The Strategic Design Driven Inspection of Machined Parts

James M. Galm and Francis L. Merat

Center for Automation and Intelligent Systems Research
Department of Electrical Engineering and Applied Physics
Case Western Reserve University
Cleveland, Ohio 44106

ABSTRACT

A system for the automatic dimensional inspection of machined industrial parts is under development. Key attributes of the system are its use of design knowledge, i.e. the CAD description of the part to be inspected and the strategic use of diverse sensors to generate geometric descriptions of the actual part being inspected as well as the designers conception of the part. Inspection reduces to the simple comparison of all components of the two models with a correct interpretation of the designer's specified tolerances. Sensors are employed in a strategic manner with low-cost sensors such as vision being used for low tolerance measurements and higher-cost sensors such as coordinate measuring machines or surface probes being used to refine object features until all object features have been compared between the CAD model and the actual object being inspected.

1. INTRODUCTION

A prototype design driven inspection system is currently being developed by the authors. As a truly design driven inspector, no initial input or "training" is required other than a CAD description of the part to be inspected. The system is strategic in the sense that a decision is made as to the dimensional integrity of the part as efficiently as possible, capitalizing on the strengths and avoiding the weaknesses, such as various levels of speed and accuracy, of the limited senses available to automatic equipment. All object features are described in a three dimensional model so that the emphasis of this paper will be upon sensors such as range imagers and coordinate measuring machines that can provide relevant three-dimensional information.

The proposed Strategic Design Driven Inspector (SDDI) receives information as to the desired geometry of the part via CAD system output. The CAD system output is assumed to contain the allowable tolerances associated with the measurable features of the object as specified by the designer. Geometric dimensioning and tolerancing provides the key by which an internal three dimensional model of the object, called the reference model, may be constructed from the CAD system output. The reference model will include, in addition to all of the relevant geometry and dimensions of the object, the required tolerances of all measurable surfaces.

Measurement of the object itself begins by the construction of an internal three dimensional model of the object based on physical observation of the object. Termed the object model, this model is represented in such a way as to allow direct comparison with the previously generated reference model.

Generation of the object model is accomplished via a fast, parallel sensor system, typically a range imager. In this context, a fast sensor is one that performs its function essentially in parallel. In general, fast sensors' tasks are not decomposable. Once enough views have been taken to permit convergence of the complete object model, the object and reference models are compared on a feature by feature basis to determine whether the object is in fact within the specified tolerances. If every feature of the object model is within the specified tolerances as defined by the reference model, the part is declared correct. If any one feature is out of tolerance, the part is rejected immediately.

Many situations will arise in which some of the feature specifications defined in the reference model will have tolerances associated with them that require measurement of the object to accuracies beyond that provided by the object model generated by a fast sensor. In order to complete the inspection, the object model is then refined on a feature by feature basis, using data from more accurate, but generally slower measuring equipment. Slow sensors generally operate in a serial mode, such that their tasks may be decomposed and planned in some optimal way. Such slow sensors may include, but are not limited to, coordinate measuring machines, optical interferometers and ultrasonic rangefinders.

The progression to slow sensors continues on a feature specific basis until a decision can be reached as to the dimensional integrity of the part. Note that ONLY those features that require refinement at any stage will be measured by progressively more accurate sensors. Thus the inspection process will reach a decision in the least possible time.

In addition to the YES/NO inspection answer demanded by high speed automated manufacturing operations, dimensional information may be recorded for analysis. Such feature specific information is important for quality control and analysis. This will help close the mechanical production loop, providing more positive feedback as to possible problems in the defined machining sequence of the part.

