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Review on Approaches to Generate Assembly Sequences by Extraction of Assembly Features from 3D Models

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Abstract

The path from a virtual 3D assembly model to an automatically generated assembly sequence is, until this day, linked to a number of challenges. For the start, the greatest challenge at this point is the reading of assembly features out of a 3D model, followed by the detection of assembly coherences based on these features and finally the systematization and analyzation of the individual part relations. Based on these topics, several approaches will be discussed and tested with a continuous use case.

Keywords: Feature Extraction, Computer-aided Assembly Planning, Assembly Sequence Planning;

1. Introduction

Assembly processes have a significant influence in the pricing of products and represent up to 50% of the final product costs [1,2]. For this, the reduction of handling and manufacturing processes is one of the key factors for a product at optimal costs [3]. To get an optimized assembly process, the process planning has be analyzed in more detail.

The process planning describes the steps from the first ideas in the product design to the production itself [4]. Thereby, the process planning becomes an important part in the act of production engineering. Based on the necessary knowledge in product designing and production engineering, Kardos et al. [5] describes the topic of an automated process planning as one of the hardest issues in this segment. However, the vision of a fully automated process planning has its limits. To find the underlying causes of this research topic, the overlapping subject of design and manufacturing engineering has to be broken down in more detail.

The vision of this research topic is to generate the ideal assembly sequence directly out of a 3D assembly model of a commercial Computer-Aided Design (CAD) system. However, the larger the product, the more designers are involved. Furthermore, every designer has his/her own ideas how to properly assemble a product and disregard the possibility of an objectively optimal assembly sequence. Accordingly, the generation of the assembly sequence should be independent from the designers. The system should be able to calculate the best assembly sequence only by being based on quantifiable factors like handling movements or tool changes.

An opportunity to overcome this dilemma is the aid of an assembly planning system [6]. This system analyzes the necessary handling processes to assemble a product and it identifies the optimal assembly sequence. “The purpose of automatically generating assembly plans is to relieve the operator of the routine of efficient plans” [7]. By this computer-aided system, useless or non-value-adding processes can be avoided and reduced, in order to improve the assembly processes in general. Briefly speaking, the best assembly process is a yet non-existing assembly process.

In 1992 Delchambre [7] defined the computer-aided assembly planning (CAAP). Nevertheless, until this day, there is no comprehensive solution for this purpose. The target of this research is to give a review about the challenges in this research

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topic and elaborate why past systems failed to generate assembly sequences automatically. The challenges will be specified and examined with a continuous use case. Chapter 2 discusses briefly why 3D assembly models are the source of an assembly planning system and how information can be gained from it. Different approaches will be examined. Hereby, some key challenges will be worked out which will then be considered in more detail in the following chapters. Chapter 3 tests and evaluates how the necessary assembly features can be directly generated out of the 3D assembly model with different approaches. Chapter 4 analyzes how these assembly features should be systemized and what the limitations of existing approaches are. Chapter 5 is dedicated to the evaluation of assembly sequences and how the systematized assembly features can be analyzed. Chapter 6 finally rounds off everything with a conclusion and future prospects.

2. Information Source and Initial Situation

The starting point of the investigation on an assembly planning system is the 3D model or to be more precise, the 3D assembly model of the designing process. The creation of these assembly models requires a lot of knowledge and effort. Nevertheless, these contentful models are barely used in the following manufacturing process. Thus, the 3D models play just a marginal role in planning the manufacturing layout. In order to plan the following processes, all necessary information must again be gathered in an effortful manual work, without any real profit from the existing 3D models.

2.1. Collision Analysis

The first issue is to find an approach to get the necessary assembly information out of the 3D assembly model. One of the most common approaches is the collision analysis. These approaches follow the mindset of “assembly by disassembly” [8]. These so-called “disassembly analysis” [8] generates assembly sequences by disassembling an assembly model. The logical background of this purpose is that if a product can be disassembled, it can also be assembled the same way.

