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A Method for the Automatic Identification of Contacts in Assemblies of Cylindrical Parts

A significant amount of research has been made on determining the optimum assembly sequence, assembly planning, etc. However, those research works consider that the necessary information for the analysis (e.g. the contacts among the parts in the assembly) is already available, which is not usually the case. This paper describes a method for extracting information within the design, aiming at supporting applications of assembly identification, which is needed for assembly planning. The system determines the surfaces to be machined and the dimensions to receive tighter tolerances, which are important for process and inspection planning. Initially, the group of parts that compose the product is input, and then the procedure for automatic identification of assembled parts begins for the given assembly. The final analysis is done by an expert system that checks the conditions of the assembled parts. The system is applied to cylindrical parts, in a design by features environment.

Keywords: Assembly, computer-aided design, features, expert system, dimensioning

Introduction

Identifying assembled parts, as well as their contact surfaces, is very important in design and manufacturing, since this information is necessary for many decisions, which include: a) determination of the optimum assembly sequence; b) identification of surfaces to be machined; c) determination of the dimensions to receive tolerances and surface roughness; and d) assignment of dimensions as a function of the parts in the assembly. A significant amount of research has been carried out on assembly planning, determining the optimum assembly sequence, etc. (Lim et al., 1995; Zha et al., 1998), but those works consider that the necessary information for the analysis is already available.

In this paper, a technique for extracting information within the assembly is presented, aiming at supporting applications of assembly planning, determination of surfaces to be machined and dimensions to receive tolerances, which are important for process and inspection planning. The determination of the dimensions to receive tolerances is done while identifying the assembled parts.

The method is applied to cylindrical parts in a feature-based design system. Initially, the group of parts that compose the product is input, and then the procedure for automatic identification of assembled parts begins for the given assembly. The final analysis is done by an expert system that checks the conditions of the assembled parts.

Previous Work on Assembly Modeling and Planning

Assembly Modeling

Assembly modeling and manipulation involves structural and spatial relations among individual parts on a much higher level of abstraction than the representation of one single part (Anantha et al., 1996). Therefore, in order to represent an assembly adequately in the computer, the data structure should enable the support to assembly constraints to all parts involved, individual selection of parts in the assembly, choice of the relative position of the parts, and manipulation of the assembly as a whole.

Some data structures for assembly modeling were developed in the past. Two examples of such data structures were the ones implemented by Lee and Gossard (1985) and Ko and Lee (1987). Both have a hierarchical structure, and they use the concept of a link between the elements involved in an assembly.

Another data structure was proposed by Gu and Yan (1995), who represented an assembly through two types of graphs: link graphs and contact relations graph. The link graph provides the connections between parts, but this information is in a generic format, without details like what the relation between the parts is. The contact relations graph describes many types of assembly relations, such as tight fit, sliding fit, key fit and threaded fit. The assembly relations are then classified into two classes, i.e. fits and contacts, where in the end every piece of information is converted into contact relations.

Chen et al. (2002) developed a system to generate mechanical product assembly drawings automatically from their 3D assembly model in a CAD software. In that system, the assembly relations among the components are collected while building the assembly model, but the procedure for determining those relations is not described in that paper.

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The authors consider that the above data structures have the limitation that they do not use features for part and assembly modeling, and the use of features was recommended by many authors (see for instance Shah, 1992). Features were used for assembly modeling in the system developed by Shah and Tadepalli (1990), which extracts the information about two coupled parts, and allows the choice of fits to be made after the parts are assembled.

The feature-based design modeling approach was also recommended by Mascle et al. (1994), who defined an assembly feature as an interaction between two connected elements (parts or features) by a link that can be mechanical (physical contact) or functional (geometrical or clearance constraints). They proposed the development of a modeler that should be not only geometrical, but also technological, where existing links between the parts should be evaluated.

In that same work, Mascle et al. (1994) proposed that two "visions" should be considered for assembly modeling. One of them adopts the kinematical vision, which is related to the utilization of robots. In this case, the size, tolerances and orientation of the surfaces of the object must be precisely known, and each surface is treated separately. The definition of the assembly characteristics includes: the part geometry (e.g. location and orientation in the Cartesian space), dimensions and directions of assembly; tolerances; relations between the part and the product; identification of similar parts. The other assembly vision utilizes the polyhedral representation of objects and parts; the model includes the following types of information: geometrical information (i.e. form and dimensions of the parts, relative position in the final assembly); information of the parts (e.g. handling, part base, part priorities); final assembly information; topological information (e.g. types of contacts, assembly constraints). Although in the present work these two visions are not contemplated, all of the above data are included in the structure of the system described in this paper.

Features were also used in the system developed by Zha and Du (2002), which is a product data modeling system for concurrent design and assembly planning based on STEP (Standard for the Exchange of Product Model Data - ISO 10103) (ISO, 1992). Their system has a hierarchical structure, and it aims at enabling practical data exchange standards for assembly in computer-integrated systems.

Assembly Planning

Mascle et al. (1994) point out that the use of computers in assembly planning is more difficult than in part manufacture. The main problems are the low level of standards of assembly operations, in contrast with manufacture, where operations such as turning and milling have been known for a long time. The complexity of the assembly planning problem is also mentioned in Gu and Yan (1995), who consider such complexity as the main cause for the slow development of research on automatic assembly of mechanical products by robots compared with the assembly of electronic products.

Bronsvoort and Jansen (1994) and Shah et al. (1994) mentioned that the assembly planning task can be subdivided into different stages, which are:

- <u>Decomposition into subassemblies</u>, which can be determined based either on the functional decomposition or on the connectivity properties that describe the interaction between the parts.
- Generation of possible assembly sequences, which is based on the given subassemblies. However, only some sequences are feasible, since the geometric configuration imposes an order to the assembly sequence.

