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A heuristic approach to detect CAD assembly clusters

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Abstract

Mechanical assemblies are very complex structures, made of many parts of various shapes and sizes with different usages. Consequently, it is challenging to manage them during all the manufacturing processes, from the design to the assembly and the recycling. Aiming to simplify the assembly structure and reduce the number of parts to deal with simultaneously, in literature many works exist on subassemblies identification starting from the CAD assembly model. However, the methods provided loose sight of many details associated with the parts, as well as the fact that the treated model represents a real mechanical assembly which respects precise engineering rules. At this regard, this work introduces a novel methodology to detect meaningful clusters in CAD assembly models. The logic applied relies on engineering knowledge, both of mechanical assemblies' components and of assembling techniques, and on the leveraging of the semantics of components. In particular, referring to general design rules, we have identified some heuristics to exploit to partition the assembly into different types of clusters, such as the symmetry along an axis and the presence of fasteners or welds. It results that the assembly's parts are meaningfully grouped, considering, at the same time, their shape, functionality, and type of contact.

Keywords: Assembly cluster; CAD assembly model; Semantic component; Engineering knowledge; Heuristic method

1. Introduction

In industrial manufacturing, managing modern assemblies of mechanical products is becoming very challenging and time consuming [7], due to their complex design, the large number of components they are made up and the several relations between parts. At this regard, the discipline of the design for manufacturing and assembly (DFMA) comes to an important role [4]. DFMA is properly meant to help designers developing products to facilitate production and assembly, thus reducing production costs and times. For traditional production processes, standards and best practices have been developed from decades to avoid complications and inefficiencies during the production. Then, a more recent research topic which can further enhance DFMA is automatic subassembly identification (SI) [5]. It is a very active and not fully explored field, which aims at exploiting the 3D CAD model information to automatically break down the assembly into smaller groups of parts which can be treated independently from one another. In the perspective of optimizing the manufacturing process, for instance, SI can be applied in the assembly sequence planning (ASP) [12, 13], as well as in the definition of parallel lines of production [1], minimizing the number of assembly operations using common datum features and primary axes. A great effort has been made with automatic subassemblies identification over the years, and thus many works can be found in literature [2, 14, 15]. Most of the provided methods rely on a common approach which first involves the CAD model processing for the extraction of topological and geometrical information, e.g. adjacency between parts and features. The generation of graphs or matrices to represent the extracted data and express parts relationships follows. The subassemblies are finally obtained by employing graph theory and optimization algorithms.

However, the only consideration of geometric information and the use of mathematics-based approaches is restrictive in the SI context [10]. In this way, in fact, many details associated with parts are lost from sight and the resulting subassemblies can't explicitly reflect engineering experience and assembly knowledge, factors that instead should strongly affect the outcome of the identification process. To overcome this issue enhancing the CAD model data extraction and interpretation

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can further improve the subassemblies identification [3] and its usage in DFMA. The geometric information contained in CAD assembly model has to be analysed deeply in order to attribute to it an engineering meaning. The knowledge and affordability of subassemblies with an intrinsic engineering value can then support the redesign of the product with the goal of minimizing both the costs and the time of the assembly tasks.

The paper presents a heuristic methodology to automatically detect meaningful and engineering usable clusters in CAD assembly models. The novelty stands in taking into account that the treated object is actually a real mechanical assembly, which respects precise engineering rules, and to leverage the semantics of components, rather than only geometrically evaluate the existence of a contact between two parts.
The next section, after pointing out the fundamental data extracted from the CAD assembly model, describes the proposed heuristic approach. Section 3 addresses the algorithm from the computation point of view, explaining it through the description of composing three main steps. Finally, results are reported together with an example of application.

2. The heuristic approach

This section introduces the proposed approach to detect CAD assembly clusters, defined as connected sets of parts sharing some characteristics.
In particular, three types of cluster are referred and the characteristics that the parts must satisfy to belong to each type of cluster are established through heuristics. Each heuristic, and hence each type of cluster, is associated with a specific engineering concept, in order to take into account that the treated CAD assembly models represent real mechanical objects and thus provide clusters with a precise engineering meaning. The pioneering choice reported in this paper is to merge common geometric processing and features recognition expertise with engineering knowledge to automatically extract and leverage the semantics of CAD assembly's components.

