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Identification of functional sets in mechanical assembly models

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Abstract*— Easy retrieval of product data and related information is extremely important for knowledge and data reuse in new product development. Nowadays the adoption of PDM (Product Data Management) systems makes the reuse easy providing means for documenting all the data related to a product, thus making possible their retrieval through the inserted metadata. Unfortunately, large datasets are available in which data are not documented; therefore, retrieval systems based on content similarities according to different criteria would be beneficial. In this paper, we face the problem of identifying functional sets. The main difficulties relay in the variety in terms of shape and representation of the components that can achieve the same functionality. To overcome this issue, we present a multi-step approach, which considers a component embedded in the whole assembly model, improving component characterization.

***Index Terms*—Assembly retrieval, part classification)**

I. INTRODUCTION

The extensive use of CAD tools has led to the creation of very complex assembly models which for some types of products such as cars and aircrafts can be made up of thousands of components. Such a high level of complexity makes hard to deal with these kind of models under several perspectives. On the one hand, it is difficult to retrieve from large databases models suited to our purposes; retrieval systems are mostly shape based and do not consider other functional information that can also be used to speed up the design process, allowing the reuse of previous solutions and knowledge. Moreover, it is difficult to formalize a single similarity criterion for assemblies, since assembly models may be similar according to different criteria such as component or global similarity of shapes, hierarchical structure or similar behavior and function. On the other hand, often it is even more difficult to evaluate the results of a retrieval system and to understand if the retrieved model really fits to our objectives.

Nowadays, many systems offer the possibility of enriching the description both of the CAD model and the development process by allowing to store much more knowledge and by limiting the information loss during the communication among the various processes. Anyhow, models in existing databases frequently miss functional information, thus computational methods are needed to extract this kind of information automatically from the available data.

In this perspective, in this paper we address the automatic identification of functional sets in assembly models, through the identification of recurrent composing parts that characterize specific devices. The classification of assembly parts and components may facilitate the product development process, for example supporting the adaptation of the model for simulation by allowing the identification of elements to be ignored or treated in predefined manners. Moreover, knowing part categories may simplify the reuse of the related knowledge (e.g. maintenance planning, production costs).

The automatic classification of parts and components in assembly models is a challenging task and normally considering only shape data leads to ambiguous situation and not correct classification.

The work presented in this paper adopts a multi-step approach for part classification, which first assigns a category to each part according to its shape characteristics and then assesses the initial shape-based classification by analyzing the context of use of the part in the assembly with the ultimate objective of identifying components representing specific functional sets. Here, a part represents the elementary unit, while components are in turn formed by several parts. The paper is organized as follows: section II gives a short overview of the most related research; section III highlights the major shortcomings of CAD assembly descriptions for part interpretation. Section IV describes the developed approach and examples of the obtained results are shown in Section V. Section VI concludes the paper.

II. RELATED WORKS

The automatic classification of 3D models has been widely addressed in literature. In the mechanical field, Ip et al. [1] define a feature space where they apply decision tree learning and reinforcement learning to classify solid models. This first effort allows the automatic classification of wheels, sockets and housing models. In [2], the authors present an automatic model classifier for CAD models integrating machine learning techniques. Using a series of shape descriptors, their approach aims at learning multiple CAD classifications and is applied to the classification of prismatic machined parts and parts with finishing features machined after part casting. The classification proposed by Pernot et al. [3] also exploits a series of shape descriptors and classifies products in terms of characteristics that might affect the simplification process for the Finite Element Analysis (FEA) of parts. Hence, their categories are: thin parts, parts with thin portions and normal. Qin et al. [4] present an automatic 3D CAD model classification approach based on the deep learning technique. Their method considers 28 different functional classes and combine different training strategies to simulate engineering manual classification process.

However, as highlighted in [5] and [6] the functional classification of 3D models requires information on the context of use of the part.

