Automatic Assembly Precedence Detection in Axisymmetric Products

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Abstract. Assembly sequence planning starting from CAD models turned out to be a relevant task in the industrial manufacturing field. To have a successful assembly sequence, the relations between the assembly's parts and the possible interferences during the assembly operations deserve to be investigated. In particular, the collision analysis is the phase in which the movement of each part along some directions is evaluated to assess if it is obstructed by any of the other parts, and according to which the precedence matrix is computed. A lot of work has been done to address the problem, however, existing algorithms need to be improved yet. Among the open issues, the following three result to be the most challenging: the combinatorial explosion of the problem complexity, the limited choice of the assembly directions, and the engineering meaning of parts that is not taken into account, or it is manually given in input by experts. In this paper, an automatic assembly sequence planning approach is introduced. The focus is on the collision detection and precedence analysis for engineering meaningful subassemblies, namely the axisymmetric. Information automatically extracted relying on geometric processing and engineering knowledge, such as parts features and semantic interpretation of mechanical components, is first exploited to identify the subassemblies and, then, to choose the feasible assembly direction, as well as to treat fasteners and deformable parts in a more realistic way. An industrial CAD model of a gearbox is selected as case study to illustrate the approach, also emphasizing the importance of axisymmetric subassemblies.

Keywords: Assembly sequence planning, Precedence matrix, Collision analysis, CAD model processing
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1 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 [11]. In order to remain competitive, manufacturers need to speed up the development time, minimize the manufacturing cost, as well as to find solutions to reuse products or parts of products. As a consequence, in the last decades, technologies have been studied to facilitate and automate the different manufacturing operations, reducing human workload and waste of material. In particular, the ability to automatically derive and plan the assembly/disassembly sequence before the product is effectively mounted/dismantled can significantly contribute, for example, to optimize the assembly sequence according to specific aims, to ensure parallel production lines and promote human robot collaboration, and finally to improve the overall product design [13, 19]. In this regard, Assembly Sequence Planning (ASP) is considered one of the most challenging topics in the industrial manufacturing field, and often it is also treated in conjunction with Disassembly Sequence Planning (DSP).

ASP aims at algorithmically identifying the order in which components have to be assembled to obtain the final product. It generally starts from a CAD assembly model and, by analyzing and extracting parts' geometric features and relations, returns admissible sequences. Multiple solutions can exist on how mounting components with each others, but the selection of one sequence rather than another has great effect on assembly feasibility, complexity, and accuracy. Moreover, since the relations between each pair of components have to be addressed, ASP is known to be a NP-hard combinatorial problem, especially when the assembly parts numbers become important. To reduce the complexity, assembly sequence planning based on subassemblies identification has demonstrated its suitability limiting the amount of parts to consider at the same time [25]. However the main weakness observed is that all the data extracted basically rely 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 pattern, would be beneficial in the selection of the assembly tools and directions and thus also in minimizing changes in the assembly orientation. Or else, the awareness of the presence of deformable components (e.g. circlips, O-ring) or fasteners allows the identification of their assembly order even when the geometric analysis of precedence is ambiguous [14].

The work here presented is placed in this context. Specifically, it introduces an automatic assembly sequence planning methodology for meaningful subassemblies, namely the axisymmetric, which are identified exploiting engineering knowledge combined with geometric and topological analysis of a CAD assembly model. The choice of focusing on the solely axisymmetric clusters is justified by the fact that often these specific groups of parts can be mounted independently of the rest of the assembly, or, in any case, the knowledge of their assembly sequences can simplify the search for the sequence of the entire assembly. The paper is organized as follows: the next section presents a brief overview of the related research works; Section 3 introduces the axisymmetric concept, while Section 4 describes the devised collision detection analysis method for the assembly sequence computation. Section 5 describes the results of the method applied on an industrial assembly model of a gearbox. Finally, Section 6 concludes the paper with current open issues and some future perspectives.

2 RELATED WORKS

The assembly sequence planning from 3D CAD models is a deeply investigated research topic. Many works have been presented in this direction from the 80's, and it is evident that different methodologies have been proposed over the years. Comprehensive surveys can be found in [2, 12].