2.1. The semantic information extracted from the CAD model

To allow a better understanding, we now briefly describe the semantic information extracted from the CAD model and exploited in the clustering algorithm.

A mechanical assembly is made of many parts of various shapes and sizes and with different usages. The engineering meaning of each part would be significant in the clustering process, but in general it is not encoded in the model, unless experts manually provide it, and it is lost when dealing with CAD assembly models in standard exchange formats, such as STEP [6]. To address this deficiency, in our method we take advantage of a classification, according to which parts with a specific mechanical role are grouped in different categories. We currently distinguish between *fasteners* and *standard components*. The first are those parts that have the function to connect or fix two or more parts (e.g. screw, nut, bolt, gasket, O-ring, circlip, stud, etc.). The latter include components the shape and the structure of which are standard, in the sense that they are easy recognizable through some geometric features analysis, and also their function is known (e.g. gear, bearing, belt, etc.). Parts that do not belong to either of the two categories will be referred simply as *parts*. In addition, all the assembly's parts (fasteners, standard parts and parts) are further classified according to their geometric type. For example, axisymmetric, sheet metal, pipe and beam parts are distinguished. In the following we are especially interested in knowing the axisymmetric parts, which are parts symmetric respect an axis.

About the contacts analysis, we assess the proximity only between parts and/or standard components, while fasteners are considered as an attribute of the contacts. Instead of generating the commonly used matrices or graphs, for each pair of parts in contact we define a *liaison*. While, in literature, the simple mating between the components is basically referred as liaison [8, 13], in our work, the liaison concept is intended in an extended way, more similar to [11]. It is defined as the element which totally describes the relation between two components by means of several properties concerning multiple aspects, from the geometry of the contact (e.g. type of contact faces, common axes, percentage of covered surfaces, etc.) to the assembly process features (e.g. mounting features, presence of connection elements, etc.). For the clustering algorithm understanding, the three crucial liaison properties are listed below.
Contacts: we define contact the surface collision between the faces of two assembly's components. Since multiple contacts can clearly exist between a pair of parts, one for each couple of colliding faces, in the liaison object we store a list containing all the identified contacts. Contacts can be planar, cylindrical or conical according to the geometric type of the surfaces.
Mountings: we define mounting the existence of two coaxial holes (or more in general slots) on two faces in contact or in proximity to each other. As for contacts, in the liaison object we store a list of all the mountings identified between a couple of assembly's parts, which can be more than one. Mountings are the key feature in inferring the presence of not modelled connectors and fasteners, such as screw, pin or stud [3], thus they have a high semantic value.
Fasteners sets: the fasteners connecting the liaison's components. Fasteners are reorganized in sets, making reference to how they are used in reality. In particular, if there are fasteners coaxial and in contact with each other, they are grouped in a fasteners set, e.g. the combination of screw, nuts, and washers. This because all these components together perform a mounting function between two parts in contact, while considered individually they have a less precise semantics.

The classification and the contact analysis have been developed as preliminary phases of the clustering algorithm. They simply take a CAD assembly model in STEP format as input and do not require human intervention, which is a considerable improvement over existing works.

2.2. Definition of the heuristics

The availability of usually ignored details of the CAD assembly model parts and their contacts suggests a new method-

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

ology to detect meaningful clusters. The guiding idea is to exploit engineering knowledge to assess and point out the primary design rules generally respected in mechanical assemblies, and match them in the geometry and topology of the CAD models.

In particular, the developed approach aims to detect different types of assembly clusters. The assembly's components belonging to the same cluster are meant to be a connected set of parts that share specific characteristics, about both to the single parts and their relationships. The characteristics are established upon heuristics, each of which is associated with a precise engineering concept corresponding to mechanical assembling processes.

Three general heuristics have been defined, which can be related to each type of mechanical assembly. These are the symmetry along an axis, the absence of fasteners or mountings and the presence of fasteners and mountings; they can be calculated exploiting the parts' semantic and liaisons' data.

