Title:
Identification of Subassemblies by Leveraging Design Information in 3D Models

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Introduction:
In the last decade, automatic subassembly identification is considered a topical problem in the industrial manufacturing field and actually it is a relevant not fully explored research subject. It results very challenging, both in the product design cycle and in the manufacturing phase, to deal with modern assemblies, due to their increasing complexity. In literature, it is a common strategy to introduce the Subassembly Identification (SI) concept to avoid working with all assembly's parts simultaneously [11, 4]. The idea is to break down the assembly into groups of connected parts which can be treated independently of one another.

The SI offers support in the design phase for the identification of reusable components [13] and finds application in different assembly manufacturing tasks. Assembly Sequence Planning and Disassembly Sequence Planning methods exploit the assembly decomposition to limit the combinatorial explosion of the problem complexity. The recognition of independent components contained in an assembly allows to simplify the assembly line. Each of the components, in fact, can be produced separately, and then all of them are joined to make the final product. Further adding the stability hypothesis to the identified subassemblies is of particular interest to manage the production in parallel: place the production of a single product among multiple supplier industries or industrial robotic assemblers is certainly a solution to obtain a visible reduction in time and costs.

In literature, works dealing with stable subassembly identification tend to focus on the specific methodology treated, without giving any general overview of the problem. Since no comprehensive and generally adopted subassembly definition exists for subassembly identification, our intent is to investigate the problem, pointing out the key concepts definitions, the main assumptions that have to be done and the techniques used for the identification. Then, we will show the issues that arise when dealing with industrial models, and some methods to address them are provided. Finally, exemplification of these concepts is proposed using the CAD model of a real ball valve.

Subassembly Identification Methods:
Subassembly identification is a research topic studied since the '90s. In this field, an accurate definition

of subassembly has been given by Dini and Santocchi [5]. They stated that a subassembly is a group of connected parts, it is stable, in the sense that, if it is manipulated, inner parts have to maintain their mutual positions, and it cannot interfere with the other assembly's parts in the assembly process. However, the tools and the methodologies adopted in these first works are very coarse and above all a massive human intervention is required both in the CAD model data extraction and in the assessment of the achieved results. As a consequence, in the last decade, subassembly identification has been taken up with the principal aim of automating the process. In many works subassembly is now defined, less restrictively, as "a generic subset of assembly's parts" which satisfy assembly constraints, e.g. [12, 9]. Then the concept of stability is introduced as an additional subassemblies' attribute and as a discriminant factor for the subassembly detection. Note that stability assumes several meanings, in addition to that given by Dini and Santocchi. It depends on the specific goal of the paper: for instance, [2] assumes that a subassembly is indistinctly every group of connected parts and it can be partially stable, if at least one component is not totally blocked, or permanent stable, if components maintain their positions irrespective of orientation. In [1] a subassembly is stable if parts can't be easily removed individually, but the overall set can be removed together. Dong et al. [6], instead, define stability through an index calculated on how parts deviate from their correct position while removing connectors.

The criteria on which stable subassemblies identification techniques are based are multiple. However, most methods rely on a common approach, that will be summarised in the following steps. Then, every method has its specific features and pioneering choices.

- *CAD Model Processing.* The processing of the assembly CAD model is the starting point: topological and geometrical information are extracted from it. The objective is to identify parts contacts and constraints as well as the possible directions for parts translations. These data are stored either in matrices or in graphs. The mostly adopted matrices are of three types: the Adjacency Matrix, where each element represents the existence of the contact between two parts, the Constraint Matrix, where elements can be 3-digital or 6-digital arrays representing constraints between two parts along the directions $d \in (\pm x, \pm y, \pm z)$ of the coordinate system of the assembly, and the Stability Matrix, where element represents the stability or the type of fastening between any pair of components. When using graphs, instead, each assembly's part is a node of the graph and the information extracted from the CAD model are included in the edges and in their attributes. The standard graphs employed are the Liaison Graph, equivalent of the Adjacency Matrix, for contact information between any pair of parts, and the Blocking Graph, equivalent of the Constraint Matrix, providing information about the blocking relationships within a component for a given direction (mainly the x, y, x axes) of assembly. These graphs can be enhanced, for example, making them weighted graphs. In the simplest case, weights are given by the type of contact, and represent the same data expressed by the Stability Matrix. In more specialized cases, weights are calculated based on the evaluation of different factors, such as the combination of functional, structural and process constraints [12].
  In general, when dealing with assemblies made of many parts, matrices and graphs have big dimensions and the increase of computational time and costs is the consequence. A simplification stage is then proposed in different works, e.g. [4, 8]: the size of the matrices or the number of nodes are reduced by removing all connector elements, which actually are standard components and can be treated separately.

- *Base Parts Identification.* In order to detect subassemblies, the concept of base parts is introduced. Base parts are m components of the assembly starting from which subassemblies are generated. The number m is always set in advance, and this can be a limitation. The choice of base parts can happen in different ways, either manually selected or automatically according to various criteria.
  The search for base parts is performed on the matrices and/or graphs resulting from the CAD

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model processing. In general, base parts can correspond to the components having highest degree of connections, although contact criterion is not enough for a right classification. As a consequence, the maximization of an objective function is introduced: it involves the evaluation of some heuristic measures, like number of contacts, volume, dimensions and boundary surfaces [4].