To assemble a product, in reality, a starting component is chosen and then all the other parts are subsequently mounted on it. Following such approach to automatically define an assembly sequence is however very challenging, since there are too many degrees of freedom in the choice of the order in which the parts can be assembled and in the choice of the mounting directions, thus experts supervision is needed. As a consequence, to reduce the complexity of the problem, the assembly-by-disassembly strategy is largely employed [10] and prevails throughout the literature in assembly planning. Assuming that the assembly sequence can be derived exploiting the reverse of the disassembly sequence, it is possible to tackle the ASP problem starting with the 3D model of complete product. This implicitly includes the constraints on its components, both relative to parts' contacts and assembly operations, and this would reduce the range of assembly motion a planner has to consider. More in details, given a CAD model of an assembled product, the contact relations between parts are usually described by means of matrices or graphs. Although there are methods that generate assembly sequences by exploiting graph theory starting from the only connection graph (e.g. [6, 24]), results are not always reliable, since geometric and motion constraints are not taken into account. To ensure feasible sequences, where parts can be (dis)assembled without obstructions, the assembly precedence relations analysis is the key point [20]. As a matter of fact, most of the researches on ASP algorithms perform a collisions detection analysis. They assess that the movement of each part is evaluated according to some directions to identify the collision-free paths according to which parts can be removed without being obstructed by other components. However, it is often assumed that the matrices are already given or they are manually defined by dragging components in a physical simulation environment with the help of commercial CAD software [16, 23, 26]. But this results a time consuming and error prone operation, that requires human intervention, can not be automate, and also it is difficult to implement in a collaborative working environment [17]. On the other hand, when internal approaches regarding collision analysis are presented, weak assumptions are made, that abstract much from real engineering situations, or some limits are pointed out. Among these: the only consideration of the orthogonal directions x,y, and z for the movement, the characteristics and semantic meaning of mechanical parts are not taken into account, and the definition of sequences that involves all the assembly parts simultaneously, regardless of the existence of functional sets.

Intending to automate and generate more realistic data, some work has been done, addressing at least one of the above issues. First of all, a common adopted strategy is to divide the assembly into smaller subset that can be treated independently and assembled in parallel. For example, Pintzos et al. [18] introduce the definition of assemblies tiers, that are groups of parts that can be assembled at the same time, and then assembled with each other. However much effort is required to the user in the base part definition, as well as in the collision analysis computation. In [1], a subassembly identification method is provided that groups parts according to their fastened relations. Anyway, fasteners are given in input and no other engineering features are taken into account. Trigui et al. in [22] provide a subassemblies identification approach to simplify the disassembly planning. The subassemblies are defined starting from the base parts recognition and removing connections between them, but this choice does not ensure feasible and engineering meaningful results. Moreover, the (dis)assembly directions considered in the mentioned works are always the orthogonal axes x, y and z. To improve this aspect, Tao et al. [21] introduce the use of Gaussian spheres to define the set of all feasible moving directions of each part. Each contact implies a sphere with a constraint. The intersection of all the constrained spheres associated with a pair of parts' contacts returns the possible moving directions for that parts. In [3] the movement directions, according to which the collision analysis is performed, are derived from the assembly constraints' axes. If the mate entity is a point, a line or a plane then associated normal vectors are chosen. If the mate entity is a revolution surface, the axis of revolution is the only admissible. Finally, as for the semantic meaning of specific mechanical parts, Neb et al. [16] take into account the existence of categories of parts, e.g. screws, nuts and circlips, that must be treated in a different manner in the collision analysis, because they have a specific function in the assembly, and thus a precise relation with other parts. However it is assumed that the type of the parts is known. In [9] a simplified ASP is proposed, where the collision analysis is carried out excluding fasteners to reduce the number of parts, and then inserting them in the resulting sequence. Nevertheless, deformable parts are not considered and standard parts are recognized only by their names.

This paper aims at fully automating the collision detection analysis and overcoming existing limitations. In particular, the proposed approach takes in input the unlabeled CAD model of an assembly in standard format, e.g. STEP. Based on engineering knowledge and geometric analysis, semantic information on parts and their relations are extracted and leveraged to identify engineering meaningful subassemblies and, then, generate their precedence matrix (Fig. 1). It is computed standing out for the choice of the assembly direction that depends on parts characteristics and taking into account the existence of fasteners and deformable parts.

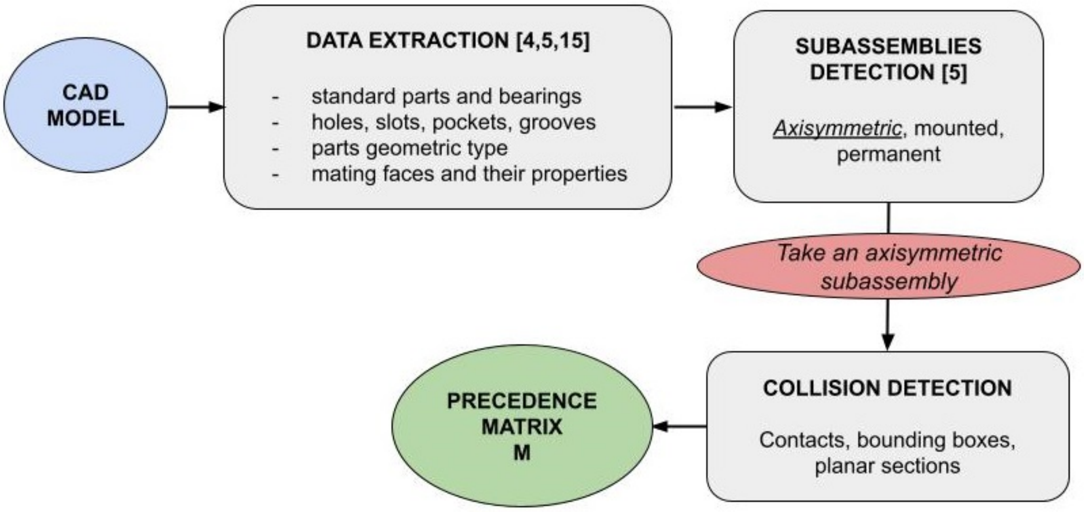


Figure 1: Flowchart that shows the main steps of the approach.