Shahwan et al. [7, 8] analyze functional interferences from the geometric interferences of parts in an assembly and identify functional designations, as cap-screw, tubular rivet, gear. The main limitation of this method is the complete entrustment in the design methodologies. The extension of this work [9] uses mechanical equilibrium state analysis for assigning to geometric interfaces only one functional interface. The approach is semi-automatic and user has to identify the start and the end of the kinematic chain in the assembly model.

The method we propose adopts a multi-step approach to classify assembly components; the first step exploits only shape characteristic, while in the second phase it combines engineering knowledge and contextual information derived from the interacting components in the assembly.

III. PROBLEMS IN COMPONENT UNDERSTANDING

Machines and functional sets are characterized by the presence of specific components and parts arranged and configured in almost standard ways. Despite the use of conventions and rules in product definition, automatic classification of parts is rather problematic. Using only shape information can be misleading, especially when parts are idealized with simplified outlines. These situations frequently occur when standardized components are acquired from suppliers. This common practice makes arduous automatically recognizing component types, in addition elements with indistinguishable shapes may have a complete different functionality and vice versa. For example, the bearings depicted in Fig.1 have different shapes though they identify the same component.

Hence, identifying components requires knowing their context of use and understanding a functional set requires knowing which are the constituent elements. Additional problems may derive from the way assemblies are modeled:

i) *Different organization in sub-assemblies.* Same functional sets can be organized according to different subassembly structures, depending on the objectives for which the model is created.

ii) *Relations between parts not available* Sometimes relations between assembly's parts are not explicitly stored (e.g. assembly conditions). Among the possible causes, this lack may derive from the file formats used by CAD systems to exchange assembly models, which does not allow storing this information.

The last issue can in principle be solved by analyzing the CAD model to identify their interfaces; however additional problems due to position errors may be present causing unwished intersections or clearances [9] making challenging the effective analysis of assemblies.

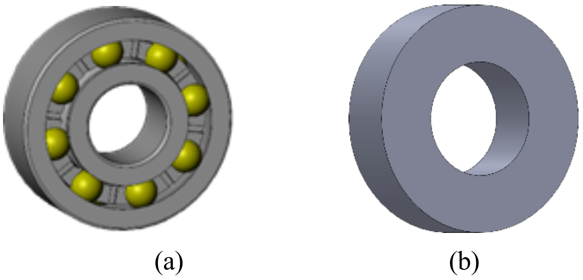
(a) (b)

Fig. 1. Different shapes for bearing components: (a) Detailed assembly (b) Simplified as a single part.

IV. OUR APPROACH

To identify assembly components representing specific functional sets we adopt a multi-step approach for part classification that first assigns a category to each part by only considering its shape characteristics and then assesses the classification by analyzing its context of use in the assembly.

The approach is illustrated in Fig. 2; while step (a) is performed only once, steps (b) and (c) are iterated such that the assignment of a specific class to components is exploited for verifying other component classifications. The shape-based classification step aims at discriminating parts with different shapes and assigns to each part the most appropriate candidate class according to its shape. The classification is based on a learning process in which objects are described by a collection of shape descriptors, that are considered the most suitable for mechanical objects [6], namely spherical harmonics, shape distribution, inner distance, surface area, proportions among the minimum bounding box dimensions. The training set has been organized according to the following categories: bearing, gear, c-clip, nut, shaft, screw and bolt, spacer, key, linkage arm, part of bearing, cylinder like, cube like, sphere like, torus like and miscellaneous[1]. Some of these classes are more geometry oriented (e.g. cylinder-like or torus-like) while others refer to specific types of mechanical artifacts (e.g. gear or shaft). This inhomogeneity is required to deal with parts designed at different level of details. In addition, parts in the generic geometry oriented classes may represent elementary components of more structured artifacts, as in the case of the rolling elements in the bearings (see the eight spheres in Fig. 1.(a)). We limited the classes of mechanical components to those meaningful for specific types of mechanism also to reduce the overlapping of the shapes in the classes, because in many cases, objects with same shape may have different functions and their real meaning can be correctly identified by only considering how they are used. For the training set and the

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[1] http://partsclassifier.ge.imati.cnr.it

ground truth specification, we used existing database organization [6, 10] and interviews with mechanical engineers. When an object could correspond to different mechanical components, it is assigned to a geometry oriented one (e.g. cylinder-like instead shaft). Thus providing an indication on the shape and highlighting the necessity to know its usage to understand its meaning, which is done in the second classification phase.

