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DIGITAL LIBRARY SUPPORT FOR ENGINEERING DESIGN AND MANUFACTURING

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ABSTRACT

This paper describes our initial efforts to deploy a digital library to support engineering design and manufacturing. This experimental testbed, *The Engineering Design Repository*, is an effort to collect and archive public domain engineering data for use by researchers and engineering professionals.

CAD knowledge-bases are vital to engineers, who search through vast amounts of corporate legacy data and navigate on-line catalogs to retrieve precisely the right components for assembly into new products. This research attempts to begin addressing the critical need for improved computational methods for reasoning about complex geometric and engineering information. In particular, we focus on archival and reuse of design and manufacturing data for mechatronic systems. This paper presents a description of the research problem and an overview of the initial architecture of testbed.

INTRODUCTION

This paper describes our initial efforts to deploy a digital library that supports engineering design and manufacturing. This experimental testbed, *The Engineering Design Repository*,[1] is an effort to collect and archive public domain engineering data for use by researchers and engineering professionals. This research attempts to begin addressing the critical need for improved computational methods for reasoning about complex geometric and engineering information.

Geometry, in the form of 3D solid models, is ubiquitous in a diverse array of fields including architecture, graphic arts, entertainment, medical informatics, computer-aided design (CAD), and engineering and manufacturing. Currently there are over 20 billion CAD models[2]—representing a digital library of immense scope, diversity, and importance. In engineering, it is conservatively estimated that more than 75% of design activity comprises case-based design (28)—reuse of previous design knowledge to address a new design problem. As illustrated in Figure 1, CAD knowledge-bases are vital to engineers, who search through vast amounts of corporate legacy data and navigate on-line catalogs to retrieve precisely the right components for assembly into new products.

This paper is primarily concerned with the libraries to support the design and manufacture of *mechatronic systems*: electromechanical systems that combine electronics and information technology to form both functional interaction and spatial integration in components, modules, products, and systems. Typical examples of mechatronic systems include automatic cameras, miniature disk drives, missile seeker heads, and consumer products like CD players, camcorders, and VCRs. These designs include mechanical and electronic components. The CAD knowledge includes product data models, such as the CAD model of a missile seeker assembly pictured in Figure 2, and related meta-

[1] Formerly the *National Design, Process Planning, and Assembly Repository* at the National Institute of Standards and Technology.

[2] Source: Autodesk, Inc.

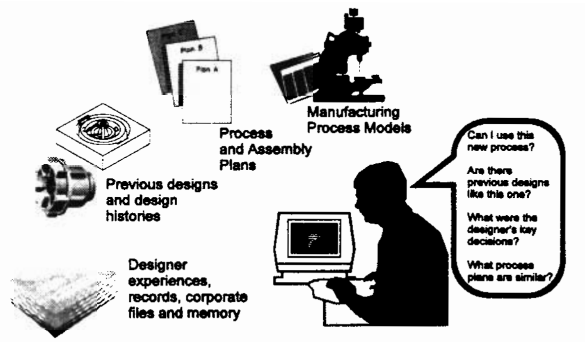


Figure 1. THE DESIGN KNOWLEDGE-BASE SCENARIO: ENGINEERS ACCESSING LIBRARIES OF PROJECT DATA TO IDENTIFY IDEAS AND SOLUTIONS TO NEW PROBLEMS.

data (process and assembly plans, documentation, etc).

The long term goal of The Engineering Design Repository Project is to develop the computational foundation and algorithmic tools to support content-based retrieval from large engineering knowledge-bases. This paper presents a description of the research problem and an overview of the initial architecture of testbed. Section provides an overview of related work and sets the context for this research. Section introduces a formalization of the problem, defines some of the technical issues, and describes the architecture (both hardware and software) for deploying the testbed. Lastly, Section discusses our current and future research directions and offers some conclusions based on current results.

