Title:

Automatic Assembly Sequence Planning for Axisymmetric Products

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Introduction:

In industrial manufacturing the production of mechanical assemblies is demanding in all its stages. Due to the increasing complexity of products, design, management, and end of life phases are becoming very onerous and time consuming tasks [8]. As a consequence, in the last decades, technologies have been studied to facilitate production and automate different manufacturing operations to reduce time and costs of production, avoid human errors and increase product quality as well as industrial collaboration. In this regard, Assembly Sequence Planning (ASP) is considered one of most challenging topic in the industrial manufacturing field, and still deserves to be explored and further developed. ASP aims at algorithmically identifying the order in which components have to be assembled to obtain the final product. It starts from a CAD assembly model and, by analyzing and extracting part geometric features and relations, returns admissible sequences. Multiple solutions can exist on how mounting components with each other, but the selection of one sequence rather than another has great effect on assembly feasibility, complexity, and accuracy. Moreover, ASP is known to be a very hard combinatory problem while the assembly parts numbers become important [13]. To reduce the complexity, Subassembly Identification (SI) often precedes the sequence planning, in order to apply sequence generation approaches to each subassembly reducing the amount of parts to consider at the same time. However the main weakness observed is that all the data extracted basically relay on geometric information, while the engineering meanings of the assembly/subassembly and its components are not considered. For example, knowing if all the parts are arranged in a specific manner, e.g along a common axis or connected by screws with a precise orientation, would be beneficial in the selection of the assembly direction. Or else, the awareness of deformable components (e.g. circlips, O-ring, etc.) or fasteners allows to make conclusions on their assembly order even when the geometric analysis of precedences is ambiguous.

The work here presented is placed in this context and, specifically, it deals with axisymmetric clusters, i.e. connected groups of parts symmetrical to an axis, all aggregated along the same direction. These groups of parts deserve to be singularly analyzed because they are elements occurring frequently in mechanics, that most of the time can be treated independently of the larger assembly containing them (e.g. crankshafts, pulleys and rollers). Distinctive features of axisymmetric subassemblies are the mounting techniques (i.e. threading by sliding or fitting hollow parts into the axis), the fasteners included (i.e.

O-rings, circlips and keys), and the presence of meaningful parts (e.g. bearings and gears). These characteristics result promising in the ASP simplification and allow to address the problem in a more realistic manner. The approach can be totally automated. Thanks to the specific geometric and topological features of the components included in axisymmetric subassemblies, these can be automatically recognized starting from the only CAD model with a moderate computational effort, and then all the necessary data for the sequence computations can be algorithmically extracted.

In the following, a brief overview on the existing literature addressing the assembly sequence planning problem is reported. Then, the proposed precedence matrix computation approach is described pointing out its key characteristics. Finally an example of matrix computation is provided.

Review on ASP approaches:

Automatically deriving assembly instructions is of great importance in industrial manufacturing to reduce the effort in the production. Moreover, in recent years, the demand for digital instructions is still increasing, for example, to enhance human-robot collaboration or to virtually support the training phase. Many studies have been done from the 80's in CAD-based assembly sequence generation, and a comprehensive survey is presented in [1].

An assumption that underlies most methods is that the assembly sequence can be considered reverse of the disassembly sequence. Therefore, the ASP is solved starting with the complete product and generating its disassembly sequence. This allows to reduce the problem complexity since much more information can be retrieved from the assembly CAD model on parts constraints [5]. In general, works adopting this strategy, then, follow a common schema. Given a CAD model, geometric and topological features are first analyzed and exploited to extract mates relations between parts that are then stored in matrices or graphs, usually defined of contact or liaison. This information describes some components constraints, but is not enough complete to infer assembly constraints. To this aim, further structures, matrices or graphs, are derived from the so called collision analysis. Namely, it evaluates if a part can be freely removed from the assembly without intersecting other components. Combining those two types of data the search for optimal sequence follows, relying on graph theory and optimization algorithm (e.g. [9, 12]). However, from a thorough review of the literature, some limitations in existing methods are evident, and especially they are related to the collision analysis. Among these: the only consideration of the orthogonal directions x, y and z for the movement of the parts, the engineering characteristics and the meaning of the parts that are not taken into account, the calculation of the interferences that involves a high computational load, especially for complex models. The factors mentioned prevent the spread of ASP approaches for large industrial products. Research has been done to overcome some of these limitations, others are still open issues which deserve to be further investigated. In particular, most of the work concentrate on the reduction of the complexity of the problem. A common adopted strategy is to divide the assembly into smaller subsets and then search for the assembly sequence for each of these [4, 11]. Then, to generate more realistic assembly sequence, some recent works presents methods that choose non-orthogonal assembly directions [2, 10], others take into account the engineering features and functionalities of the assembly components [7, 6]. Nevertheless, it can be assessed that only a small number of researches use internal approaches for the collision analysis and give details on the precedence matrix computation algorithm, which instead is a very complex operation.