2. GEOMETRIC DIMENSIONING AND TOLERANCING

The ultimate source of nearly any mechanical component is a human engineer or designer. Along with the basic shape and dimensions of the part, the designer will assign tolerances to the various dimensions of the part. It is imperative that tolerances be assigned at the first stage of the part's design, as it is only at that point that the entire context in which the part operates can be evaluated[1]. Once tolerances have been assigned to the part, this information must be communicated to subsequent manufacturing operations in a clear and unambiguous way. The system of Geometric Dimensioning and

0-8186-0888-9/88/0000/0122/$01.00 © 1988 IEEE

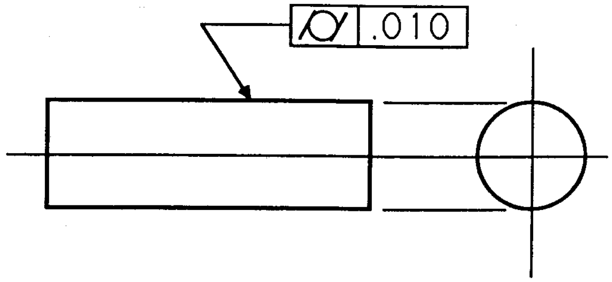

Figure 1 - Typical Feature Control Frame

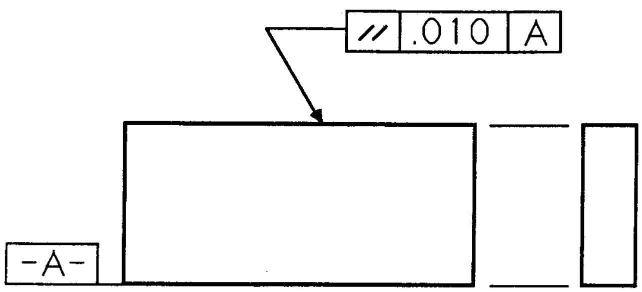

Figure 2 - Tolerances Assigned with Respect to Part Feature

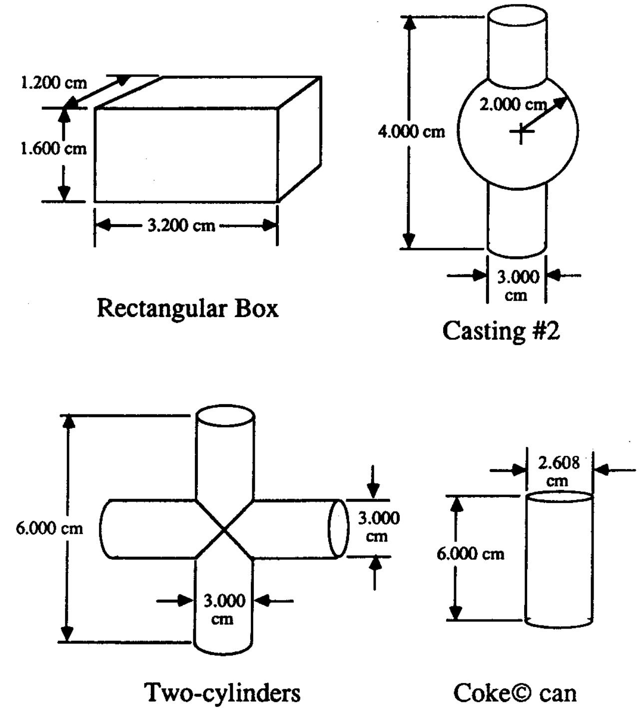

Figure 3 - Example objects

Tolerancing (GDT) has evolved as a standard terminology by which this information can be conveyed and interpreted. The precise rules of GDT are defined in the ANSI 14.5 and ANSI 14.5M standards.

The fundamental concept behind GDT is that any part may be considered as a collection of features, or measurable entities, to which tolerances may be assigned on a feature specific basis. A designer applying GDT to a part assigns Feature Control Frames (FCF's) to the features to individually define the dimensional limits within which the feature must exist in the finished part. For example, Figure 1 displays a typical FCF which describes the concentricity tolerance that the outer diameter of the shaft must posses.

Not all features may be toleranced as simply as that in Figure 1. In many cases, a tolerance must be assigned with respect to some surface or other feature of the part, as in Figure 2. Here a particular surface is defined as a base datum, here denoted by the letter 'A'. The feature control frame references base datum 'A' as the surface against which the measurement coordinates must be established to tolerance the parallelism of the opposing surfaces.