BACKGROUND AND RELATED WORK

In engineering practice, indexing and storage of parts and part families had been done with group technology coding (24). Group technology facilitated process planning and cell-based manufacturing by imposing a classification scheme on parts. GT codes specified classes using alphanumeric strings. These techniques were developed prior to the advent of inexpensive computer technology, hence they are not rigorously defined and are intended for human, not machine, interpretation.

Database developers and academic researchers are actively researching how to handle multimedia data (19). This includes digital libraries (2) and commercial systems (12; 11). In general, the approach has been to develop domain-specific layers to be built on top of a standard relational (or object-oriented) databases—providing an API that is focused on the particular needs of an application area (such as solid modeling and engineering design). For example, Jain et al. and Virage Inc. (3; 12) have methods for multimedia data such as pictures (GIF, JEPG, etc.). The approach draws on work in computer vision and is based on the creation of feature vectors from 2D images to capture concepts such as color, density, and intensity patterns. Their work in extending these techniques to 3D CAD data treats the CAD information as sets of 3D feature vectors.

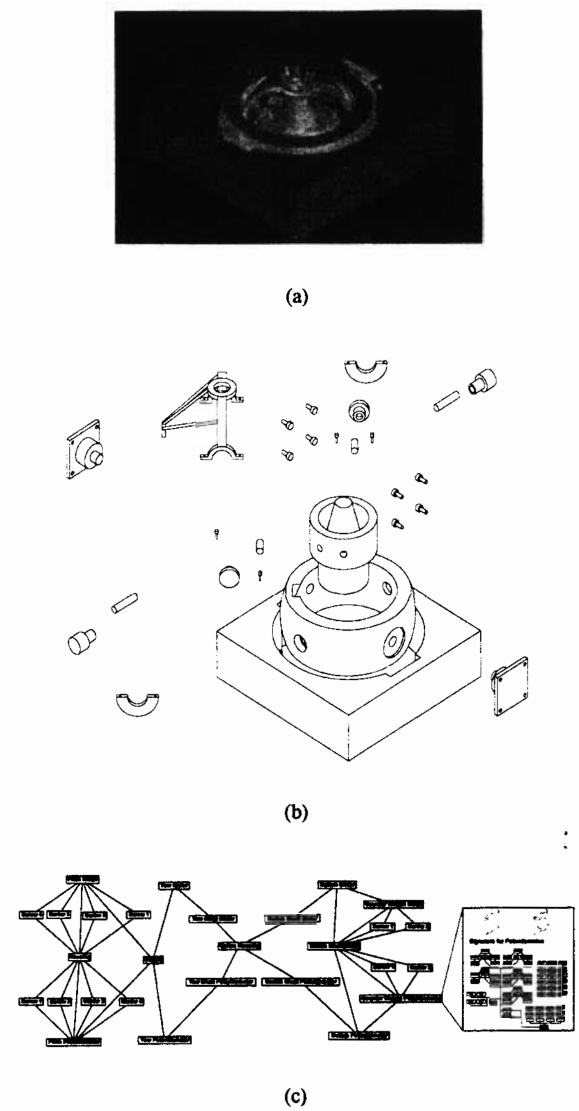


Figure 2. AN EXAMPLE OF A MECHATRONIC SYSTEM: A SIMPLIFIED MISSILE SEEKER ASSEMBLY (13) ALONG WITH ITS ASSEMBLY STRUCTURE.

In broader computer vision research, a fundamental problem is the identification and matching of models of interest in images. There have been many more research efforts in this direction than can be cited here; however, some of those more relevant to the recognition of engineering data and solid models include (4; 25; 5; 26; 29; 18). These efforts address a different problem than the one introduced in this paper–one in which the main technical challenges focus on the construction of models from image data obtained from cameras and range finders. One example is 3D Base (4) from Dartmouth, which operates by converting CAD models (a solid model or surface model) into an IGES-based neutral file then deriving a voxel (3D grid) representation. The voxels are used to perform pair-wise comparisons among the CAD files using the geometric moments of the voxels and by comparing other per-computed part features (such as surface area). These vision-based matching techniques are highly dependent on data types relating to pixels, range information, color and texture, hence they are not directly applicable to domains in which one has ready access to exact representations of geometry and topology in the form of solid models.