The collision analysis disassembles the assembly by moving a part in the positive and negative X, Y and Z direction [9,10]. With that, the intersections between the parts can be tested and the degree of freedom defined. In this manner, assembly restrictions can be generated.

Thomas, Barrenscheen and Wahl [10] afterwards generated a AND/OR graph based on the results and they analyse it with an accurate graph search algorithm [10]. For this reason, the whole AND/OR-graph is evaluated after the two criteria separability and parallelism. Until this day, this approach has been advanced [11] and is now one of the most progressive methods to generate assembly liaisons.

However, this approach also has its limitations. Not every part can be disassembled by intersection checks. Non-rigid parts for example usually have contact in every direction and have to be handled differently [12]. Furthermore, also rigid parts like the axial circlip (DIN 471) cannot be shaken out of an assembly.

In conclusion, the collision analysis provides information about the assembly restrictions. It defines which parts have to be disassembled before another part can be disassembled and whether a contact connection exists. However, it is not able to define the type of connection.

2.2. Feature-based Approaches

The foundation to generate assembly sequences are the relations between the single parts in the assembly. These so-called assembly features describe the type of connection and dependencies between the parts. The assembly features are relevant for the definition of the assembly processes, such as mating, joining, alignment, handling etc. [13].

To identify these assembly features, an access to the designing tool is required. 3D assembly models in CAD systems are basically feature-based. These features can be used to restore the missing relationships between the different parts.

However, this intent is until this day very complex and struggles with information losses, especially in the case of a conversion to a neutral format [14]. At this point, there are still crucial gaps in the implementation. There are several approaches to extract features, but all have their own advantages and drawbacks. To bridge the gap, these approaches will be analyzed and tested in the upcoming chapters with a continuous use case.

3. Feature Extraction

There are different definitions for assembly features. Van Holland [15] defines assembly features as „features with significance for assembly processes“ [15]. Furthermore, assembly features can also be separated in groups like “connection features”, which define the final position or insertion path/point or “handling features”, which describe the location of a part where it can securely be handled by a gripper [16,15]. The most important one for this work is the “joining feature”, which describes the assembly relation, including joining entities, constraints and joining methods [13,17].

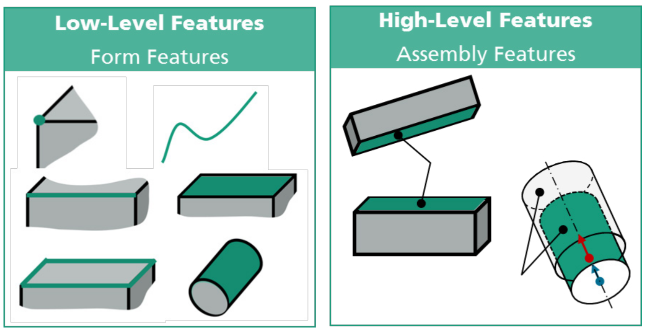

Fig. 1. Systemization of features.

To receive these assembly features, they have to be structured more in detail. Generally, features of a product are classified into low-level features and high-level features (figure 1). Low-level features are form features, which again are basic topological and geometrical entities [18]. They can represent holes, notches, slots and so on. High-level features on the other hand are specified by a form and a specific application, like an assembly attribute [13,18]. In conclusion, an assembly feature can be created by two form features from different parts in an assembly(figure 2) [18].

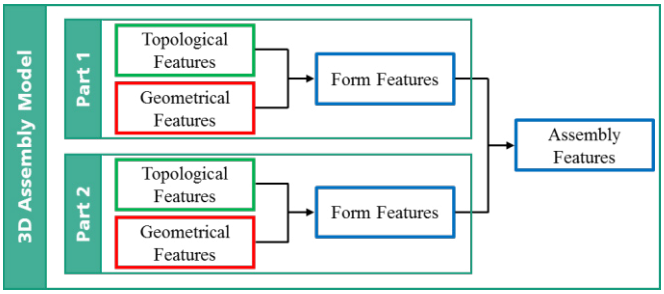

Fig. 2. Structure of assembly features.