Very often, the surfaces called out as base datum planes or features in a part description coincide with convenient planes upon which to rest the part on the table of the SDDI. Such surfaces are often load bearing faces of the part, providing a ready reference from which to automatically define a coordinate frame required for operation of the various advanced sensors, such as coordinate measuring machines. However, it is possible that an abstract feature, such as a bolt circle or axis of rotation may be called out as a base datum in a particular feature's FCF. In this event, the exact location of the base datum must be extracted based on the measured locations of physical features on the part. Procedures for accomplishing this step are defined in the ANSI definition of GDT.

It can not be over stressed that the assignment of tolerance information and feature control frames is an essential part of the design process and must be available for subsequent manufacturing and inspection procedures. The existence of this a priori information regarding the location of the critical surfaces against which feature based tolerances are measured is crucial to GDT inspection.

3. DESIGN DATA INPUT

In designing a particular mechanical object, a design engineer typically visualizes the proposed device as a conceptual solid that fits within the context of a larger assembly. Traditionally, the designer's ideas are conveyed to the rest of the manufacturing world via two dimensional drawings, such as the blueprint. CAD technology has provided a mechanized means of creating these two dimensional drawings quickly and efficiently. In fact, some advanced CAD systems allow the designer to model the proposed object in three dimensions. In either case, the result of the CAD effort is a description of the part in a machine readable form, that is suitable for storage and retrieval via database systems, or migration to other processes such as automated generation of machining sequences.

The inclusion of tolerance information in the CAD data of an object follows as a logical consequence of the role such information plays in the overall design of a workable and cost effective assembly. As described previously, the GDT information is inseparable from the design itself, therefore it will be included in any CAD system output.

At the most basic level, CAD descriptions of an object, or CAD models, are stored in the International Graphics Exchange Standard (IGES) format[2]. The IGES is a machine readable code by which any geometry that might appear on the blueprint for an object may be defined. The IGES contains no direct three dimensional representation of the object, other than that contained in the multiplicity of views required to define a given geometric configuration. Thus the construction of a reference model from an IGES description will require some deductive logical operation to fill in the missing information, as outlined in the next section.

More sophisticated methods of part information communication such as the Part Definition Exchange Standard (PDES) and the Product Definition Data Interface standards are under development. Each higher level datum may represent a complete operational history of a part, including, but not limited to, geometry, GDT, materials specifications and machining sequences. At this point, such standards are in the process of formalization; hence, little is known as to the exact contents of such datums. If these standards contain explicit three dimensional information regarding the part, the construction of the reference model will be greatly simplified.

4. REFERENCE MODEL CONSTRUCTION

Once the basic design data has arrived at the SDDI, it must be interpreted into an internal model of the object in question. The basic format of this internal model is a surface adjacency graph with the nodes of the graph representing characteristics of the individual object surfaces and the arcs of the graph representing the geometric adjacency or connection of surfaces. Figure 3 presents some specific objects which have been used in this work[3], a simple box and a corresponding schematic representation of an internal reference model.

In the case of CAD input in the form of the IGES, a level of interpretation will need to be applied to the CAD data to deduce a three dimensional model. Drafting standards vary slightly from organization to organization, however the basic methodology remains consistent. Interpretation of these CAD pictures will require the existence of a consistent set of rules for geometric interpretation. Note that while we require these logical rules to form a consistent set, we do not require them to form a complete set. Indeed, since the exact details of various drafting standards are not constant, such a complete set would be impossible without constraining the set to one specific organization's drafting standards.

The rules of geometric interpretation are most concisely expressed in terms of the predicate calculus[4]. Any set of rules expressed in this way will be verifiable, in that it will always be possible to form the closure of the set, thus expressing all possible deductions with respect to a given premise. The natural vehicle for programming in the predicate calculus is the PROLOG language[5].

As described in Section 2, the GDT applied to the object follows a specific set of logical rules. These rules are defined as unambiguously as possible by the ANSI committee responsible for the maintenance of the ANSI 14.5 and ANSI 14.5M standards.