- <u>Assembly sequence planning</u>, since there are alternative assembly sequences. The objective of a plan is to analyze the different costs involved with respect to tools, transport, and storage, allowing verifying the best conditions for performing the assembly.
- <u>Assembly operation planning</u>, which is responsible for generating the instructions for the equipment in the assembly cell (e.g. robots, conveyors, etc.).

The present work contributes directly to automate the determination of the interactions between the parts in the assembly, thus helping speed up the assembly planning process.

It is generally recognized that the assembly process has low quality, low efficiency and high cost, which are all inter-related. These factors have lead to Design for Assembly ("DFA") (Boothroyd and Dewhurst, 1989), which aims at selecting the most economical production process during the design stage, adapted to the characteristics of the chosen assembly method.

According to Ko and Lee (1987), in order to generate assembly procedures automatically, there are three problems to be considered: a) how to represent an assembly in a computer; b) how to structure the parts hierarchically; c) how to generate assembly procedures from a hierarchical tree of parts. Some works were found in the literature that consider these problems, and one of them was developed by Dini and Santochi (1992), who analyzed subassemblies and assembly sequences based on the mathematical model of the product, obtained through the definition of three matrices: interference, contact and connection. The possible subassemblies are detected automatically when they satisfy some mathematical conditions applied to those matrices. However, the source of those matrices is not revealed, nor how they are obtained so that the analyses can be made.

Another computer-aided assembly system was proposed by De Fazio and Whitney (1987), which questions the user about the assembly, and these questions require geometric reasoning and understanding by the user, which requires the user to have a significant design experience. A system with a higher degree of automation was proposed by Eyada and Ong (1991), which is a CAD system capable of identifying an assembly and specifying the tolerances automatically. The assembly is defined through the recognition of "block" entities that compose the parts in the CAD system. The combinations of parts are identified based on the comparison of lines that compose the different blocks. The system utilizes this information to specify the tolerances automatically.

An expert system called KOMPASS (Weule and Friedman, 1989) utilizes the disassembly sequence for assembly analysis. In that system it is assumed that all the surface connections be known, e.g. the external surfaces of each part that touch other parts, which can become constraints to assembly.

Mazouz et al. (1991) applied artificial intelligence and a knowledge-based system in order to generate an optimum assembly sequence without intervention from the user. They define the parts as external and internal, and assume that contacts occur among the parts in order for the assembly to occur.

Gu and Yan (1995) proposed the utilization of a feature-based CAD system to support the extraction of information from the product in order to perform assembly sequence analysis for robots. However, the algorithms proposed by them assume that the assembly description is available, and so the task becomes to find the best assembly sequence.

De Lit et al. (2001) developed a genetic algorithm to generate the assembly trees. The algorithm starts with a group of assembly plans generated randomly, and it chooses the best plan through an expert system. Again, the assembly relations among the parts in this system are assumed to be already known.

Zha and Du (2002), in their feature-based product modeling system for assembly planning using STEP, a knowledge-based expert system was implemented to support the main assembly design and planning process. Those authors mention that the relations among the parts are needed for assembly planning, but they assume that the part relations are already available.

Gottipolu and Ghosh (2003) developed a method for automatically generating assembly sequences from a solid modeler. Based on the assembly model, that method generates two types of matrices indicating the presence or absence of contacts. Those matrices are used by an algorithmic procedure that generates feasible assembly sequences. This method is not feature-based, and the procedure for generating the matrices is not described in that paper.

Different methods were described above for solving the assembly planning problem, and it can be noticed that in those research works the importance of identifying assembled parts for assembly planning decisions to be made. In this paper a computer system that performs automatic identification of assembled parts is described.

Data Representation in the Developed System

In order for a computer software to perform the identification of parts that are assembled in a product, a data structure is necessary, and in this work such a data structure corresponds to a feature-based modeler. This modeler has a hierarchical structure, where a product is composed of an assembly, an assembly can be composed of many subassemblies, a subassembly is composed of the collection of many parts, and each part by one or more features. Each element in this hierarchy has its attributes.

In the present work, it is considered that only one assembly exists, which is composed of many parts, and these are composed of features. The assembly has a name, a list of parts and other attributes. Similarly, the part has a name, a list of features and other attributes

When analyzing an assembly, it is important to perceive each part in the assembly and each feature in each part. Therefore, it is necessary to define the attributes that will represent each part and each feature involved that have some meaning for assembly. Some of the attributes of a part are: *Name*, *Source* and *Material*. The *Name* is given by the user; the *Source* relates to whether the part is manufactured by the company itself, by a supplier or whether it is a standard part (e.g. bearings, bolts, etc).

The features are classified into: (i) *Basic*, which are the cylindrical shaft and the cylindrical hole (it can also be a conical hole), and (ii) *Modifiers*, which alter the basic features (e.g. fillets, chamfers).

The attributes of a feature cylindrical shaft/hole are:

Name:

Type: cyl_shaft / blind_cyl_hole/ through_cyl_hole Position: internal/external

Direction: axial/radial Way: right/left (1/-1) Centerline: Ycoord Initial Face: Icoord Final Face: Fcoord

Volume: positive/negative (1/-1)

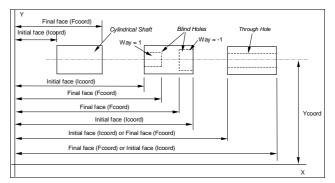


Figure 1. Graphical representation of the features cylindrical shaft and hole.