Briefly speaking, assembly features are able to describe connections between different parts in an assembly. Consequently, these connections define the kind of liaison between the parts (concentric, coincident, parallel, etc.). Finally, assembly sequences can be generated out of these assembly liaisons. The next step is it to extract these assembly features out of a 3D assembly model.

There are different possibilities to get this kind of information. Hasan and Wikander [16] differentiate from a technical view into three categories, interface (internal) approaches, file-based (external) approaches and ontology-based approaches. However, ontological approaches require an additional step to be generated from CAD. These approaches indeed are able to work with features and transfer information between different applications, but to get to the ontology an internal, external or manual intermediate step is necessary. Therefore, the ontological approach is a very promising approach to exchange data between different domains, but it is no independent approach to generate features directly from a 3D assembly model.

In summary, based on the purpose to extract features directly from 3D assembly models only the internal and external approaches are relevant and in the focus of this investigation. To compare the different approaches of feature extraction processes different external and internal approaches have been conducted.

3.1. External Approaches

External approaches are file based approaches, using neutral data formats, like IGES, XML or STEP files [16]. These standard formats are supported by every common CAD system and even most 3D systems [19]. This means that these formats can be read across a variety of systems and it can also be generated from those systems. The big advantage is by using neutral formats, the number of direct interfaces required between n systems decreases from n × (n-1) to just n × 2 [14].

However, compared to the internal approaches it is not conceivable to access the information directly from the CAD system. For this reason, data losses are expected during the conversion from the original format to the neutral one [16]. Another limitation are the missing assembly features. To generate assembly features out of a neutral file it is necessary to create them out of low-level features (figure 2). Furthermore, standard formats are more complex to analyze and systemize. Of course, these formats are machine-readable, yet not easy to understand for humans.

In the manner of neutral CAD formats, especially the STEP-file (Standard for the Exchange of Product Model Data) with the ISO 10303 [20] should be mentioned. The STEP-file is the most common method to read CAD models. The ISO 10303 is an established machine-readable format that is supported by a variety of applications. One of the special characteristics of this format is the long history of accurate 3D data transmission [19]. Furthermore, this format has also been able to prove its advantageous reusability and long-term capability [19]. The easiest way to exchange information between CAD systems has therefore always been the STEP format. However, in this way, much information, such as the assembly features between the parts, gets lost and has to be restored.

Feature Extraction with the STEP AP 203 and AP 214

To test and evaluate the external approaches a feature extraction based on the STEP AP 203 and AP 214 was conducted. The considered assembly features are plane contacts, cylindrical mates and screwing connections. Plane contact define to solids, which have at least one point of contact. Cylindrical mates describe the connection between a solid cylinder and a hole that have the same or a larger radius. In the case of a cylindrical connection, a second check reveals screwing connections. If the radius of the hole is smaller than the radius of the solid cylinder and the system checks for a thread feature or a helix feature. In the case of a positive check, a screwing connection can be assumed. The data extraction was conducted with the use of the Open Cascade Technology packages (OCCT) and the pythonocc. OCCT fulfil industrial requirements and provide libraries for topological and geometrical operations.

As use case the bolt-nut plate fixing of Viganó and Gómez [21] was used (figure 3). This makes it possible later to compare the results and to draw conclusions about the success of the feature extraction. The use case contains five plane contacts, five cylindrical mates and one screwing connection.

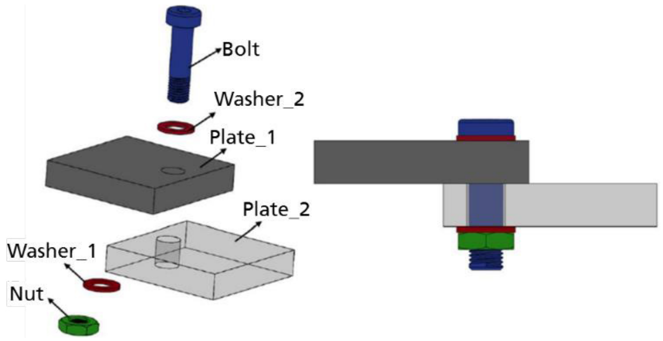

Fig. 3. Bolt-nut plate fixing as use case contains elven assembly features [21].