In order to interpret the rules of GDT, they must be encoded into a machine usable form. The logically expressive nature of the predicate calculus provides a natural means for encoding the GDT rules. Rules expressed in the predicate calculus are easily maintained and updated as necessary, since their clarity is as easily exploited by humans as by machines. PROLOG provides a number of unique advantages over other languages commonly used for deductive programming, such as Lisp. Since the fundamental format of the PROLOG language is the predicate calculus itself, encoded GDT rules may be programmed with very little modification.

In the situation of reference model construction, it should be stressed that at no time is the SDDI required to make inferences as to the details of the model. The CAD data input, if correctly executed, will contain a complete, unambiguous description of the relevant geometry and GDT for the object. The SDDI is thus freed from the necessity of inductive logic to accomplish its goal of reference model construction. Inductive logic would require the use of artificial intelligence or expert system techniques, which although quite powerful, can lead to unverifiable results when confronted with a new situation. By forcing the SDDI to operate in a strictly deductive manner, the SDDI may be freely expanded by new rules without danger of generating unwanted side effects or compromising the verifiability of the results.

The PROLOG language is a naturally deductive programming system, releasing as output the SDDI's reference model as the direct deductive consequence of the CAD input under the rules of geometric interpretation and GDT.

5. OBJECT MODEL CONSTRUCTION

The object model is constructed in the form of a surface adjacency graph similar to that produced by the reference model generation process. This particular construct allows efficient estimation of the pose and orientation of the object by decoupling surface specifications and intrasurface relationships from their environment. Isolation of the object from its immediate surroundings is an important consideration in automatic inspection in the FMS environment. The very nature of the FMS environment prevents the development of specialized inspection fixtures for all parts that could be manufactured by the FMS cell due to its intrinsic flexibility. A fast sensor such as vision can be used to recognize an object and to estimate its pose. In the inspection scenario, the part is always known in advance and only fixturing and dimensioning fall into the domain of the inspector. The surface adjacency model referred to above separates the relationship between the object features, which are pose-independent, from the object orientation or pose. In traditional manual inspection practice, the pose-dependent information is usually removed from the inspection process through the use of specialized fixtures. Our system performs this step in software. The major restriction of the existing software system is that it is restricted to three dimensional objects described by quadratic surfaces. In practice, this eliminates objects which use higher order surfaces or splines for this definition as well as specialized surfaces such as screws and turbine blades; however, quadratic surfaces account for approximately 85% of all manufactured objects[6].

Because of the importance of the object model description we will describe the object model in greater detail and how it can be constructed from fast sensor information. Model refinement and decision making will be discussed in later sections.

This discussion will assume the use of a fast sensor of sufficient information density to permit recognition of sufficient object features to estimate object pose. The actual information is processed using a coarse-to-fine resolution strategy based upon detected geometric discontinuities as described below. The object model is based upon a hierarchical feature space composed of points, patches, edges and surfaces. This ordering represents increasing abstraction as well as the more global nature of the knowledge. A set of smoothly connected points in a very small area forms a patch which possesses curvature and surface normals. Edge points occur where there are sharp discontinuities in point depth values, surface normal direction, or curvature. A set of smoothly connected edge points represents a edge. A set of patches having similar local characteristics such as surface normals or surface curvatures in a connected area forms a surface. Finally, global surface

object id: 2
class: cast2

surface id: 4
class: CIR_CYL
centroid: 0.000, 0.000, 0.000
rtype: 1
pos: 0.000, 0.000, 0.000
vec: 0.000, 0.000, 1.000
orient: -1.571, 0.000, 0.000
normalized surface eqn:

$$\begin{bmatrix} 1.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 1.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & -2.250 \end{bmatrix}$$

constype: 1
pos: 0.000, 0.000, 0.000
vec: 0.000, 0.000, 1.000
orient: -1.571, 0.000, 0.000
transformed surface eqn:

$$\begin{bmatrix} 1.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 1.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & -2.250 \end{bmatrix}$$

surface id: 5
class: SPHERE
centroid: 0.000, 0.000, 0.000
rtype: 1
pos: 0.000, 0.000, 0.000
vec: 0.000, 0.000, 0.000
orient: 0.000, 0.000, 0.000
normalized surface eqn:

$$\begin{bmatrix} 1.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 1.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 1.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & -4.000 \end{bmatrix}$$

constype: 0
pos: 0.000, 0.000, 0.000
vec: 0.000, 1.000, 0.000
orient: 0.000, 0.000, 0.000
transformed surface eqn:

$$\begin{bmatrix} 1.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 1.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 1.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & -4.000 \end{bmatrix}$$

surface id: 6
class: CIR_CYL
centroid: 0.000, 0.000, 0.000
rtype: 1
pos: 0.000, 0.000, 0.000
vec: 0.000, 0.000, 1.000
orient: -1.571, 0.000, 0.000
normalized surface eqn:

$$\begin{bmatrix} 1.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 1.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & -2.250 \end{bmatrix}$$

constype: 1
pos: 0.000, 0.000, 0.000
vec: 0.000, 0.000, 1.000
orient: -1.571, 0.000, 0.000
transformed surface eqn:

$$\begin{bmatrix} 1.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 1.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & -2.250 \end{bmatrix}$$

neighboring relations: 4—5 5—6

Figure 4 - Example of object and surface descriptions for "Casting #2" of Figure 3.

characteristics such as the surface type and surface equation can be extracted from the surface. An object is then described by a structural combination of surfaces and their characteristics. The form of this object description is a surface adjacency graph similar to that described in Section 4 except without tolerance information. Adjacent surfaces will be connected at their edges and adjacency relationships are inferred from the measured edges. The surfaces in this graph are identified by a surface identifier (for internal use only), a surface classification (such as parabolic, spherical, planar, etc.), a normalized surface equation, a non-normalized surface equation, a surface orientation, a surface position, the number of image points represented by this surface, the image coordinates of the center of the image area, and a list of all neighboring (connected) surfaces. This is illustrated in Figures 3 and 4 for a finished casting.

The reference object description contains a complete surface adjacency graph of the object since all object information is known from the CAD model. The object model description will be a subgraph containing (at first) only those object features that can be seen in a single view (assuming a vision sensor is first used). This subgraph will become more complex as the model is successively refined by additional views (either by object manipulation or additional sensors) or slower sensors.