3 INTRODUCTION TO AXISYMMETRIC SUBASSEMBLIES

The proposed approach deals with a specific type of engineering subassemblies, namely the axisymmetric. Axisymmetric subassemblies refer to connected sets of components symmetrical to an axis, all aggregated along a common axis, both concentric and side by side.

These groups of parts deserve to be identified and analyzed because they are elements occurring frequently in mechanics, that most of the time can be treated independently of a larger assembly containing them. Examples are assemblies having power or movement transmission function. They always include one or more crankshafts, consisting of axisymmetric parts mounted along a common shaft. Or else, subassemblies such as roller or pulley are very common. Furthermore, the mounting technique used in these situations involves threading by sliding or fitting hollow parts into the axis or into the central part. Fasteners used to join parts are mainly deformable axisymmetric components (i.e. circlips and O-rings), with the exception of keys. Besides, some meaningful parts can be found, such as gears and bearings.

These distinctive features that characterize axisymmetric subassemblies result promising in the ASP simplification and allow to address the problem in a more realistic manner. First, the axis of symmetry suggests the direction of assembly of the parts. While in standard methods the x, y, and z axes are often taken as the only possible movement directions, not being bound to that orthogonal axes avoids trivial errors. For example, those issues deriving from the use of a rotated reference system or from the diagonal positioning of the axisymmetric sets in the assembly. Also, the availability of semantic information about some of the components allows to optimize the resulting sequence, taking into account engineering features that are usually overlooked. Another advantage of working with axisymmetric subassemblies, which improves existing ASP methodologies, is that the approach can be totally automated, from the subassembly identification to its sequence computation. In fact, 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 this work, the identification of the subassemblies of interest takes up the methodology provided in [5]. The engineering requirements for parts belonging to axisymmetric subassemblies are described in terms of parts' geometric characteristics and their contact features. In particular parts must be symmetric with respect to an axis, and they must be placed in the space with all axes coinciding. Each component must be in contact with at least another one, and the faces in contact can be planar, conical or cylindrical. The only fasteners accepted are those typical for the connection or locking of axisymmetric parts. Namely, circlips and O-rings, which have a axisymmetric geometry too, as well as keys, which, instead, have no axial symmetry, while threaded connectors are excluded.

All the needed information are obtained relying on geometric processing and features recognition, as well as applying previous developed standard parts and functional components recognition algorithms [4, 15]. Once detected the subassemblies, the available information relative to parts and their relations is exploited in the precedence matrix computation and thus in the assembly sequence planning. The information includes:

- axis of the parts, and thus axis of the subassembly;
- features of each part, i.e. existence of holes, slots, pockets, and grooves;
- part type, i.e. when they are standard parts the related class, as circlips, O-rings, keys;
- pair of parts in contact;
- properties of each contact, i.e. number of mating faces, their geometric type and orientation.

4 THE COLLISION DETECTION METHOD

The method for the automatic detection of collisions between axisymmetric subassembly's components to be disassembled is detailed in the following. It strongly exploits the characteristics of this type of subassembly in order to reduce and simplify the interference analysis. In fact, due to their nature, the 3D collision detection can be reconducted to a 2D profiles intersection problem. Works already exist that take advantage of the 2D projections of parts for collision analysis (e.g. [7, 8, 17]), but false intersections can occur, or other steps (e.g. ray tracing) are needed to assess the obstructions during the parts movement. Thus, the proposed approach is distinguished from the others by the only use of planar sections of the assembly's components to simulate the disassembly operations and evaluate collisions.

4.1 Preliminary Concepts

The collision analysis consists of a broad phase and a narrow phase, as are defined in literature [27]. The first is a qualitative analysis, aimed at excluding trivial cases, it involves the use of contacts' knowledge and bounding boxes. The latter is a more accurate, but computationally complex too, analysis which exploits axisymmetric hypothesis to solve the collision detection in a reduced 2D space.

Algorithm 1 shows the scheme implemented to address the collision detection. In particular, the subassembly's parts are considered one at time. Each part has to be ideally moved along the disassembly direction $\mathbf{d}$, corresponding with the axis of symmetry of the subassembly, and whether it intersects any of the other parts is evaluated. The expected output is a matrix $\mathbf{M}$, namely the precedence matrix, that is a n-by-n square matrix, with n the number of parts of the axisymmetric object. The element (i,j) of $\mathbf{M}$ can assume value 0,1 or 2. More precisely:

- $m_{ij} = 0$ if $i = j$ or if part i does not intersect part j when moved along the direction $\mathbf{d}$;

- $m_{ij} = 1$ if part i intersects part j when moved along the direction $\mathbf{d}$;
- $m_{ij} = 2$ if there is a blocking contact (where a blocking contact refers to a contact between planar faces with normal vectors parallel with $\mathbf{d}$.)

