RESEARCH ARTICLE

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Automatic Extraction of Mechanical Interlocking Features from CAD Model

Shantanu K. Das*

Department of Mechanical & Industrial Engineering, Indian Institute of Technology, Roorkee-247667, Uttarakhand, India

G H Raisoni University, Saikheda, Madhya Pradesh, Pin-480337, India

Abstract

This paper represents, classifies, and automatic extracts the mechanical interlocking features (MIFs) from the CAD model. MIFs are geometric features of two or more components when physically interlock that prevent the relative movement in any or certain directions. A set of contact faces in proximity and their characteristic arrangement are usedto represent the MIFs. This characteristics arrangement of contact faces and their topological relationships help in classification of MIFs. It is very difficult to manually extract the large number of MIFs from CAD models. It is therefore desirable to develop a set of algorithms to extract the MIFs from CAD model. CAD assembly models from industrial domain has been used in order to validate the proposed approach.

Keywords: Assembly feature, Extraction, Mechanical interlocking joint, Representation.

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Introduction

Mechanical interlocking feature has wide application in aircraft, defense, construction, furniture and automotive industry.[1-3] Mechanical interlocking features (MIFs) are now receiving increased attention for its advantages like, low cost, easily disassemble, ability to join dissimilar material with no change in its microstructure and generation of lightweight product as compared to other joining processes like welding and adhesive bonding process.[3] Different forms like liaison,[4] connection interface,[5] joint design type[6] etc. are used in different literatures to study assembly features in disassembly sequence generation,[7] assembly planning,[8] collaborative product design[6] etc. The features associated with the welding, riveting and gluingprocesses are mostly addressed in the literature.[4,6,9] Therefore, there is a need to extract the MIFs for various assembly design and its process planning application.[10]

Over the last few decades, several assembly features have been studied.[4,6,9] In most literatures,the relation between components are taken for the representation of assembly features to solve design problems.[11] Holland and Bronsvoort[8] addressed few elementary and compound MIFs in very abstract level without any proper representation to capture the MIFs. Popescu and Iacob[6] used the connection features for disassembly planning which includes some MIFs like rib-slot,T-shape, rectangular and pin-hole connection. The joint information of these MIFs are used as input data for determination of valid escape directions. In most of the literature, the MIFs are explicitly represented where connection type is already known to the designer.

Corresponding Author: Shantanu K. Das, Department of Mechanical & Industrial Engineering, Indian Institute of Technology, Roorkee-247667, Uttarakhand, India, e-mail: shantanuds0206@gmail.com

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Several methods have been used to extract MIFs from CAD model.[4,12,13,14] The tongue and groove elementary MIFs are extracted by using graph based algorithm by matching the features with a user defined feature library.[13,14] Das *et al*.[9] developed algorithms to extract adhesively bonded assembly features from CAD model which can be extended with addition of some algorithms to extract MIFs. Therefore, a new and modified algorithm is developed to automatically extract the MIFs from CAD model. The MIFs are classified into three types (i) Rigid (ii) Elastic (iii) Plastic. In this paper the static complete rigid MIFs are addressed. The static complete rigid MIFs are classified as below:

- Elementary MIF: The commonly used mechanical interlocking features generated due to involvement between two form features (ex. plain dovetail) available on the surface of the components called elementary MIF as shown in Figure 1(a).
- Compound MIF: The combination of more than one elementary MIF [8, 14] as shown in the Figure 1(b) is

called Compound MIF. The extraction of compound mechanical interlocking features are rarely studied in the literature.

The systematic classification and automatic extraction of MIF helps in better integration of design information with assembly process planning, variant design etc. The focus of the paper is the automatic extraction of mechanical interlocking features as these information are explicitly not available either in the part model or in the assembly model. Towards this objective the following contributions of this paper include (i) Definition of elementary and compound MIFs as a typical arrangement of joint surface (ii) Generic Classification of MIFs (iii) Automatic identification of both elementary and compound MIFs by developing several algorithms.

Rest of the paper is organized as follows. The various studies pertained to proposed work are reviewed in section 2. A data structure is created for representation and classification mechanical interlocking features in section 3 using various attributes. The automatic identification of mechanical interlocking features with detail descriptions are defined in section 4. In section 5, the results of implementation along with its discussions are explained. The paper concludes with the discussion of the propose work and its various future applications in section 6.

Literature Review

Extraction of mechanical interlocking feature (MIF) is rarely addressed in literature. There are many ways of representation of assembly feature have been defined in the literature but very few researchers have tried to automatically identify some of the MIFs from the CAD model.[4,9] The literature related to MIFs representation and its extraction are studied in this section.