In Fig. 1 the attributes of these features in the absolute coordinate system are represented. For a shaft, the initial face (Icoord) is always on the left-hand side, whereas the final face (Fcoord) is always on the right-hand side. For a blind hole, the initial face (Icoord) is always the start of the hole (its position is chosen by the user with the mouse), and the final face (Fcoord) is the bottom of the hole. For a through hole, the initial face corresponds to the face input by the user, and the final face is opposite to the initial face.

Analysis of the Modeled Product

The decision about having a machined surface and the assignment of a certain tolerance to a dimension, as well as the arrangement of the dimensions to be controlled, is a function of a rigorous analysis of the assembly. Therefore, it is very important the specification of correct attributes to each part and feature, and this is not a result of the analysis of the part alone, but considering the assembly where it will work. In order to decide on the tolerance, surface roughness aspects, and the identification of their surfaces as well as the functional dimensioning, it is essential to have a global vision of the assembly, i.e., the description of how the parts are assembled.

It is necessary a data structure that supports the product representation with its hierarchy. With this information, which is normally analyzed manually by the designer, it is possible to automate these analyses through a computer software.

The first analysis consists of identifying what parts are assembled to one another, as well as the features that have contact between the parts. In other words, which cylindrical surfaces are in contact (i.e. diametrical contacts) as well as the axial contacts that occur. After determining the shaft and the hole that have diametrical contact, it is possible to affirm that these dimensions must be assigned tighter tolerances compared to those surfaces that will not be in contact. If the assembly pair is identified, it is possible to choose interactively, with the help of a program, the type of fit that best suits the pair. The surface finish that must be assigned to these surfaces is determined as a function of the chosen tolerance.

After determining the axial contacts, it is possible to define the tolerances of the axial dimensions, as well as the surface finishes of these surfaces. These surfaces that have axial contact work as references for the axial dimensioning of the parts, from which the assembly conditions of the part can be obtained. As a result, if a surface has a contact, it must be machined, and therefore a good surface finish should be assigned to it.

With the knowledge of tolerances and fits, it is possible to check which tooling is necessary to perform certain assemblies, such as a press-fit, where a press should be chosen for the task. This information can also be utilized for process and inspection planning, and also for operation sequencing.

Characterization of an Assembly

In the present work, during the detailed design phase, the graphical representations are made with nominal dimensions, i.e. neither manufacturing deviations nor functionality problems related to the clearance and interference that should occur between the assembled parts are considered. These problems are solved in another phase, after the design is represented.

When identifying the assembled parts, the system asks the user for information about tolerances and fits, according to the way the assembly pairs are identified. So, when each pair is identified, a module that provides information about the tolerances is activated, and the user selects the one that is most convenient for the coupled pair depending on the application.

Identification of Cylindrical Parts

In order to check whether two parts have diametrical contact, the initial condition is that the nominal dimensions of the hole and of the shaft are the same. Another condition is that the centers of rotation of the parts are coincident. The last condition is that they occupy the same position in space.

In Fig. 2(a) diametrical contact occurs, because: (i) the diameters are the same, (ii) the centers of rotation of both parts are coincident, and (iii) they occupy the same position in space. In Fig. 2(b) the condition of diametrical contact does not occur, since the nominal diameters are different. In Fig. 2(c), although the nominal diameters are the same, and they occupy the same position in space, the centers of rotation are not coincident, and therefore there is no diametrical contact. In Fig. 2(d), the parts do not occupy the same position, and thus there is no diametrical contact, even if the other conditions are satisfied.

In an assembly of cylindrical parts, usually the axial contact performs the positioning of parts in the assembly. If the position of the end surfaces of two parts is the same, they have axial contact (Fig. 3(a)). In Fig. 3(b) there is no contact because the end surfaces do not coincide.

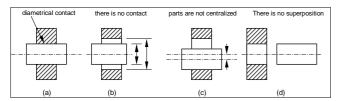


Figure 2. Conditions for diametrical contact.

The occurrence of two contacts of the same type and at the same time in a part is not adequate for assembly, and an example of this situation is given in Fig. 4(a). However, Fig. 4(b) shows an adequate assembly where there is a contact of each type between the parts. In Fig. 4(c) there are two axial contacts between two parts, resulting in an inadequate assembly. The best solution is represented in Fig. 4(d). The presence of adequate contacts reduces the necessary precision, resulting in easier manufacture, assembly, inspection, etc.

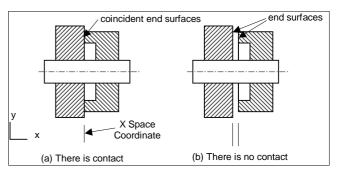


Figure 3. Conditions for axial contact.

An axial contact is defined based on the coordinates that correspond to the plane faces of the features. In Fig. 5 the external axial contacts are represented, and they occur at the plane faces of the features, which in this case are shafts and holes. In Fig. 5(a) it occurs both diametrical contact and axial contact. But in Fig. 5(b), parts 1 and 2 have axial contact despite they do not have diametrical contact, and thus this is another form of assembly. In Fig. 5(c) contact occurs between a face of one internal feature with the face of another external feature.

There are cases where axial contact does not occur between two parts due to the diameter. In Fig. 6(a), diametrical contact occurs between Part0 and Part1, but there is no axial contact. In Fig. 6(b) Part0 and Part1 do not have diametrical contact, and the axial contact does not occur due to the fact that Part0 has an internal diameter greater than the external diameter of Part1. And in Fig. 6(c) there is only diametrical contact between the two parts.