- *Subassemblies Identification.* Once the base parts are identified, the generation of subassemblies follows. There exist two different ways for associating parts to base components. Some works provide Iterative Optimization Algorithms to partition the assembly, e.g. [3, 9]. In this case some fitness values are defined and a fitness function has to be minimized. At each iteration the clusters' center and members are updated, until a certain threshold is reached. Other papers suggest to generate subgroups of parts by removing connections between all base parts, e.g. [4]. If any of these subgroups contains only a single base part, it is considered a subassembly itself. On the contrary, if a subgroup includes two or more base parts, it has to be subdivided in as many subassemblies as the number of base parts. To define the membership of a part to a base part's group, some evaluations are done analysing the previously described matrices/graphs.

Limits and Problems:

Almost all works in literature give the description of the specific approach proposed, and assess the efficacy of the method on error free CAD models of simple assemblies with a limited number of parts, or by relying on the human intervention to make available the required information. Moreover, many details are ignored, such as the presence of gravity, the possible existence of deformable parts, as well as the several assembling modes, like fasteners, weldings, glueing, permanent deformation and interference fits, some of which are even irreversible constraints. Other information is, instead, taken for granted, for instance the knowledge of the standard components (fasteners and connectors).

However, to provide reliable and effective tools for industrial application, experiments on real business product models should be taken into account. Indeed, working with CAD models of real assemblies provided by industries is very demanding and many problems arise, which, instead, are usually neglected. In general, in fact, only few limitations of the presented methods are mentioned. Among these, the only possibility of translating parts along the x, y and z axes, the excessive human intervention and the high computational cost.

When dealing with industrial CAD models, several issues arise to automatically extract the necessary information for applying the subassembly detection algorithms.

First of all, CAD models often have missing parts or parts represented in a simplified way. This may refer to different situations. On the one side, it could be a choice of the designer to omit insignificant details, with the aim of making the CAD model leaner and lighter. On the other side, a common practice is not to physically include connections and fasteners (screws, bolts, studs, gaskets, pins, etc.) in the model because they are standard components. Their presence can thus be identified through some specific features: for instance, screws may be inferred from coaxial threaded holes between two distinct parts.

Furthermore, some components can be wrongly positioned or badly modelled (possibly because of import/export numerical issues), generating intersections (volumetric interference) or, vice versa, empty spaces (clearance) among parts [10, 7]. These false features, certainly, cause a misleading interpretation or a missing detection of the contacts.

As a consequence, some hypotheses have to be assumed and a pre-processing phase is required to make the model suitable for the subassembly identification. A detailed analysis of the CAD model is, in fact, crucial for the outcome of the SI methods and all these aspects, very hard to address, which are usually overlooked, should be taken into account.

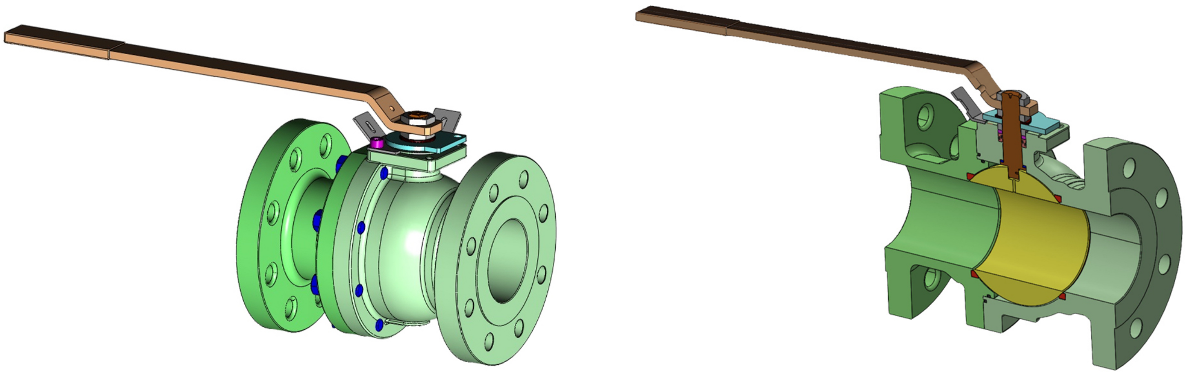

Fig. 1: CAD model and section view of the ball valve.

Ball Valve Testcase:

In order to better clarify the concept of stable subassemblies of a product, we provide an example using the CAD model of a real ball valve (Fig. 1). A ball valve is a quarter-turn rotary motion valve that uses a ball-shaped disk to stop or start the flow. When a port in the ball is in line, it allows flow whereas when you rotate the valve 90 degrees, solid part of the ball stop the flow.

Analysing the assembly, we can distinguish two groups of parts: a body, with inside the ball-shaped disk that can be rotated, and a small hand-wheel, necessary to operate the valve. It can be assumed that these two components could theoretically be two stable subassemblies of the proposed assembly. In fact, they can be assembled separately, and then joined together. This example is also meaningful to point out an aspect of subassembly identification that is never explicitly mentioned. That is to say, once identification is complete, not all parts of the assembly will have been included in one of the recognized subassemblies. Some parts will be excluded from the grouping, because they exactly are the fasteners that connect the identified subassemblies.

This ball valve CAD model also provides some of the issues summarized in the previous section, such as the volumetric intersection between screws and body, some badly modelled parts, as well as the presence of deformable components.

Conclusions:

Automatic subassembly identification is an industrial manufacturing topic where research is active, but many different definitions of subassembly and stable subassembly are employed in literature, and this is confusing. Our work aims to analyse the problem in all its aspects. With the help of industrial CAD models, the issues that are usually overlooked can be highlighted, especially those resulting from the application to real products. In addition, methods, or shortcuts, to address some of these limitations will be proposed.

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