Search & Retrieval in CAD Databases
A User-centric State-of-the-Art Overview

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Abstract: This article presents a state-of-the-art overview on shape, information and design retrieval systems in the context of CAD engineering. In contrast to existing surveys, we classify the different approaches from a CAD application user point of view. As a consequence, we focus on features of surveyed techniques such as: supported shape data types, handling of geometric invariances, support of metadata, supported query types, quality of retrieval results, and the availability of implementations.

1 MOTIVATION

The popularity of Computer-Aided Design (CAD) and Product-Lifecycle-Management (PLM) systems is based on a large amount of product information being generated and stored in engineering databases in practice. This information is a source for new ways to analyse and reuse existing designs. The reuse of design information is one of the important approaches to increase design quality and productivity: An existing design provides a basis for improvements incorporating the assemblies or components whose quality and correctness have been proven in the past (Hoffmann et al., 2014).

In engineering, it is conservatively estimated that more than 75% of design activity comprises reuse of previous design and manufacturing knowledge to address a new design problem. Design reuse is achieved by adaptation; i.e., the existing product is adapted to a given requirement specification. In order to make a design reusable, the key requirement is an information retrieval system. Although PDM systems have greatly improved productivity in the design and manufacture of new products, one of the disadvantages with such systems is the possible difficulty of reusing the product information stored by the system. Engineers spend about 60% of their time searching for the right information (Li et al., 2004).

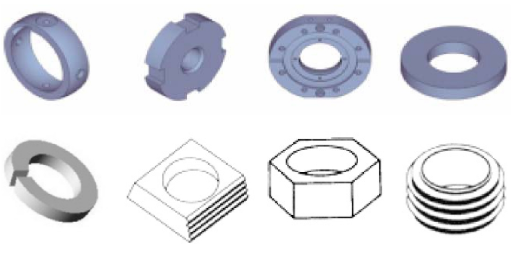

Figure 1: The top row shows a gimble ring, a lock nut, a flange and a washer (from left to right), which have a similar shape but a different classification according to their function. The bottom row shows several washers (spring lock washer, regular washer, hexagonal washer, knife-edge washer; from left to right) with same name but different shapes. – Image Source: (Jayanti et al., 2006) –

In contrast to retrieval systems for multimedia databases, 3D shape repositories or general purposes, the engineering context reveals several challenges (Jayanti et al., 2006):

1. Engineering shapes are characterized by features such as holes, tunnels, cavities, etc. The relative position of these features are more important for a part's functionality than its overall shape.
2. The classification of parts in the engineering context has a low level of abstraction; e.g. a category "airplanes" is not very reasonable in the context of CAD, as an airplane would be considered as an assembly of many much smaller objects.
3. In the CAD context, parts are often classified according to their functionality and not according to their geometric shape (cf. Figure 1).

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2 RELATED WORK

2.1 Technical State of the Art

3D object retrieval is an important topic in product lifecycle management. The various approaches to tackle this problem have their roots in different research domains: geometry processing, computer vision, pattern matching, knowledge management, etc. Since almost two decades, many methods for 3D shape description and retrieval have been researched. Consequently, there is a need for surveys that systematize this research space. Within the last few years, many state-of-the-art overviews have been published and most of them are based on a taxonomy of the technique used. Table 1 lists important surveys in chronological order including bibliographic metrics.

Table 1: For each survey (in chronological order) this table lists its number of pages, the number of included references and the number of articles citing the survey. The citation numbers are based on the “Web of Science” database by Thomson Reuters and on the “Microsoft Academia” database (as of November 2016).

	number of pages	included references	Web of Science	Microsoft Academia
Loncaric, 1998	19	223	–	1176
Li et al., 2004	9	79	–	6
Zhang and Lu, 2004	19	101	664	1866
Bustos et al., 2005	51	79	178	392
Iyer et al., 2005	22	154	201	556
Bustos et al., 2006	16	41	10	92
Babic et al., 2008	17	70	68	160
Qin et al., 2008	8	63	0	86
Tangelder and Veltkamp, 2008	31	136	265	1638
Jayanti et al., 2009	9	35	8	11
Savelonas et al., 2015	26	79	0	9

2.2 Benchmarks

Information retrieval in the context of Computer-Aided Design and Product-Lifecycle-Management should reflect a part’s functionality and not only its geometric shape. General purpose shape benchmarks, such as the Princeton Shape Benchmark (Shilane et al., 2004), are only suited to a limited extent, as they contain generic shapes.

