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S. Biasotti, G. Lavoué, B. Falcidieno, and I. Pratikakis (Editors)

A 3D CAD assembly benchmark

Katia Lupinetti† [1,2], Franca Giannini [1], Marina Monti [1] and Jean-Philippe Pernot [2]

[1] Istituto di Matematica Applicata e Tecnologie Informatiche "Enrico Magenes", CNR Via De Marini 6, 16149 Genova, Italy
[2] Arts et Métiers, LISPEN EA 7515, HeSam, Aix-en-Provence, France

Abstract

Evaluating the effectiveness of the systems for the retrieval of 3D assembly models is not trivial. CAD assembly models can be considered similar according to different criteria and at different levels (i.e. globally or partially). Indeed, besides the shape criterion, CAD assembly models have further characteristic elements, such as the mutual position of parts, or the type of connecting joint. Thus, when retrieving 3D models, these characteristics can match in the entire model (globally) or just in local subparts (partially). The available 3D model repositories do not include complex CAD assembly models and, generally, they are suitable to evaluate one characteristic at a time and neglecting important properties in the evaluation of assembly similarity. In this paper, we present a benchmark for the evaluation of content-retrieval systems of 3D assembly models. A crucial feature of this benchmark regards its ability to consider the various aspects characterizing the models of mechanical assemblies.

CCS Concepts

• ***Information Storage and Retrieval*** → *Information Search and Retrieval;* • ***Computer graphics*** → *Miscellaneous;*

1. Introduction and motivations

The evolution of the 3D digital systems, which make available a huge amount of 3D content belonging to different domains, has incremented the interest in the methods to retrieve 3D digital objects. Also the domain of the mechanical engineering industry has shown its interest in CAD assembly model retrieval, as in [LGMP18, HWYP13, CGGB12, GCD06].

To evaluate and compare the effectiveness of 3D-shape retrieval algorithms, it is essential investing in community benchmarks. So far several benchmarks have been defined and distributed for the evaluation of retrieval systems as the Princeton Shape Benchmark [SMKF04], the National Design Repository [RFH*01] and the Engineering Shape Benchmark [JKIR06]. In addition, the SHape REtrieval Contest (SHREC) has provided additional resources to compare and evaluate 3D retrieval methods. In case of CAD mechanical products, these benchmarks can be applied to evaluate characteristics related to the shape of parts, but they are not suitable for the evaluation of assembly retrieval. Indeed, they do not consider important properties, such as the mating surfaces involved among the parts of a product that contribute in the definition of the assembly plan. Moreover, all these benchmarks do not support systems directly working on B-Rep models, which are the de-facto standard for Computer-Aided Design (CAD) systems adopted in industrial engineering contexts.

The authors of assembly retrieval methods have developed their own datasets. Iwaya et al. [IRH13] produced a dataset involving twenty students of the Polytechnic School of the University of Sao Paulo and the Santa Caterina State University. Deshmukh et al. [DBGS08] collected 200 Pro/E assemblies from different student projects at the University of Maryland, Hu et al. [HWYP13] composed a dataset of 614 assemblies containing 5100 parts of which 2814 are unique, while Chen et al. [CGGB12] collected 2249 parameterized assembly models, and two graduate students were invited from Mechanical Engineering Department to label all assemblies in the library as relevant or irrelevant to the queries. Katayama and Sato [KS15] have evaluated their approach over 3 product models (a clutch, a die and a gear) with 5 different structures. More recently, Zhang et al. [ZPYW18] built an experimental assembly model library, while exploiting free engineering models repository, such as `https://www.3dcontentcentral.it` and `http://www.zhizaoyun.com`; Wang et al. [WLZY16] and Han et al. [HMYH18] created their own library for assembly retrieval containing several mechanical assembly models.

Anyhow, these datasets are not public. In addition, as deducible from Table 1, the average number of components per assembly model (meant as the ratio between the number of parts over the number of assemblies present in the different datasets) is small and not comparable with respect to industrial databases. Indeed, from

† Corresponding author. Tel.:+39 010 6475570; Fax: +39 010 6475660; Email addresses: katia.lupinetti@ge.imati.cnr.it

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Table 1: *Characteristics of the datasets used to evaluate available assembly retrieval approaches*

Approach	Number of assemblies	Number of parts	Number of unique parts
[KS15] [KS17]	15	-	-
[ZPYW18]	160	1135	-
[DBGS08]	200	-	-
[WLZY16]	409	6315	-
[HMYH18]	502	6348	-
[HWYP13]	614	5100	2814
[CGGB12]	2249	10062	-

these data, we can imagine that the assemblies have on average 5 parts (for the dataset [CGGB12]) up to 15 parts (for [WLZY16]).

