A computer tool to extract feasible assembly sequences from a product CAD model, in automated way

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1 Introduction

Nowadays, at industrial level, the assembly sequence planning for a mechanical discrete product is often carried out manually; generally, making use of CAD software to detect geometrical interferences and to analyze possible movement of components. This process is very expensive and time consuming and optimal solutions are not always guaranteed. Besides, through this planning method it is very difficult to implement a collaborative work intended to better solutions attainment.

Coming up with an efficient assembly sequence is the essential result to improve the production process and reduces the time and the costs related to assembly machines and equipments [1]. For this, it is important to explore alternatives and identify the best assembly sequence.

Current methodologies, developed at academic level for assembly sequence planning, involve querying to experienced skilled staff during the assembly definition process, in order to generate feasible sequences through identification of technical and oriented decision rules or precedence relationships between parts [2]. Most of the approaches start from well-defined product architecture, just like those proposed by Bourjault [4] and De Fazio and Whitney [5], while CAD-based approaches, as those proposed by Gottipolu [6] and Lin [7], require a previous knowledge of the assembly sequence and/or proper definition of assembly mates, which still depend on human intervention.

Such procedures could result impracticable at industrial level because of longer times and monotonous and repetitive inquiries required for the great number of solutions generated.

Mathematical considerations ensure that the assembly sequence problem is addressed through a combinatorial approach based on the total number of parts which are present in the product. The authors argue that further aid in reducing possible feasible assembly sequences can be derived from the extraction of information from the CAD model [8]. Due to the nature of CAD systems and methods currently used in the creation of the virtual assembly models, it is very difficult to base the generation of the feasible sequences on the assembly relationships entered by the user in order to identify assembly precedence. Instead, better results are obtained only considering the spatial interaction between the parts since this approach allows users to define and use conceptual models in early stages of design, to neglect the correct definition of assembly relationships and to spend less time in manual assembly sequence generation or validation.

So, through computer tools it is possible to extract information of either contact or interference between components, in an automatic way, useful for the generation of topological information matrices and/or graphs. From this information is possible to identify independent subassemblies and reduce the problem complexity.

In fact, the assembly planning process based on subassemblies identification has been demonstrated as a viable tool in order to reduce the number of all possible sequences decreasing considerably the combinatorial problems encountered by other assembly planners.

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Purpose: Justify the capability to obtain feasible assembly sequences through an automatic approach based only on contact and interference information between components of a mechanical discrete product, independently of adopted virtual modelling techniques and human intervention.

Method: Analysis of assembly information available at early stages of design in virtual model of a product in order to identify reliable information to be used in a systematic methodology based on identification and evaluation of subassemblies.

Result: Methodology and computer tool to automatically extract possible assembly sequences for mechanical discrete products, starting from topological contact information between components, and guaranteeing at least one feasible solution.

Discussion & Conclusion: Results show that this approach allows obtaining automatically a lower finite number of assembly sequences than theoretical approaches with human intervention, in a faster way to be implemented at early stages of design using virtual model.
working on large real world problems [...]

Lee and Shin presented a methodology for assembly planning directed to minimize the assembly cost and based on subassembly extraction decomposing an attributed liaison graph into a set of sub-graphs according to feasibility and difficulty of disassembly. To do this, the part geometry, physical properties, the information of mating characteristics and tools is required in order to decide the feasibility of an assembly operation [10]. Automated approach presented here is very similar to Lee’s methodology seeing that possible sub-assemblies, with their own sequences, are identified through the definition of node and sub-assembly indices derived from experimental data and validation.

After a brief consideration upon assembly modelling, the automated procedure for assembly sequence generation is explained and applied on a theoretical comparison example.

2 Modelling for Assembly Sequence Planning

Either Assembly Sequence Planning (ASP) or Assembly Sequence Analysis (ASA) depends on the information and knowledge available for a product and its assembly process. Such information could be retrieved from virtual 3D models and so, Computer Aided Assembly Planning (CAAP) methods are generally based on information of assembly relationships between parts (coplanar, coaxial, mate, angle, etc.), defined with the modelling software, to obtain such data. This is essential to guarantee the feasibility of identified assembly sequences.

