GEOMETRIC REASONING IN SUPPORT OF ASSEMBLY-ORIENTED CAD

S J Tate, G E M Jared
SIMS, Cranfield University, Cranfield, Bedfordshire, MK43 OAL, UK.
S.J.Tate@eng.hull.ac.uk G.Jared@cranfield.ac.uk

K G Swift
Department of Engineering, University of Hull, Hull, East Yorkshire, HU6 7RX, UK.
K.G.Swift@eng.hull.ac.uk

ABSTRACT

Assembly-oriented CAD has long been accepted as a necessary development from the current component-focused solid modelling systems. It is proposed that such an environment should incorporate assembly sequence generation and Design for Assembly (DFA) analyses to assist the designer, including some automatic inference to facilitate ease of use. The key to enabling the various assembly analyses lies in interrogation of the CAD model and this poses some interesting challenges in the field of geometric reasoning. Statistics from case studies show that, in particular, the identification of part symmetry and principal axes is fundamental to many of the required algorithms which have been identified. This paper reviews methods for symmetry detection. However, no pre-existing method suitable for this application is found and so a new technique is proposed which exploits the existence of loops within the CAD model. This entails the comparison of loop areas to discover exact symmetry, partial symmetry and repeated features. Implementation of this technique is described and in conclusion the benefits and problems associated with it are discussed.

Keywords: DFA, Symmetry, Assembly-Oriented CAD, Geometric Reasoning, Design Methodology

INTRODUCTION

It has long been recognised that up to 70% of a product's cost is determined in the design stage and that much of this cost is incurred during assembly. Hence, the aim of the project giving rise to this research is to provide an environment which encourages the designer to systematically consider assembly in the early stages of product design, thereby reducing the costs and time-to-market associated with high part-count and unnecessarily complex assembly procedures.

Design for Assembly (DFA) is a methodology which, although effective in reducing part-count and simplifying the assembly process, has traditionally been a reactive tool. Hence the work described in this paper forms the basis of a 'proactive' DFA methodology, developed as part of a first generation demonstrator which combines facilities for assembly sequence construction, validation and evaluation with an ACIS-based CAD environment.

ASSEMBLY-ORIENTED CAD

Computer-aided design software has been in evidence in industry for many years. Most current commercially available packages still tend to concentrate upon component oriented design, where individual parts are modelled and then assembled to create the final product. This fails to afford an assembly-oriented view of the product leading to problematic assembly, rework and ultimately redesign. Assembly-oriented CAD aims to overcome these issues by providing a top-down design software environment to enable the consideration of assembly design issues such as materials and processes, including the complex interactions between parts as well as the logistics of assembly sequences.

This approach is supported by the findings of Sodhi *et al* [Sodhi94] who produced a comprehensive review of the literature and established basic requirements for assembly-oriented CAD and top-down design support to facilitate the creation of a useful and appropriate software environment. It was concluded that a top-down approach is fundamental for the appropriate support of the design process.

Integrating DFA [Lucas93] with a suitable solid modelling package has been proposed as one way to provide an assembly-oriented CAD system. Sturges *et al* [Sturg92] defined a framework for automating the DFA evaluation procedure within a CAD system. Kim *et al* [Kim95] presented their system INSPIRE-2 which integrates assembly planning, DFA and redesign. However, these proposals implement DFA on completion of the design and little consideration is given to the potential benefits which could be gained from analysing products concurrently within the design process. Enabling earlier DFA investigations could identify possible assembly and manufacturing problems as the design progresses.

However, the DFA methodology in its current form is not suited to early application. The current analyses are very specific and require detailed part information, often not available until towards the end of the design process. Thus modifications must be made to the methodology to enable interactive assemblability analysis of a developing design. Since meaningful DFA results are dependent on the plausibility of the assembly sequence it is proposed that generation of the assembly sequence holds the key to enabling a proactive DFA methodology [Barne97] and thus providing an assembly-oriented CAD environment.