Consequently, the rows of the matrix represent the movement of the parts along the direction $\mathbf{d}$, while the columns represent the movement of the parts along the opposite direction $-\mathbf{d}$. If a row/column is zero, it means that the associated part can be disassembled in the direction $\mathbf{d}/-\mathbf{d}$ with no obstructions. If a row/column has instead some non-zero elements, it implies that the parts associated with the non-zero elements have to be removed before the part associated with the row/column.

In the following, p indicates the part whose movement is simulated, and q the part that may obstruct the removal of p.

Algorithm 1: Collision detection

```
Data: PARTS:=list of parts; $n \geq 0$ number of parts
Result: $\mathbf{M}$ precedence matrix
for $i = 0 : n$ do
    for $j = 0 : n$ do
        if $i = j$ then
            $m_{ij} := 0$ Continue for
        end
        $p :=$ PARTS($i$); $q :=$ PARTS($j$) ;                         /* Phase 1 */
        if $p$ in contact with $q$ then
            if contact is blocking then
                $m_{ij} := 2$ ;
                Continue for;
            end
        end
        $B_p :=$ bounding box of $p$; $B_q :=$ bounding box of $q$;
        if $min_z(B_p) > min_z(B_q)$ then
            $m_{ij} := 0$;
            Continue for
        end
        $S_p :=$ section of $p$; $S_q :=$ section of $q$ ;              /* Phase 2 */
        $S'_p :=$ extrusion of $S_p$;
        if $S'_p \cap S_q \neq \varnothing$ then
            $m_{ij} := 1$
        else
            $m_{ij} := 0$
        end
    end
end
```

4.2 Phase 1: Contacts and Bounding Boxes

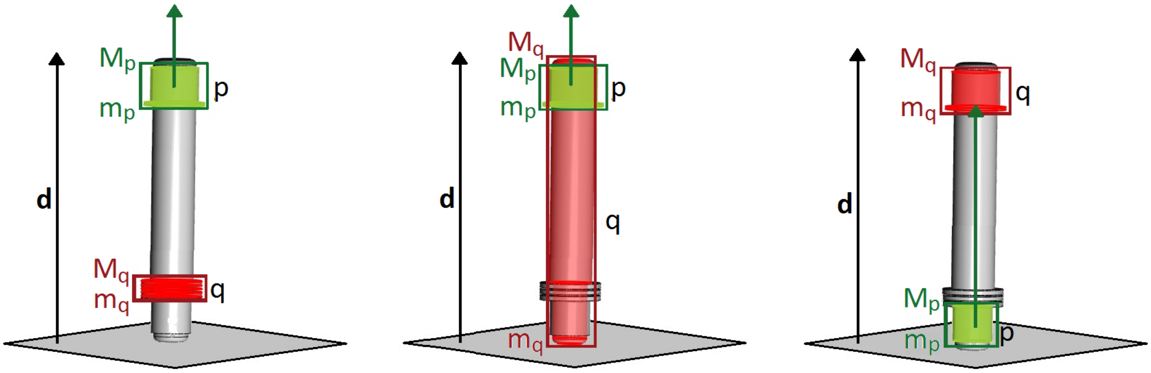
This step of the collision analysis is basically a static evaluation. According to the space occupied by parts and their relative positions in the assembly, considerations are made both on the certainty that a part is blocked and on the possibility of moving a component without interferences.

(a) $\mathbf{n}_p // \mathbf{d}$ (b) $\mathbf{n}_p // {-\mathbf{d}}$

Figure 2: Examples of blocking contacts.

Contacts. The availability of detailed information on parts contacts pointed out in Section 3 is one of the peculiarities of the proposed approach and can be exploited at this stage to fix some entries of the matrix with no further computations. When p and q are in contact and, at least, they have a contact between planar faces, the orientation of the faces is crucial to define if one part is definitely blocked in a certain direction by the other. In the considered case, i.e. under the axisymmetric hypothesis, if the planar faces in contact have normal vectors $\mathbf{n}_p$ and $\mathbf{n}_q$ parallel to the direction of movement $\mathbf{d}$ or to the opposite direction $-\mathbf{d}$, it can be concluded that the contact is blocking (Fig. 2). In details:

- $\mathbf{n}_p // \mathbf{d}$: p is blocked by q in direction $\mathbf{d}$ and thus can not be moved along $\mathbf{d}$ (Fig. 2a). The matrix element associated with p and q is fixed at 2.
- $\mathbf{n}_p // {-\mathbf{d}}$: p is blocked by q in direction $-\mathbf{d}$ and thus can not be moved along $-\mathbf{d}$ (Fig. 2b). For the matrix properties, this information is reported in the matrix by fixing the the element associated with q and p at 2.



