Using a Context-based Inference Approach to Capture Design Intent from Legacy CAD

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ABSTRACT

There exist numerous design intent systems that convert captured information into structured design intent while providing intent representation and retrieval. These systems woefully neglect the design intent that is present in legacy CAD such as 2D drawings and 3D models. We address the issues that arise when dealing with the capture, representation and retrieval of design intent from the legacy CAD data. A definition for design intent in the CAD domain is presented which forms the basis of the proposed approach. The approach uses a unique context-based inference system to capture design intent from legacy CAD data. A brief explanation of context is provided along with the advantages of using context for this task. The need and use of an inference system is detailed. Additionally a prototype system is implemented to address these issues from a software system point of view.

Keywords: design intent, legacy CAD, context, inference system.

1. INTRODUCTION

As the design and the manufacturing processes evolved around the geometric shape of the product, the current generation of CAD systems is based on geometric modeling techniques. These techniques have proved to be deficient as their usefulness is limited to recording detail of the form of the product. Designers are no longer merely exchanging geometric data but more general information about the product such as the design intent, constraints, specifications and manufacturing knowledge. As design becomes increasingly knowledge intensive, the need for computational frameworks to effectively support the formal representation, capture, retrieval and reuse of product knowledge, becomes more critical. While the industry already uses such engineering frameworks to improve their product development process, the bulk of the product knowledge that resides in their current design data, such as 2D drawings and 3D parametric models, needs to be propagated to a more reusable, intelligent and structured format. The goal of this paper is to report on the results of our research in this area and present the approach taken to address some of the issues that arise when capturing design intent from legacy CAD. One significant result of our survey is providing a definition for design intent in the limited domain of legacy CAD. We also propose a system that uses the definition of design intent in legacy CAD, the idea of context and an inference-oriented approach to classify CAD entities and capture design intent from legacy CAD.

2. PROBLEM AND APPROACH

Much progress has been made on the development of design intent systems and tools since the early 1980's. The research has ranged from basic observations about the design process to different approaches to capturing design intent. In this previous work, basic concepts were discussed and frameworks for design intent systems were proposed [1]. Yet there is a lack of design intent systems or frameworks that address the problem of design intent capture from legacy CAD. The overall problem statement can be summed up as - What constitutes design intent in legacy CAD and how do you capture it? To address this overall problem our approach fell into two broad areas: A detailed survey of the state-of-the-research and recent literature, reported in [2] and Design Intent analysis of legacy CAD presented here.

3. RESULTS

The results of our research fall into four categories: a) Implications for a design intent capture systems for legacy CAD including a definition of design intent, b) the importance of context in design intent, c) recognizing that many of the entities in legacy CAD documents form a context surrounding the part or assembly, d) a method, based on context theory, for identifying and categorizing all the entities in the CAD model (2-D or 3-D), and e) an approach to a system for capturing and representing design intent from legacy CAD. These are discussed below.

3.1 Implications of the Literature Survey for Design Intent Capture Systems

The literature review revealed numerous insights and implications about design intent and systems that capture design intent. While design intent has been defined in a generic sense we were unable to find a definition for design intent in the limited domain of legacy CAD. Defining legacy CAD design intent helps researchers formalize the interpretation of the entities present on the legacy CAD and how they contribute to capture of design intent. A further insight was that almost all solutions to capture design intent from legacy CAD address the problem as mostly a geometric one with possible input from the supporting symbols and text that may be present on the legacy CAD. We believe that by identifying, characterizing and organizing the non-geometric information present on the legacy CAD, the process of capture of design intent is made easier. This implies that we need a uniform method to identify and organize all the information present on the legacy CAD and we suggest the use of context to do so. Before an automated system can be built for this purpose we need to document possible inferences that designers can make about design intent from the legacy CAD. For this purpose we would need to perform design intent analysis of legacy CAD.

3.2 Definition of Design Intent in Legacy CAD

From the literature survey the following working definition of design intent in the limited domain of CAD emerged [2] and we use this as our working definition in the rest of the paper:

"Design intent contained in legacy CAD is the insight into the design variables (design objectives, constraints, alternatives, evolution, guidelines, manufacturing instructions and standards) implicit in the structural, semantic and practical relationships between the geometric, material, dimensional and textual entities present in the CAD representation".