GEOMETRIC REASONING SUPPORT

This approach generates some interesting problems associated with incomplete information, automatic inference and the timing of the different analyses. It has long been established that interrogation of the CAD model can provide much of the information required for DFA analyses [Jared94]. In addition, knowledge engineering and the evaluation of case studies from industry have identified those heuristics which can assist in assembly sequence generation. The geometric reasoning elements for both these areas have been extracted and are shown in table 1.

Assembly Sequence & DFA Requirements		Geometric Reasoning Algorithms												
		Current State of Assembly	Max/Min X Section	Swept X Section Props	Insertion trajectory	Degrees of Freedom	Mass	Volume	Mating Faces	Major/Minor Axis	C of G	Symmetry	Internal/External Features	Bounding Box
Collisions	- component	✓		✓	✓				✓	✓				
	- gripping tool	✓		✓	✓									
	- joining tool			✓										
Stability	- current orientation	✓				✓			✓		✓			
	- turnover	✓				✓			✓		✓			
Compatability	- material/material								✓					
	- material/joining process								✓					
Manufacturing	- shape complexity		✓							✓		✓	✓	
	- cost analysis		✓					✓						✓
Handling/Feeding	- part characteristics		✓				✓	✓		✓		✓	✓	
	- part orientation									✓		✓	✓	
Fitting	- gripping				✓				✓	✓				
	- fitting process			✓	✓				✓					

Geometric Reasoning Requirements of an Assembly-Oriented CAD System

Table 1

Some of this information is input by the designer either implicitly or explicitly whilst the remainder must be extracted from the solid model. For instance the degrees of freedom of a component will be determined by the order of assembly operations including the defined type and timing of joining processes. However to analyse stability, the centre of gravity of the component relative to its position and orientation within the assembly must be evaluated. Most solid modellers are able to calculate this but many other required aspects of the geometry are difficult to infer. For example the determination of mating faces, which affect the degrees of freedom, requires a complex algorithm.

In particular, the definition and validation of insertion trajectories requires identification of mating faces and cross-sectional properties, particularly the maximum and minimum dimensions perpendicular to the axis of insertion. Table 2 shows that in 45% of cases the component is inserted along its major axis defined, by the DFA methodology, according to its longest dimension (parallel to its surfaces). The remainder are inserted along a minor axis, perpendicular to the major axis, apart from 5% in which the axes cannot be defined according to the simple criteria above. 95% of components possess some degree of symmetry, of which 79% is rotational, and in 54% of cases the axis of symmetry and the major axis are coincident. Hence the importance of symmetry and major/minor axes in assembly can be seen.

		Rotational Symmetry				Reflective Symmetry				Thin Wall Refl. Symm.				
Case Study	No. of components	Exact	Partial	Symm = Major Axis	Major Axis Insertion	Exact	Partial	Symm = Major Axis	Major Axis Insertion	Exact	Partial	Symm = Major Axis	Major Axis Insertion	Other
Gear Change Assembly	22	15	2	11	7	1	1	1		3		3		
Oil Pump 1	33	20	5	14	14	1	1	2	1	2	2	3	1	2
Oil Pump 2	12	9	2	9	9	1		1	1					
Grating Arm Assembly 1	39	17	3	15	15	11		3	1	4		2	1	4
Grating Arm Assembly 2	8	3	2	5	5	1		1	1					2
Pintle Hook Mtg Assy 1	60	40	14	18	18	1				5		3	2	
Pintle Hook Mtg Assy 2	28	20	4	8	8	1				3		3	3	
Lens Assembly	18	14	2	9	9									2
Injector Assembly	25	16	7	14	14									2
Total	245	154	41	103	99	17	2	8	4	17	2	14	7	12

Case Studies from the Automotive Industry

Table 2

The geometric reasoning requirements of DFA evaluations contain some common elements. A major part of a manufacturing analysis is the definition and evaluation of shape complexity which requires identification of major and minor axes and the global shape type such as rotational, prismatic or thin-walled. Analysis of component handling and feeding also requires knowledge of the major axis, axes of symmetry and features, internal and external, which corrupt the symmetry. Analysis of component gripping requires knowledge of the insertion trajectory and mating faces and is therefore also ultimately dependent on the evaluation of major axes.