Representation of MIFs

In literature, the region of parts of assembly components and the associated geometric and non-geometric information which has significance in an assembly activity is defined as an assembly feature. In most of the literature, assembly features are represented using different forms like liaison,[4] connection interface[5] etc. Also, these assembly features are represented for different joining processes like riveting, welding and gluing.[4,9] But, the representation of mechanical interlocking features is very rare. Popescu and Iacob[5] proposed unit ball mobility operator concept and used the connection interface for disassembly sequences generation which includes some MIFs like rib-slot, T-shape, rectangular and pin-hole connection. The valid escape directions are determined from the interface information of these MIFs. Holland and Bronsvoort[8] developed a product model using connection features includes some MIFs like dovetail, compound tongue and groove feature etc. The connection feature class in this product model stores and retrieves information for a particular connection where the connection type is already known. Shyamsundar & Gadh[15] used the assembly feature relational graph for the representation of assembly features and relation between the assembly features. The assembly features are categorized into form and relational assembly features. The form assembly features define the common shape features between the two form features of components which includes some MIFs like peg and hole and lacks the details information about the interface. Further, this representationis used to perform real time modification of product components during collaborative product design. However these connection types are not explicitly existing in the CAD model.

Hamidullah *et al*.[16] classified the assembly features into fit, against; single, multiple; soft, hard, composite and functioning, interlocking type using the concept of assembly intents like mating relations, assembly operation, position and orientation of feature or degree of freedom etc. Chan *et al*.[17] developed a method to automatically generate the assembly feature by splitting of a single solid model and also classified these assembly features into elementary, compound type and positioning, interlocking type based on the complexity and degree of freedom of connecting feature respectively. The literatures provide very few information about MIFs and in most of the cases the MIFs are explicitly defined.

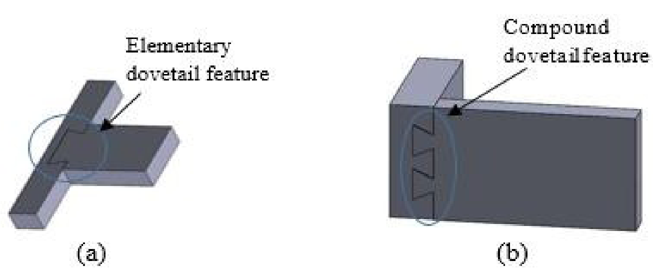


Figure 1: (a) Elementary MIF (b) Compound MIF

Extraction of MIFs

Graph based method have recently evolved for the extraction of MIFs in the literature. Vemulapalli *et al*.[14] developed a framework for the identification of some MIFs like tab and slot from the user defined feature library using multi graph matching algorithm from a STEP file. Xiao *et al*.[13] used the improved subgraph isomorphism algorithm for the identification of MIFs like tongue and groove; and dovetail. However, the major disadvantage of these graph matching techniques of feature recognition are high computational complexity in case of complex assembly and not applicable to features that only differ geometrically. Swain *et al*. [4] automatically extracted different basic liaison like lap, butt, corner, t-joint, edge joint from the CAD assembly model useful for riveting, welding and gluing purpose. Das *et al*. [9] extracted various adhesively bonded assembly features from CAD model where algorithms are developed to extract the joint feature. But, algorithms for capturing the interlocking joint features are not addressed in this paper.

Most of the assembly features available in the literature are applicable to riveting, welding and adhesive bonding purpose. It is concluded from the extensive literature survey that various representations exist are not directly capable to capture MIFs required for different product design applications.

Mechanical Interlocking Features

The mechanical interlocking features are categorized and represented in terms of number of joint surfaces exist in particular joint feature and the adjacency relationships exist between joint surfaces. The definitions and classification of these MIFs attributes are defined below.

Terminology

In order to capture the MIFs, various attributes like contact faces (shown in Figure 2(a)), joint surface (number and its types (shape and topology)), joint feature (shown in Figure 2(c)), Euler angle are required. The definitions of some of these attributes are defined already by Das *et al*. [9] and its diagrammatic representations are shown in Figure 2 to capture MIFs.

Joint Surface: Common surface generated due to overlapping between two contact faces is calledjoint surface as shown in Figure 2(b).

Euler Angle: Maximum value of angle between the unit normal of the all joint surfaces of a joint feature is called as Euler angle of a respective joint feature as shown in Figure 2(d).