Specific to engineering applications, database management has been an area of active study for many years. Will et al. is pursuing an ontology-based approach to catalogs (17), though at present not tightly coupled with geometric data or with representation of tolerances and features. In the domain of civil engineering and architecture-engineering-construction (AEC), Eastman et al. (6; 9; 8; 7) have been developing methods for linking design entities (such as windows, doors, etc.) with semantic information to manage design constraints among multiple users operating simultaneously on a project.

While a great deal of work exists on geometric databases and digital libraries for Geographic Information Systems (GIS) (1), relatively little exists on digital libraries for the specific domain of 3D CAD and solid models. Part libraries and catalogs have been an area of active study by the standards community (15; 20). A survey on geometric databases in general can be found in (16). Hardwick et al. (14) have merged databases with the Internet and STEP-based standards. Lastly, over the past three years the author has initiated the National Design Repository (21; 27), a publicly accessible collection of engineering designs and engineering data.

RESEARCH APPROACH

Previous research in diverse areas such as computer-aided process planning, case-based design, and AI have developed many techniques for modeling the function, intent, and behavior of mechatronic systems. The common element in the vast majority of these representations are symbolic models of the design, manufacturing operations, plans, etc.

Our approach is to develop structures for capturing the relationships among design attributes (geometry, topology, features) and symbolic data representing other critical engineering and manufacturing data (tolerances, process plans, etc.). This section give a brief overview of our techniques for associating heterogeneous sources of engineering data with the geometric and topological description of the CAD or solid model defining the mechatronic artifact.

Problem Formalization

A *design*, D, for a mechatronic artifact (i.e. a part, assembly, etc.) is defined (recursively) as a tuple $D = \langle P, \mathcal{D}, A, M, L \rangle$ where: P is the geometric/topological model of the artifact consisting of the component's (or the assembly's) boundary representation; $\mathcal{D}$ is a finite set $\mathcal{D} = \{D_1, D_2, \ldots D_n\}$ of zero or more designs that are subcomponents of $\mathcal{D}$; A is a finite set $A = \{\alpha_1, \alpha_2 \ldots \alpha_n\}$ of zero or more design attributes. Intuitively, a design attribute is a symbolic piece of information about the design—examples include design and manufacturing features, tolerances, functional models, etc.

M is a finite set of methods (functions) associated with the design attributes in A,

$$M = \{M_{\alpha_1,1}, M_{\alpha_1,2} \ldots M_{\alpha_1,j}, M_{\alpha_2,1}, M_{\alpha_2,2} \ldots M_{\alpha_2,k} \ldots\}.$$

The functions in M are specific to the particular attributes being modeled; for example, $alpha_1$ is a engineering tolerance, $M_{\alpha_1,1}$ returns the tolerance value, and $M_{\alpha_1,2}$ the type of the tolerance (e.g., planarity). The attribute set can also represent relationships among components in an assembly design: $alpha_2$ can be an assembly joint, $M_{\alpha_2,1}$ notes the subcomponents of $\mathcal{D}$ that are mated, and $M_{\alpha_2,2}$ the relationships and transformations among these components.

Lastly, L is a mapping $L : A \to 2^P$ that relates the attributes to subsets of the geometric and topological elements in the boundary model, P, of the design. Given a design attribute α_1, $L(\alpha_1)$ returns the collection of boundary model entities associated with the design attribute α_1. A design D is a primitive design if the set $\mathcal{D}$ of subcomponents is empty.