The International Shape Retrieval Contest (SHREC, http://www.shrec.net/) is a comprehensive forum in which benchmarks and novel retrieval challenges are defined, with the goal to compare retrieval algorithms. To date, the benchmark has addressed many different retrieval problems, including global and local similarity, non-rigid similarity, or multimodal retrieval. However, CAD retrieval to date was not a core topic in SHREC.

A set of CAD-specific benchmarks have been published by BESPALOV et al. in “Benchmarking CAD Search Techniques”(Bespalov et al., 2005). A comprehensive engineering shape benchmark for CAD models has been developed by JAYANTI et al. (Jayanti et al., 2006). The benchmark is publicly available at: engineering.purdue.edu

3 CAD MODEL RETRIEVAL

3.1 Information Retrieval

Information retrieval algorithms need to be evaluated for the quality of provided retrieval results. To this end, many measures are avialable (Baeza-Yates and Ribeiro-Neto, 2008). Basic important measures to rate a retrieval result include numbers of relevant and retrieved documents (see Table 2).

A more expressive evaluation can be performed by using precision and recall. These measures are defined in terms of a set of retrieved documents and a set of relevant documents. Precision p is the fraction of true positive (tp) and the number of true positives plus the number of false positives (fp), whereas recall r is the fraction of true positives and the number of true positives plus the number of false negatives (fn):

$$p = \frac{tp}{tp+fp} \quad , \quad r = \frac{tp}{tp+fn}$$

The two measurements are typically used to create graphs – the precision/recall-plots. Since precision can be seen as a measure of quality, and recall as a measure of quantity, a curve at the top of the plot is what systems are aiming at in information retrieval. To evaluate measures likes precision and recall, example queries and ground truth information needs to be defined in advance, e.g., by means of benchmarks as mentioned in Section 2.2.

Table 2: Relevant and retrieved documents can give an insight about the performance of an information retrieval system.

	relevant	not relevant
retrieved	true positives tp	false positives fp
not retrieved	false negatives fn	true negatives tn

3.2 The Meaning of Shape

In the beginning of the 20. century MAX WERTHEIMER began the formal founding of Gestalt psychology ("Gestalt" is the German translation of "shape", "form") (King and Wertheimer, 2005), which attempts to understand the laws behind the ability to acquire and maintain meaningful perceptions. The central principle of gestalt psychology maintains that when the human mind forms a percept, the whole has a reality of its own, independent of the parts.Conversely, IRVING BIEDERMAN explains object recognition by a bottom-up process (Biederman, 1987). According to his theory, we are able to recognize objects by separating them into the object's main component parts–basic 3-dimensional shapes such as cylinders, cones, etc. These basic shapes form a simple "alphabet" that can be combined to complex objects.

These principles have influenced many computer graphics and computer vision techniques (Attene et al., 2006). In "the meaning of shape and some techniques to extract it" (Havemann et al., 2012) highlight some of the fundamental but maybe less obvious limitations of current methods for representing and processing 3D shape. They introduce semantic enrichment as central concept relating the subjective nature of interpretation to the objective of classification. This semantic information, which describes an object on a high, abstract level, is needed in order to provide digital library services such as indexing, markup and retrieval (Ullrich and Fellner, 2011). A digital library provides services based on metadata. In the simplest case, metadata is of the Dublin Core type (Dublin Core Metadata Initiative, 1995) (title, creator/author, time of creation, etc). This is insufficient for large databases with a huge number of 3D objects, because of their versatility and rich structure.