2.2.1. Symmetry along an axis

A frequently encountered situation in mechanical assemblies is the aggregation of components along a common axis. We can think both to sets of parts mounted along a shaft and sets of concentric parts (e.g. crankshaft, roller, pulley, etc.). These components have a specific function inside the assembly, namely they transmit power or movement. Furthermore, from an engineering point of view, they have a distinctive structure. In fact, the groups of parts aggregated along an axis mostly consist of axisymmetric parts and usually include gears and bearings as well as circlips and gaskets. Besides, the mounting technique used in these situations expects to thread by sliding or to interference fit hollow parts into the axis or into the central part.
It results evident that the identification of clusters of parts aggregated along a common axis would be very helpful in SI and ASP, because they respect a precise assembly sequence and may be considered subassemblies themselves. As a consequence one type of cluster we define in our approach is actually that of axisymmetric clusters. These clusters have indeed a specific engineering and semantic meaning and the features of the parts from which they are composed are recognizable from the CAD model without too much computational effort.

2.2.2. Permanent joints - Absence of connection elements

A further engineering concept, we are going to exploit in our clustering method, is the permanent joint, which includes welding, gluing and interference fit. Those are assembling processes performed to stuck the parts together, defining a strong and irreversible relation between them. As a consequence, units jointed in a permanent way are stable and behave as a single independent object. From a structural point of view, the parts usually involved in a permanent connection process have geometrically simple shapes, e.g. sheet metal and plates. The contacts between each pair of parts, in most cases, concerns few side planar faces, and above all no extra connection elements are involved. In an engineering prospective, the welding, gluing and interference fit processes do not interfere with the assembly of the other components, but rather they are executed in a preliminary phase. In addition, one of the main functions of these groups in mechanical assemblies is to serve as basis on which the other subassemblies are then mounted. We can assess that the knowledge of the assembly's permanent units can contribute in the subassembly identification, since the information they contain and their semantic meaning are remarkable. For example, a suggested strategy in some SI works is even to collapse all the welded parts in a single part. However, the gap is in the recognition of welds, gluing and interference fit which is not automatic, but rather it requires human intervention. This because, most of the time, the information are not represented at all in CAD models, neither as annotations nor as solid modelled beads. In this paper, among the different types of cluster we define the permanent clusters. The identification of these clusters is algorithmically performed starting from the CAD model. It especially relays on contacts features, easily accessible from the liaisons' properties.

2.2.3. Mounting by fasteners

The third basic aspect of primary importance and present in all mechanical assemblies is the mounting by fasteners. The presence of fasteners, such as screws, bolts, studs and pins, connecting two or more assembly's parts is a very meaningful feature which embodies a stable but non-permanent joint between the parts. On the one hand mounting is used to connect different subassemblies, on the other a set of parts connected by fasteners can constitute an independent subassembly. Referring to the second situation, the groups of mounted parts, for instance, may be associated to the external cover of an assembly or its chassis. Moreover, as far as the structure is concerned, the components which can be found in mounted groups do not have to meet many requirements of shape, they just need to be drilled in order to allow the placement of the connectors.
Thus the recognition of mounted groups would be substantial in SI processes. Hence, due to the massive use of fasteners in mechanical engineering and their relevance in the assemblies, the last type of cluster we outline is that of mounted clusters. To identify them in CAD assembly models the parts classification developed and the liaisons' data are sufficient.

3. Clusters detection

The heuristic method proposed in this paper aims to divide a CAD assembly model into disjoint clusters of parts, accordingly to the three types of cluster described in section 2.2.

The algorithm we have developed consists of three steps: selection of the parts which satisfy the requirements for each type of cluster, clusters computation, clusters refinement.

Notice that both parts selection and cluster computation are based on liaisons analysis, however they have been defined as two separate phases. This choice is justified as the implemented algorithm is integrated in an industrial software and existing libraries are exploited for computational simplicity.

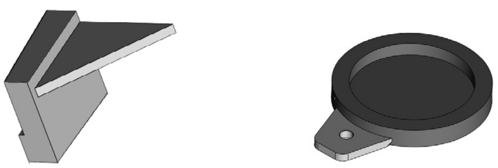
3.1. Parts selection

Assuming that the CAD model has already been processed and all the data are stored in liaisons, the first step of the clustering approach is to select the parts that meet the conditions established for each type of cluster. In order to automate the selection, the engineering requirements are described in terms of the extracted information, i.e. parts' geometric characteristics and their contact features. As a consequence, the selection algorithm simply works through conditional statements referred to liaisons' properties and it returns three lists of parts, one for each type of cluster.