3.3 Context in Design Intent

The exact nature of context is still very much under discussion but some progress is being made [3]. The importance of context has been mentioned in numerous research works. Some of the leading researchers in this field have offered the following definitions for context:

- Turner: A context is any identifiable configuration of environmental, mission-related, and agent-related features that has predictive power for behavior" [4].
- Turner: A context is a distinguished (e.g., named) collection of possible world features that has predictive worth to the agent [4].
- Bremond and Thonnat: Contextual information of a process is information whose value remains constant during processing and changes when the process is used for another application [5].
- Motschnig-Pitrik: The primary use of contexts is a means to provide a flexible and powerful decomposition- and customization mechanism for OO applications [6].
- Bigolin and Brezillon: The delimitation of a domain, that allows to restrict the possible solution-space of a problem [7].
- Pomerol and Brezillon: Context is what constrains a problem solving without intervening in it explicitly [8].
- Mills and Goossenaerts: A context surrounding an entity of interest is a set of properties (with values), that are (a) provided by a set of entities in the same symbolic or physical space as the entity of interest, (b) relevant to the entity of interest in that situation of interest during some time interval and (c) added to the properties of that entity only within that context [9].

Mills' and Goosenaerts' definition of context is the one this research is based on. This definition can be elaborated on to understand it better. At any point in the design, the focus is on some entity of interest (the problem, a function, etc) which exists in a symbolic or physical design space. The surrounding situation (i.e. the context) adds to that entity of interest a set of relevant properties which are in the same design space. A change in either the entity of interest or the surrounding situation would change the context that is applicable.

The above definition and explanation - while very useful - does not provide a formal structure for context. Sowa [10] has discussed a structure for context based on linguistics where the idea of context has been studied the most. He suggests three levels:

(i) Syntax: partial basic meaning of a word or phrase along with its position in the parent document,

(ii) Semantics: further meaning of the word/phrase based on its location in the sentence, paragraph or chapter,
(iii) Pragmatics: the final level of meaning based on the surrounding situation in which the document of interest was created.

We draw similarities between Sowa's [10] structure for context and the context found in legacy CAD as follows:
(i) Syntax: the geometric, dimensional, tolerance, feature or textual characteristics of the entity of interest.
(ii) Semantics: the functional, objective, constraint, manufacturing, maintenance etc characteristics of the artifact.
(iii) Pragmatic: this refers to the situation/environment that the design was created in. Examples of the information contained in this level are the corporation type (e.g. CAD representations created by the US Army may conform to Military Specs), the designer information (e.g. may provide the domain in which the design exists), project information etc.

The collection of entities contained in a candidate legacy CAD represents a design object, which is the product of numerous design decisions taken to traverse the path from requirements to detailed design. These design decisions, which form the bulk of the designer's intent, were reached taking into account the context in which the design was created. The following is a sample list of the elements that form the design context:

- The type of the organization viz. government, commercial, non-profit etc
- The domains in which the design exists viz. mechanical, electrical, software
- Functions, objectives, and constraints
- Information about the designer (education, experience, discipline etc)
- Standards and guidelines applicable to the design. The standards may apply globally to the whole corporation or locally to the concerned design group.
- The type of design viz. novel design (new idea or working principle), redesign (changes – minor or major – to existing design), adaptive (incremental advance using existing concepts maybe for different objective, function or constraint), variant design (change of scale or dimension)
- Design alternatives considered
- Relevant project information such as project number, project participants etc

4. DESIGN INTENT ANALYSIS OF LEGACY CAD

Legacy CAD contains only unstructured graphic entities such as lines, text and symbols. Humans add the syntax, semantics and pragmatics to the 2D drawings and 3D models and interpret these graphic entities as a coherent representation of some design object [11]. Automated approaches to identify these context levels have been lacking. One reason for this is due to the lack of understanding of what constitutes design intent when concerned with legacy CAD. To further our understanding we used the method suggested by Stauffer, Ullman and Dietterich "Protocol Analysis of Mechanical Engineering Design" [12] and performed design intent analysis of legacy CAD".
Interviews involving experienced engineering designers and modelers were conducted to ascertain the varying views of design intent extracted by the subjects. The following is a sample list of questions posed to the interviewees:
(i) How do you rate the importance of entities contained in the legacy CAD – geometric, textual, material, dimensional etc?
(ii) Is there ever a need to determine the function or behavior of the CAD artifact from a source external to the CAD representation? If yes, what are these sources – design databases, the original designers etc?
(iii) What steps do you take when presented with a CAD artifact for modification/redesign?
(iv) How do you deal with assembly representations? Is there a need for individual part representations to determine intent?
(v) Do manufacturing instructions included in the legacy CAD provide any design intent?
(vi) What importance do referenced standards have in design intent capture?
(vii) How do you deal with design alternatives shown on the legacy CAD?
(viii) Do the change notes included in the CAD representation provide any insight into the design evolution of the artifact?
(ix) Does the name of the artifact allow you to make inferences about the function or objectives?