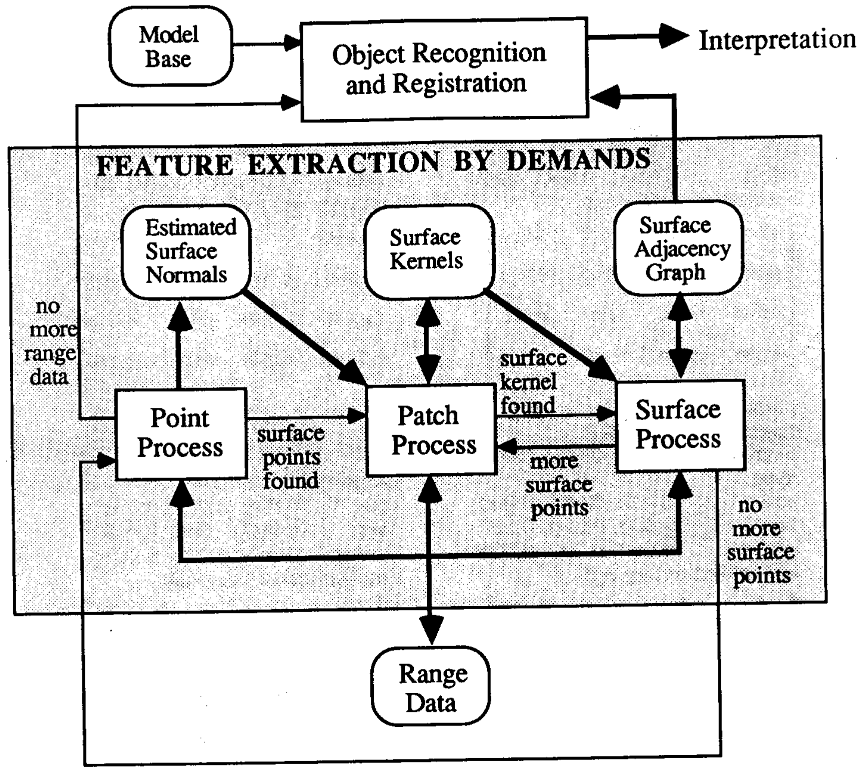

Figure 5 - Schematic of object model generation from range data

Surfaces in both models are described in terms of surface equations referenced to the centroid of the object where the object centroid is defined by intersections of the principal axes of individual surfaces. The principal axes of an object is defined by relationships between the surfaces. The pose of the object can then be described as a rotation and translation of the reference model so as to exactly match the object model. Note that certain objects such as spheres and cylinders may not have a unique pose in one or more dimensions. For many geometric objects, it has been shown that recognition and registration of three surfaces is usually sufficient to uniquely identify the position and pose of an object.

Object model generation has been implemented in a three-dimensional vision system and is currently in operation using the system shown schematically in Figure 5. The incoming range data (initially from a raster scanned sensor) is decomposed into overlapping patches to extract local characteristics. Surface segments are extracted using local object characteristics estimated from the patches. Global object characteristics are then extracted from each segment. With the guidance of global characteristics, surface patches are grown and global object characteristics are again extracted. The segments and object characteristics associated with segments form surfaces. Finally, extracted surfaces are combined into object descriptions using their adjacency relations.

The system extracts different object characteristics and combines different levels of object features from three dimensional image data using three different processes: point, patch and surface processes. One aspect of this system is its ability to mask out areas of the object as uninteresting. The system uses a variable focus principle which concentrates data processing near regions of geometric discontinuity (range, normal or curvature) and masks out regions of slowly varying range, normal or curvature as uninteresting. This is possible due to the bottom-up, top-down nature of the communications between the processes shown in Figure 5. The complete process of reducing the three-dimensional data to a surface adjacency graph is known as Feature Extraction by Demands and has been described elsewhere[7].

The above model has immediate applications in computer vision and object recognition; however, it is easily extended to be useful for geometric inspection. The extension of the above described model based vision system to include geometric tolerancing has been dubbed the Geometric Description System or GDS and is currently implemented only for polyhedral objects. The major distinction between the inspection model used by GDS and the previous surface feature based model is the use of edge information to generate geometric dimensions. The model based vision system prior to GDS did not use the edge information. GDS identifies edge points and fits a parametric straight line to each edge (all edges will be straight for polyhedral solids). A priori design information can be used to globally optimize edge and corner estimates for certain classes of dimensional specifications. Because the edges are boundaries of individual surfaces rather than unique entities, each surface has its own edges. Corner points are often difficult to find in the original imagery due to spatial tessellation, lighting, segmentation algorithms, etc. However, the use of design

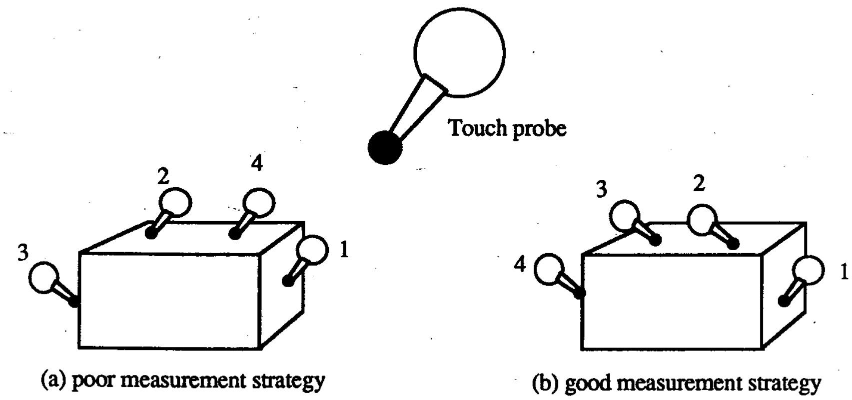

Figure 6 - Possible strategies for guiding a CMM for surface refinement

constrains such as equal edge lengths, parallel edges, right corner angles, etc. may be used to constrain the location of corner points (for each surface). The constraint that rectangular surfaces have equal length diagonals has proved extremely useful in locating the corners of such surfaces and detecting missing corners.