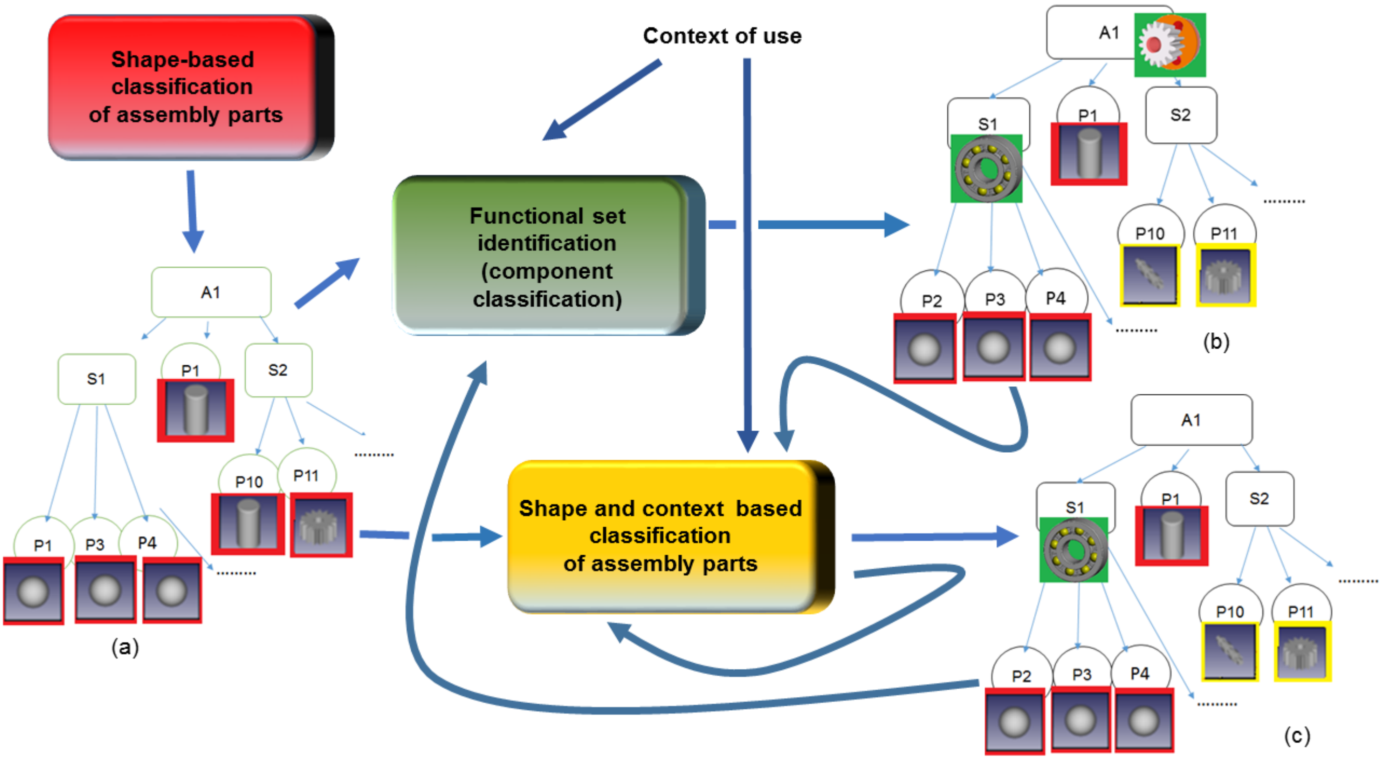


Fig. 2. The approach. Colors of the rectangles surrounding the images of the objects indicate the module who provided the final classification for the object

The second and third steps are parts of an iterative process, which aims at the identification of specific functional sets and the refinement of the initial part classification (Fig. 2 (a)) by analyzing the context of use in the assembly model.