Typical candidate legacy CAD representations are shown in Fig. 1 and Fig. 2. The interviewees were presented with numerous such CAD representations.

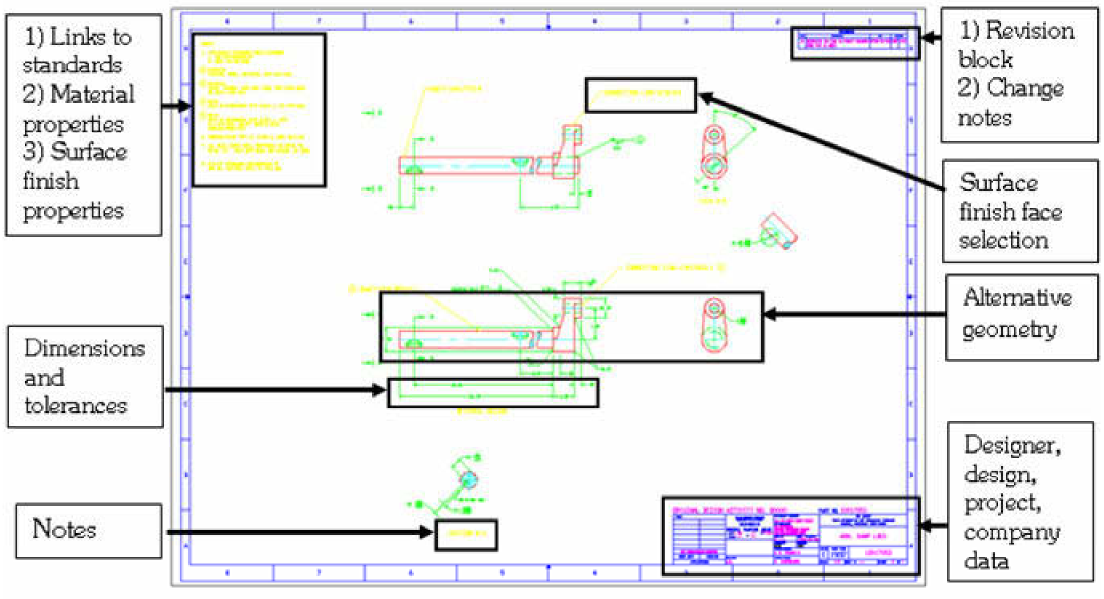

Fig. 1. Sample of entities present on legacy CAD (2D).

One of the results of the protocol analysis was that the experienced designers were inferring much from various pieces of information on the drawing or CAD model. These analysts could infer information about costs, application, mating surfaces and function by comparing some of the information with details such as surface finish, the part name, tolerances and the material and processing given in the notes. During the protocol analysis sessions, we recognized that the subjects were identifying the non-geometrical information as information that was related to other work by some of the authors [Iyer and Mills] on Context in Design in General. This led further to the recognition of these entities as a form of context surrounding the drawing or CAD model. This line of reasoning resulted in the suggestion that by identifying this context we would essentially have captured a large part of the design intent surrounding this particular entity. These steps then permitted the categorization of this information as follows: a) Structural (or Syntax), b) semantics and c) practical (or pragmatics). The following is a selection of the information that the subjects involved in the Design Intent Analysis sessions construed as design intent organized in this way.

4.1 Syntax:

- The geometry of the drawing to determine overall shape of the part.
- The tolerance values, including number of decimal places, as an indicator of tight vs. loose tolerances that may be critical for assemblies and part function.
- The use of firm and relative dimensions to infer the datum plane and feature dependencies in the resulting 3D model. Use of dimensions, table data for validating geometry.
- Importance of precise placement of holes for connectivity between related parts to form assemblies.

