Title:
Enriched Assembly CAD Model Representation Based on Liaison Data Structure

Authors:
Brigida Bonino, brigida.bonino@ge.imati.cnr.it, IMATI, Consiglio Nazionale delle Ricerche
Franca Giannini, franca.giannini@ge.imati.cnr.it, IMATI, Consiglio Nazionale delle Ricerche
Marina Monti, marina.monti@ge.imati.cnr.it, IMATI, Consiglio Nazionale delle Ricerche
Roberto Raffaeli, roberto.raffaeli@unimore.it, DISMI, Universitá degli Studi di Modena e Reggio Emilia

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Introduction:
In the last decades, mechanical engineering sector has been largely affected by the advent of digitalization and the increasing potential of technologies to make the production process more efficient in all its phases. In particular, the production of mechanical assemblies usually relies on the use of a digital model of the final product to analyze, plan, and simulate complex manufacturing operations in an automatic manner, avoiding waste of material, as well as reducing time and costs.
The availability of a consistent and expressive digital model of the final product results thus a crucial condition that enables both a beneficial use and integration of the different technologies and the achievement of optimal and feasible results from the modeling, assembly planning, and reuse standpoints.

For this purpose, the representation of the 3D model of a real product is commonly provided through commercial Computer-Aided Design (CAD) software by means of which the geometric and topological properties of the components of an assembly are ensured. However, especially when dealing with industrial CAD models of mechanical assemblies, the inclusion and availability of semantic information, i.e. all the non-geometric information, such as category membership, technological data, and functionality, is not given for granted. Also, due to the gathering up of different design conventions, components belonging to same class can be modeled according to different criteria, or vice versa, components belonging to different categories can be quasi-identical in shape, and this generates misleading situations. Moreover, parts can be missing, or else purposely omitted (e.g. fasteners), making even more challenging the parts relations understanding.

According to the above considerations, before actually algorithmically addressing assembly tasks, a first CAD model processing phase is required to infer the necessary data associated with components and their relations and interpret the assembly from the engineering point of view. Performing a complete data extraction is not trivial and usually most of the analysis is limited to low-level information detection (e.g. existence of contact, presence of features, etc.), while high-level information (e.g. type of connection, functionality of parts, etc.) is often neglected or manually provided by experts. This, on the one hand, limits the use of engineering meaningful data, which instead would affect the CAD model management, on the other hand, avoids the automation of the assembly tasks performance.

The authors' research is placed in this context and aims at automatically extracting from CAD models of mechanical assemblies high-level semantic information and, then, leveraging it to address assembly tasks. One of the key features of the work, which is the focus of this paper, is the definition of an enriched CAD model representation according to which the semantic data can be stored in a meaningful manner and can be read intuitively. In particular, a crucial point is in the definition of a data structure, called *liaison*, able to comprehensively express the relation between two mating parts of the assembly, both from the geometric and the engineering point of view.

In the following sections, first, a brief overview of the structures usually adopted for storing information about CAD model's parts relations is reported, pointing out the need for a more comprehensive and engineering meaningful one. Then, the liaison data structure is introduced and defined, highlighting its key aspects. Finally, the benefits in using liaisons to represent a mechanical assembly are discussed.

CAD model representations:

When importing a model of an assembly in standard format in an ordinary CAD system, usually the only information that is definitely available is the set of the parts, represented by means of their topological and geometrical entities. The assembly's components can be typically arranged according to a hierarchical tree, where parts are grouped in subassemblies respecting some parent-child relationships or in groups that follow some logical criteria (e.g. same material, same function, same mounting technique, etc.), or else they can be all at the same level, like in a list. However, the existence of the grouping and its characterization depend on the designer choice and on the importing/exporting operations. It is, thus, not necessarily reliable and meaningful in the engineering sense [8]. In addition, this representation does not explicitly describe the contacts between pairs of parts and their properties. These might be implicitly contained in the tree, but they must be computed by means of surfaces or volumes proximity evaluation to be available. Also, parts' type and the functionality are unknown, unless some names may refer to them or else codes are added as descriptions, but it is not mandatory and human intervention is needed to insert and interpret them.

In this context, the automatic enrichment of CAD models with semantic information gained much interest in the last years. A great effort has been made in the enhancement of the product modeling process to represent product knowledge and technology information [7]. It results a crucial step to improve product knowledge exchanging and sharing. Several works can be found in literature that are focused on that topic and address it under different aspects. Some aim to mitigate the semantic gap by providing functional semantic annotation methods for CAD models based on ontologies (e.g. [1, 5]). Some others, instead, are more focused on the recognition and extraction of specific engineering knowledge implicitly contained in the geometry of CAD models (e.g. [3, 4, 6]). However, the semantic interpretation of CAD models and the next leveraging of high-level information in approaches that address assembly tasks are still open issues that deserve to be further investigated.