As a consequence, automatic techniques for semantic enrichment of CAD data is a vital research topic. However, for many methods to calculate shape signatures their relation to human perceptions of geometric similarity is unknown (Clark et al., 2006).

3.3 Apples and Oranges

The problem of ill-defined properties such as "geometric similarity" can be illustrated even with a simple geometric shape: a circular sector. A feature vector to (completely) describe a circular sector may consist of the disk radius r and the central angle α; for example:

$$\mathbf{c}_A = (5.0\text{cm}, 30^\circ), \mathbf{c}_B = (5.5\text{cm}, 30^\circ), \mathbf{c}_C = (5.0\text{cm}, 32^\circ)$$

In order to measure "similarity" a metric is used in many cases to define the distance between a pair of feature vectors returning a non-negative real number. A metric for two circular sectors $\mathbf{c}_1 = (r_1, \alpha_1)$ and $\mathbf{c}_2 = (r_2, \alpha_2)$ is, for example, $d(\mathbf{c}_1, \mathbf{c}_2) = \sqrt{(r_1 - r_2)^2 + (\alpha_1 - \alpha_2)^2}$. Each metric is faced with the problem to compare elements with each other which have no natural order. In our example, switching the specification of the angles α from degrees $[0^\circ, 360^\circ]$ to radians $[0, 2\pi]$ changes the order of elements significantly:

$$\begin{aligned} \text{degrees}: &\quad d(\mathbf{c}_A, \mathbf{c}_B) = 0.500 < 2.000 = d(\mathbf{c}_A, \mathbf{c}_C) \\ \text{radians}: &\quad d(\mathbf{c}_A, \mathbf{c}_B) = 0.500 > 0.035 \approx d(\mathbf{c}_A, \mathbf{c}_C) \end{aligned}$$

The effects of different distances using different metrics is illustrated in Figure 2. An overview on distance and similarity measures can be found in the survey by SUNG HYUK CHA (Cha, 2007).

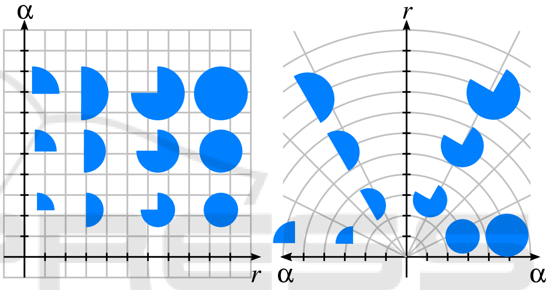

Figure 2: The metric used to measure the distance between feature vectors defines the "similarity" of shapes. Different metrics (illustrated by different coordinate systems; left ↔ right) result in different distances and different similarities.

4 CLASSIFICATION

This state-of-the-art overview on shape and information retrieval systems classifies the different approaches to design retrieval from a CAD application user's point of view[1]. The classification consists of four categories inspecting different aspects of a digital library application.

4.1 Data and Metadata Representation

The first category analyses the design retrieval approaches according to supported input data. Assuming a user with an already existing CAD database, the supported features within input data are an important selection criterion. This criterion does not address

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[1] The classification results are listed in the Tables 3 and 4. Despite every precaution these tables may contain errors. If any errors are found, we ask your forgiveness, and request you send us a short note pointing them out.

file formats but the geometric entities (point clouds, polygonal meshes, NURBS, etc.) and the non geometric entities (annotations, material properties, etc.) which can be handled natively without conversion.

Geometric Input. Which geometric shape types and model representations (point clouds, polygonal data, analytical surfaces (NURBS, etc.), volumetric data, constructive solid geometry (CSG), generative data) are supported natively without conversion?

Manifoldness & Noise. Is the approach able to handle inconsistencies, namely non-manifold geometric input, and/or noisy input?

Level-of-Detail. If the database contains CAD models in different resolutions, does the inspected approach identify these "similar" models?

