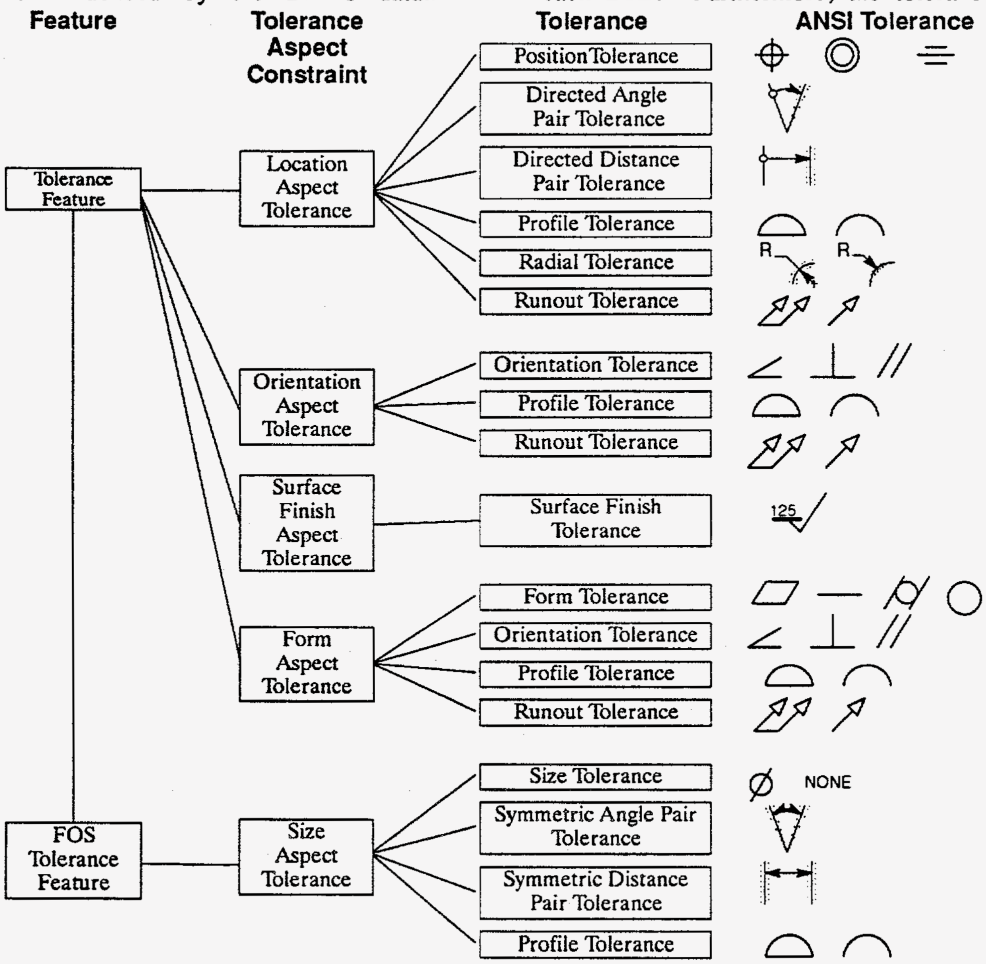

Figure 7. Tolerance Aspect Constraint Implementation.

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derive ANSI Y14.5M tolerance classes from the feature-tolerance relationship. Many tolerances must have qualifiers to help control specific aspects. Usually, these qualifiers help resolve the feature to a lower dimensionality, allowing it to incorporate specific 2D tolerances. For example, a cylindrical tolerance feature toleranced by a form tolerance with an intersection qualifier would result in an ANSI circularity tolerance. Qualifiers include FOS resolution, intersect/section, and cross-section qualifiers. Next, the tolerance model performs distance evaluation for determining dimension requirements. This is easily performed by the solid geometric modeler's capabilities. Additionally, the basic dimensions are obtained from the nominal geometric solid model.

Datum Reference Frame Evaluation. The tolerance model evaluates the defined DRF by checking for valid datum features and by creating a transformation matrix that mathematically represents a coordinate system. Datum features for a DRF must resolve to a point, line, or plane. Furthermore, if a datum feature is a FOS, then it must have a material condition modifier assigned to it.

Tolerance Model Checking. For a part to be unambiguous and fully toleranced, the location of every feature must be fully controlled and every FOS feature must have a size tolerance. The tolerance modeler performs location tolerance checking. To facilitate this capability, the modeler determines the feature's locating dimensionality, determines the part's overall datum reference frame, determines location of features with respect to DRF or implicit datums, and checks for size tolerance for any FOS features.

Geometric Reconciliation. The tolerance capability is designed to have mechanism for reconciling tolerance features upon any changes to the solid model geometry. If the topology remains intact, reconciliation is usually possible. However, if the model is unreconcilable, then any detached tolerance features will be identified for user disposal or reconciliation.

Change Propagation. The architecture permits change propagation based on tolerance modifications. The architecture allows associativity between tolerance features and associated process definition. The capability is permitted via their common "shape aspect relationship" that was modeled after STEP.

3.6 Tolerance Modeler Programmers Interface

For a tolerance modeler to successfully support advanced manufacturing applications, it must provide a programmatic interface. The Feature-Based Tolerance Modeler provides a programming interface through methods or through direct access to C++ objects. As the capability migrates to an ACIS husk, Scheme extensions will be implemented. The programmatic interface allows the capability to extract all tolerance features, tolerances, datum reference frames, and topology connectivity information. The interface is designed to provide, at a minimum, the following:

- Set and get overall and default tolerances and part DRF.
- Perform model configuration control.
- Create and delete tolerance feature instances.
- Set and get tolerance feature attributes.
- Create and delete tolerance instances.
- Set and get tolerance attributes.
- Create and delete datum reference frame instances.
- Set and get datum reference frame attributes.
- Attach and release tolerances to/from features.
- Attach and release solid model entities to/from features.
- Query features of assigned tolerances.
- Query DRFs of referencing tolerances.
- Query tolerances of a feature.
- Query tolerances of an implicit datum feature.
- Query DRFs using an explicit datum feature.
- Query solid model entities or parent feature of a feature.

4. SUMMARY

The Feature-Based Tolerance Modeler defines an approach for representing conventional and geometrical tolerances and general property attributes. The model is based on the interrelation of tolerance features, tolerances, and datum reference frames, while the tolerance features are associated to ACIS solid model entities using STEP shape aspect objects. A tolerance feature hierarchy necessary to represent ANSI Y14.5M tolerances is incorporated. The fundamental notion that every tolerance feature has toleranceable aspect constraints is discussed and implemented. Currently, the tolerance definition has been analyzed and designed using Booch's object-oriented software development methodology. C++ code has been created that supports the classes, relations, operations, attributes and inheritances represented in the design. Methods using C++ objects are presently being defined and incorporated

An objective of this work is to develop a feature-based tolerance husk. A husk is a toolkit built on ACIS that can be used along with ACIS by end-user applications developers. The husk will require both a C++ and Scheme application programmer interface. We have also demonstrated the capability of storing tolerance information as attributes to ACIS entities in a single part file. We plan to use the Visual C++ application studio to develop a Windows NT PC-based graphic user interface for creating tolerance definitions.

The described feature-based tolerance capability will explicitly represent the tolerance specification for mechanical piece parts in both final and in-process states. Methods will verify correctness and check for completeness of the tolerance definition. This capability will supply advanced manufacturing applications with accessible tolerance data and provide the product definition with complete and unambiguous tolerances.

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6. BIOGRAPHICAL SKETCH

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