To overcome these limitations, this work aim to encourage the evaluation and the comparison of the assembly retrieval methods in engineering contexts by using a common dataset. In this paper, we present a benchmark for the evaluation of the retrieval of B-Rep CAD assembly models according to multiple criteria. For the specification of the benchmark we took into consideration various aspects characterizing the digital models of mechanical assemblies that are created using commercial CAD systems in industrial as well as in academic contexts. In particular, we consider both aspects that characterize assemblies (i.e. criteria according to which the similarity of the models has to be judged) and practices in modeling the products (e.g. the volumetric intersections that are frequently present in the models either created on purpose or due to modeling issues).

In the following, Section 2 illustrates the adopted methodology; Section 3 describes the ground-truth to evaluate and compare assembly retrieval systems; while Section 4 concludes this paper.

2. Methodology

The proposed dataset is centered on gearboxes because of their wide use in industrial applications [LZF18]. Their presence inside many assembly models (e.g. helicopters, wind turbines, tracked loaders and milling machines) makes them suited to evaluate partial and local retrieval systems. Moreover, according to the arrangement of the gears, gearboxes can be classified in different categories (e.g. simple gear train, compound gear train, reverted gear train and planetary gear train). This variety of configurations is useful for the evaluation of the retrieval systems' effectiveness because it offers the possibility of highlighting the system capabilities of exploiting the arrangement of the parts. To test the precision of the proposed retrieval system, i.e. its ability to discard non-relevant models, models have been added to the database with different shapes and functions from those of the gearboxes.

2.1. Main issues

In the following, we describe the main issues to consider for assembly retrieval in mechanical field that have driven our choices in defining the presented benchmark; descriptions of how we addressed them are provided as well.

3D CAD model representation Product models are represented as B-Rep, which can be stored in systems, e.g. Product Life-Cycle Management (PLM) systems that abound of information [RFH*01]. B-Rep representation allows also to capture design rationale by analyzing the product hierarchical structure. Finally, B-Rep provides the exact geometry of the parts and (at least implicitly) of their contacts. Conversely, polygonal representations allow a fast visualization of the model but do not include the precise and complete information provided by the B-Rep, which is the reference representation created during the detailed product design phase.

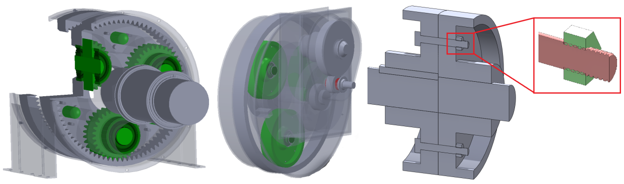
To support the evaluation of assembly retrieval systems, which could also be incorporated in PLM systems as an additional service, the models included in the proposed benchmark are represented as B-Rep.

Plurality of the similarity levels and criteria Two assemblies may be *globally* or *partially* similar. In addition, there exist multiple similarity criteria, since the evaluation of the similarity between digital models depends also on user's purpose. The necessity of adjusting the similarity criteria according to the application scenario has been illustrated by several example by Deshmukh et al. [DBGS08].

The simultaneous presence of speed reducers configured in different ways to achieve the final purpose in a wide variety of mechanical systems makes this functional set extremely useful for the assessment of retrieval methods based on the evaluation of various similarity levels according to similarity criteria.

Plurality of components' description Some components may be not necessarily fully detailed, such as standard components (e.g. screws, bearings, gears or seals) that are imported from supplier as well as specific product components that are designed by external companies. This practice gives rise to multiple geometric representations at multiple resolutions for the same component affecting the capacity of retrieving models. Indeed, when the shape is idealized, it is hard to deduce what the part corresponds to. It also must be noted that, some shapes, like a simple cylinder with a through hole, can correspond to the detailed shape of a given part, e.g. a spacer, or to the abstracted shape of other parts, e.g. a gear. Moreover, different types of components may be simplified using the same shape abstraction; for instance, a gear and a bearing when the bearing functional set is simplified as a single part. Therefore, the proposed dataset includes models containing both fully detailed and idealized components, such as the models in Figure 1(a) and Figure 1(b). In addition, the dataset contains some models having parts with different functionality (e.g. spacers and gears, screws and shafts) but described by similar simplified shapes.