Signature Structures

A mechatronic design and its design attributes can be represented as a graphical structure we call a *design signature*. The *design signature* for a design D, S_D, is a hypergraph $H(V,E)$ with labeled edges, where V is the set of vertices $V = \{v_1, v_2, ..., v_n\}$, and E is the set of edges $E = \{e_1, e_2, ..., e_m\}$, $e_i = (v_j, v_k)$ and $e_i \in E$ if and $v_j \in A$ and $v_k \in L(\alpha_1)$. Two design signatures, D and D', are equivalent ($D = D'$) if their hypergraphs are isomorphic; two signatures are similar ($D \sim D'$) if $|V| = |V'|$ and $|E| = |E'|$.

Consider the design of a bracket. Figure 3 illustrates a design signature (slightly simplified) for a very simple example of a machined bracket. Figure 3 (a) shows the solid model of the bracket and the topological relationships in its boundary model. Figure 3 (b-d) show the design attributes for this model: design features, tolerances, and machining features.

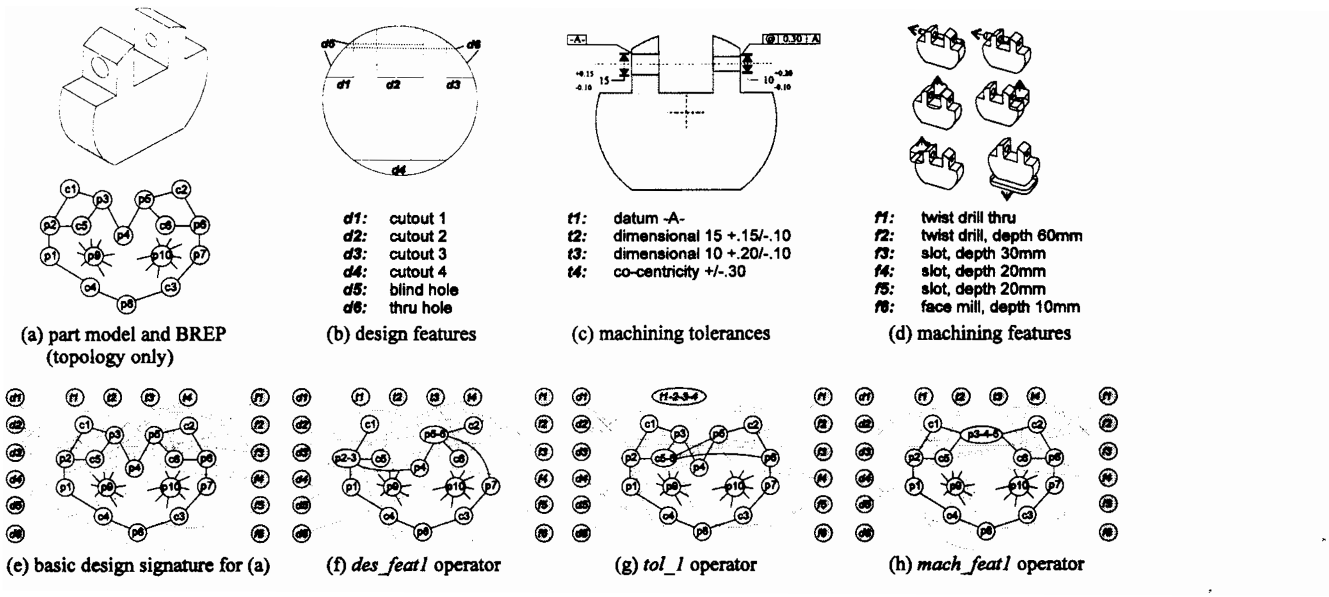


Figure 3. SIGNATURE STRUCTURES: AN ILLUSTRATION OF (A) A DESIGN OF A SIMPLE BRACKET AND ITS ATTRIBUTES (B-D); A DESIGN SIGNATURE (E); AND THE EFFECT OF THREE TYPE OF OPERATORS THAT ACT ON SIGNATURES (F-H).