Detection of both exact and partial symmetries associated with these axes can provide a useful means of evaluation of practical assembly issues such as component orientation. Indeed one of the major recommendations of the DFA methodology is that components should exhibit either exact symmetry or marked asymmetry to avoid confusion during the assembly process.

Hence the determination of mating faces, major and minor axes, axes of partial- and exact-symmetry and cross-sectional properties, have been identified as research priorities. They are all closely related and interdependent since if symmetry is found then the major and minor axes can be defined accordingly. If the major/minor axes are found then the search for symmetry can be confined to these axes. If the mating faces have been resolved then the definition of major/minor axes is simplified. If the major/minor axes are used to define insertion trajectories then cross-sectional properties can be found relative to these.

SYMMETRY DETECTION

The concept of symmetry is of major interest in many fields of research, from human psychology [Wehl] and medical imaging [Fukus97] to crystallography and atomic physics [Rosen95]. Hence methods for the detection of symmetry are many although their cross-disciplinary relevance is limited due to the domain-specific interpretation incorporated in each technique.

The detection of symmetry is an issue in many aspects of design. Besides its proven use in DFA analyses it is also useful for sectioning prototype or FEA models to reduce the size and hence the required resources and analysis times. In their work on symmetry detection for the correction of unintentional or inappropriate asymmetry, Martin and Dutta [Marti96] provide a thorough review of the literature. These methods generally exploit pattern matching algorithms to detect exact symmetry or to find a measure of symmetry. Techniques which typify this approach are the symmetric difference method of Kulkarni *et al* [Kulka94] or the technique presented by Zabrodsky [Zabro95] which gauges the symmetry of a set of points relative to a 'symmetry transform', a symmetric set of points produced by averaging the original set. Perhaps the only method to date which tackles the detection of partial symmetry in a manner appropriate for this application is that of Parry-Barwick and Bowyer [Parry93] which uses a multi-dimensional template matching algorithm. Unfortunately this is based on a CSG model as opposed to boundary representation and is very computationally expensive.

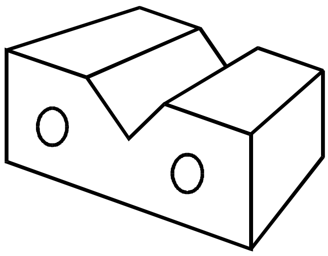
The relevance of symmetry has not been overlooked by the assembly modelling community. Lui and Popplestone [Lui90] utilised symmetry group theory to express the relationships between two bodies in the field of automatic robotic assembly to solve the problem of finding all possible assembly configurations. Van Gool *et al* [VanGo95] used a more generalised concept of symmetry to solve a similar 'peg-in-hole' assembly problem. Ong *et al* [Ong97] and Ruixiao *et al* [Ruixi97] both devised methods for detection of rotational symmetries parallel and perpendicular to the predefined insertion trajectory in a component-focused approach to assembly.

However, none of these methods really satisfy the requirements described herein. A novel method is proposed in this paper which aims to establish axes of symmetry, and those elements of the surface which corrupt that symmetry, in a form appropriate for use within the assembly-oriented CAD environment. The following definitions of symmetry have been adopted for the purposes of this application which coincide with definitions of shape complexity described in the DFA methodology [Lucas 93].

Definitions of symmetry

- **Exact Reflective symmetry**

  This includes prismatic solid or thin-wall parts which exhibit reflective symmetry. A typical example is shown in Fig.1.