In addition, once the data is extracted, it is rarely referred to the definition of specific structures aimed at collecting and providing all the types of data inferred, both relative to the single components and the relation between two or more parts, in a meaningful manner that can facilitate their exploitation. For this purpose, common strategies are found in literature to represent the relationships and the constraints between the parts of an assembly by means of matrices or graphs [10].

These structures have aroused great interest over the years because they can be managed as computational objects and then given as input data to well-known algorithms to address different assembly tasks. However, the weaknesses in that assembly representations are several. First, when dealing with assemblies made of hundreds of parts, matrices and graphs have big dimensions and the increase of computational time and costs is the immediate consequence. Secondly, matrices are too abstract structures that can not comprehensively describe the contact between two parts, both from the geometric and engineering point of view. Moreover, in general, the data stored are not at all intuitive to read, since even high-level information is associated with a numerical value (i.e. items of the matrices or weights of graphs' edges).

To overcome the limitations, the paper presents a new semantically enriched product model representation for mechanical assembly. The key idea is to enrich and organize the original CAD model as a list of elements defined as *liaisons*, each of which identifies a couple of mating components. It is to underline that, in general, the term liaison refers to the simple contact between the components but, in this case, the liaison concept is intended in an extended way, more similar to [9]. Namely, a liaison is defined as a new data structure that totally expresses the relation between two mating parts of the assembly. That is, a liaison provides high-level semantic information 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.).

The Liaison Structure:

Starting from a complex CAD model of a mechanical assembly, it is first processed by an automatic and standalone system developed by the authors [2]. Thus, geometric and topological information relative to parts and parts' relations are extracted, as well as semantic information associated with the engineering meaning of components. More in details, as for the single parts, the features associated with mechanical seats are recognized (i.e. holes, grooves, keyways, and keyseats) and a part recognition approach is carried out that classifies standard parts, such as threaded fasteners, locating elements, and seals, according to class and dimensions. As for parts' relations, each surface contact between the faces of two parts, denoted as coupling, is detected and classified based on the faces' geometric properties, as well as the existence of coaxial concave features lying on two contact faces, defined as mounting, is verified.
Once those data are available, the liaison turns out to be a promising structure that allows to gather up them and further enhance the semantic meaning of the relations between parts giving an engineering interpretation.

More in practice, given two parts P_1 and P_2 of an assembly, such that P_1 and P_2 are not standard parts and at least a coupling exists between P_1 and P_2, the liaison between P_1 and P_2 is defined as $L(P_1, P_2, C, M, S)$, where :

- $C = \{c_1, \ldots, c_r\}$ with $r > 0$ is the list of couplings between P_1 and P_2;
- $M = \{m_1, \ldots, m_s\}$ with $s \geq 0$ is the list of mountings between P_1 and P_2;
- $S = \{s_1, \ldots, s_t\}$ with $t \geq 0$ is the list of standard parts connecting P_1 and P_2.

The presence of a list of couplings can be mentioned as one of the features that distinguish liaisons and encourage their use to describe an assembly and its parts' relations, instead of the conventional matrices or graphs. The availability of all couplings associated with the same pair of parts and accessibility to their data ensure a more in depth description of the contact. The knowledge of the number of mating faces (i.e. the number of couplings), their geometry (i.e. planar, cylindrical, conical) and orientations (i.e. common axes for cylindrical and planar faces, normal vectors for planar faces), as well as the overlapping area extension, allow to infer meaningful information on the level of relative clamping between the parts, the degrees of freedom, and possible movement directions.

The list M of mountings is another key element of a liaison, that considerably improves the description of a CAD model by giving engineering sense to the contacts between parts and that is generally overlooked. As a matter of fact, it is important to underline that a mounting is not only a topological attribute of a contact, rather it conveys a deeper semantic meaning. From the engineering point of view, the existence of coaxial holes, in fact, is a typical situation of parts mounted by threaded fasteners or pins. Thus, the presence of mountings results in a crucial feature to understand components' relations and to enforce their connection properties, as well as deducing the assembly process. The knowledge of mountings results fundamental because it is the unique way to infer the presence of fasteners when they are not modeled.