The feature extraction tool indicated that every plane contacts and all cylindrical mates could be found and matched to the solids. However, the system was not able to find the threads. Further investigations showed that the STEP files do not contain any information about cosmetical threads. Cosmetical threads are threads which the designer generated with the aid of the thread feature tool of the specific CAD system. These cosmetical threads will be indicated as threads in 3D and the 2D drawings, but will not be stored in the neutral

STEP file. The only way to find screwing connections in the STEP files is to generate threads manually with the geometrical helix feature tool. In that case, the thread will be cut out of the solids. However, this option is much more elaborative for the designers and is not conform to the designing standards of a professional designer.

Feature Extraction with the STEP AP 242

In 2014, the latest generation of the neutral STEP interchange format accordance with the ISO 10303-242 was published [22] and is now for the first time capable to transmit model-based information [22]. In order to the new standard, it is also possible to get high-level features like assembly constrains or tolerances out of a neutral exchange format. Since 2018, also the first 3D systems support the newest format.

However, attempts in this work with the new and promising format have only led to small improvements. Although some high-level features can now be read out directly from the format without the elaborative analysis of low-level features, but this is only possible with some features. Furthermore, the found enhancements are very limited. This is based on the fact that the same results have been achieved in the previous investigations with the STEP AP 203 and AP 214 in a reasonable effort. Therefore, the great improvement in the extraction of features with the STEP AP 242 cannot be confirmed.

The advantages of this new format are more in the graphical presentation, which allows to share complex Product Manufacturing Information (PMI) between different systems [23]. 3D PMI representations are not included in the previous STEP formats. For this reason, the uniqueness of this format is rather based on the machine-readable transfer of PMI according to the ISO 16792.

3.2. Internal Approaches

Internal approaches recognize and extract the features directly from CAD systems, like Dassault SolidWorks*, CATIA† or Siemens NX‡ [16]. For this purpose, the systems specific Application Programmable Interface (API) functions are utilized. A drawback of this approach is the dependence on the CAD system. Some former authors used the SolidWorks API [13] and some other the CATIA API [24], but it is not possible to use the same API compiler for different systems.

For further investigations the SolidWorks API was examined pertaining their ability to extract high-level and low-level features. Furthermore, the SolidWorks API was chosen because it is the most common CAD API and has the biggest demand from industry and research.

The SolidWorks API provides the opportunity to customize the designing software SolidWorks and to get access to further design information. It can be operated by the programming language Visual Basic for Applications (VBA) and allows the extraction of information that concern the CAD product assembly model as well as its modification.

Feature Extraction with the SolidWorks API using high-level features

The major advantage of this approach is the direct access to the defined assembly information. The API can be used to get the connections in the assembly between the parts (assembly features), which the designer defined in the first place. Therefore, if a part has three of these assembly features with the existing assembly, it has no degrees of freedoms left, which means it cannot move within the CAD system anymore. These assembly features can be read out by the API.

However, these connections define the degree of freedom on a part, but it does not represent all existing connections between the parts. Figure 4 displays an assembly based on three parts. Part (A) is three times connected with part (B). Consequently, the API would find three assembly features (1,2,3), thus three connections between part (A) and (B) and no connection between (A) and (C). Unfortunately, the API overlooks the assembly feature (4), since the designer did not define the relation between part (A) and (C).

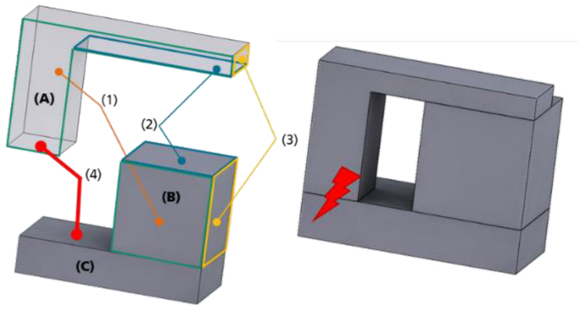

Fig. 4. Assembly liaisons – manual connection of parts in an assembly.