Anyway, it is worth observing that into feature-based CAD systems, the modelling task could be conducted in different ways. Positioning the parts either according to a specific assembly sequence or, conversely, the different parts could be positioned without a predefined order. In both cases, when a part is related to other two or more parts, its position becomes completely defined. So, for the whole product there is a lower number of assembly mates respecting to those required for an automatic assembly sequence definition. In the pulley-support assembly model shown in Fig. 1, for example, the assembly conditions defined by the CAD user result in the graph reported in Fig. 2 while the real graph, useful for sequence definition for that assembly, is shown in Fig. 3. In this way, it is very difficult to obtain a reliable liaison graph for further development of feasible assembly sequences through the analysis of standard assembly relationships, even though the designer is aware of assembling the different parts in a correct order into the modelling software.

Same considerations can be done with regards to the top-down modelling and assembly methods. In this case no mating connections can be extracted from the assembly, since the reference geometry used on the reference sketch or skeleton could be very rough according to the design intent, and later definition of assembly relationships would conduct to model reconstruction problems.

Independently of the chosen modelling technique, in order to capture design intent, different attempts for assembly relationships definition at conceptual stage have been carried out. For example, with the definition of the assembly formalisms and with an abstract representation where the relative positions of the parts are described specifying the relationships among them [11][12][13]. Equally, with the systematic methodology for
assembly design proposed by Whitney [14], where a kinematic constraint structure and a systematic scheme by which parts are located in space relative to each others are defined, all followed by the declaration of assembly features that connect parts in such a way to create the desired constraint relationships. However, in both theories, the definition of the relationships between the parts is still a designer’s job.

Arun and Rao [ HYPERLINK "Aru10" ] proposed an API for a CAD software to extract assembly related data (links and type of links between the assembled parts and involved features), instead of total human interpretation of the assembly design, in order to facilitate assembly analysis and planning. But, anyway, the assembly sequence is not automatically generated.

Wang et al. [16] state that “most of CAD tools currently do not have the capability to directly analyzing the feasibility of a given assembly plan for a product or to generate an optimal or near-optimal assembly plan”, and so, human intervention is required.

Su [ HYPERLINK "SuQ09" ] presented an integrated software prototype system to find out the geometric assembly precedence relations based on the assembly CAD model and to automatically infer feasible assembly sequences, applying an optimization algorithm; but man-computer interactive analysis is required between each pair of components.

Neelamkavil [18] stated that the creation of the assemblies involves the components relationships, often informally, and a detailed CAD modeling. He proposed a matrix-based analysis in order to identify sub-assemblies and possible sequences, but matrices are compiled manually and those sub-assemblies are identified by the user and not by the system.

In conclusion, most of previous researches related to computer tools require some human interaction and depend on the modelling technique to obtain specific information for their functionality. So, the proposed automatic approach is able to obtain specific information for assembly sequence definition regardless of the adopted modelling technique and of the definition of detailed information only available at later stages of design [8].

3 Automatic approach for assembly planning with case study

Frequently, the production process is defined during the detail stage when all technical aspects of the product are defined, but layouts with technical information can be obtained between conceptual design and embodiment design stages. Such layouts contain qualitative or topological information, related to disposition of components of the product, which seldom changes when quantitative data, i.e. dimensions, tolerances, etc., are defined during detail design stage.

According to this, it is possible to generate a reduced finite number of assembly sequences, where at least one feasible solution exists, starting from basic-level product information generated at early stages of design. For example, Based on topological information derived from contacts and interferences between components of a 3D modelled assembly system defined with non complex geometries but representing and respecting all the functional and technical requirements.

3.1 Case study

In order to better explain the proposed approach and to compare obtained results, a case study has been derived from bibliography. Such example, named “Assembly from Industry (AFI)”, has been presented by De Fazio and Whitney [ HYPERLINK "DeF87" ] concerning to a transmission for trucks assembly (Fig. 4). They argue that such example represents the essence of the assembly problem in all details, and no feature is a product of the author’s imagination. The assembly has a geometry sufficiently represented by circular symmetry about the axial centreline and instead of separate nodes and liaison for fasteners it is assumed that when two parts secured by threaded fasteners are mated, the fasteners are placed and secured.