(a) $m_p \geq M_q$ (b) $m_p \leq M_q$ (c) $m_p \leq M_q$

Figure 3: Possible relative positions between two bounding boxes.

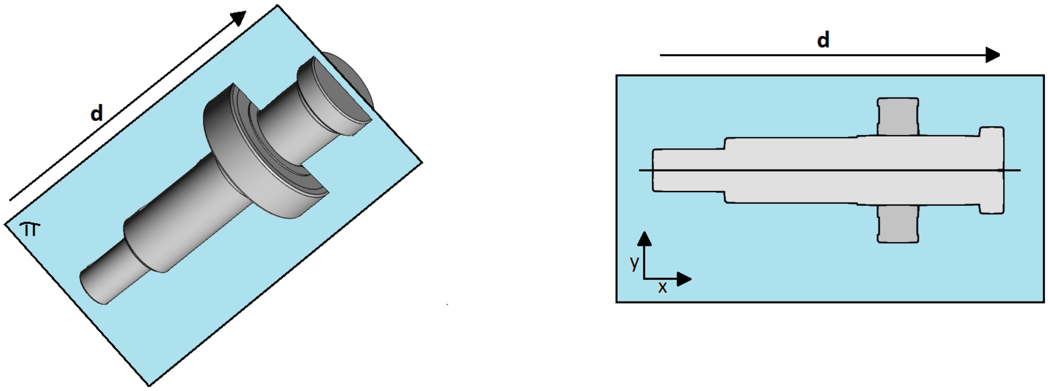
Bounding boxes. To simplify the analysis, the bounding boxes of the parts p and q are defined in a reference system such that the direction $\mathbf{d}$ corresponds to the z axis.

Since we are considering axisymmetric assembly with parts aggregated along a common axis, it always exists a direction along which when p moves it intersects q. As a consequence, the information of non-intersection between the two bounding boxes is not sufficient to exclude an intersection along $\mathbf{d}$, and, thus, to set the matrix element associated with p and q to 0. Indeed, it is necessary and sufficient to compare the minimum m and maximum M of z coordinates of the two bounding boxes. In particular:

- $m_p \geq M_q$: it means that p is beyond q relative to direction $\mathbf{d}$, and they will never intersect (Fig. 3a). The matrix element associated with p and q is fixed at 0.
- $m_p \leq M_q$: it can indicate both that p is overlapped with q (Fig. 3b) or p precedes q (Fig. 3c) relative to direction $\mathbf{d}$, and they may intersect when p is moved along $\mathbf{d}$. The matrix element associated with p and q remains undefined and is then solved by reasoning on the intersection of their planar sections, as described in the next chapter.

4.3 Phase 2: Planar Sections

This step consists in the analysis of the intersections of the planar sections obtained cutting the parts p and q along their axis with a plane parallel to direction $\mathbf{d}$. To simulate, then, the movement of p in direction $\mathbf{d}$, its section is extruded for a certain length so that it can be brought over q.



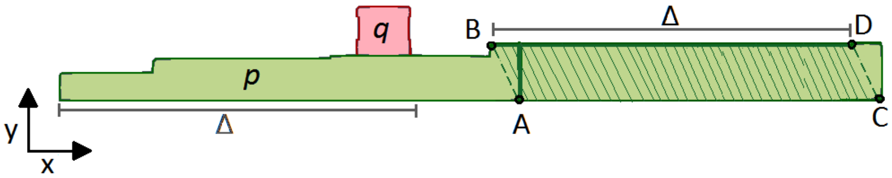
(a) Parts 3D models with section plane π.

(b) View of the planar sections.

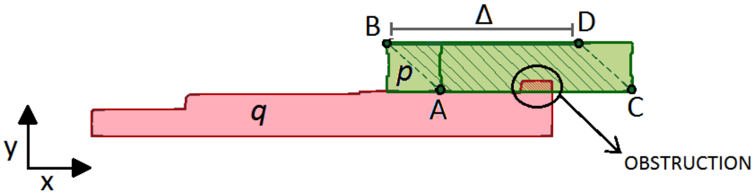
Figure 4: Example of a pair of parts (i.e. bearing and shaft) that require planar sections analysis.

To do this, the cutting plane π is defined with a normal vector perpendicular to the direction $\mathbf{d}$, passing through the parts' axis, and a reference system is set such that π corresponds at the xy plane (Fig. 4). The analyzed components p and q are then cut, and the respective sections are obtained. In the rest of the analysis we consider only half of the sections. In fact, thanks to the symmetry conditions of axisymmetric parts, the behavior of half of a section corresponds with the behavior of the whole part, and thus a planar analysis of a restricted portion of the components is sufficient to evaluate obstructions. After the sections computation, the movement of p along direction $\mathbf{d}$ has to be simulated to verify if q obstructs its disassembly. At this aim, the section of p is considered. It has to be extruded in direction $\mathbf{d}$ until the space occupied by q is taken.