Specification of the Contacts

The identified contacts in an assembly should be represented in a form such that one could know what parts are involved in the assembly, the features in each part and the type of contact that occurs. In order to achieve that, the types of contacts are represented as shown in Fig. 7. In Fig. 8 an example is given with regard to the axial contact, whose attributes are:

- Contact coordinate: it corresponds to the axial coordinate which is the same for both faces in contact;
- Part axial shaft: it is the part that owns the shaft which is in contact with the face of the hole;
- Part_axial_hole: it is the part that owns the hole that is being analyzed;
- Feature axial shaft: it corresponds to the shaft that has axial contact with the part that owns the hole;
- Feature axial hole: it is the hole whose face is in contact with the shaft in Part axial shaft.

With regard to the diametrical contact, its attributes are defined as follows (see Fig. 9):

- Contact diameter: nominal dimension that is equal to the shaft diameter and hole diameter which are assembled;
- Part Diameter Shaft: it is the part that owns the shaft which is in contact with the part that owns the hole;
- Part Diameter Hole: it is the part that owns the hole that is in contact with the part that owns the shaft;
- Feature_Diameter_Shaft: it is the shaft feature that is in contact with a hole;
- Feature_Diameter_Hole: it is the hole that is in contact with the shaft;
- Feature Type: it is the type of features that have diametrical contact (e.g. cylindrical features).

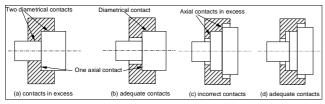


Figure 4. Occurrence of contacts.

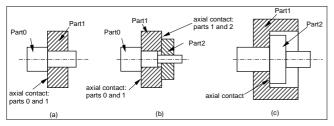


Figure 5. Axial contact between shafts and holes.

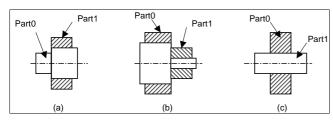


Figure 6. Situations where axial contact does not occur.

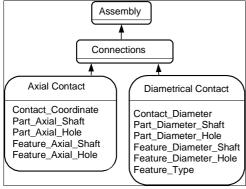


Figure 7. Attributes of the axial and diametrical contacts, which compose the connections class.

Identification of Diametrical Contact

In order to identify the parts and features that are in contact, and to describe the assembly conditions, a procedural algorithm combined with an expert system is applied. This algorithm searches the possible assembly pairs, whereas the expert system verifies the assembly conditions. The flowchart of the procedural algorithm to identify possible diametrical contacts is shown in Fig. 10, where n and m are indexes that refer to two different parts that are to be identified as having diametrical contact (i.e. pair hole/shaft).

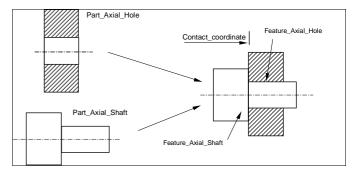
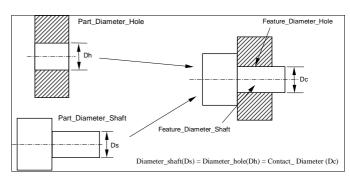


Figure 8. Definition of the features and parts involved in an axial contact.



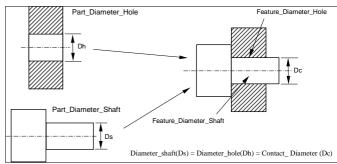


Figure 9. Definition of the features and parts that have diametrical contact.

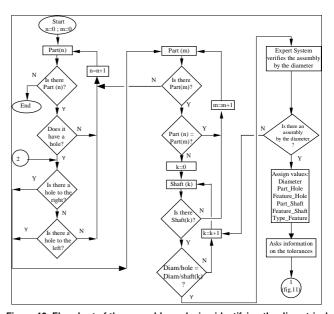


Figure 10. Flowchart of the assembly analysis - identifying the diametrical contacts.

The process of identification of assembled parts in an assembly begins with the search for the first part in the assembly, and if there is no part (Part(n)), the algorithm ends. If there is a part, the next step is to verify whether the part has a hole. If there is no hole, the algorithm searches the next part in the assembly (Part(n+1)). If there is a hole, it is checked whether the hole is to the right or to the left. Whatever is the way, the algorithm searches the first part in the assembly (Part(m)). If the assembly does not have a part of index m, the algorithm returns to the starting point and gets the part Part(n+1). If there is no other part, the algorithm ends.

If part Part(m) exists, it is checked whether both parts (n and m) are the same, i.e., if they have the same name. If that is the case, the next part (Part(m+1)) is obtained, it is checked whether the first feature in this part (i.e. a shaft) has its nominal diameter equal to the diameter of the hole. If they are different, the algorithm searches the next shaft, and repeats the operation until it finds a shaft with nominal diameter equal to the hole diameter. If no shaft is found, the algorithm starts to traverse the next part.

If there is a shaft and a hole with the same nominal diameters, the information about them is sent to the expert system, which verifies the occurrence of assembly or not. If there is no assembly, the next shaft in the part is searched. If the expert system confirms the assembly, the information that characterizes the assembly by the diametrical contact is stored in the data structure.

Identification of the Axial Contact

If the assembled pair hole/shaft is accepted (diametrical contact, exit 1 in the flowchart in Fig. 10), it is verified whether there are axial contacts between the hole in the part and the other parts in the assembly; also, the axial contacts between the features are verified (Fig. 11). This information is stored in the attributes described in the *connections* class (Fig. 7).