3.2 Automatic approach

This automatic method is intended to identify possible subassemblies inside complete mechanical systems which are hierarchically arranged till completion of the whole assembly system. For each subassembly, a base node or platform element is identified in order to generate internal sequences. When identified subassemblies have been mounted, they are considered as new components inside the mechanical system and in this way, the procedure starts again to find new subassemblies and so on, until no subassemblies or cycles are found.

Grouping of different components into subassemblies and definition of their sequences are done merely on the basis of the existence of the interactions. No other architectural or resource criteria, such as manufacturability, orientation, personnel capabilities or product line strategy, have been considered. This because their implication requires the participation of expert staff during the assembly sequences definition.

The proposed approach is developed in the following steps:

1) Identification of contacts between components through automatic inquiry of global clearances of zero value or interferences between components from a 3D-CAD assembly model of the mechanical system, where all components are located in their equilibrium position. As stated by De Fazio and Whitney [5] the contact relationship between components include

![Fig. 4 Representation of a Whitney’s transmission](adapted from [ HYPERLINK "DeF87" ])

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force fits, threaded fits, adhesion, compression contact, and even contact by virtue of a part resting on another part. At this point, a list where each row corresponds to a pair of related components is obtained. Fig. 5 shows the contact list between components obtained from the CAD assembly model for the case study. In this case, the information is retrieved from the PTC – Pro/E/Wildfire software.

**Fig. 5 Interaction list obtained from CAD software**

2) Generation of square symmetric binary adjacency matrix and its corresponding graph from both the list of components and the list of their contact information. Fig. 6 presents the liaison graph for the example and it is obvious its correlation with that presented by De Fazio and Whitney in theory.

**Fig. 6 Liaison graph obtained from adjacency matrix**

3) Iterative reduction of nodes with only one connection, that is with degree value equal to one. An iterative reduction process is carried out in order to group nodes with degree value equal to “one” with their adjacent nodes. Assembly sequence for components with degree “one” to their adjacent node corresponds to the first activities carried out during assembly. This step is carried out according to the degree value of the adjacent nodes since the order of grouping is defined by this parameter. For the example, at this step, the component F is joined to the component E and this is considered the first independent sub-assembly to be carried out.

4) Identification of induced cycles through implementation of a new developed algorithm. In graph theory, an induced cycle has no chords or straddling links. A chord or a straddling link is an edge joining two vertices of a cycle but is not itself an edge of the cycle. The new algorithm is based on a combined algorithm of Breadth-Depth First Search [19] and explores first all possible fundamental cycles travelling over an initial node and then removes that node from the given network to avoid enumeration of repeated cycles. Every node is then progressively explored until no further nodes remain in the network. In addition, the algorithm checks for all expanded nodes to find a node connected to the prior node, because this node should be on a straddling link of the cycle, if so, this node is removed from the path list of nodes for definition of the cycle. For the example, at the first exploration thirteen cycles have been identified (Tab. 2).

5) Ranking of nodes based on centrality indexes, $I_{CT}$. The centrality condition of a node is defined for a group of parameters or indexes which helps the approach to identify such important nodes that must be assembled first than their corresponding neighbours. Such indexes are: the degree of the node, its relative participation about all the set of induced cycles of the graph, the mean degree of its neighbours and its weighted clustering coefficient. For the proposed example, Tab. 1 presents the centrality node indexes for the first analysis of the graph.

6) Ranking of either cycles or independent sub-assemblies based on importance indexes, $I_{CI}$. The importance of a cycle is measured by the influence of some indexes defined to evaluate the inner and outer situations of the cycle. Tab. 2 presents the centrality indexes for the cycles identified at the first step of analysis for the transmission example.

7) Subassembly identification. At this point the induced cycle with a higher value of importance index $I_{CI}$ is selected as the initial sub-assembly for the whole sequence and its base component or component platform will be the component node with greater value of centrality index $I_{CT}$. For this subassembly,
the possible sequences start from base node and, respecting the liaisons reduction, $2^{(k-2)}$ sequences are generated. Where $k$ is the length of the concerned cycle. If more than one node is identified as a platform (several nodes with the same value of ICT (0)), as many possible sequences as platform nodes will be generated. For the example, the first independent sub-assembly identified, according to the Tab. 2, is the group with components A-C-B-G, and the base node A is identified for the sub-assembly sequence, according to the Tab. 1.