We now point out the rules defined to evaluate liaisons' parts membership to each type of cluster; the rules are then summarized in Table 1. Notice that the first discriminant factor is the geometric type of the two involved parts. The cases in which one, both ore none of the components in contact are axisymmetric are distinguished. Then, the mountings and the fasteners sets are investigated.

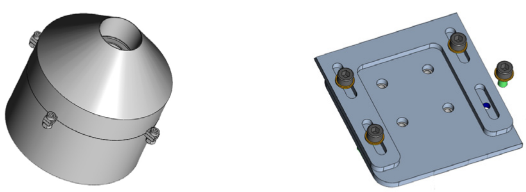
(a) (b)

Fig. 1. Examples of liaisons' parts selected for axisymmetric clusters: (a) two axisymmetric parts with closed cylindrical contact and circlip; (b) two axisymmetric parts with planar contact and one mounting.



(a) (b)

Fig. 2. Examples of liaisons' parts selected for permanent clusters: (a) two not axisymmetric parts with neither fasteners nor mountings; (b) one axisymmetric part and one not with opened cylindrical contact.



(a) (b)

Fig. 3. Examples of liaisons' parts selected for mounted clusters: (a) two axisymmetric parts with mountings and threaded fasteners; (b) two not axisymmetric parts with mountings and threaded fasteners.

Axisymmetric clusters. Liaison must be between two axisymmetric parts. The only fasteners accepted are the axisymmetric ones, such as circlip or O-ring (Fig. 1(a)); threaded connectors are excluded, otherwise it falls into the case of mounted clusters. For the same reason, at most one mounting can exists between the two parts (Fig. 1(b)), as the presence of a pattern of holes suggests a mounting operation. Finally, the cylindrical contacts must be between closed cylindrical surfaces.

Permanent clusters. At most only one part of the liaison can be axisymmetric; in both possible cases there must be neither fasteners of any type, nor mountings, since those two properties are strongly connected with mounting features (Fig. 2(a)). If one of the two parts is axisymmetric, an additional condition is imposed for contacts, that is the cylindrical contacts, if there are any, do not have to be closed (Fig. 2(b)). A closed cylindrical contacts in fact is easily attributable to mounting by sliding, and thus typical of axisymmetric clusters.

Mounted clusters. It is allowed that both, one or none of the liaison parts are axisymmetric. If both the parts are axisymmetric, it has to be considered the situation excluded in the axisymmetric clusters analysis; that is to say, only threaded fasteners are accepted and at least two mountings there must be recognized (Fig. 3(a)). In the case only one part is axisymmetric, all the type of fasteners are accepted and at least two mountings there must be recognized. Meanwhile, in the last situation, that is none of the parts are axisymmetric, at least a mounting is sufficient and all the types of fasteners can be found (Fig. 3(b)).

3.2. *Clustering of the parts*

At this point we have grouped the assembly's parts in three lists, each of which contains all the parts satisfying the requirements for one of the types of cluster. We now apply a function to the three lists to cluster their parts by contact. This implies that if two parts are in contact, i.e. it exists a liaison between them, they are assigned to the same cluster. Since a part may belong to more than one list associated with the types of cluster, the resulting clusters are not necessary disjoint. For example, a component could be assigned both to a mounted cluster and a permanent one. To provide disjoint clusters an evaluation and update are needed.

3.3. *Clusters refinement*

This step concerns the evaluation of the obtained clusters and their update in order to provide, at the end of the computation, a set of disjoint clusters. In particular, what has to be done is to detect the parts included in more than one cluster and establish their membership to only one of them, by removing the part from the other cluster. To make the assignation of a shared component to a specific cluster, rules to algorithmically establish the precedence of one type of cluster over another are specified based on engineering considerations. At this regard, we can assess that axisymmetric clusters, in general, are correctly grouped, due to the distinctive requirements parts have to satisfy. Therefore, if a component is shared between an axisymmetric cluster and another type of cluster, it would be assigned to the first. Another assumption is that permanent joints are usually performed before the mounting operations. As a consequence, if a component is included both in a mounted and a permanent cluster, it is reasonable to prefer the permanent one.