The **functional set identification** step (Fig. 2 (b)) aims at identifying the assembly components that represent some specific functional sets characterized by the presence of restricted component types generally positioned according to specialized rules. This step exploits the previous part classification and the relationships between parts automatically extracted from the assembly model through geometric reasoning and explicitly stored in the Enriched Assembly Model (EAM) [11]. Since the EAM is a graph structure, the identification algorithm is performed by graph matching, where sub-graphs are compared with predefined templates characterizing the mechanical components to be identified.

The **shape-and-context-based classification** step (Fig. 2 (c)) aims at confirming or adjusting the initial part classification by analyzing the context of use of the part in the assembly model. The analysis of the context of use of a part in an assembly relies on some a priori engineering knowledge related to generally present interactions between components in specified mechanisms. The rationale behind is that a specific mechanical component may perform its function within a functional set if it is positioned according to specific conditions with respect to certain classes of components. Hence, to determine if a component effectively belongs to the assigned class it is necessary to check with which types of components/parts the part interacts. Currently, we are considering only parts that are in contact, but a proper context of use for a part should also include components/parts that interact indirectly with it, e.g. being in contact with a component/part that is in direct contact with the part. We intend address this analysis as future extension of this work.

The shape-and-context-based classification starts confirming or, if necessary, adjusting the classification of parts belonging to some specific classes and, according to the resulting classification, completes the verification on the remaining classes. One important issue of the undertaken approach is that it needs to trust on the existence of correctly classified parts. To identify trustful classified components, we considered the precision of the shape-based part classification, identifying classes with high and low recognition rates and detecting recurrent and well identifiable subassemblies corresponding to specific components. These steps are further detailed in the section *IV.B*, which describes the process for the identification of the functional sets considered so far described in the next section.

A. The considered functional sets

Among the various functional sets, we currently focus on those whose function is to alter the amount of speed and torque generated by an input source and/or change the direction of the output source. In particular, we focus on speed reducers. They are present in a wide variety of mechanical systems, e.g. beam pumps, wind turbine and clutch transmission. In many cases, a single unit is not sufficient to reach the right variation. Hence, several units are present simultaneously, configured in different ways to achieve the final purpose.

Most of the speed reducers are composed by a set of gears with different radius assembled with shafts. Bearings are used to support various loads so that the gears can be held in the proper alignment. Such components are also referred to as gear boxes, speed increasers, and gear reducers.

Shafts connect the speed reducer with input/output sources. Typically, their surface is smooth, where bearings are located, and with limited groves to install gears; if carving is not present, some slots are predisposed for inserting key parts, which prevent gear rotation.

Thanks to the ability of supporting radial load with possibility of low axial load and the suitability for high rotation speed, the most widespread kind of bearing employed in the considered mechanism are the groove ball bearings. They usually consist of an inner ring, outer ring, and rolling elements (balls or rollers) arranged in a circular pattern, and a cage, which holds the rolling elements at fixed intervals between the ring raceways (Fig. 3). Tapered roller bearings are less common but possible.

When it is not suitable to fasten two parts by shrink-fitted, auxiliary parts are inserted to secure their position, e.g. spacers, c-clips and keys.

Last, to ensure oil-tight, seals are present at the extremity of driven shaft.

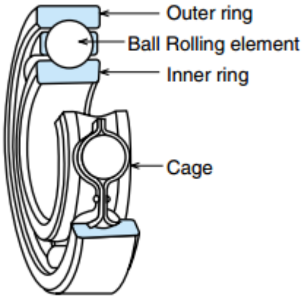


Fig. 3. Bearing component and its constituting elements.