Classification of Joint Surfaces

The joint surfaces in each part that creates the MIF are categorized based on two concepts like topology and shape. The joint surfaces are classified based on their shape into several types (i) Planar surface (PS) (ii) Cylindrical surfaces (CS) (iii) Conical (CC) and (iv) Spherical (SC) surfaces. In this paper, the topology representing a cylinder or cone or sphere is taken as two half-cylindrical or conical or spherical faces. The classification of joint surfaces based on their topologyis defined as follows:

(i) Common Base surface (CBS) and (ii) Wall surfaces (WS): The joint surface whose edges are at least connected to edges of two joint surfaces is called as CBS and the adjacent joint surfaces connected to the common base surface is considered as WS.

(iii) Distant joint surfaces (DJS): Distant joint surfaces are the joint surfaces which don't share a common edge. Further, these non-adjacent joint surfaces are classified onto two sub types: Directional blocking joint surfaces (DBJS) and directional free joint surfaces (DFJS).

The one of the non-adjacent joint surface sweep through space in a specified direction with other surfaces and its collision are checked. If there is collision, both are called directional blocked jointsurfaces (DBJS). If there is no collision then both are called directional free joint surfaces (DFJS). If it is collided with more than one non-coplanar surfaces along the normal, then the joint surfaceis called as repeated directional blocked joint surfaces (RDBJS), otherwise it is called as single directional blocked joint surfaces (SDBFS). Again the above each DBJS and each DFJS are classified as two types depending upon the angle between them. If the DBJS are parallel then theyare called parallel directional blocking joint surfaces (PDBJS), otherwise they are inclineddirectional blocking joint surfaces (IDBJS). Similarly the DFJS surfaces are classified into PDFJSand IDFJS types. The diagrammatic representation of these different types of surfaces are shown in Figure 3.

Interlocking Feature

A joint feature is said to be an interlocking feature (IF) based on the classification of joint surfacesand various attributes defined above. The following condition should be satisfied for capturing theinterlocking feature:

- The root gap between the contact faces of two opposite part should be zero.
- Check if all the surfaces of a joint feature are planar or not.
- If planar and number of joint surface greater than equal

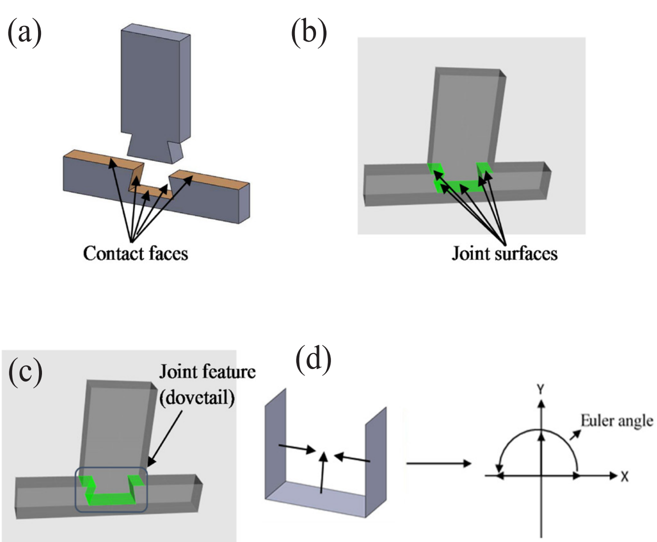


Figure 2: Pictorial representation of MIFs attributes

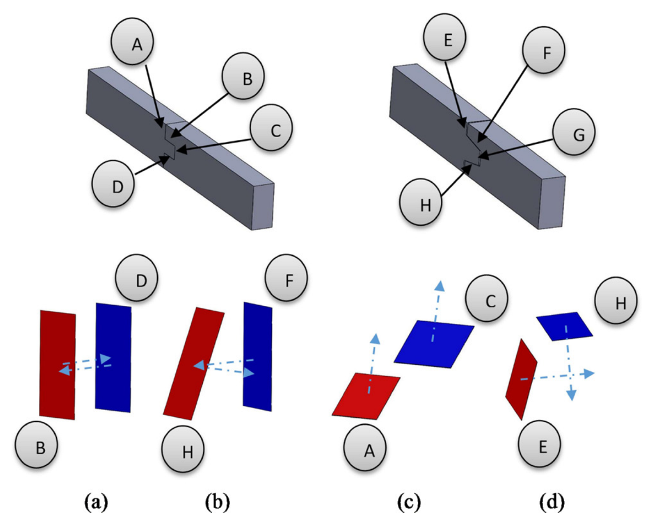


Figure 3: Types of distant joint surfaces
(a) PDBJS & SDBJS (b) IDBJS & SDBJS (c) PDFJS (d) IDFJS

to three then check whetherboth DBJS and CBS exist in a joint feature.