At the end of the process, we obtain a set of clusters, each of a defined type, namely axisymmetric, permanent or mounted,

Table 1. Table of the rules defined to evaluate liaison's parts membership to each type of cluster.

	Liaison properties				
	Part 1 is axisymmetric	***Part 2 is axisymmetric***	***Accepted type of fasteners***	***Number of mountings***	***Restrictions on contacts***
Axisymmetric clusters	✓	✓	Axisymmetric and not threaded (e.g. circlip, O-ring, washer, ...)	0 or 1	Cylindrical contacts: closed
Permanent clusters	✓	×	-	0	Cylindrical contacts: not closed
	×	×	-	0	-
Mounted clusters	✓	✓	Threaded (e.g. screw, bolt, nut, ...)	>1	-
	✓	×	All types	>1	-
	×	×	All types	>0	-

and therefore associated with a specific process and engineering concept. This result can be further exploited in assembly sequence planning. Especially the clusters refinement phase is a quite strong hint to define an assembly order among the clusters. The parts in common with multiple clusters, in fact, imply a connection between the clusters. When assigning the component to only one cluster, we indirectly are affirming that this cluster will be assembled first and then mounted on the other thanks to the part they share.

4. Implementation and results

Since this research is part of a project carried out in partnership with the Italian company Hyperlean (https://hyperlean.eu), the proposed algorithm is implemented as a module of their industrial software LeanCOST, developed using Visual Basic language.

In order to obtain a preliminary assessment of the algorithm, the validation of the method is carried out on 20 CAD models. These are of various type: ten of them belong to the class of rotor wind turbines and are selected from an online repository [9] (http://3dassemblyrepository.ge.imati.cnr.it); the others are real industrial mechanical assemblies part of automatic machines. The main characteristics taken into account for the models are the number of parts, which varies in the range from 35 to 426, the number of standard parts and the presence of modeled or not modeled fasteners. The number of parts does not affect the quality of the clustering, but it only increases the computation time. The more standard parts are modeled and classified, instead, the more results are reliable. This because not recognized fasteners are treated as parts and this can cause misleading interpretation of the contacts, especially wrong permanent joints detection, and consequently false permanent clusters are returned. Absence of fasteners together with modeling errors (e.g. holes misalignment) generate similar issues, since mountings are not recognized and thus the liaisons satisfy requirements for permanent clusters. In general, we can assess that the resulting grouping is promising and, even if more than half of the total parts can results in common with multiple clusters after the clustering phase, most of the final clusters are meaningful and meet the theoretical expectations. For example, all the parts of assemblies' covers are correctly grouped in mounted clusters, as well as welded subassemblies are properly identified as permanents clusters. We can affirm that, among the three types of clusters, the axisymmetric ones are the most reliably identified, thanks to their precise requirements. The only thing to notice is that some extra axisymmetric clusters, made up of screws, nuts and spacers not classified as standard parts, can be provided, but this is consistent with the implementation, and actually they are not to be considered false positives. As for the other two types of clusters, some false permanents clusters can be identified, according to the mentioned issues, and consequently some mounted clusters are missing.

To permit a better understanding, the application of the algorithm on one of the tested CAD models and the relative clusters obtained before and after the refinement phase are shown.

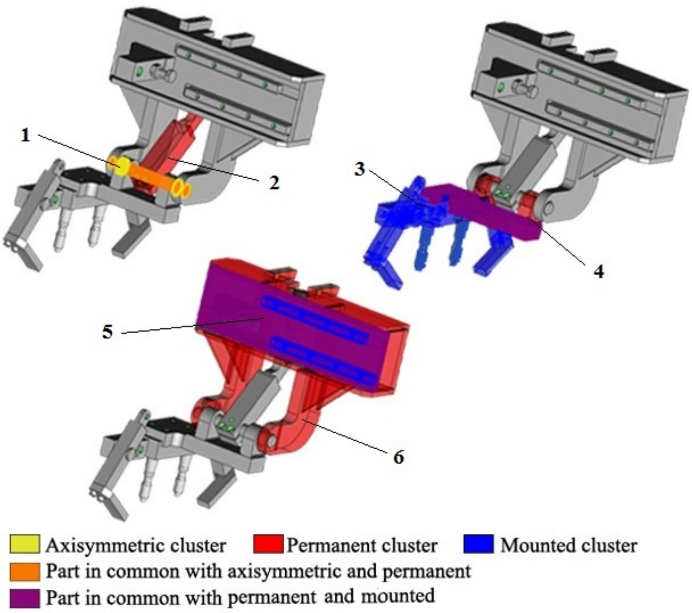


Fig. 4. Gripper mechanism after the clustering phase.