Figure 3 (e) shows the hypergraph of the basic design signature, S_D, for the bracket. Figures 3 (f-h) illustrate the effect of different operators on S_D. The operator `des_feat1` takes a signature S and a design feature d as input and returns a signature S' with the nodes of S created by d combined into a single node.

An operator, g, is a function that transforms design signatures into simpler signatures by modifying nodes and vertices in the hypergraph S_D. Operators can define sequences of signatures for a given design, $\{S_{D,k}, S_{D,k-1}, \ldots, S_{D,1}\}$, where $S_{D,k}$ is the most detailed basic design signature and for each i, $S_{D,i-1}$ is either isomorphic to $S_{D,i}$ or is more abstract (i.e., has fewer nodes and/or edges). Figure 3 (f) shows the result of applying an operator `des_feat1` to each of the two cutout features, d_1 and d_3. The operator tol_1, shown in Figure 3 (g) takes a signature S and a tolerance attribute t as input and modifies S by (1) combining all nodes in S that share edges with t into a single node n and (2) combining all tolerance nodes sharing edges with n into a single node. Lastly, Figure 3 (h) shows an operator that acts on machining features.

Knowledge Storage

Generation of design signature, operators and their storage in the knowledge-base is accomplished via feature recognition from the CAD models (23; 22). In practice, information about tolerances, design features and other knowledge is already associated with the design data in some fashion. For these cases, feature extraction is a relatively straightforward translation of the attribute data for the CAD model into attribute data in the design signature graphs. This can be implemented using the native functions for the particular CAD system the data is stored, or using standard data exchange formats (such as STEP). For example, if the data was created in SDRC I-DEAS, one could create an I-DEAS plug-in (using their CORBA-based Open I-DEAS development API) to export the needed data and relationships.

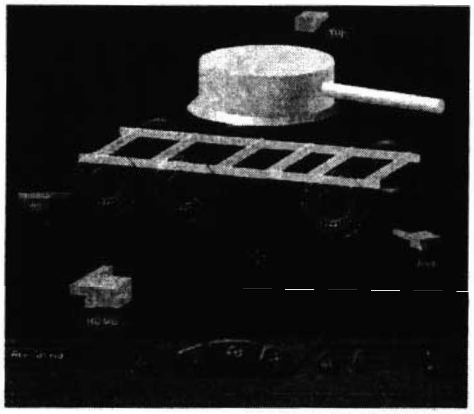
In cases where the data is not associated with the CAD model a priori, feature recognition can reconstruct the needed indexing information. Working feature identification systems have been demonstrated for finding manufacturing, design, and some types of assembly features (23; 22).

Knowledge Retrieval

Knowledge retrieval from the Repository is accomplished using graph matching and approximation algorithms to compare design signatures. The basic process is to *hash* the signature structures and insert them (along with the CAD data and attributes) into the knowledge-base. The operators, such as those described in Figure 3, are use to form a hierarchical index into the knowledge-base.

While the core of the retrieval process is NP-hard (testing graph isomorphism to determine if pairs of signatures are equal), based on our previous experiments (10), we know that making extensive use of engineering domain knowledge and domain-specific heuristics significantly improves the performance, both reducing the number of isomorphism-based equivalence checks and directing the search toward application of more promising operators.

In addition, these experiments have indicated that the task of computing isomorphism among signature graphs is largely a matter of symbolic comparisons on integer data; and proves to be considerably cheaper than the extensively floating-point geometric computations required for reasoning directly with complex CAD.



(a)

(b)

Figure 4. CONCEPTUAL DRAWING FOR A COLLABORATIVE QUERY INTERFACE FOR THE REPOSITORY. (A) OUR GOAL IS TO ALLOW A USER, OR GROUP OF USERS, TO ENTER AN ABSTRACTION OF THE DESIGN, (B), AND HAVE IT GENERATE A SIGNATURE STRUCTURE FOR USE IN THE QUERY.