4.2 Semantic:

- The part name as an indicator of the part's function (e.g. bracket, pump, gear etc).
- The material as an indicator of cost, strength, part thickness, manufacturing process, etc. of the part.
- The surface finish as an indication of possible exposure to elements, mating connections, etc.
- Any notes referencing markings and etchings as an indicator that the part may be a replacement part in the field.
- Correlation of elements in notes and geometry to infer the treatment and/or manufacturing operations.
- Symbols for manufacturing processes such as finishing, welding, assembling, etc
- Geometry and attributes of part as an indicator feature objective (i.e. ribs in a part add strength while pockets make the part lighter.)

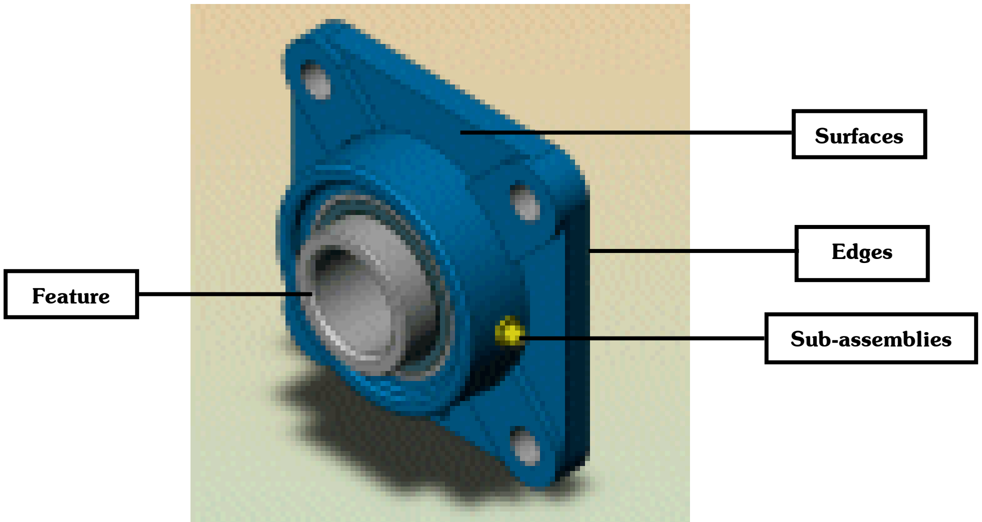

Fig. 2. Sample of entities present on legacy CAD (3D).

4.3 Pragmatic:

- Company and department name along with appropriate knowledge as a method to infer information such as applicable standards, specifications, applicable disciplines etc,
- Designer information to gauge project information,
- Date/time information to gauge document revision/completion information.

5. OVERALL APPROACH TO A DESIGN INTENT CAPTURE SYSTEM

As an alternative to the process-oriented and feature-oriented approaches to design intent capture, Ullman [13] has suggested an inference approach. While Ullman's inference system type is meant to be a part of larger design intent systems, which follow the traditional approaches, we contend that in the case of legacy CAD the only viable approach is inference-oriented. Our approach to a design intent capture system is then as follows: use a context-based approach to classify the raw data that is extracted from the legacy CAD and then use an inference system interacting with a knowledge-base to convert the organized data into design intent.

6. DETAILS OF THE CONTEXT-BASED INFERENCE APPROACH

The design intent system follows the approach shown in Fig. 3. The summary of the approach is: (i) Extract the raw data from the 2D drawing, (ii) Classify the identified entities using the context levels provided in sections 4.1, 4.2 and 4.3, (iii) Build relationships between the categorized entities, (iv) The entities are classified further into the larger design space based on their context level, (v) Draw inferences on the design intent of the categorized entities (or groups of them) with validation.

The approach, shown in Fig. 3, deals with a single, legacy CAD candidate at a time and is outlined below .

6.1 Entity Extraction

At this stage all entities contained on the legacy CAD are extracted, and, for simplification, sorted into either geometric or textual entity types. Basic computer vision and pattern recognition techniques are used to informally group and classify the entities into these types. A temporary data storage is used for the output of this step.

6.2 Context-based Classification

To capture design intent we use the three context levels listed in section 4 to organize the entities extracted from legacy CAD. Using comprehensive pattern search and analysis methods we classify the extracted entities into one of the three levels. To do this we focus on the extracted entity along with its context as defined by the entity's surrounding properties, which are also extracted in step 1. The class to which the entity belongs allows us to determine the significance of the entity and whether additional information is needed to draw further inferences. Fig. 4 shows the formal context levels in a graphical form. The output of this step is an information-base.