Invariants. Each approach uses a metric to identify "similar" elements. Are a model and the same model with an applied non-rigid/affine/isometric transformation similar according to the used metric? In other words, is the used metric invariant towards non-rigid/affine/isometric transformations?

Metadata. Input data may contain metadata (material properties, semantic annotations, copyright information, etc.). Which kinds of metadata are supported to be queried?

4.2 Queries and Results

Query Method. Which types of queries are supported (by example, by an image, by a taxonomy, by a sketch, etc.)?

Subsets. Is it possible to query for a subpart only? In other words, does the retrieval algorithm support subpart matching?

Goodness. Are the queries and the corresponding results evaluated and benchmarked? And are the benchmark results available?

4.3 Technology Readiness Level

Availability. Even though a retrieval algorithm may be a significant scientific contribution, without an available implementation its benefit from a CAD application user's point of view is limited. What is the availability level of the presented approach (only article published, reference implementation available, library commercially/open-source available, software released)?

Integration. If the implementation is available (commercially or non-commercially), how can it be integrated into an existing CAD environment?

4.4 Technology

Method. A primary search method uses the (geometric and non-geometric) content. A secondary search method relies on a primary search method and uses additional sources not contained in the in the (geometric and non-geometric) content – such as relevance-based user input. Is the analyzed approach a primary search method or a secondary search method?

Performance. Are the results of computational benchmarks considering speed and memory requirements available?

5 CONCLUSIONS

This article presents a state-of-the-art overview on shape, information and design retrieval systems in the context of CAD engineering. In contrast to existing surveys, we classify the different approaches from a CAD application user point of view.

5.1 Open Problems

The classification scheme in Section 4 has been designed before the classification took place. The scheme is strongly influenced by interviews with industrial partners. Having classified the most important methods, some options of the classification scheme remain unused. Especially the availability of implementations is limited. As a consequence, the comparison of different approaches with each other is complicated.

5.2 Benefit

The presentation of an overview on state-of-the-art techniques for CAD retrieval methods is beneficial for CAD users. In contrast to existing surveys, we focus on critiria which are important from a CAD application user point of view: supported shape data types, handling of geometric invariances, support of metadata, supported query types, quality of retrieval results, and the availability of implementations.

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Table 3: This tabular overview lists the analyzed CAD retrieval approaches from a CAD application user's point of view. All approaches are ordered alphabetically according to the lastname of the first author. This table is continued on the next page (cf. Table 4).