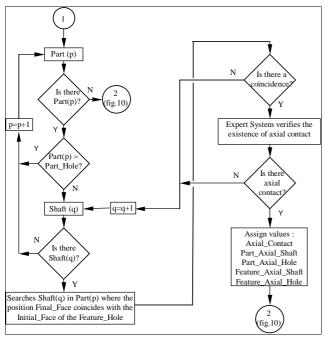


Figure 11. Flowchart of assembly analysis - identifying the axial contact.

After the parts and features involved in the description of diametrical contact are identified, the identification of the axial contact starts with the feature Part_Hole and Feature_Hole that have diametrical contact. The assembly structure is traversed in order to

find a shaft in a part whose initial face (Icoord) or final face (Fcoord) coincides with the initial face of Feature_Hole.

If there is a shaft in these conditions, the expert system performs the analysis and returns a conclusion. If the conditions satisfy the assembly and the axial contact, the information is stored in the data structure as attributes of the subassembly, in the *connections* class. If the conditions do not occur, the next shaft in the part chosen for analysis is searched, or the next part. In the end the system returns to node "2" in the flowchart in Fig. 10, and continues the search in the assembly.

Implementation of the Expert System

The implementation of the expert system consists of modeling situations in the form of rules. Each situation should be described considering both the conditions that cause its approval and the conditions that disapprove them.

The shell for the development of expert systems CLIPS was used. It allows the description in the form of classes, and it provides the inheritance mechanism, which permits to simplify significantly the definitions.

Implementation of the Knowledge Base for Assembly

The procedural algorithm verifies the conditions that characterize the assembly, whereas the expert system performs a more detailed analysis, which can be of two types, i.e. diametrical and axial contacts. They correspond to two independent modules within the same knowledge base, and they are activated through the algorithm represented in figs. 10 and 11.

Rules for Identifying Diametrical Contacts

The information about the parts and features is provided to the expert system through a communication interface that converts the data recorded in the product model into the format read by the expert system. The information in feature format in the product model is independent of the CAD system database, which is utilized here as a graphical tool.

In order to identify a diametrical contact, it is necessary information on: a) the part that owns the hole, and about the hole itself; b) the part that owns the shaft, and about the shaft itself. The attributes described in the definition of the features are utilized for writing up the rules.

The system in its current implementation has 80 rules in its knowledge base, and one example of rule is presented below. Note that in the rules the letter "H" refers to a hole, and the letter "S" refers to a shaft.

Rule 1:

Assembly occurs if the shaft has Fcoord outside the hole and IcoordS=IcoordH (Fig. 12)

```
IF (YcoordH = YcoordS) and (Type=through_cylindrical_hole) and (DiameterH = DiameterS) and (Way = 1) and (IcoordH = IcoordS) and (FcoordH < FcoordS) and ((FcoordH - IcoordH) \geq DiameterH/2) THEN Flag = 0 (assembly occurs)
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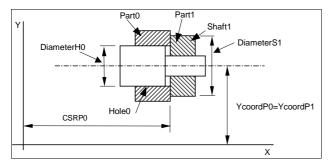


Figure 12. Graphical representation of Rule 1 of diametrical contact.

As initial condition, the centers of rotation of the hole and the shaft must coincide, and the feature is a through cylindrical hole; another condition is that the hole and the shaft must have the same nominal diameter; and the hole must have its way to the right.

The axial positioning condition between the hole and the shaft is analyzed with regard to the positioning of their respective initial and final faces. The initial faces of the hole and shaft should coincide, and the final face of the hole does not coincide with the final face of the shaft, and it must be located closer to the initial face of the hole. Finally, the supporting dimension between the hole and the shaft must be equal to half of the hole diameter.

If this rule is triggered, the expert system sends a message confirming that the coupled pair of features is an assembly, and at the same time this message activates a module for selecting interactively the tolerances for that assembly pair.

Rules for Identifying Axial Contacts

For the occurrence of axial contact, it is necessary that the position coordinates (Icoord and Fcoord) of two faces of features in different parts have the same nominal value. The verification of axial contact is done only for the features that have diametrical contact, and the assembly condition accepted (see figs. 10 and 11). Some rules are presented below.

Rule 1:

Axial contact between a part with a hole to the right and any other part (Fig. 13)

IF (YcoordP0 = YcoordP1) and (CSRP0 = FcoordS0) and (WayH1 = 1) and (DiameterH0 < DiameterS1) and (FcoordS0 = IcoordH1) THEN Flag = 0 (there is axial contact between the parts)

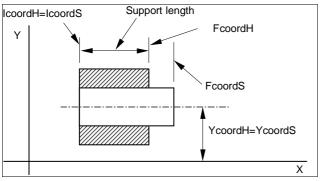


Figure 13. Graphical representation of Rule 1 of axial contact.

This rule analyzes two parts that have axial contact only, and the diametrical contact occurs through a third part. The first condition is that the center of rotation of the involved parts must coincide. Also,

the shaft in Part0 is the last on the right-hand side of the part (CSRP0 = FcoordS0).

The hole is towards the right, and in order to occur axial contact the hole diameter in Part0 must be smaller than the shaft diameter in Part1, otherwise Part0 and Part1 would have only coincidence of positioning. In order to confirm the axial contact, the final face of the shaft in Part0 must coincide with the initial face of the hole in Part1.

Rule 2:

There is no axial contact between a part with a hole to the right with any other part (Fig. 14)

IF (YcoordP0 = YcoordP1) and (CSRP0 = FcoordS0) and (WayH1 = 1) and (DiameterH0 > DiameterS1) and (FcoordS0 = IcoordH1) THEN Flag = 1 (There is no axial contact between the parts)

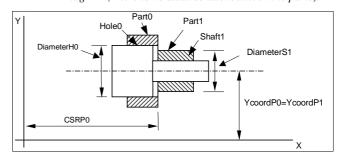


Figure 14. Graphical representation of Rule 2 of axial contact.

This rule is similar to the previous one, and the difference is that the diameter of the hole in Part0 is greater than the shaft in Part1, which is not an axial contact between the faces of both parts involved.

Application Example

An assembly of cylindrical parts is presented in Fig. 15. The assembly is composed of a rear housing that is closed by a front housing, and a stepped_shaft is located inside, over which a rotor and a bushing are assembled. The shaft is supported by the holes located in the rear housing and the front housing.

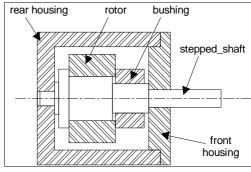


Figure 15. Assembly based on Dini and Santocchi (1992).

The rear housing is composed of a cylindrical shaft (CLSH0), a blind cylindrical hole (CLHL0) and a through cylindrical hole (CLHL1) (Fig. 16(a)). In Fig. 16(b) the features that compose the front housing are shown, i.e. two cylindrical shafts (CLSH0 and CLSH1), and a through cylindrical hole (CLHL0). The attributes of the features that compose the parts in Fig. 16 are presented in Table 1.

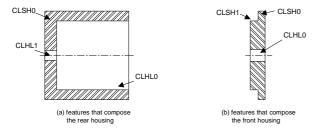


Figure 16. Description of the features that compose the rear housing and the front housing.

In Fig. 17 the parts stepped_shaft, rotor and bushing are represented, with their respective features indicated. The attributes of those parts are presented in Table 2.

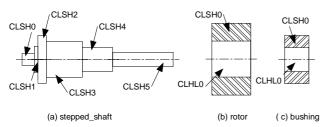


Figure 17. Indication of the features that compose the parts stepped_shaft, rotor and bushing.

The process of assembly identification begins with the rear housing, which was the first part to be created through the feature modeler. Since the rear housing has a hole (CLHL0), another part that has a shaft with the same diameter of the hole (= 70, according to Table 1) is searched. The next part is the front housing, which has a shaft (CLSH1) with diameter equal to 70 (see Table 1).

After the algorithm identifies the shaft, the expert system receives the data referring to the involved features. The rule below sets the conditions for assembly between the above parts:

```
IF (YcoordH = YcoordS) and (Type = blind_cylindrical_hole) and (DiameterH = DiameterS) and (WayH = -1) and (IcoordH = FcoordS) and (IcoordH < FcoordS) THEN Flag = 0 (assembly occurs)
```

All the conditions in the LHS of this rule are satisfied (see Table 1), and therefore this rule is triggered. Notice that the last two conditions guarantee that CLSH1 in the front housing is inside CLHL0 in the rear housing. So, this rule assures that there is an assembly with diametrical contact between the rear housing and the front housing. These data are sent as attributes to the *connections* class. The diameters that have diametrical contact are shown in Fig. 18, and their characteristics are shown in Table 3 in the form of attributes that belong to the *connections* class.

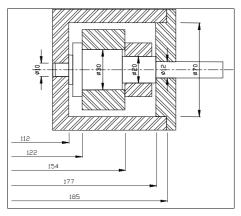


Figure 18. Diametrical and axial contacts among the parts in the assembly example.

	Features in part rear housing			Features in part front housing			
Name	CLSH0	CLHL0	CLHL1	CLSH0	CLSH1	CLHL1	
Type	cylindrical_shaft	blind_	Through	cylindrical_shaft	cylindrical_shaft	through_	
		cylindrical_hole	cylindrical_ hole			cylindrical_hole	
Position	external	internal	internal	external	external	internal	
Direction	axial	axial	axial	axial	axial	axial	
Way	1	-1	-1	1	-1	1	
Ycoord	100	100	100	100	100	100	
Icoord	100	185	112	185	185	177	
Fcoord	185	112	100	192	177	192	
Leng/Depth	85	73	12	7	8	15	
Diameter	90	70	10	90	70	12	
Volume	1	-1	-1	1	1	-1	

Table 1. Attributes of the features in parts rear housing and front housing.

Table 2. Attributes of the features in parts stepped_shaft, rotor and bushing.

	Features in stepped_shaft					Eastura	s in <i>rotor</i>	Easturas	in bushing	
		reatures in sieppea_snaji					reature	S III TOIOT	reatures	in busning
Name	CLSH0	CLSH1	CLSH2	CLSH3	CLSH4	CLSH5	CLSH0	CLHL0	CLSH0	CLHL0
Туре	cyl_shaft	cyl_shaft	cyl_shaft	cyl_shaft	cyl_shaft	cyl_shaft	cyl_shaft	through_cy l_hole	cyl_shaft	through_cy l_hole
Position	external	external	external	external	external	external	external	internal	external	internal
Direction	axial	axial	axial	axial	axial	axial	axial	axial	axial	axial
Way	-1	1	1	1	1	1	1	1	1	1
Ycoord	100	100	100	100	100	100	100	100	100	100
Icoord	112	112	115	122	152	177	122	122	154	154
Fcoord	100	115	122	152	177	227	154	154	174	174
Leng/Depth	10	3	7	30	25	50	32	32	20	20
Diameter	10	22	40	30	20	12	60	30	40	20
Volume	1	1	1	1	1	1	1	-1	1	-1

		Diametrical contacts		
Contact_Diameter	Part_Diameter_ Shaft	Feature_Diameter_ Shaft	Part_Diameter_ Hole	Feature_Diameter_ Hole
10	shaft	CLSH0	rear housing	CLHL1
30	shaft	CLSH3	rotor	CLHL0
20	shaft	CLSH4	bushing	CLHL0
12	shaft	CLSH5	front housing	CLHL0
70	front housing	CLSH1	rear housing	CLHL0

Table 3. Diametrical contacts and the attributes in the class connections.

After making sure that there is diametrical contact, it is verified the presence of axial contact that may occur between the cylindrical hole CLHL1 in the rear housing with a shaft in another part. Therefore, a search for a new part in the assembly that owns a shaft whose Icoord or Fcoord attributes coincide with the Icoord attribute of hole CLHL0 (see Table 1) is started.

In this case, there are two shafts in the front housing (CLSH0 and CLSH1), that may have axial contact with hole CLHL0 in the rear housing, and shaft CLSH0 has Fcoord=185, while shaft CLSH1 has Icoord=185. However, only shaft CLSH0 in the front housing has a diameter greater than the diameter of the hole CLHL0, and so it allows the contact between the initial surface of the hole and initial surface of the shaft. The rule below sets the conditions for verifying this axial contact (index "0" corresponds to the features in the front housing, and index "1" to the features in the rear housing):