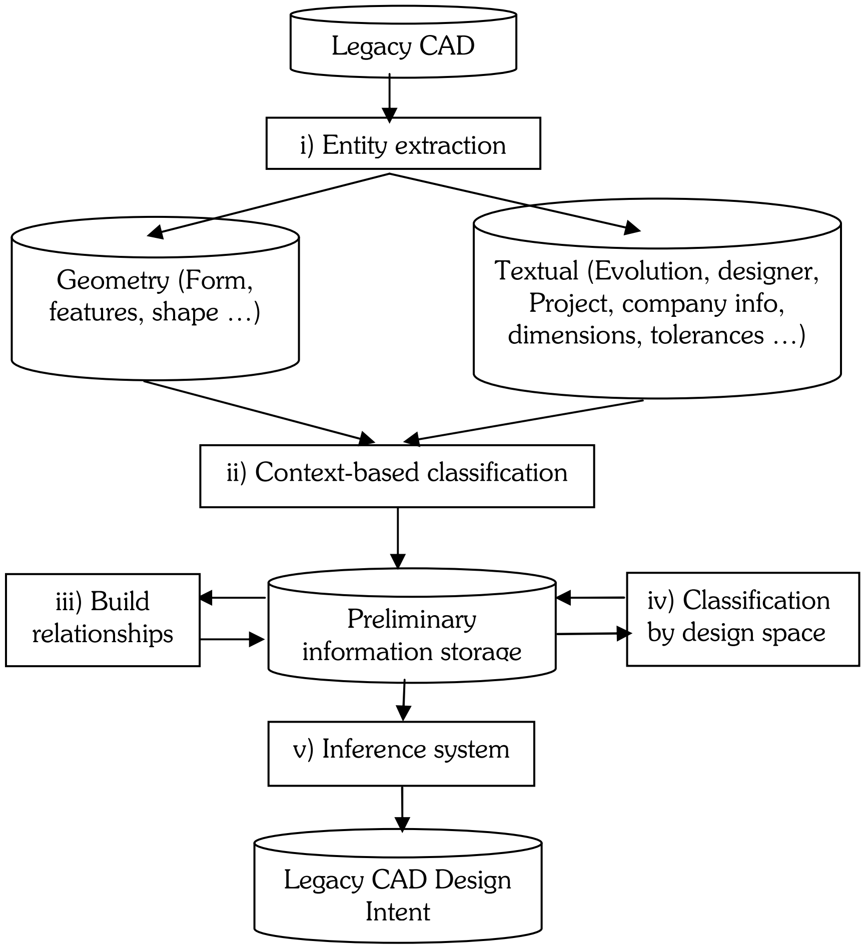

Fig. 3. Overall approach of context-based inference system for legacy CAD design intent capture.

6.3 Build Relationships

Having identified the context level the individual extracted entities belong to the next step is to build comprehensive syntactic, semantic and pragmatic relationships between the entities. This is yet another area where context plays an important role as the context (or properties) surrounding the entities are used to identify the relationships that exist between the entities. Semantic and pragmatic relationships are formed from the inferred syntactic relationships between the entities. During this step textual entities are associated with geometric entities viz. part name is associated with the part, surface finish information is associated with the particular surface, notes on features are analyzed to relate them at the appropriate level – surface, feature, part, assembly or manufacturing instruction, tolerances are associated with dimensions, features or datum. This step accepts input from the information-base and also stores its output in the information-base.

6.4 Classification by Design Space

At the end of step 6.2 it may be required that additional information is required to draw inferences about the entity. This additional information comes from the simple concept that every entity exists in a design space. The design space thus adds information in the form of properties to the entity's context. Thus focusing on the entity of interest allows us to infer the significance of the entity in the larger design space. Two sample classifications of design space are shown in

Fig. 5 viz. a corporation level on the left side of the figure and a design level on the right. It can be seen from the figure that design space is a classification that acts at multiple levels on the entity of interest. It is possible to progress from the lowest level to the highest level depending on how much additional information is required to draw inferences about the entity. The design space is a predetermined list and is sensitive to the current problem and context. It can also be seen from Fig. 5 that a node like “Standards” applies at multiple levels similar to a UML class structure and similarly each instance of “Standards” may be different from the parent node.