8) Subassembly reduction. Having identified the subassembly to be mounted, the approach generates possible assembly sequences for that subgroup and reduces all components to the base node without generation of loops or doubled edges.

9) Return to step 3 and repeat previous steps until the last remaining cycle is analyzed and reduced. In the example, these steps have been carried out and the final result is presented in Tab. 3.

At the end of the procedure a list with all obtained assembly sequences is presented. Each row corresponds to a unique sequence and if it is required, the final result can be translated to any type of presentation presented in theory, such as either AND/OR graphs [2], directed graphs, graphical representation schemes or whatever else.

According to the variations found during the procedure, the approach delivers all possible assembly sequences corresponding to the multiplication among the number of possible assembly sequences for subassemblies found at each step of the procedure. These solutions are equivalent from a topological point of view and user can filter some potential solutions using technical parameters of the current assembly line, identifying preferred precedence relations or through implementation of virtual tools intended to visual evaluation. That is, each possible assembly sequence will be presented to the user should evaluate its feasibility. Anyway, the number of queries can be reduced if the user evaluates the feasibility of each possible sequence for subassemblies obtained at each step of the procedure rather than their combination. In this way, the final number of possible assembly sequences corresponds to the multiplication among feasible assembly sequences for subassemblies obtained at each step of the process. This query-answer process must be executed observing the order of the steps, since an unfeasible subassembly is identified; the mechanical system should be reviewed.

Following table 3 summarizes all subassemblies found during procedure application and possible sequences for each of them. The total number of possible sequences corresponds to the multiplication among the number of possible sequences for each step of the process, in this case, this problem presents $(1 \times 4 \times 2 \times 2 \times 6) = 96$ different possible assembly sequences. Anyway, as mentioned before, the number of possibilities can be reduced evaluating the feasibility of the sequences for each subassembly obtained at each step of the process, that is answering to $(1+4+2+2+6) = 15$ queries as presented in Tab. 3.

In this way, only the positive answered questions are considered for the total number of possible assembly sequences for the system. Here, $(1\times 1 \times 1 \times 1 \times 4) = 4$ different feasible assembly sequences are obtained.

In conclusion, this approach generates automatically 96 different feasible and unfeasible assembly sequences in an automatic way and the number of possibilities is reduced to four sequences, answering to 15 queries corresponding to possible assembly sequences for identified subassembly groups in contrast with 36 queries and 440 possible assembly sequences proposed by De Fazio and Whitney’s method.

So, this proposed automatic approach allows automatically obtaining a lower number of possible assembly sequences respecting to theoretical approaches based on querying and answering techniques. Besides, the information required for its implementation could be retrieved in early stages of design with rough virtual models.

4 Conclusions

Proposed automatic approach allows specialized or non-specialized personnel to obtain initial feasible assembly sequences for physical discrete mechanical products in advance during definition of first layouts for promising principle solutions, starting from basic topological information regarding to physical interaction between components.

Owing to the nature of information required (contact) no dimensional or material information is required to be included into the assembly model, making this approach very suitable for assembly sequence generation starting from 3D layouts of solution principles identified at the conceptual and embodiment stages of design.

The method has the potential to generate at least one feasible assembly starting plan. In this way, if no one feasible solution is obtained, this situation indicates that such mechanical system design should be controlled in order to identify instability or over constrained conditions.

The sub-assembly identification approach is adequate to industrial configurations where multiple assembly workstations are introduced in order to speed the product process up, since the assembly plan offers parallelism and flexibility in assembly when independent subassemblies are identified.

It is expected that such proposed methodology opens a possibility for better integration of assembly planning topics into the early stages of design in order to reduce product development time and cost and to increase the product quality. As well as open the possibility to the product assembly analysis without the human intervention but through the use of PDM/PLM systems’ features. In this way, it is possible to ask about assembly issues in less time and to evaluate a greater number of obtained solutions in an objective way; seeing that the virtual 3D model should not be opened in the modelling software to pull out the contact information between parts and the whole management system is able to define the feasible assembly sequences.

Tab. 3 Assembly sequences for the transmission example
References