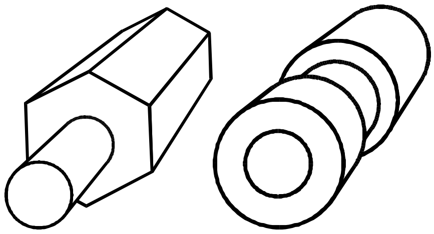


Example of Exact Reflective Symmetry

Figure 1

- **Exact Rotational Symmetry**

  This covers parts whose envelope is a solid of revolution and also those parts with *n*-fold rotational symmetry. It has been assumed throughout the course of this investigation that the threaded portion of fasteners is unlikely to be modelled and hence these have been assumed to have exact rotational symmetry. Typical examples of exact rotational symmetry are shown in Fig.2.



Examples of Exact Rotational Symmetry

Figure 2

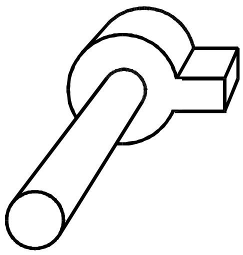
- **Partial Symmetry**

This covers parts whereby portions of the boundary can be identified as symmetric. These will fall into three categories of part:

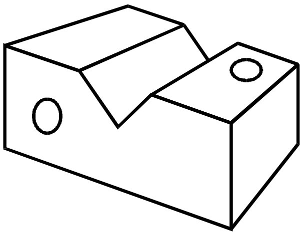
(a) those where the part is largely rotationally symmetric with additional features which corrupt that symmetry (Fig.3a);

(b) those where the part has overall reflective symmetry but with additional features which corrupt that symmetry (Fig.3b);

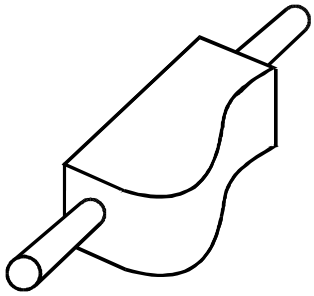
(c) those parts whose basic overall shape is not symmetric but which contain repeated features at intervals around the boundary (Fig.3c)



(a)



(b)



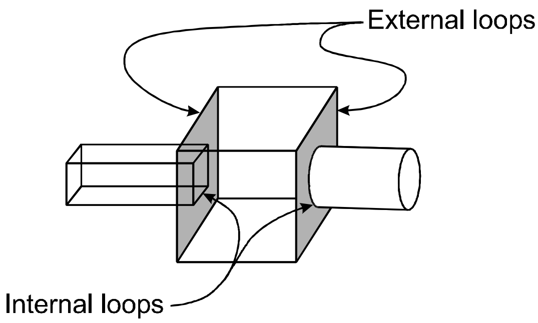
(c)

Examples of Partial Symmetry

Figure 3

Proposed methodology

The proposed technique also involves the use of search algorithms. The general principle involves the calculation of the surface area bounded by each loop of a face, for each face belonging to the part. This enables the association of faces, whose only difference is the type of feature which they contain (Fig.4). In this way, partial symmetry and repeated features are as easy to identify as exact symmetry. The process can be broken down into 6 steps:



Shaded faces indicate partial symmetry based
on the area of surfaces bounded by external loops

Figure 4

Step 1 - Determine the properties of each loop

A loop is a continuous set of edges marking a boundary of a face and for planar faces there always exists an external loop, intersecting features resulting in internal loops. It is a simple matter to compare the bounding box of each loop to identify its nature in this respect. The same is true for all occurrences of non-intersecting B-spline surfaces. However, this is not true of some commonly occurring face types of major importance in manufacturing and hence further interrogation is required in order to classify the loops defining each face. Fortunately ACIS provides the facility to identify particular types of face; cylindrical, conical, spherical and toroidal in addition to planar and spline surfaces, so each type of face can be treated according to its particular properties.

For example, a cylinder can be considered as a special instance of a cone and hence the two can be treated similarly. The loops of these types of face cannot be distinguished as internal or external because the distinction is not relevant. For example, a complete cylindrical face possess two circular loops bounding the ends. In such cases it is therefore necessary to differentiate between those 'end' loops and the 'internal' loops belonging to intersecting features.