Geometrically, this operation is addressed by searching for two points A and B on the profile of the section of p. Respectively, A corresponds to the vertex with the maximum x (if there are multiple, the one with the minimum y is chosen), while B corresponds to the vertex with the maximum y (if there are multiple, the one with the minimum x is chosen) (Fig. 5). Two new points C and D are then obtained translating A and B in the direction parallel to $\mathbf{d}$ for a distance Δ such that p will result completely extracted from q. The planar domain given by $ABDC$ covers the maximal space occupied by part p during its disassembly movement. As a consequence:



(a) The bearing (q) does not obstruct the shaft (p) movement.



(b) The shaft (q) obstructs the bearing (p) movement.

Figure 5: Evaluation of the obstruction of the bearing when the shaft is moved along d, and vice versa.

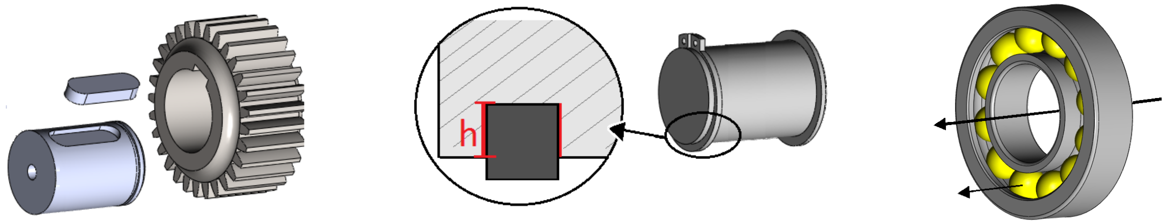
- if the planar domain given by $ABDC$ does not intersect the planar domain given by the section of part q, then q does not obstruct p when moved along $\mathbf{d}$ (Fig. 5a). Consequently, the matrix element associated with p and q is fixed at 0;
- if the planar domain given by $ABDC$ intersects with the planar domain given by the section of part q, it means that the parts intersect during the disassembly (Fig. 5b), and then the matrix element associated with p and q is fixed at 1.

It can happen that the sections of p and q intersect already before doing the extrusion. It can be due to modeling issues or numerical errors. This may return a false obstruction during the analysis. To avoid errors, it must be verified the presence of intersections between the two original sections. If there is any, and the ratio of its area to the total area of the planar domains is below a given tolerance, it will not be considered as an obstruction in the analysis.

4.4 Particular Cases: Fasteners and Bearings

In CAD assembly model, situations can occur in which the collision analysis fails due to the distinctive shape of some parts and their modeling. These can be summarized in three particular cases: the use of non-axisymmetric fasteners for connecting two parts (i.e. keys), the use of deformable fasteners for blocking parts (i.e. circlips and O-rings), the existence of parts that need to be treated as a single component (i.e. bearings). We have addressed these particular cases exploiting engineering knowledge combined with the available geometric information on assembly's parts (see Section 3). In details:

Non-axisymmetric fasteners. Axisymmetric subassemblies often involve the use of keys to restrain/align pulleys or gears to shafts. Keys, however, are not axisymmetric parts and need to be mounted perpendicularly



(a) Key. (b) Blocked circlip. (c) Bearing.

Figure 6: Examples of particular cases for the precedence computation.

to the axis direction. Thus, the planar sections analysis is not suitable for evaluating their movement. But, thanks to the preliminary assembly processing [4], keys are known, as well as the parts they connects are recognizable, because of the identification of pockets features which are associated with keyseat and keyways. As a consequence, in the precedence computation, the collisions between a key and any other part are not evaluated, and keys are not included in the precedence matrix. Rather, the associations between keys and the parts they are mounted in are stored separately and, then, exploited in the assembly sequence definition. A key, in fact, will be disassembled after the outer part and before the inner (Fig. 6a).

Deformable fasteners. In axisymmetric subassemblies, circlips and O-rings are commonly used to retain components, but they are standard parts with a particular behavior since are deformable. In fact, these fasteners are axisymmetric-like and are fitted in their seats, namely in the grooves, by enlarging. They are usually modeled with resting shape, therefore from the collision analysis they would always be blocked by the part in which they are inserted. The classification of circlips and O-rings can be exploited together with the recognition of grooves to identify the pairs fastener-part and make some considerations. In particular, to overcome misleading results of the planar sections analysis, the suggested strategy is to simulate the dilation of the deformable components by translating their sections perpendicular to the axis direction for a distance h equal to the depth of the groove (Fig. 6b), as if the parts were enlarged and then removed by sliding. This would avoid the wrong intersection.