For that reason, it is not recommended just to search for high-level features. The API of CAD systems is also able to search for low-level features. Thereby, it is also possible to generate high-level features by recognizing and comparing form features like holes, cylinders or planes (figure 2). Certainly, that procedure is much more complex and time-consuming than just searching for the existing assembly features.

Feature Extraction with the SolidWorks API using low-level features

The analyzation of low-level features from the SoildWorks API follows a similar approach as the external approach with the STEP files. Therefore, for comparison of the results the same use case of the bolt-nut plate fixing as used (figure 3).

As mentioned before the use case contains elven assembly features (five plane contacts, five cylindrical mates and one screwing connection). It was indicated that the search algorithm to build high-level features from low-level feature is very similar to the algorithm to analyze step files. However, the SolidWorks API is quite less abstract and needs less quires.

As result, the system was able to identify every single assembly feature of the existing eleven. With the aid of the FeatureManager, which contains the features, the designer

*https://www.solidworks.com/
†https://www.3ds.com/de/produkte-und-services/catia/
‡https://www.plm.automation.siemens.com/global/de/products/nx/

generated with feature tools, like the thread feature tool, even cosmetic threads can be found.

In conclusion, a combined approach of a low-level feature search algorithm and a complementary access to the SolidWorks API FeatureManager result in all necessary assembly features to specify assembly processes. In a next step, these assembly features have to be systemized and analyzed pertaining their best assembly sequence.

4. Systemization of Assembly Features

To systemize the relationships between all parts assembly liaisons were used in the past. Assembly liaisons describe the relations between the parts in an assembly and how they are related to each other [25]. Based on these assembly liaisons, an assembly sequence can be generated. However, the ratio of the number of parts (n) to the quantity of existing assembly sequences is n! [1]. Therefore, every additional part in the assembly leads to an exponential incensement of assembly sequences, which again make it more challenging to generate an optimal assembly sequence [26,1,6].

Unfortunately, a major part of this n! assembly sequences are physically not possible or logically not feasible. Figure 3 represents the assembly of the bolt-nut plate fixing use case with six parts. Every assembly sequence, which starts with the bolt and orders to assemble the parts in the wrong order to the bolt is an impossible assembly sequence and should be filtered out.

Based on that reason past research figured concepts for systemizations out to reduce impossible assembly sequences. Viganó and Gómez [21] investigated the approach of contiguous liaison graphs. By connecting the parts in order to their contact liaisons the liaisons graph is generated (figure 5) [21]. In that case, the liaisons between these parts are represented by assembly features based on contact connections. To generate assembly sequences, the starting part of the graph has be defined. The subsequent part is now a connected part of the start part. This procedure takes place until its back at the starting part. By moving along the graph and generating all available assembly sequences, only 12 assembly sequences can be generated. With that procedure the number of generated assembly sequences reduces from 720 (6!) to 12 [21]. Nevertheless, Viganó and Gómez [21] also mention that the generated assembly sequences rapidly rise by more complex products and that different techniques to assemble the same part can lead to different graphs and therefore to different assembly sequences [21].

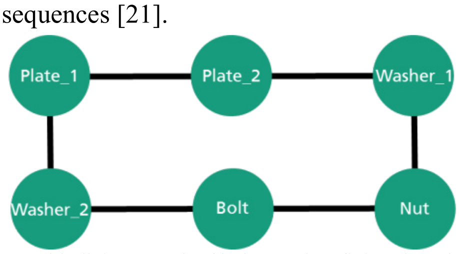

Fig. 5. Assembly liaison graph of bolt-nut plate fixing (based on [21]).