Analyzing this type of mechanism, we can identify a series of features that indicate how parts are in general assembled together. Here we report some of the indicators generally valid for functional sets where a shaft is guided in rotation using bearings:

i. In most of the configurations, a shaft is guided by two bearings.
ii. The shaft and the bearings share the same axis.
iii. The main technological solutions to limit the axial translation of the bearings are: a shoulder on the shaft (i.e. bigger diameter on the shaft), a spacer, a lock ring, a cap, a bearing housing, circlips (or elastic ring) which can be put on the two external planar surfaces of the bearing or on an inner ring of the bearing.
iv. Bearings often are present between gears and shafts.
v. When gears do not rotate along the shaft, then they are blocked with either: grooves, keys, mechanical shrinking, or shrinking without elements (not visible in the CAD model).
vi. Gears can have multiple cylindrical contacts except along the external surface, which can have only a linear contact to preserve the rotation.
vii. The parts that rotate have their gravity center on the rotation axis to avoid extra loads due to dynamic effects.
viii. Spacers are tube-like part for which the outer (resp. inner) cylindrical surface is not in contact with something.
ix. To prevent oil leak, seals are normally positioned at the extrema of the components along the shaft.
x. Auxiliary elements along a shaft (e.g. spacers, bushings, gears, bearings) have cylindrical contact with the shaft and usually have not contact with screws or nuts.

B. Component and part classification combining shape-based classification and context of use

Analyzing common errors in the shape based classification of assembly parts and components, we notice that *c-clip* class has the lowest failure rate together with *bearing* components when designed as sub-assembly (i.e. *part_of_bearing sphere_like*, *cylinder_like*). It appeared that also parts like seals or washers might be classified as *bearings* or *part of bearing*.

Gears are generally well classified in presence of teeth, while in their simplified form they are frequently confused with spacers.

The components more misleading are shafts, which can be classified as *screws*, *cylinder_like* or *miscellaneous*. Fig. 4 shows an example of three different shafts that are wrongly classified by simply considering their shape isolated from the context.

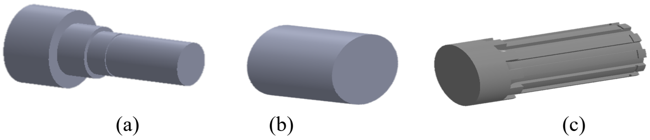

(a) (b) (c)

Fig. 4. Shaft component pre-classified as Screw (a), Cylinder_like (b) and Miscellaneous (c).

Therefore, taking into consideration the results of the shape classification and the characteristics of the considered functional set, the **shape-and-context-based classification** process starts after the **functional set identification** applied to bearing as assemblies. So far, we focused on non-linear bearings.

The identification of bearings is achieved through a sub-graph matching between the EAM graph of the assembly under investigation and a set of EAMs corresponding to different bearing templates. In the EAM graph, nodes correspond to sub-assemblies or parts and arcs represent different types of relationships, e.g. assembly hierarchy, contacts between parts and kinematic pair equivalence [11]. Attributes are attached to both nodes and arcs describing their characteristics. In case of contacts, attributes specify if the contact is though surface area, curves or points and the type and number of elements in contact, e.g. number of planar or cylindrical surfaces of the contact. The part class determined after the shape-based classification process is one of the attributes of the node.

The nodes of the bearing template graphs represent the main elements characterizing a bearing, which include the repeated elements (balls or rollers) arranged in a circular pattern or idealized with a toroidal/cylindrical shape, the inner and outer rings. The cage is not considered since its shape may vary too much. Arcs represent the interaction among these elements. For instance, balls (rollers) are always in contact by a vertex (a curve) with the inner and outer rings. To focus on the most promising candidates, the matching consider parts classified as *part_of_bearing* for inner and outer rings, *sphere_like* for balls*, cylinder_like* for rollers, *torus_like* and *spacer* in case of simplification of rolling elements. Details on the adopted matching method are reported in [12] and its generalization for assembly models using the EAM is described in [13].