Step 2 - Calculate the area of surface bounded by each loop

Each loop is associated with a face which is associated with a surface. Using the ACIS functionality, a new face can be created with the loop as the external boundary of a portion of the same surface. It is then a matter of calculating the area of this new face using the appropriate ACIS function. Of course exceptions such as the end loops of cylinders must be dealt with accordingly.

Step 3 - Rank loops

Loops are ranked according to their type, bounded area and number of edges, 'external' loops ranking higher than 'internal' loops.

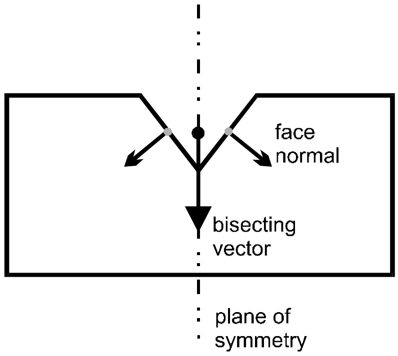
Step 4 - Identify matching loops

Loops with matching type and area are identified and then further checks are required to validate their relationship such as face type and number of edges.

Step 5 - Construct a set of planes of symmetry

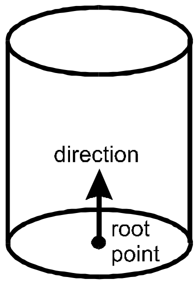
For each matching pair of loops a plane of symmetry can be constructed. This plane will pass through a point bisecting the centroids of the two loops. Its orientation will be defined by a vector bisecting the face normals at the centroids (Fig.5). Again, cylindrical and other types of face must be treated slightly differently. For instance, cones and cylinders are partly defined by a root point and a direction which can be used in a similar way to the centroid and face normal (Fig.6).

It was shown from the case studies that a large proportion of manufacturing parts have rotational symmetry but this would not necessarily be identified if the part is essentially cylindrical as there would be no 'matching' loop. Therefore the axes of cylindrical faces can be considered independently and ranked alongside the planes of symmetry according to the cylindrical face area.



Plane of symmetry defined by bisecting matching loops

Figure 5



Cylinder and Cone - Face Definition

Figure 6

Step 6 - Determine the principal axes

This set of bisecting planes can be ranked according to the area of the loops that they bisect and the number of pairs of loops that they bisect. The axes can then be defined by the intersection of these ranked planes. The major axis will be defined by the intersection of the plane associated with the maximum co-oriented loop area, with the plane associated with the next largest co-oriented loop area. Then the first minor axis can be defined as the intersection with the subsequent largest co-oriented loop area, perpendicular to the major axis and so on.

This methodology is in its infancy and several issues are outstanding:

- This method involves the determination of principal axes associated with symmetry. The notion of the maximum co-oriented loop area is also effective for determining principal axes when no symmetry exists since by the DFA definition, the major axis is that lying parallel to the longest face.

- The method enables the identification of features as those elements of the topology associated with internal loops. The feeding analysis requires the identification of features apparent in silhouette which would therefore affect the orientation in transition. Hence the method requires further development in order to identify the nature of features in terms of protrusion and depression.

- For parts with *n*-fold rotational symmetry, several planes of reflective symmetry will be identified using this method. Although this will not affect the determination of the principal axes it is desirable in some instances to differentiate between the two types of symmetry. It is anticipated that by using the theory of symmetry groups [Rosen95] it will be possible to infer other forms of symmetry.

- At the present time little consideration has been given to the robustness of the method. Further testing is required.

CONCLUSIONS

This paper has demonstrated the need for geometric reasoning to support an assembly-oriented CAD environment and this has been supported by case studies gathered from industry. It proposes a solution to the problem of symmetry detection and determination of principal axes which is immune to the confusion that small changes to topology can generate.

At the time of writing this method has not been rigorously tested and it is anticipated that further refinement will be required. Despite the fact that loops are explicitly represented in the boundary representation of the solid model, this method has the disadvantages of many search algorithms which are inelegant and notoriously slow. Although the ACIS functionality has enabled a simple implementation of the technique, efficiency could be improved by a more direct approach to the calculation of loop areas which does not involve the creation of additional faces.

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