System Requirements

The mathematical formalization of Sections and Section identifies several of the major technical aspects of the project. However, the Design Repository is intended to be a knowledge archive for engineers, researchers, and students. Hence, it is worth noting several user scenarios and describing the types of interactions with our store of engineering knowledge that the Repository will have to support. In particular, recalling Figure 1, we envision the following user community:

1. *Undergraduate and Graduate Students:* The Repository will eventually be a living textbook of examples and case studies that can be used for reference, training, and as a source for benchmark challenges. This activity will involve the participation of graduate and undergraduate students at many universities.
2. *Researchers and Developers:* The R&D community can now access case studies and new examples; benchmarks and standards can be defined; plus use the Repository as a vehicle for enhanced collaboration. This will allow researchers to focus on new research areas instead of on data acquisition. The CAD dataset has already been used extensively by those in the standards, data translation, and CAD visualization communities.
3. *Designers and Practicing Engineers:* Professionals will have access to online check lists for design-for-manufacture rules, manufacturing constraints, process capabilities, and example designs. This will enable them to perform better design-for-manufacture, access rapid prototyping services and browse a living online textbook of design experiences.

To deliver a prototype platform for this user community, we are developing data structures and methods for the creation and manipulation of design signatures. Of particular practical importance will be determining what the underlying ontology for the signature structures must include to enable the fast computation of distance measures, search heuristics, equivalence tests and operators. Initially, we are implementing tools to satisfy the following requirements:

1. *Navigation System:* We are developing an ontology for categorizing and classifying the design models in the Repository. Currently, our dominant data types and users are from mechanical engineering. Eventually, the Repository will encompass all means of CAD data (for example, Architecture/Engineering/Construction models). The initial navigation system will enable users to proceed hierarchically through the stored data and search for specific models of interest.
2. *Query Interface for Conceptual Designs:* The area for most the significant impact of the Repository on design practice occurs during the conceptual phase of design, when designers do not have detailed CAD models—rather they are deal-

ing with abstractions of the new design. These abstraction might include back-of-the-napkin-style functional component diagrams, performance specifications, and behavioral and geometric constraints.

At this point, we are developing an interface through which teams of designers, collaboratively, might query a knowledge-based to determine (1) if designs fitting (or similar to) these requirements have been attempted previously; (2) if there are other current project designs that could share components and subassemblies; (3) estimates of cost for the candidate design (calculated from the known costs of similar designs. Figure 4 shows a schematic of our current design for this query interface.

3. *Contributor Tools:* The last of our three near-term projects is to develop and evaluate tools for contributors to add designs and related information into the design knowledge-base.

System Architecture

The Repository will be accessible in three ways: (1) through standard FTP; (2) as a web-based service; (3) though an API for Internet-based agents. Currently we are developing 1-2, with the agent API to be determined as user requirements are determined.

Figure 5 shows the current system architecture for the Design Repository. The site is run off a two-processor Ultra-SPARC 2 with 150+ gigabytes[3] of storage using the Apache Web Server and the Metaphase Product Data Management (PDM) system. A PDM system is a special database layer specifically tailored to the collecting and sharing engineering data (of any form) throughout the engineering enterprise. This includes all information created to describe, configure and build a product—including relationships between data and the product structure. PDM systems enable storing and tracking of data[4] throughout the product life cycle.

By employing commercially available PDM and database tools (Metaphase is based on the Oracle database), we hope to build a commercial-strength, scalable infrastructure for the Repository. We also believe that the use of industrial-strength systems will free us to perform research on a more complex and realistic scale.

Current Status and Future Research Issues

The *Engineering Repository* described above is expected to become fully operational during 1999. This experimental research platform will enable us (and other researchers) to address the following long-term research objectives:

[3]Of this, five gigabytes are currently occupied with over 6500 engineering artifacts. We expect this figure to increase rapidly.

[4]This data can include workflow and document routing; review and approval processes; change/version control; work orders and instructions; engineering bills of materials; configuration management; support for the maintenance of different engineering views, design alternates and substitutes.