The **shape-and-context-based classification** is based on the translation of the mechanical characteristics described in the previous section into a set of indicators specifying admissible or mandatory relations between classes of components/parts

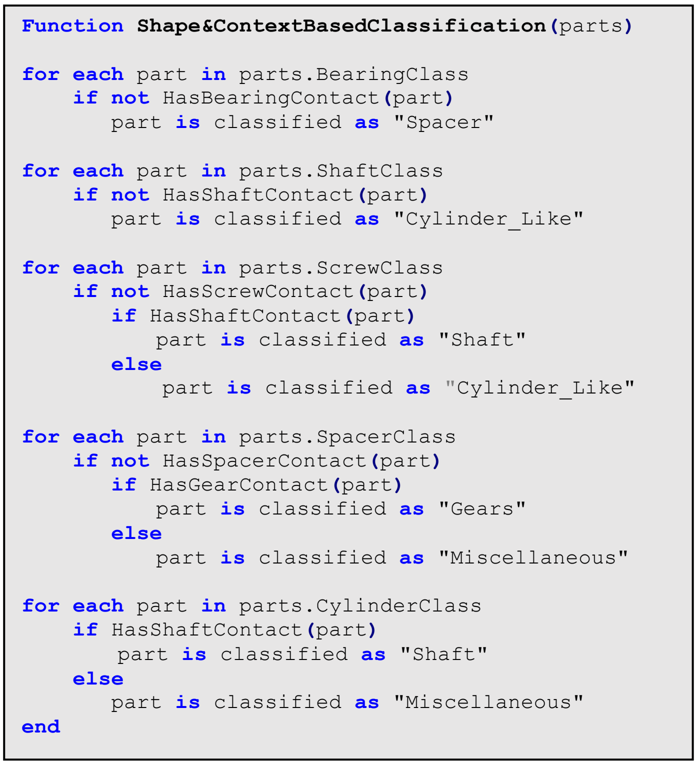
Using these characteristics and the results of the shape-based classification, we apply the iterative procedure, illustrated in Fig. 5, to verify the part classification. The procedure analyses the class of the elements in contact with the examined part and their type of contact. Table 1 indicates for each class in the columns the categories of components/parts, expected to be in contact and checked to confirm or invalidate the classification proposed at the first shape-based phase.

	Bearing	*Gear*	*Shaft*	*Spacer*
Bearing		X	X	X
Cylinders_like	X	X		X
C-clip	X	X	X	X
Gear	X	X	X	X
Key		X	X	
Shaft	X	X		X
Spacer	X	X	X	

Table 1: Expected contacts between component types

We start the validation process analyzing components that should be recognized as bearing. If a part labeled as *bearing* has among its contacts those expected indicated in Table 1, then that part is confirmed as bearing, otherwise its category is changed in *spacer*.

We proceed with shaft components. If a part cannot be confirmed as shaft (i.e. it is not in contact with some elements indicated in Table 1), then its category is transposed to *cylinder_like*. Then, we check if among parts classified as *screw* or *cylinder_like* there are components that satisfy shaft assembly characteristic. If they do, their associated class is modified to *shaft.* Then, we verify parts recognized as *spacer,* if they do not satisfy the expected contacts, the class is amended to *gear.* As last step, we validate *gear* parts. If these parts satisfy the expected contact then they are validated as *gear* otherwise are classified as *miscellaneous.*



```
Function Shape&ContextBasedClassification(parts)

for each part in parts.BearingClass
    if not HasBearingContact(part)
       part is classified as "Spacer"

for each part in parts.ShaftClass
    if not HasShaftContact(part)
       part is classified as "Cylinder_Like"

for each part in parts.ScrewClass
    if not HasScrewContact(part)
       if HasShaftContact(part)
          part is classified as "Shaft"
       else
           part is classified as "Cylinder_Like"

for each part in parts.SpacerClass
    if not HasSpacerContact(part)
       if HasGearContact(part)
          part is classified as "Gears"
       else
          part is classified as "Miscellaneous"

for each part in parts.CylinderClass
    if HasShaftContact(part)
       part is classified as "Shaft"
    else
       part is classified as "Miscellaneous"
end
```