The actions of the GDS on any specific feature will be a function of the contents of any feature control frames associated with that specific object feature. Although GDT allows a rather large number of possible specifications for any given object most manufactured objects only possess several features which are actually toleranced. GDS only evaluates those dimensions and tolerances specifications which have been specified by the designer.

A subset of GDT specifications has been implemented in the current GDS. For example, intrasurface distances (i.e. between edges) are dimensioned. In GDT, a rectangular surface is NOT dimensioned by the distance between the two "parallel" edges; rather it is dimensioned by an actual measured edge relative to a reference plane. This reference plane can be a physical plane or it can be a software construct based upon known surface points. The perpendicular distances from known edge points to the reference plane are easily calculated and the maximum and minimum distances then define the tolerance band around the average distance. Distances between surfaces are generated using the present GDS. A reference surface must be known (or automatically generated) for this type of measurement. Since GDS contains surface equations the mean distance between the reference surface and the surface of interest is easily calculated. Tolerance bands are calculated using the minimum and maximum perpendicular distances from the measured surface to the reference surface. Another specification implemented in the present GDS is surface flatness. This is defined in three dimensions using the maximum perpendicular distance of identified surface points from a "least squares fit" surface equation.

Many GDT specifications require additional information in the form of feature control frames and reference plane information which is not yet implemented in GDS. Reference planes can be automatically assigned by the inspection system but such practice does not represent design knowledge. Additional knowledge about load bearing surfaces, use of the part, etc. MUST be present for correct tolerance measurements.

6. MODEL COMPARISON AND REFINEMENT

Once both the reference model and the object model have been derived from the available CAD and fast sensor data respectively, they are compared on a feature by feature basis. Since the number of individual features of a part seldom exceed the order of 10^2, they are most conveniently stored in the form of an ordered linear list designated the feature list. Features may then be compared by examining the tolerance information in the reference model, and performing a check to determine whether the corresponding feature of the object model falls within the prescribed limits. Since there exist a number of different measurement situations within the scope of GDT verification within the GDS framework, other features of the object may be referenced in the comparison process. For example, an FCF specifying a cylindricity tolerance is "self contained", in that only the non-normalized surface equation must be employed to reach a decision. However, a diameteral tolerance zone FCF applied to a drilled hole under maximum material conditions requires the specification of three base datum planes to locate and decide on the location of the hole.

If at any point within the traversal of the feature list, a feature is located whose object model representation falls outside the bounds of the tolerances associated with the corresponding reference model feature with certainty, the part under inspection is rejected. If required, a notation of the defective part and particular feature may be made to aid in quality improvement procedures.

Reaching the end of the feature list having found only features that exist with certainty within the limits of the prescribed tolerances, the part is accepted. In general, however, there may be features whose prescribed tolerances are smaller than the accuracy associated with the object model generated by the GDS. In this case, the object features in question are added to a list of features in need of refinement. A corresponding list is generated of the corresponding reference model features. Upon reaching the end of the initial feature list, the basic model refinement cycle is commenced.

In contrast to the initial data acquisition by a fast sensor, data required for refinement is generally acquired by one of the class of slow sensors. Typical of slow sensors, the coordinate measuring machine (CMM) is a serially operating, tactile device, whose operational throughput may be greatly enhanced by optimization of the data collection task. For example, Figure 6 presents two possible measurement strategies for guiding the CMM.

Optimization of the slow sensor data acquisition process then becomes a matter of reordering the elements of the list of features to be refined. The decomposition of serial robotic tasks has been the topic of much recent research, and can be accomplished by any one of a number of techniques[8].

As noted in the description of the GDS under the constraints of GDT, a priori knowledge of the required base datum planes is mandatory for successful refinement of a feature whose FCF references other surfaces. Depending upon the particular characteristics of the FCF data on surfaces other than the feature in question may be required. Completion of all requested dimensions and feature specifications using the initial fast sensor will initiate examination of the feature feature refinement list. The refinement requests will be examined and sensor measurements planned so as to represent an ordered inspection strategy. For example, measurements on an exposed surface with a CMM should be executed before the object is manipulated to examine a previously obscured surface by any sensor. The resulting refinement process can then be considered in some sense to be optimal.