Bearings. Bearings are functional sets typical of assemblies for movement transmission. On the whole, bearings are axisymmetric objects, mounted by sliding on a shaft. However, they consist of multiple parts, some of which (i.e. the inner balls) have axis not corresponding with the axis of the shaft (Fig. 6c). In the collision analysis, considering each part of a bearing singularly would be misleading. Therefore, to simulate engineering meaningful operations and obtain reliable results, also reducing the size of the precedence matrix, bearing's parts have to be treated as they were merged in a single object. In literature, this topic is never handled specifically and bearings knowledge is taken for granted. In practice it is not a trivial operation, especially when working with CAD assembly models in standard format. Here the work described in [15] is exploited to automatically recognize bearing allowing the analysis of their movement as a single part.

5 TEST CASE

In this section the application of the proposed approach on a real industrial CAD model of a gearbox is discussed. It is a significant example that underlines the importance of identifying subassemblies according to engineering meaningful criteria and, especially, it allows to justify the choice to investigate the ASP problem under the axisymmetric conditions.

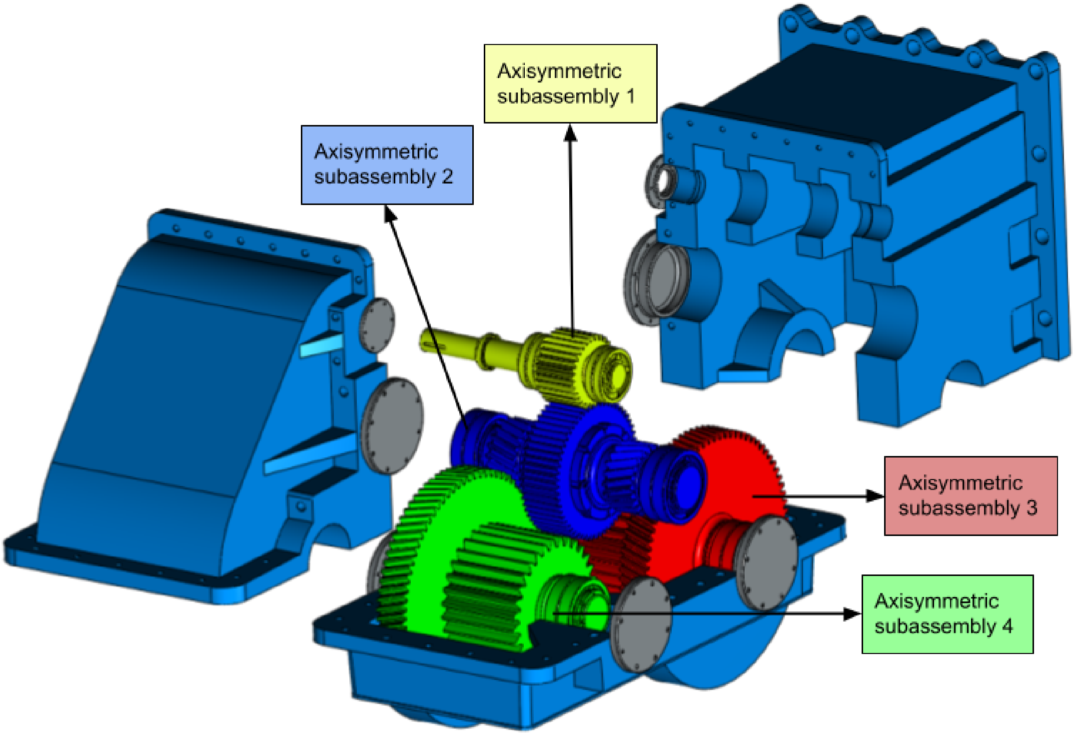


Figure 7: Exploded view of the CAD model of a gearbox, with highlighting of its axisymmetric subassemblies.

The gearbox is made of 426 parts and, as shown in Fig. 7, it turns out to be composed of 4 independent axisymmetric subassemblies contained in the cover (fixed by 290 screws, nuts and washers). The number of parts of which the subassemblies are made up ranges from 8 to 13, already taking into account bearings' parts merged in a single component (i.e. each bearing is actually composed of 10 parts). The identified subassemblies mainly include a principle shaft on which bearings, gears, and hollow cylindrical components are mounted with the help of keys and circlips. Thus, thanks to the semantic analysis of the CAD model parts, the parts classification and the meaningful subassemblies identification, it is possible to compute the ASP of the entire gearbox by first addressing the collision analysis for restricted groups of parts, rather than for 426 parts simultaneously.

In the following, the collision analysis for one of the identified subassemblies is outlined, namely the subassembly 3 (as it is referred in Fig. 7). It consists of 13 parts, 2 of which are bearings and 4 are keys (Fig. 8). As explained in section 4.4, keys are not included in the precedence matrix, but they are separately associated with the parts they fasten together. Thus, the precedence matrix $\mathbf{M}$ computed with the collision analysis algorithm is a 9-by-9 square matrix (Fig. 9a), and a 9-by-4 matrix $\mathbf{K}$ is also reported to show the relations between the keys and the relative shaft and/or gears (Fig. 9b). The provided approach results promising. The obstructions between the subassembly's components are correctly detected and the computation is totally automatic, without the need of human intervention. Moreover, the pair of parts that have to be evaluated by means of the sections analysis is reduced from 81 to 36 thanks to the contacts and bounding boxes phase, allowing to reduce the required computational effort.