The model is an industrial CAD assembly of a gripper mechanism. It consists of 48 parts, 6 of which are classified as fasteners, but many not modelled fasteners are inferable from the mountings analysis too. In Fig. 4 the outcome after the clustering phase is shown. The detected clusters are six, more precisely: 1 is axisymmetric (in yellow); 2, 4 and 6 are permanent (in red); 3 and 5 are mounted (in blue). Three parts in common with multiple clusters are then identified and their color derives from the overlapping of the colors of the belonging clusters. A part is in common with the axisymmetric cluster 1 and the permanent cluster 2, while the other two are in common with mounted and permanent clusters, respectively clusters 3 and 4, 5 and 6. During the refinement phase, for the first case the shared part is assigned to the axisymmetric cluster 1 and removed from the permanent cluster 2; in the second case the shared parts are assigned to the permanent clusters 4 and 6, while the mounted clusters 3 and 5 are updated. Fig. 5 provides the resulting disjoint clusters after the refinement phase, revealing, for example, that cluster 5 is splitted in two separate clusters after its update. Additional useful information, in-

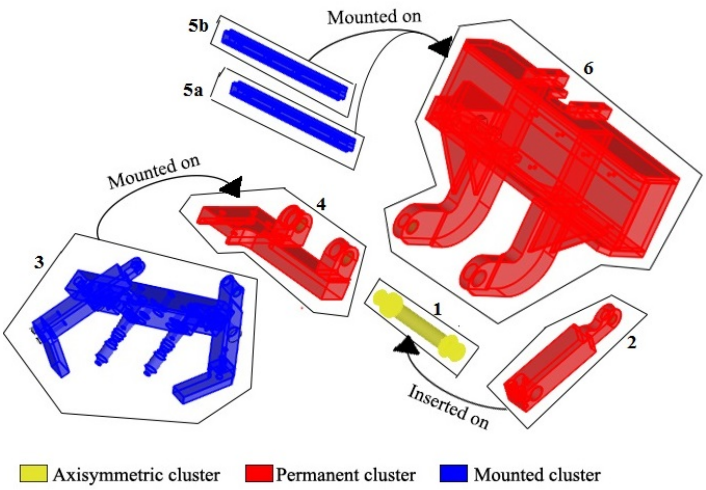


Fig. 5. The gripper mechanism's disjoint clusters after the refinement phase.

ferred from the refinement phase, about the clusters assembly precedence are displayed in figure: for instance, cluster 3 will be mounted by fasteners on the welded cluster 4, since they shared a part, as well as single-parts clusters 5a and 5b will be mounted on cluster 6; cluster 2, instead, will be inserted on the axisymmetric cluster 1.

5. Conclusions

This paper introduces an innovative subassembly identification approach for the detection of meaningful and engineering usable assembly clusters starting from CAD models.

By combining an extensive semantic analysis of the assembly's parts and their relationships with some heuristics based on engineering knowledge and design rules, assemblies are more realistically partitioned in three different types of cluster, namely axisymmetric, permanent and mounted. The algorithm has been implemented as module of an industrial software and validated on a set of different CAD models. Results are overall promising. The type of clusters more reliably recognised is the axisymmetric one, independently from the CAD models characteristics. Permanent and mounted clusters identification is instead less affordable when both absence of fasteners and modeling errors/simplifications occurs.

Next improvements will focus on the assignation of a part to a cluster rather than another in the refinement phase, which actually is not always the optimal. At this regard, we are working on the definition of more accurate rules possibly taking into consideration the specific mechanical assembly class treated (e.g. engines, mechanical arms, valves, etc.). Furthermore, the study of new heuristics to take into account is underway.

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