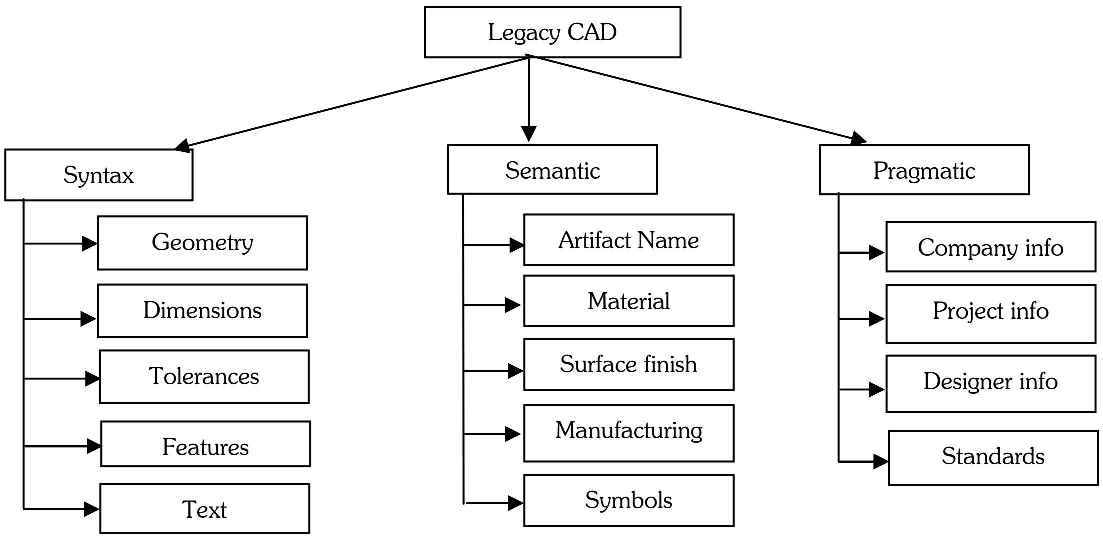

Fig. 4. Formal levels for context in legacy CAD.

6.5 Inference Step

The goal of the inference step is to capture design intent from the categorized entities using the context levels. During this step the context levels and the design space are used to identify patterns and capture design intent. The following sub-sections detail this step and the design intent captured. Each sub-section provides examples to illustrate operation. The input at this step is the group of related entities that have been organized based on context as well as design space.

6.5.1 Geometric Patterns

Patterns in the geometric entities and their relative locations on the CAD representation are identified. The first part of this inference is to identify a set geometric features viz. the holes to classify them as belonging to an array. Then the syntactical or structural relationship between this identified array and a geometric entity viz. the surface is established. For example, an array of holes implies a mating relationship of the surface on which these holes appear with a comparable surface on another artifact. Next the system looks at the semantic properties to identify this relationship pattern as an assembly with at least two parts. To identify the other, mating part it looks at the pragmatic properties: specifically the project or design information to match relevant parts. Details on the notes attached to the array of holes will strengthen the inferred intent of an assembly relationship between the current artifact of interest and the other sub-assembly artifact.

6.5.2 Name-Function Inference

The name of the current artifact is identified and looked up against domain knowledge-bases to identify possible functions of the artifact. For instance, an artifact with the name “tube” clearly has a function to conduct either liquid or gas. An artifact with the name “bracket” has the function of supporting another artifact. Since these inferences cannot guarantee 100% accuracy a probability factor is associated with each function inferred. Inferences from other sources such as the material strength, mating features and constraints of the artifact will support or contradict the inferred functional intent.

6.5.3 Manufacturing Instructions

Artifact tolerances and tolerance values are extracted and those values that are tighter than standard part tolerances are identified. Tight tolerances imply an assembly relationship between the current artifact of interest and other artifact subassemblies. By combining the tolerance values with the name of the part and the mating surface identified in Paragraph 6.5.1, the kind of mating features to identify can be inferred. For example a tight or "limits and fits" designated tolerance on a hole would imply with some probability that the mating artifact might be a shaft or bearing and the clearances between the hole and the shaft/bearing and the surface finish would imply type of fit: sliding, force etc. Text on the CAD representation may provide information on post-manufacturing processes which can be used to support or contradict the function of the artifact e.g. an artifact that is painted is normally an external facing artifact visible to the end user. The presence of loose values for the fillets and radii on corners can be used to infer a fatigue application. Correlation with a material with high fatigue limit would further substantiate this inference.