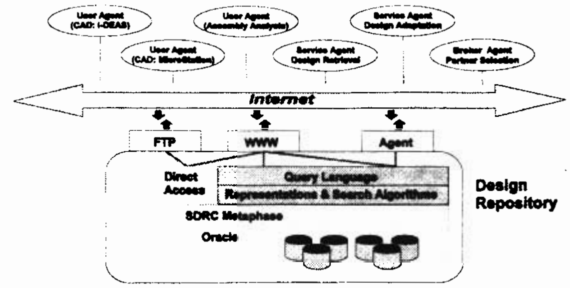


Figure 5. SYSTEM ARCHITECTURE.

1. *Linking design signatures with functions and methods from other engineering data types:* These structures will capture traditional engineering data types, such as assembly relationships, tolerances, and features.

We hope to extend these ideas to develop queryable graph-based relations that link geometric dimension and tolerance models, CBR-based structure-behavior-function models of design, and manufacturing plans with geometric representations. Figure 6 illustrates one view into the Repository, via a VRML-format file. In the figure, the annotations are all active links pointing to other data about this design that is resident in the Repository and elsewhere.

Figure 6. VRML VERSIONS OF THE CAD MODELS WILL BE SERVED FROM THE REPOSITORY, COMPLETE WITH ENGINEERING ATTRIBUTES AND LINKS. THIS MODEL HAS BEEN PROVIDED COURTESY OF SDRC.

2. *Automated generation of design signatures and geometry-intensive knowledge-bases:* We are implementing algorithms that generate design signature graphs given a design's solid model and engineering attributes. Our approach is to recognize engineering and manufacturing features from the design data. Existing systems for case-based design and knowledge-based engineering often require a large amount of human input to create the cases-bases of design knowledge with which to reason. This work will contribute to automating this process.
3. *Techniques to manage geometric complexity:* Computational operations on geometric information (such as CAD and solid models) are floating-point and memory intensive, placing unique burdens on software and hardware. Large knowledge-bases contain millions of assertions and facts that can occupy gigabytes of memory—but this data is primarily symbolic in nature. As shown in Figure 2 on page 3, individual CAD models can occupy megabytes of memory and single assemblies can occupy gigabytes. We are working on techniques to effectively manage large amounts of complex geometric and engineering data.
4. *Adaptable Search Interfaces:* Existing commercial systems for Product Data Management (PDM) and engineering databases support data management very effectively in closed enterprises where all users, user needs, and datatypes are defined (and delimited) a priori. Unfortunately, this is not a satisfying general situation; rarely do the pre-defined views provide all the perspectives that are needed and rarely can all datatypes be taken into account. We plan to develop an API through which agents can customize access to the knowledge archived in the knowledge-base.

CONCLUSIONS

Research Contributions This paper has presented our initial attempt to formalize the problem of managing knowledge-bases of highly geometric CAD data and related engineering metadata. We see this work filling an important need for digital library support for engineering design and manufacturing applications.

It is our observation that much of the current generation of digital library and database technology focuses primarily on pictorial and multimedia information: 2D digital images, movies, and geographic systems. Many existing techniques are not directly applicable to digital libraries of 3D solid models and engineering information. Existing work has not yet exploited the availability of 3D solid models or included important engineering information, often attached to the solid model, such as tolerances, design/manufacturing features, inter-part relationships in assemblies, etc. Previous work has addressed only the gross shapes of single designs; none of the existing approaches is directly applicable to electro-mechanical (mechatronic) assemblies, where inter-part relationships and models of function are more significant.

Future Directions It is our hope that our research expands the understanding of this new problem domain and lays the foundation for exploring new techniques to enhance our ability to search and retrieve 3D solid model data and related engineering design and manufacturing knowledge. Further, we believe that existing approaches to multimedia libraries can be augmented with geometric reasoning techniques that are tightly coupled with engineering knowledge and solid models—such as those developed in the future as part of this research.

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