Model inconsistencies Despite volume overlapping between components is not possible in physical objects, in digital CAD models volumetric interferences are sometimes designed on purpose to convey a particular meaning; for instance, when considering flexible parts, as springs or seals. This may apply to multiple devices such as brakes, couplers, lifters, plugs, cushions, and gripping devices, then it is worth to consider this design common practice. In addition, some positioning errors can simply occur making challenging the effective analysis of assemblies. The proposed dataset includes some CAD models with volumetric intersections among their own parts, such as the coupling flange illustrated in Figure 1(c), where the screw and the nut intersect along the fillet.



(a) (b) (c)

Figure 1: *Example of CAD models included in the dataset. Models in 1(a) and 1(a) have gears at different resolution; model in 1(c) has a volumetric intersection*

2.2. Model collection

To support the evaluation and the comparison of assembly retrieval systems, this dataset includes B-rep models stored in a neutral file format generally used for the CAD data exchange. In particular, "Standard for the Exchange of Product model data", known as STEP format, is adopted to store the CAD models in STEP AP 203 (Configuration controlled 3D designs) or STEP AP 214 (Core data for automotive mechanical design processes) formats.

The 3D models in the database come from different sources. Most of the models representing functional sets to modify an energy source input (e.g. turbines, rotors or differentials) have been created by students in the undergraduate design class at the ENSAM engineering school; additional models, most of them with different functionality (e.g. coupling flanges, landing gears, or linear actuators) have been collected from the on line repositories `http://www.grabcad.com/` and `http://www.traceparts.com/`. In this way, we are guaranteed to have models with different functional units, with different level of details and with imprecisions.

2.3. Model classification

The proposed dataset contains 137 assembly models arranged in 11 classes (Table 2). There are 12783 parts in total, out of which 4871 parts are unique. The complete dataset is available at `http://3dassemblyrepository.ge.imati.cnr.it/#`. Downloading the models, also the statistics (number of parts and number of unique parts) of each model are available.

The classification of the models have been performed manually considering the resulting objects. Thus, double rotor turbine and rotor wind turbine, although both convert mechanical rotation into useful work, such as electrical power, are classified as two different classes because the final products will be powered by different source inputs (wind and fluid) satisfying two different requests. The digital models belonging to the classes coupling flange, landing gear, mill max and linear actuator are generally not included in rotors, speed or torque modifiers; then, they are included in the dataset with the aim of introducing "noisy" elements to evaluate how retrieval methods perform on them. In addition, the models in the coupling flange class present some parts that considered individually can be confused with rotors' parts, as, for example, shafts and simplified gears. Finally, among the models in the "Other" class, there are for instance CAD models representing segways, cement mixers, or gear pumps.

Table 2: *Classification of the CAD assembly models*

Category	Model	Part	Unique Part
Coupling flange	5	70	23
Differential	5	1520	278
Double rotor turbine	17	1080	554
Hydraulic reduction	9	1473	439
Hydraulic rotor	8	1240	508
Landing gear	6	81	57
Linear actuator	6	77	30
Mill max	8	103	30
Propeller mixer	20	2599	1253
Rotor wind turbine	24	2969	946
Other	29	1571	753
Total	**137**	**12783**	**4871**

3. Evaluation

The evaluation of a retrieval method can be performed through several techniques, such as the precision-recall plot, the distance image and tier image [SMKF04]. To evaluate the quality of search results of different methods by using the proposed dataset, we also made available a tool for evaluating the precision-recall (PR) [MRS08a]. To compute the PR, a set of queries (which express a user information need) and a set of relevant judgments (ground-truth) are required [MRS08b]. The models described in Section 2.3 represent the dataset, while the set of queries and the ground-truth need to be defined. For more details on the possible similarity criteria according to which two assemblies may be similar, and consequently how to define a set of queries, we refer to the article [LGMP18]. Finally, the ground-truth is expressed by a binary assessment for each model in the dataset that indicate if it is relevant or non-relevant for each defined query (see Section 3.1).