Finally, considering standard parts as an attribute of contacts rather than treating them like any other component results an innovative idea. It definitely distinguishes the liaison structure defined in this

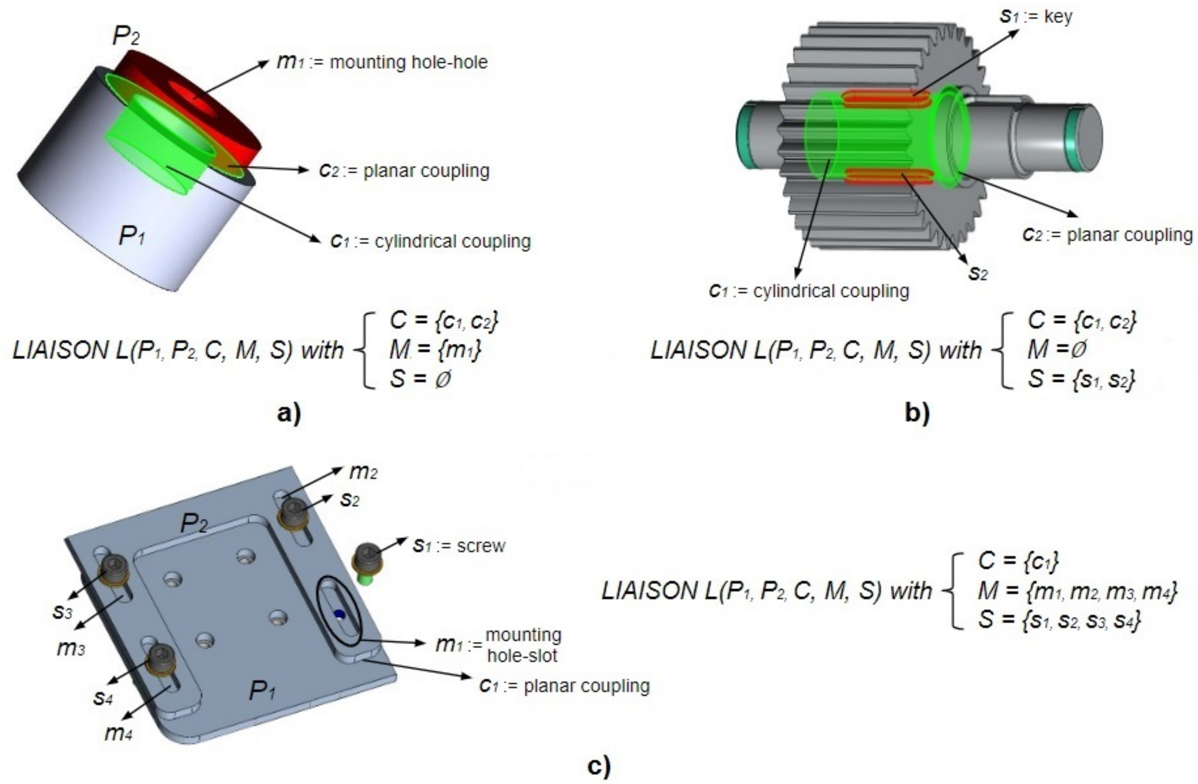

Fig. 1: Examples of liaisons.

work from that presented in [9], which does not address this meaningful aspect, and does not actually mention the possible presence of standard parts.

In Figure 1 three examples of liaisons are provided to better visualize their characteristics. The first liaison (a) consists of a pair of axisymmetric parts with common axes, two couplings and a mounting. The knowledge of the geometric type of the parts and the existence of both a planar and a cylindrical contact allow to infer that the two parts can not slide freely with each other, rather they are blocked in one direction, that is relevant in the assembly process. The second case (b) shows a typical liaison between a shaft and a gear. It has two couplings and two standard parts, i.e. the keys, but no mountings. The awareness of the keys and their positioning in a keyway and a keyseat is crucial to understand the mechanical meaning of the two parts underlying the liaison and the fact that their relative rotation is avoided. Finally, the third example (c) shows a liaison characterizing two parts mounted by fasteners. The liaison includes only one coupling, i.e. there is a single planar contact between the parts, but there are four mountings, each given by the alignment of a hole and a slot, and four standard parts. The presence of multiple mountings already suggests the fact that the parts are tightened through fasteners, then the knowledge of the screws inserted in them strengthens and confirms the assumption, allowing to interpret the contact from the engineering standpoint.

The enriched CAD model representation based on liaisons, where geometric and semantic data regarding assembly's parts and their contacts are collected, can then be considered as the starting point for addressing more complex assembly tasks in an innovative way. In fact, engineering meaningful data, usually overlooked, can be read through the properties of the liaisons, without the need for further computations, and can be leveraged to make more realistic considerations.

Conclusions:

In this paper a new data structure is defined that stands at the basis of an enriched CAD model representation. It is meant to integrate and provide product model and assembly process information in a unique object that meets the requirements of completeness and ease of use. Respectively, completeness concerns the capability of combining in the same object both geometric data and high-level information. Ease of use refers to the availability of the semantic data stored in the new representation avoiding further computations and in the possibility to leverage them in the data exploitation phase through simple queries. Moreover, the new representation is structured in such a way that allows the understanding of the relations of the parts in an intuitive way, trying to include all the information that an engineer would deduce from the observation of a real mechanical product.

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