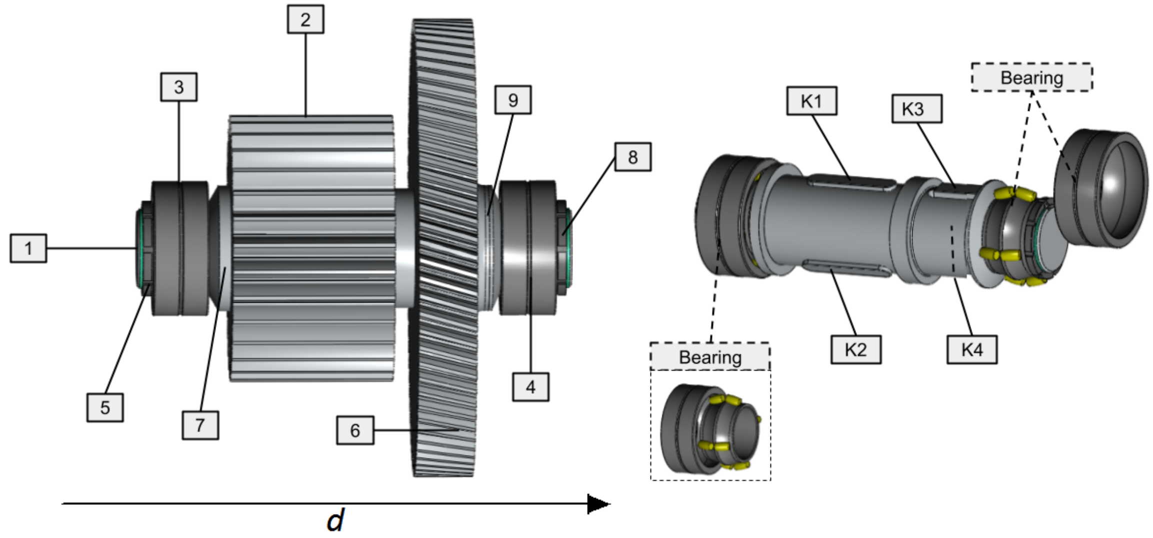


Figure 8: Visualization of the axisymmetric subassembly 3 and its parts.

$$\begin{array}{c|ccccccccc|}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
1 & 0 & 0 & 0 & 1 & 0 & 2 & 0 & 1 & 1 \\
2 & 2 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\
3 & 1 & 1 & 0 & 1 & 0 & 1 & 2 & 1 & 1 \\
4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 \\
5 & 1 & 0 & 2 & 0 & 0 & 0 & 1 & 0 & 1 \\
6 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 2 \\
7 & 1 & 2 & 0 & 1 & 0 & 1 & 0 & 1 & 1 \\
8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
9 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 1 & 0
\end{array} = M$$

(a) Resulting precedence matrix.

$$\begin{array}{c|cccc|}
 & K1 & K2 & K3 & K4 \\
\hline
1 & x & x & x & x \\
2 & x & x & - & - \\
3 & - & - & - & - \\
4 & - & - & - & - \\
5 & - & - & - & - \\
6 & - & - & x & x \\
7 & - & - & - & - \\
8 & - & - & - & - \\
9 & - & - & - & -
\end{array} = K$$

(b) Matrix of the keys' relations.

Figure 9: Results of the collision analysis applied to the axisymmetric subassembly 3.

Finally, starting from $\mathbf{M}$, a first disassembly sequence can be derived based on the assumption that a zero row implies that the corresponding part can be removed with no collisions from the subassembly in direction $\mathbf{d}$, and a zero column implies that the part can be instead freely removed in direction $-\mathbf{d}$. Removing at each time a zero row/column of $\mathbf{M}$ and reevaluating the obtained sub-matrix, a possible order according to which parts can be disassembled is obtained. This task will be further investigated in future work.

6 CONCLUSIONS

The paper presented a method for the parts precedence detection for the disassembly of the axisymmetric assemblies. The method has been developed as a prototype module of the industrial software LeanCOST, provided by the Italian company Hyperlean (`https://hyperlean.eu`). It is a part of a wider research aimed at automatically deriving semantic information from CAD assembly models coupling geometric processing with engineering knowledge for model reuse and for supporting the automation of production processes and design analysis. Axisymmetric assemblies are present in several products. They can generally be independently assembled and then mounted in larger assemblies. The method exploited (provided by Hyperlean) for the detection of axisymmetric parts is robust with respect to the presence of small features, e.g. keyseat or screwseat. This, together with the developed capability of recognition of standard parts, allows automatically finding axisymmetric subassemblies in larger assemblies. Future work will focus on the (dis)assembly sequence definition starting from the proposed precedences detection including deformable parts and additional not axis-aligned standard parts (e.g. screws and keys), and on the precedence parts' detection in non-axisymmetric subassemblies.

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