6.5.4 Material Inferences

The artifact material noted on the CAD representation also provides valuable insight into the designer's intent. This identified materials information is looked up in a materials database to retrieve relevant information regarding that material. The information returned by the database contains the properties of the material allowing inference of probable objectives and functions of the artifact. For example materials such as aluminum, magnesium, titanium or composites imply a lightweight objective for the artifact. A strong alloy such as 4140 in a heat treated condition implies that the part has a function to support a heavy load and that an intended objective was safety. Corrosion resistant alloys such as stainless steel imply an intended objective of resistance to corrosive environments. For the purpose of this inference we use a commercial database viz. the CES-4 materials database.

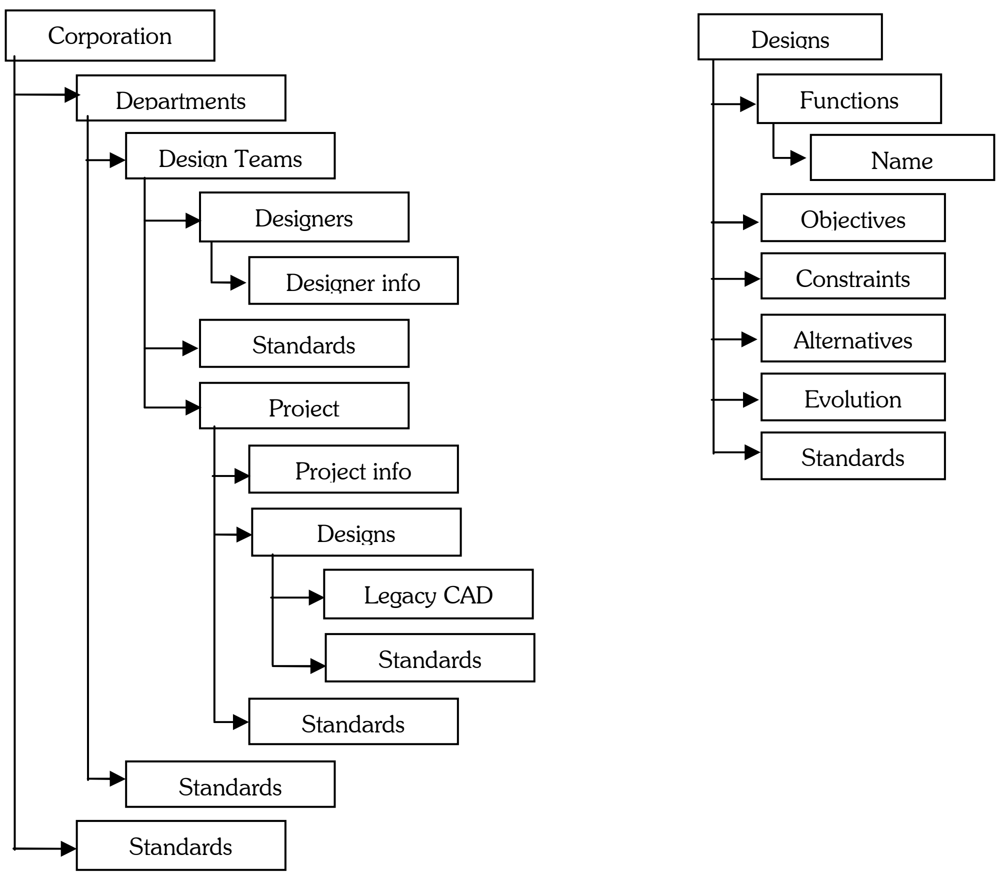

Fig. 5. Design Space showing two levels – corporation level (left) and design level (right).

6.5.5 Design, Project, Corporation Information

Determining the environment in which the artifact was designed provides valuable insight into design intent. Specifically we mean the design, project or corporation information such as the domain of design, the relevant and applicable standards, the experience of the designers, the time during which the artifact was designed, company guidelines etc. The capture of this information allows the limitation of possible inferences that could be drawn for the artifacts design intent. The design space levels in Fig. 5 shows how the properties at the higher levels such as the project or even the corporation type contributes to the properties at the level of the legacy CAD. For example if the corporation is identified as the Army then this could imply that Military Specs were possible relevant standards that form part of the design intent.