The liaison graph concept is very promising and follows a structured approach. However, this approach reaches its limits. Assuming bolt and plate_1 were in an additional relationship, the derivation of the assembly sequences would no longer be so trivial [21]. Furthermore, only contact connections are stored. However, these are not enough to generate a complete assembly sequence.

Based on these limitations the approach was extended with the assembly features found in chapter 3. In this extended concept (figure 6) all eleven assembly features are represented. The search algorithm follows, as in the concept of Viganó and Gómez [21], the approach that just connected parts can be selected. Furthermore, a value of the assembly features is presumed. Thus, the thread feature as fixation can only be chosen when all intermediate parts have been assembled before. Finally, a rule-based expert system uses these weights to read the graph determine the best mounting sequence.

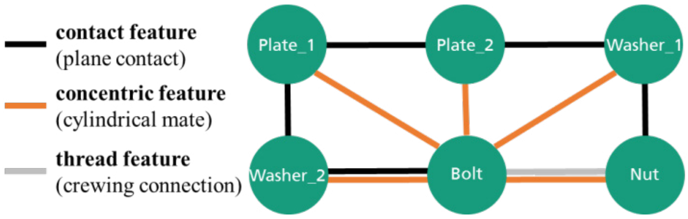

Fig. 6. Advanced assembly graph of the bolt-nut plate fixing.

5. Generation of Assembly Sequences

The next step is to determine the best possible assembly sequence from the assembly graph. Unlike in the preceding works, however, it is not about generating all possible assembly sequences, but the most efficient one.

Based on the values of the assembly features the Bolt is the most connected and is indicated as the base part. The Bolt is related to all parts in the assembly. However, the Nut cannot be selected as next part because not all parts between the bolt and the nut are yet assembled. Based on the remaining parts, the Washer_2 has the highest value and is consequently the next part. It is not allowed to select parts twice. Therefore, afterwards it is simple, because only Plate_1 can be selected. The same procedure apply also for the next parts (Plate_2 and Washer_1). Finally, all parts between the Nut and the Bolt are assembled and the Nut becomes the last assembled part. In summary the assembly sequence is: Bolt>Washer_2>Plate_1> Plate_2>Washer_1>Nut.

In this work, the developed rule-based expert system was able to indicate the best valid assembly sequence based on the assembly features. However, in a more complex assembly often the values given by the assembly features are not meaningful enough to generate an optimal assembly sequence. There is still the question to solve, why is a sequence step better than its alternatives? To differentiate between a good and bad assembly sequence additional evaluation criteria have to be defined.

To determine an optimal assembly sequence, it is necessary to systematize the individual assembly steps and rank more necessary values. Over the past years, the cost function [27,10] has established itself as the standard of evaluation. By this, factors such as accessibility, tool change costs or assembly time can be quantified [12,28]. Admittedly, with this kind of information it is not possible to make conclusions about the quality of the assembly. For that reason, an additional consideration of the mechanical stability of the assembly is suggested. This stability monitoring provides information about the step-by-step assembly status of the assembly and thus evaluates the quality of the assembly from a mechanical point of view.

6. Conclusion and Future Prospect

There are many existing approaches and techniques, which focus on generating assembly sequences. Every approach has its benefits and a special focus. However, until this day, there is no comprehensive solution to generate automatically assembly sequences out of 3D assembly models. Every approach struggles with the exponential rising of complexity with every additional part in an assembly.

One of the todays most advanced approaches is the collision analysis of Thomas, Barrenscheen and Wahl [31]. This approach has been advanced and further functionalities were added, like exploded views [11]. This approach is very contrary to the feature-based approach stated in this work. Both technologies have their specific advantages and approach-based restrictions.

Nevertheless, the ideal solution is often a compromise of different approaches. A combination of a “disassembly analysis” by a collision analysis and a system of assembly rules (figure 6) could lead to an advantageous initial situation. Rules of an accurate assembling in combination with assembly restrictions could therefore empower a system to generate automatically ideal assembly sequences just based on a 3D assembly model. This approach will be investigated in more detail in near term.

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