```
IF (YcoordP0 = YcoordP1) and (IcoordS0 <> CSLP0)
and (Type = blind_cylindrical_hole) and (WayH = -1)
and (IcoordH1 = IcoordS0) and (DiameterH1 < DiameterS0)
THEN Flag = 0 (assembly occurs)</pre>
```

The condition (IcoordS0 < > CSLP0) assures that the initial face of the shaft in the front housing does not coincide with the leftmost face of the part. The condition (IcoordH1 = IcoordS0) assures that the shaft CLSH1 in the front housing is inside the hole CLHL0 in the rear housing. The condition (DiameterH1 < DiameterS0) means that the diameter of the hole CLHL0 in the rear housing must be smaller than the diameter of the shaft CLSH1 in the front housing, which guarantees the support between the two end surfaces. This can be seen in Fig. 18 in position=185, and in Table 4, where the conditions of axial contact in the *connections* class are shown.

Since the rear housing has another hole (diameter = 10), this is the next hole to be analyzed. The system then searches a shaft that has an equal diameter, which corresponds to shaft CLSH0 in the part stepped_shaft (Fig. 17). The triggered rule is as follows:

```
IF (YcoordH = YcoordS) and (Type = hrough_cylindrical_hole) and (DiameterH = DiameterS) and (WayH = -1) and (IcoordH = FcoordS) and (FcoordH < IcoordS) THEN Flag = 0 (assembly occurs)
```

The result of the analysis can be seen in Table 3 in the line Contact_diameter = 10. The procedure to identify the axial contact is the same as was described previously, and it corresponds to the contact between the bottom of the hole CLHL0 in the rear housing and the shaft CLSH1 in the stepped_shaft.

Since there are no more holes in the rear housing, the next part to be analyzed is the front housing, which has a through cylindrical hole with diameter equal to 12 (i.e. CLHL1, see Table 1), which has diametrical contact with the cylindrical shaft CLSH5 (see Table 2) in the stepped_shaft. This situation is confirmed by the following rule:

```
\label{eq:coordH} IF (YcoordH = YcoordS) \ and \ (Type = hrough\_cylindrical\_hole) \\ and \ (DiameterH = DiameterS) \ and \ (WayH = 1) \\ and \ (IcoordH = FcoordS) \ and \ (FcoordH < FcoordS) \\ THEN \ Flag = 0 \ (assembly \ occurs) \\
```

The axial contact is made at position=177 (see Fig. 18), which is confirmed by the rule below, and also from the indications in Tables 1 and 2 (index "0" corresponds to the stepped_shaft, and the index "1" to the front housing).

```
IF (YcoordP0 = YcoordP1) and (FcoordS0 <> CSRP0)
and (WayH = 1) and (IcoordH1 = FcoordS0)
and (DiameterH1 < DiameterS0)
THEN Flag = 0 (assembly occurs)
```

The condition (FcoordS0 < > CSRP0) means that the final face of the shaft must not coincide with the right-end of the part.

The next part that has a cylindrical hole is the rotor, in which the diametrical contact between hole CLHL0 and shaft CLSH3 in the stepped_shaft (diameter = 30) was identified (see Fig. 18). In this case the length of the shaft CLSH3 in the stepped_shaft is smaller than the depth of the hole CLHL0 in the rotor. The next rule describes these conditions, and the result is found in Table 3 in the line Contact_diameter = 30.

```
IF (YcoordH = YcoordS) and (Type = hrough_cylindrical_hole) and (DiameterH = DiameterS) and (WayH = 1) and (IcoordH = IcoordS) and (FcoordH > FcoordS) THEN Flag = 0 (assembly occurs)
```

This rule confirms that axial contact occurs between shaft CLSH2 in the stepped_shaft and the hole CLHL0 in the front housing. The description of this axial contact is shown in Table 4 in the line Axial_contact=122.

Since the rotor also has only one hole, the algorithm searches for the next part, which is the bushing, and it has one hole (CLHL0) with diameter=20 (Fig. 18). The algorithm also finds a shaft CLSH4 in the part stepped_shaft, and the assembly is confirmed by the following rule:

```
\label{eq:coordH} IF (Y coordH = Y coordS) \ and \ (Type = hrough\_cylindrical\_hole) \\ and \ (DiameterH = DiameterS) \ and \ ((WayH = 1) \ or \ (WayH \ -1)) \\ and \ (IcoordH > IcoordS) \ and \ (F coordH < F coordS) \\ THEN \ Flag = 0 \ (assembly \ occurs) \\ \end{aligned}
```

The axial contact is given by rule 1 described in section 4.3. The information that results from this analysis is shown in Table 3 in the line corresponding to $Contact_diameter = 20$, and in Table 4 in the line $Contact_coordinate = 154$.

Assignment of Dimensions and Tolerances

When the diametrical contact is identified (i.e. equal nominal diameters of both shaft and hole), the developed system automatically calls a function that accesses a database with information about tolerances and fits. This information refers to the type of application, indicating the recommended fit for a type of assembly already known. After searching the database, the system returns the recommended fit and tolerances for the given diameter, and these are assigned as attributes of the shaft and hole that compose the assembly. The features that do not compose an assembly are given predefined standard tolerances.

Since it is known which parts have diametrical contact, it is possible to access this information in the *connections* class, and through the recommended tolerances to define automatically what roughness to assign to the surface.

Since in the present work the surfaces with axial contact are also known, it is possible to define what dimensions must be assigned special tolerances. The identification of the reference surfaces in each part corresponds to verifying in the *connections* class what parts and features have the same contact surface, which can be used for nominal dimensioning, and then to decide the tolerances to be applied.

In Fig. 19 the stepped_shaft is presented, on which the surfaces that have axial contact are indicated. In the figure it is also shown the dimensions that must be controlled rigorously (A, B and C), where "C" is the depth of the hole CLHL0 in the rear housing. In this way, each part has one or more surfaces with axial contact recorded in Table 5, which is a result of Table 4. Such surfaces are references for the dimensioning of each part.

Axial Contacts							
Contact_	Part_Axial	Feature_Axial	Part_Axial	Feature_Axial_			
coordinate	_Shaft	_Shaft	_Hole	Hole			
112	shaft	CLSH1	rear	CLHL1			
			housing				
122	shaft	CLSH2	rotor	CLHL0			
154	bushing	CLSH0	rotor	CLHL0			
177	shaft	CLSH4	front	CLHL0			
			housing				
185	front	CLSH1	rear	CLHL0			
	housing		housing				

Table 4. Axial contacts.

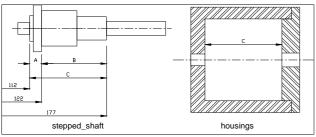


Figure 19. Surfaces with axial contact and dimensions to be controlled.

References of contact for dimensioning							
Part Name	Reference 1	Reference 2	Reference 3	Reference 4			
shaft	112	122	177				
rear housing	112	185					
bushing	154						
rotor	122	154					
front	177	185					
housing							

Table 5. References for dimensioning.

Software and Hardware Utilized

The algorithm was implemented in C++, running under AutoCAD for Windows on a Pentium PC. The features are represented in a data structure that is independent of the CAD database. In order to do that, an element that links the data structure to the CAD database was used, which permits the correspondence between the graphical and technological data about the features and the graphical entities of the CAD system.

As mentioned previously, the CLIPS expert system shell was used, which allows object-oriented programming, besides providing an easy communication with the independent data structure.

The system's communication is done in the following way: ADS (Autodesk Development System, which is Autodesk's proprietary programming language) \leftrightarrow C++ (used for part and feature management, aiming at sending assembly candidates to the expert system) \leftrightarrow CLIPS (used for assembly verification). When the user runs the system, he/she is in the AutoCAD environment; but depending on the choice made in the main menu, actually C++ and CLIPS will be running transparently.

Conclusions

In this paper a method to identify assembled parts automatically in a feature-based design environment was described. This method was implemented in order to reduce the time to perform the assembly design process using the computer.

The utilization of features for assembly modeling was important, because through the features it was possible to identify the information necessary to perform assembly analysis. The implemented data structure allowed the representation of assemblies, parts and features, which helped identify the diametrical and axial contacts among the features, consequently enabling decisions to be made on the relations between the parts.

The information extracted from the product about the assembly must be stored in a format that can be interpreted, and in the present work it corresponds to the *connections* class, which is an attribute of the assembly. The information in the *connections* class is used to generate a list describing the links between the assembled parts, the involved features and the type of link (i.e. diametrical or axial). This list was successfully used to generate the functional dimensions for the parts in the assembly, and this procedure is described in (Maziero et al., 2001). Also, this list helped identify the parts that need to be assigned tighter tolerances due to contacts that occur between them.

Although the developed system allows the automatic identification of the assembly relations among the parts based on features, in the present implementation modifications to a part cannot be made after the part is positioned in the assembly, i.e. such modifications do not propagate to the other parts in the assembly. The authors intend to implement a solution to this problem in the future, which can be facilitated because the contacts among the parts are already available in the system.

One of the difficulties in the development was the use of a graphical representation of the model in 2D, but the authors consider that it was sufficient for validating the applied concepts.

The utilization of an expert system gives flexibility to the developed software, since it is possible to alter the knowledge base without modifying the main system. However, careful attention should be given when defining the parameters that represent the physical situation of assembly, which must be included in the rules.

The authors consider that the developed knowledge base encompasses the types of assemblies that can occur with the features described in the system.

When the dimensions, tolerances, fits and their relations among the parts and features are known, this information can be sent to a process planning system, an inspection planning system, or a program that analyzes the assembly sequence performed by robots.

The system so far considers only simple features, but it is intended to extend it to other types of features, such as threaded parts

In this research, the approach concerning feature classification, i.e. "Basic features" and "feature Modifiers", has been successfully applied to the problem of modeling the assembly of cylindrical

parts. However, the authors have not yet contemplated the applicability of this approach to prismatic parts, which is considered a subject of further investigation.

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