Fig. 5. The shape-and-context based classification algorithm

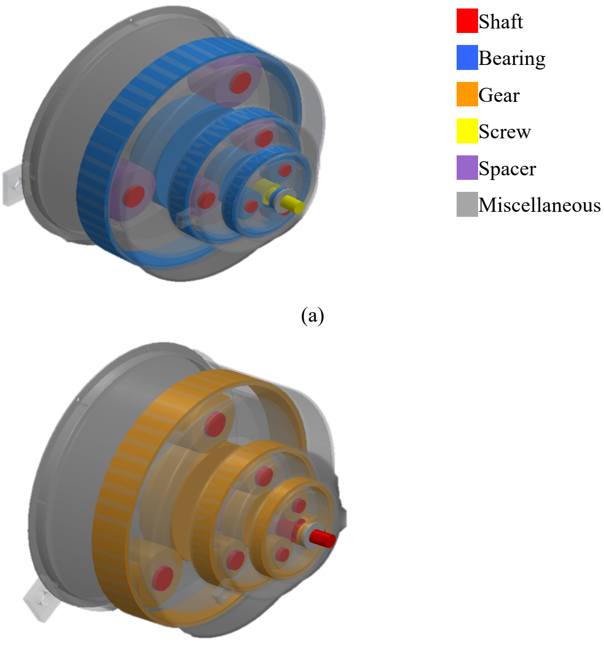
V. RESULTS

Examples of the proposed classification are discussed in this section.

Fig. 6 shows the importance of the validation of part category achieved by capitalizing engineering knowledge in the analysis of the context. It shows a turbine gear whose gears are simplified as drilled cylinders. In this model, analyzing only shape features, a shaft is classified first as screw while gears are pre-classified as spacer and bearing. Using the context, they are well classified despite their meaningless shape.

The gearbox illustrated in Fig. 7 represents a result example where almost all the components are well classified by the **shape-based classification**. Then, thanks to the **shape-and-context-based classification,** parts classified as *part of bearing* and *torus_like* are grouped together as single bearing components (see the left zoom area). On the other hand, parts incorrectly recognized as bearing in the first phase are discarded (see the right zoom area) considering the context.

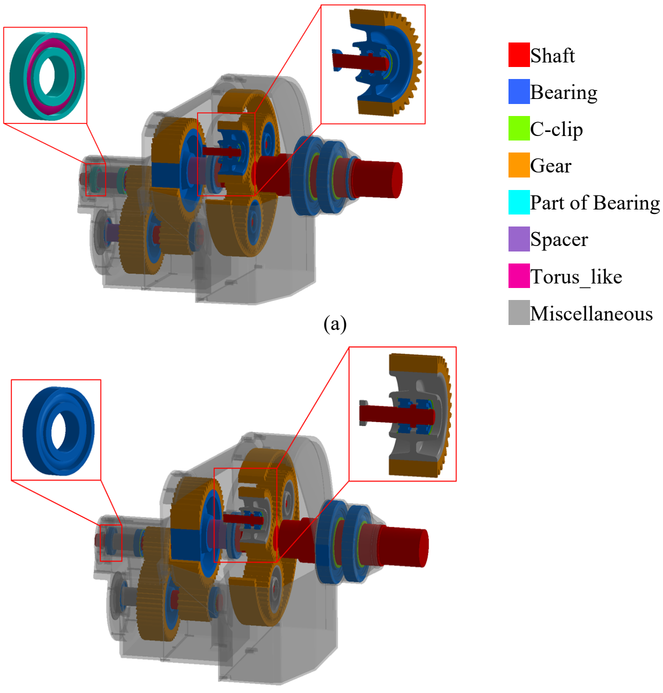
In the current stage, we can observe that our approach still confuses ring-block and bearings. Discerning these components requires a further analysis at the level of contact types. Another solution may consist in considering a wider context, for instance the second level of contacts; that is to analyze also the type of components in contact with those directly in contact with the part to classify.