	Geometric Input	Non-Manifoldness & Noise	Level of Detail	Invariants	Metadata	Query Method	Subpart Matching	Goodness	Availability	Integration	Method	Performance
Abouel Nasr and Kamrani, 2006	②			②		①	✓				①	
Akgül et al., 2009	②	✓	✓	②		①		✓			①	✓
Ansary et al., 2007b	②	✓✓	✓	②		①		✓		C++	①	✓
Ansary et al., 2007a	②	✓✓	✓	②		① ② ③		✓		C++	①	✓
Bai et al., 2010	② ③			①	✓	①	✓	✓			①	
Bespalov et al., 2006	②	✓	✓	②		①	✓	✓			①	
Biasotti et al., 2006	②		✓	③		①	✓	✓			①	✓
Cao et al., 2006	②	✓		②		②		✓			①	
Cardone et al., 2006	②		✓	③		①	✓	✓			①	✓
Chen et al., 2012	②			③		①	✓	✓			①	✓
Daras et al., 2006	②	✓✓	✓	②		①		✓			①	✓
Daras and Axenopoulos, 2009	②	✓✓	✓	②		① ② ③		✓			①	
Daras and Axenopoulos, 2010	②	✓✓	✓	②		① ② ③		✓			①	✓
Eitz et al., 2012	②	✓✓	✓	③		②	✓	✓	✓	Python, C++	①	
El-Mehalawi and Miller, 2003b	② ③ ④			②		①		✓			①	
El-Mehalawi and Miller, 2003a	② ③ ④			②		①		✓			①	
Fisher and Hanrahan, 2010	②	✓✓		③	✓	⑥		✓			②	
Fu et al., 2008	① ② ③			①		①		✓			①	
Funkhouser et al., 2003		✓		③	✓	② ④ ⑤		✓	✓	C	①	✓
Gao et al., 2006	② ③		✓	③		①	✓	✓			①	
Gao et al., 2010	② ③	✓		①		①		✓			①	
Getto and Fellner, 2015	②	✓✓		③		⑤		✓			②	
Grabner et al., 2014	① ② ③	✓✓	✓	①		④ ⑤					②	
Grabner et al., 2015	① ② ③	✓✓	✓	①		④ ⑤		✓			②	✓
Hong et al., 2006	② ③	✓✓	✓	②		①		✓			①	
Hou et al., 2005	②			②		①		✓			②	
Huangfu et al., 2016	② ③			①		①	✓	✓			①	✓
Izadinia et al., 2016	②			②		③					①	✓
Kriegel et al., 2003	②	✓	✓	②		①		✓			①	✓
Kuo and Cheng, 2007	②	✓✓		②		①		✓			①	
Leifman et al., 2005	②	✓✓	✓	②		①		✓	✓		② ②	✓
Leng and Qin, 2008	②			②	✓	① ④		✓			② ②	✓
Leng and Xiong, 2009	②			②	✓	① ④		✓			② ②	✓
Liu et al., 2006	②			①		①	✓	✓			①	✓
Mademlis et al., 2006	② ③ ④ ⑤	✓	✓	②		①		✓			①	✓
Mademlis et al., 2009	② ③ ④ ⑤	✓	✓	②		①		✓			①	✓
Min et al., 2003	②			②	✓	① ② ④					①	✓

Table 4: (continued from Table 3) This tabular overview lists the analyzed CAD retrieval approaches from a CAD application user's point of view. All approaches are ordered alphabetically according to the lastname of the first author.

	Geometric Input	Non-Manifoldness & Noise	Level of Detail	Invariants	Metadata	Query Method	Subpart Matching	Goodness	Availability	Integration	Method	Performance
Ohbuchi et al., 2005	②	✓	✓	①		①		✓			①	
Papadakis et al., 2007	②	✓		②		①		✓			①	✓
Papadakis et al., 2010	②	✓		②		①		✓			①	
Pu et al., 2007	②	✓✓		①		②					①	✓
Shih et al., 2007	②	✓✓		③		①		✓			①	✓
Stavropoulos et al., 2010	②	✓✓		②		①		✓	✓	C++	①	✓
Sunil and Pande, 2008	②	✓	✓	①		①	✓	✓			①	✓
Tao et al., 2015	② ③			①		①	✓	✓			①	✓
Vranic, 2005	②	✓		②		①		✓			①	✓
Wang et al., 2008	② ③	✓		②		① ④ ⑤		✓			② ②	
Yoon et al., 2010	②	✓✓	✓	②		②		✓			①	
Zarpalas et al., 2006	②			②		①		✓			①	
Zehtaban et al., 2016	② ③			①		① ⑤		✓			①	

Legend:

Geometrical Input	① point clouds, ② polygonal data, ③ analytical data, ④ CSG data, ⑤ volume data
Manifoldness & Noise	✓, if non-manifold / noisy input data is supported
Level Of Detail	✓, if level of detail matching is supported
Invariants	metric is invariant towards ① isometric, ② affine, ③ general non-rigid transformations
Metadata	✓, if a content's metadata is used by the matching algorithm
Query Method	① by example, ② by sketch, ③ by image, ④ by free text, ⑤ by taxonomy, ⑥ by context
Subpart Matching	✓, if it is possible to query for a subpart only
Goodness	✓, if the presented approach is evaluated towards precision and recall
Availability	✓, if the source code of the reference implementation is available
Integration	the programming languages natively supported by the implementation
Method	① a primary, content-based retrieval method, ② a secondary method on top of primary method
Performance	✓, if the presented approach is evaluated towards computational time and memory consumption

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