In general the feature by feature refinement strategy may be carried out iteratively, employing progressively more accurate measuring equipment with each iteration. However, in most practical industrial environments, the accuracy of a CMM (up to ±0.000005 inches for high quality machines) will be sufficient for refinement of an object model.

7. SUMMARY AND CONCLUSIONS

The SDDI research program, although only partially implemented at this time, has provided a number of unique operational components in addition to demonstrating proof of concept for several others. The generation of view independent object models from range imagery has been successfully demonstrated. Reasonable execution times have been noted in actual operation. A typical standard range image from the University of Utah database yields an object model in approximately 30 seconds, with unoptimized software running on a Digital Equipment Corporation MicroVAX II system. Furthermore, a priori information has been successfully used to implement a subset of the Geometric Dimensioning and Tolerancing specifications on key features of polyhedral objects. The extension of this technique to more general tolerance specifications and object geometries seems achievable.

Near term goals for the SDDI research program include encoding a verifiable set of geometric interpretation rules in the predicate calculus. Straightforward translation of this set of rules into the PROLOG programming will yield an automatic procedure by which three dimensional models of a class of objects may be deduced from a CAD description of the object. In addition, logical interpretation of a subset of the Geometric Dimensioning and Tolerancing standards will allow these models to contain complete tolerance specifications for the object to be inspected.

The concept of progressive refinement of object models via data from multiple diverse sensors will allow decisions to be made as to the dimensional integrity of the inspected object in minimal time. By concentrating the use of slow, costly sensors to those features of the object whose tolerances demand their use, at least part of the inspection process may be carried out in a time optimal manner.

8. References

[1] Joshua U. Turner and Michael Wozny, "Tolerances in computer-aided geometric design," *The Visual Computer,* Volume 3, p.214-226, 1987.

[2] See for example J.Encarnacao, R.Schuster and E.Voge, Product Data Interfaces in CAD/CAM Applications, Springer-Verlag: Berlin, 1986.

[3] C.Hansen and Tom Henderson, UTAH Range Database, University of Utah, Salt Lake City, Technical Report UUCS-86-113, 1986.

[4] Mendelson, Elliott, *Introduction to Mathematical Logic.* New York:Van Nostrand, 1979.

[5] Sterling, Leon and Shapiro, Ehud. *The Art of Prolog.* Cambridge: MIT Press, 1986.

[6] B.F.Nource, R.C.Hillyard and P.F.Malraison, Natural Quadrics in Mechanical Design, SIGGRAPH/81 Seminar: Solid Modeling, Texas, August 1981.

[7] See for example:

H.S.Wu and F.L.Merat, "Recognizing and Locating Objects Using Partial Object Descriptions Generated by Feature Extraction by Demands," 1987 SPIE Conference on Intelligent Robotics and Automation, Cambridge, Mass., 1987.

F.L.Merat and H.Wu, "Generation of Object Descriptions from Range Data Using Feature Extraction by Demands," 1987 International Conference on Robotics and Automation, Raleigh, North Carolina, April 1987.

Hsiang-lung Wu, "Recognizing and Locating Three-Dimensional Objects From Range Data Using Feature Extraction by Demands," Ph.D. dissertation, Case Western Reserve University, 1988.

[8] See for example:
Richard E.Fikes, Peter E. Hart and Nils J. Nilsson, "Learning and Executing Generalized Robot Plans," Artificial Intelligence, Volume 3, p.251-288, 1972.

Supachai Tangwongsan and K.S.Fu, "An Application of Learning to Robotic Planning, " *Int, J. of Computer and Information Science*, Volume 8, No.4, p.303-333, 1979.

Scott Fahlman, "A Planning System for Robot Construction Tasks, " *Artificial Intelligence*, Volume 5, p.1-49, 1974.