(a)

(b)

Fig. 6. Turbine gear with the shape-based classification of its components (a), and final component classification (b).



(a)

(b)

Fig. 7. Gearbox for wind turbine with the shape based classification of its components (a), and final component classification

VI. CONCLUSIONS

The paper presents the preliminary results of a research work aimed at the identification in assembly models of components representing specific functional sets and the classification of its parts. The results indicates the validity of the multi-step approach to overcome the limits of approaches solely based on shapes. However, limitations are still present, which can be overcame by further extending the component characterization to the surrounding context, i.e., (i) by analyzing also the class of parts/components in contact with the parts/components directly in contact with the part to classify; (ii) by involving other information layers, such as the mutual positioning of the components. Both these aspects together and the extension to other components and part types will be faced as future work.

REFERENCES

[1] C. Y. Ip, W. Regli, L. Sieger and A. Shokoufandeh, “Automated learning of model classifications,” Proceedings of the eighth ACM symposium on Solid modeling and applications, 2003.

[2] C. Yiu Ip and W. C. Regli, “Content-based classification of CAD models with supervised learning,” Computer-aided Design and Applications, vol. 2, no. 5, pp. 609-617, 2005.

[3] J.-P. Pernot, F. Giannini and C. Petton, “Thin part identification for CAD model classification,” Engineering Computations, vol. 32, no. 11, pp. 62-85, 2015.

[4] F.-W. Qin, L.-Y. Li, S.-M. Gao, X.-L. Yang and X. Chen, “A deep learning approach to the classification of 3D CAD models,” Journal of Zhejiang University SCIENCE C, vol. 15, no. 2, pp. 91-106, 2014.

[5] H. Laga H., M. Mortara, and M. Spagnuolo. “ Geometry and context for semantic correspondences and functionality recognition in man-made 3D shapes”. ACM transactions on graphics (Online) 32. Issue 5, 2013

[6] S. Jayanti, Y. Kalyanaraman, N. Iyer and K. Ramani, “Developing an engineering shape benchmark for CAD models,” Computer-Aided Design, vol. 38, no.9, pp. 939-953, 2006.

[7] A. Shahwan, G. Foucault, J.-C. Léon and L. Fine. Towards Automated Identification of Functional Designations of Components Based on Geometric Analysis of a DMU. Presented at GTMG2011, Grenoble, France.

[8] A. Shahwan, J.-C. Léon, G. Foucault, M. Trlin and O. Palombi, “Qualitative behavioral reasoning from components’ interfaces to components’ functions for DMU adaption to FE analyses,” Computer-Aided Design, vol.45, no. 2, pp. 383-394, 2013.

[9] A. Shahwan, G. Foucault, J.-C. Léon and L. Fine. ” Deriving functional properties of components form the analysis of digital mock-ups. Engineering Computations, Emerald, 2014, pp. 16.

[10] https://www.tracepartsonline.net

[11] K Lupinetti, F. Giannini, M. Monti and J.-P. Pernot. May 2016. CAD assembly descriptors for knowledge capitalization and model retrieval. Presented at TMCE 2016, Aix-en-Provence, France.

[12] F. Giannini, K. Lupinetti and M. Monti, “Identification of similar and complementary subparts in B-rep CAD models,” ASME. J. Comput. Inf. Sci. Eng, on-line published 2017. 10.1115/1.4036120.

[13] L. Chiang, K Lupinetti, F. Giannini, M. Monti and J.-P. Pernot, “Regular patterns of repeated elements in CAD assembly model retrieval,” Computer- Aided Design and Applications, vol. 14, no. 4, pp. 516-525, 2017.