At this purpose, the paper wants to provide a collisions detection algorithm for engineering meaningful subassemblies, namely the axisymmetric. The precedences computation stands out for the choice of the assembly direction that depends on parts characteristics and relations, the fact that it is a multi-step approach, and it is reported in a simplified 2D space.

Precedence matrix definition:

Given a CAD assembly model, it is assumed that the procedure implemented in [3] has been applied.

By combining a semantic analysis of the assembly's parts and their relationships with some heuristics based on engineering knowledge and design rules, the assembly is partitioned in different types of clusters and relevant information on contacts between the parts of each cluster (i.e. the faces in contact, their geometric type and orientation) is retrieved. Despite the distinction of different types of cluster according to parts geometric and topological characteristics (e.g. symmetries, presence of holes, etc.) and mounting operation, as already said, this work deals with axisymmetric clusters and exploits their characteristics.

First, the distinctive features of the axisymmetric clusters and their engineering interpretation allow to realistically establish the assembly direction, which will not necessarily be the x,y, or z axes. Namely, regardless of how the cluster is oriented, its axis corresponds to the assembly direction according to which parts are mounted, and thus have to be moved in the collision analysis. Once the direction, defined as d, is identified, the computation of the precedence matrix M follows. M is a n-by-n square matrix, with n the number of parts of the axisymmetric cluster. The element (i, j) of M can assume value 0 or 1. More precisely: $p_{ij} = 0$ if $i = j$ or if part i does not intersect part j when moved along the direction d; $p_{ij} = 1$ if part i intersects part j when moved along the direction d. Consequently, the rows of the matrix represent the movement of the parts along the direction d, while the columns represent the movement of the parts along the opposite direction $-d$. If a row/column is zero, it means that the associated part can be disassembled in the direction $d/-d$ with no obstructions. If a row/column has instead some not zero elements, it implies that at least the parts associated with the non zero elements have to be removed before the part associated with the row/column.

Precedence matrix computation:

To fill the matrix, the cluster's parts are considered one at time. Each part has to be ideally moved along d and whether it intersects any of the other parts is evaluated. In the following, let be p the part whose movement is simulated, and q the part that may obstruct the removal of p. The evaluation consists of two steps, increasingly accurate but computationally complex too: bounding box and contact analysis and planar projection analysis.

Bounding box and contact analysis The first step of the obstructions' evaluation is based on simple considerations on part positioning, which allows to exclude some trivial situations, and thus reduce the number of pairs of parts to consider in the next step. That is, the contacts and the positions in the space of each pair of parts p and q are considered. In particular, if part p has a planar contact with q and the normal of the face in contact is parallel to d, it ensures that it is a blocking contact and thus, it can be definitely concluded that q obstructs p. On the contrary, if all the bounding box of p is above that of q with respect to d along the cluster axis it can be concluded that p does not intersect q neither in the initial position, nor if moved along d. In these two cases no further checking is needed for this pair of parts, and it will be skipped in next step.