7. CASE STUDY

In this section we study of the prevalence of the context information on legacy CAD in addition to evaluating the proposed approach to design intent capture.

7.1 Prevalence of Context Information on Legacy CAD

The primary goal of the approach detailed above is to identify and organize the context information contained in legacy CAD. In this section we clarify the prevalence of context information contained in legacy CAD. With this project we had access to thousands of legacy CAD files that belonged to various groups within the US Army's Tank Automotive and Armaments Command Research center. We studied 48 files from this large collection to gauge the type, similarity and frequency of occurrence of information that we construe as context. It can be seen from

Tab. 1 that the data needed from the legacy CAD for the different types of inferences that our approach draws viz. geometric patterns, function, material, manufacturing, and pragmatic information (e.g. project, designer, design, standards and company), is available and shows large amounts of similarity among different CAD candidates. The frequency and similarity of certain types of data such as that contained in the legacy CAD's title block is much higher than that pertaining to material information. The sample set (total 48 files) was chosen based on the diversity of data contained and from various groups ensuring that the suggested approach is sufficiently generic.

Contextual information	Percentage of occurrences	Similarity of information (%) among CAD candidates
Manufacturing instructions (e.g. surface finish, burr and sharp edges, paint, quench, heat treatment)	70	40
Material information (aluminum, steel, 356 TEMPER T6)	100	25
Standards/specifications (DOD-STD-00100D(AR), ANSI Y14.5M-1982)	100	75
Pragmatic information (part number, scale, units, company name, engineer, designer, related parts, next assembly)	100	75

Tab. 1. Prevalence of context information on legacy CAD.

7.2 Evaluation of Proposed Approach

This project was performed in conjunction with the US Army's Tank Automotive and Armaments Command Research center and the proposed approach was tested primarily on the center's legacy CAD files. The research center has a collection of over 10,000 legacy CAD drawings that can be used as test cases for this approach. The numerous steps of this approach are in various stages of maturity. The geometric pattern inference step is the most mature. We have developed numerous geometric libraries that allow us to extract a feature-based, parametric shape of the part. Additionally these libraries also provide the necessary mathematical algorithms to build syntactic, semantic and pragmatic relationships based on entity type, location and properties. The geometric pattern inference has been tested on a large percentage of parts. Other steps are still in alpha stages of development and have been tested on a small sample of parts to evaluate feasibility. Even with these alpha stages the effectiveness of this approach is visible. By breaking down the inference stage into the five parts detailed in section 6.5, we are essentially using a context-based classification approach to build syntactical, semantic and pragmatic relationships and using these relationships to draw inferences from knowledge-bases. Some of the authors provide elsewhere [14] taxonomies that allows us to draw inferences about the function and flow of the represented artifact. We are working to incorporate these and other similar taxonomies that relate function, flow and solution artifact into our proposed approach to augment the knowledge-base which already contains known material and manufacturing knowledge. The output of the proposed approach is numerous reports that provide weighted design intent inferences allowing design documentation and further analysis perhaps by a re-designer.

8. CONCLUSION

This paper has presented our study of design intent in the limited domain of legacy CAD, a method to capture it using contexts and an approach to a prototype system using this method. The prototype system does rely on a few assumptions regarding the representative legacy CAD that is under consideration. The performance of the system depends on the amount of information that can be extracted from the CAD candidate. The system feeds on a large amount of context and design space information such as related artifacts, project information, corporation information etc. The system's performance improves when dealing with a group of related legacy CAD candidates belonging to a design project as opposed to an isolated CAD candidate. The use of a domain knowledge-base is necessary for many of the systems operations, e.g. the function-name inference, materials database. Lack of a knowledge-base will hinder the system's operation. The task of building the knowledge-base is simplified by developing an extensible base that caters to one design project or corporation at a time depending on the information available. The system also needs numerous passes to capture a good amount of design intent, trying various combinations and inferences till a satisfactory probability is reached. While at this point no user intervention is possible in some of the steps, it will be included in all steps to allow designer validation of captured intent. The prototype in its current status currently allows user intervention for steps 6.1 and 6.3.

9. ACKNOWLEDGEMENTS

This project was performed under the US Army Tank Automotive and Armaments Command Research, Development and Engineering Center, Warren, Michigan contract number W56HZV-05-C-0131. The authors acknowledge their support and contribution to this research.

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