The requirement for the proposed evaluation is that each retrieval method returns a similarity value between 0 and 1 for each pair of CAD assemblies; where small values indicate a low similarity, while values close to 1 suggest high similarity between the compared 3D models. In this way, given a certain query, the models in the dataset can be ranked from the best to the worst according to similarity measures provided by each method. This ordered list corresponds to the retrieval results for a certain query and represents the input data of the proposed tool for the computation of the PR. To facilitate further comparisons with other methods, the tool produces also two PR-plots (for partial and global retrieval) showing curves interpolating the results of the single queries.

3.1. Precision and recall requirements

In order to compute the PR of a method, it is essential to know which models should be retrieved according to a certain query, i.e. which models belonging to the dataset are considered relevant

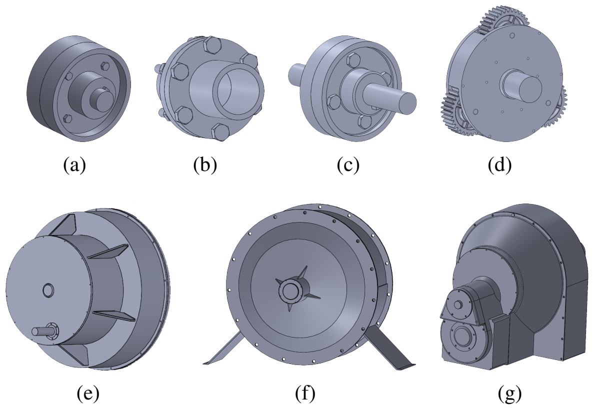


Figure 2: *Example of relevant and non-relevant models*

given a CAD model and a set of similarity criteria. This concept is named *ground-truth*. Hence, all the assemblies in the dataset have been labeled as *relevant* or *non-relevant* according to 8 different queries. Four of the documented queries aim to retrieve models globally similar to the query model; the others four search for models that include the query model and are partially similar. For each query, the CAD model, the selected similarity criteria and the similarity level are specified; finally, the list of relevant models is provided.

The similarity criteria that can be set are divided into *part similarity criteria* and *relationship similarity criteria*. This decision is supported by the fact that in an assembly model the shape of the single parts and how parts are arranged represent key elements for the characterization of products, then they are much relevant in the identification of similarity.

For each query, one or more of the following part similarity criteria must be selected:

- **Shape**: that requires the similarity of the shape of the constituting parts of two assemblies.
- **Size**: that requires the similarity of the dimension of the constituent parts of two assemblies.
- **Pattern**: that requires the similarity of the patterns made up of multiple instances of an identical part.
- **Component type**: that requires the similarity of the functionality of the constituting parts of two assemblies, where, according to [LGMP18], the considered values are *axis, bearing, c-clip, gear, key, linkage arms, nut, screw and bolt, spacer and miscellaneous*.

In addition, one of the following relationship similarity criteria can be selected:

- **Contact**: that requires that pairs of similar parts preserve the same relation (contact or non-contact).
- **DOF contact**: that requires the similarity of all the contacts between two pairs of similar parts.
- **DOF joint**: that requires the similarity of the movement allowed between two pairs of similar parts by considering the Degree Of Freedom (DOF) defined by the resulting joint.

The complete list of all the defined queries is available at http://3dassemblyrepository.ge.imati.cnr.it/#groundtruth. Concerning the partial similarity, models are tagged as relevant if they contain similar parts arranged in similar configurations independently by their model organization in sub-assemblies.

As an example, we may consider the evaluation of the global similarity, the CAD model in Figure 2(a) as query model and *shape* and *contact* as criteria of similarity. Then, among the models in Figure 2, the relevant models are (a), (b) and (c), while the models from (d) to (g) are considered not-relevant. Differently, considering the evaluation of the partial similarity, the CAD model in Figure 2(d) as query model and *component type* and *contact* as criteria of similarity, then, among the models in Figure 2, the relevant models are those from (d) to (g), i.e. models that contain the query model or some if its components.

4. Conclusions and future works

In this work, we have presented an assembly benchmark for the evaluation of content-based CAD assembly retrieval systems. The goal of this work is providing a common test evaluation to facilitate the comparison among different methods. In the future, the ground-truth can be enriched by defining other meaningful query and labeling its relevant models.

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