Planar projection analysis. The second step consists in the analysis of the intersections of the planar domains given by the parts' projections on a plane π perpendicular to direction d. The plane π is chosen tangent to part p and such that p entirely stays in the semi-space over π with respect to d, while q may be also intersected by π. From the projections point of view, it means that the portion of q standing below p should not be projected, since it can lead to mistakes. This because only the portion of q standing above p in relation to d can cause intersections between p and q during the disassembling of p in the direction d. Geometrically, given a part, the output of the projection is a set of co-planar curves that corresponds to the silhouette of the considered portion of part. The set contains at least one curve, the bigger external profile of the part, but it can include other internal curves corresponding to holes. Once p and q have been projected, their resulting curves define two planar domains which lie on the same plane π. If the planar domains do not intersect each other, it means that p can be moved along d without colliding with q (Fig. 1). If instead the planar domains intersection is not empty, the obstruction is re-evaluated, but inverting the roles of p and q, as well as the normal of the projection plane π. That is to say, π has normal parallel to $-d$ and q lies on one side of π, and thus is always totally projected, while p can be totally or partially projected according to its position relative to part q. This second evaluation of the planar projection analysis assesses if q collides with p when disassembled along $-d$, and thus always corresponds to the same entry of the matrix, since columns' matrix represent the movement of the parts along the opposite direction $-d$. If intersections are found, it indicates that p is obstructed by q when moved along the direction d.

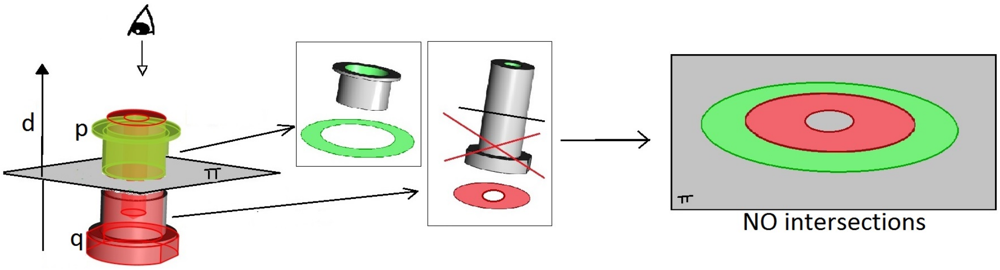
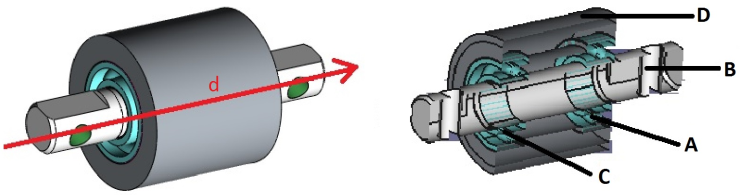


Fig. 1: Example of planar projection analysis of the parts p (to be moved) and q (possible obstruction).

Testcase:

In this section a simple test case of a roller is presented. From Fig. 2 it is evident that the axis of symmetry of the roller is the assembly/disassembly direction d, in fact all the parts are inserted by sliding into the axis (part B). Once d is identified, the collision analysis follows. The bounding box and contact analysis step is sufficient to establish that part A will not intersect part C when moved along d, since it is totally above part C in respect to direction d. Part C is instead obstructed by part D because they have a planar contact with normal vector parallel to d, as well as part D is obstructed by part A. The collisions between the remaining pairs of parts are evaluated with the projection analysis, and the results are reported in the precedence matrix M. Looking at M, it can be correctly affirmed that part A and part B can be first removed in direction d, because the associated rows of M are zero, while part B and part C can be freely moved without intersections in direction $-d$, because the associated columns are zero.



$$M = \begin{array}{c|cccc} & A & B & C & D \\ \hline A & 0 & 0 & 0 & 0 \\ B & 0 & 0 & 0 & 0 \\ C & 1 & 0 & 0 & 1 \\ D & 1 & 0 & 0 & 0 \end{array}$$

Fig. 2: Testcase of a roller.

Conclusions:

The paper presents a method for the automatic detection of collisions between assembly components to be disassembled, with the final aim of identifying assembly sequence for axisymmetric clusters. The approach is independent of the disassembly directions and applies 2D analysis on the projection of potentially obstructive parts. The preliminary results are promising. Future work will focus on the extension of the method to general assemblies, i.e. not characterized by axisymmetric conditions.

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