- If both exist, then the joint feature is an interlocking feature.
- Else, if one or more joint surfaces are cylindrical or conical or spherical, then the degreeof freedom is one (either in x or y or z direction), so the joint feature is an interlocking feature.
- If number of joint surfaces is equal to two and type of surface is planar, then find the Euler angle of the joint feature.
- If Euler angle is greater than 180°, then the joint feature is an interlocking feature.
- If one or more joint surfaces are cylindrical or conical or spherical and number of jointsurface is less then equal to two, then then find the Euler angle of the joint feature.
- If Euler angle is equal to 0^0 or 90^0, then the joint feature is an interlocking feature.

Before classification of MIFs, the joint feature needs to checkwhetherthefeatureisaninterlockingtype or not. Then, the MIFs classified using the attributes described in section 3.2 and its detail taxonomy is defined below.

Classification of MIFs

The generic classifications of various MIFs are defined with the help of basic parameters such as Euler angle, number and types of joint surfaces and its different characteristics after checking if the joint feature is an interlocking feature or not. This generic MIFs are further classified into elementary and compound MIFs as described below.

Classification of Elementary MIFs

The classification of elementary MIFs are done based on various attributes i.e. Euler angle, numberof joint surface and its different characteristics as given in the Table 1 and 2 with some illustrative example.

Classification of Compound MIFs

The compound joint features are evolved due to the combination of more than one elementary feature. The compound features which are in a pattern are called sequential compound MIFs and those are having feature with in a feature are called mixed compound MIFs. The MIFs attributes like Euler angle of joint feature, joint surface types and its characteristics help in classification of compound

Table 1: Classification of elementary MIFs (open)

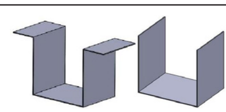
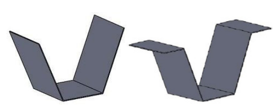
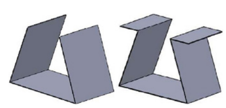
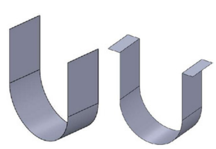
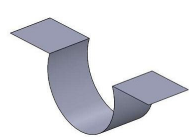
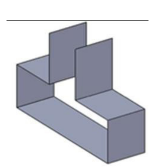
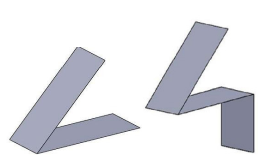
Interlocking feature	*Illustrative example*	*Eulerangle(E)*	*Joint surface(JS)*	*Characteristics*
Plain tongue and groove		180^0	3≤JS ≤5	IF, OPWS, PDBJS=1, SDBJS
Tapered tongue and groove		<180^0	3≤JS ≤5	IF, OPWS, IDBJS =1, SDBJS
Dovetail		>180^0	3≤JS ≤5	IF, OPWS, IDBJS=1, SDBJS
Cylindrical tongue andgroove		180^0	3≤JS ≤5	IF, OPWS,CS, PDBJS=1, SDBJS
U tongue and groove		0^0	3	IF, OPWS, CS, PDBJS=0
T-slot		180^0	7	IF, OPWS,PDBJS=4, SDBJS
Dovetailed step		>180^0	2 3≤JS ≤4	IF, OPWS IF, OPWS,IDBJS= 0

Table 2: Classification of elementary MIFs (closed)

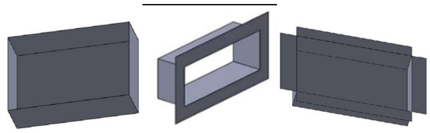
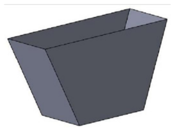
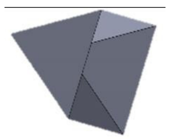
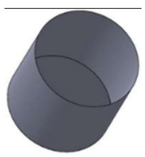
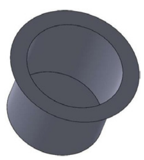
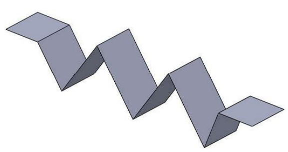
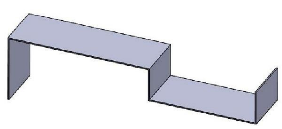
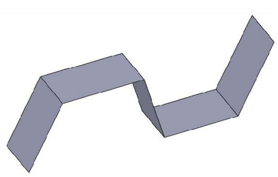
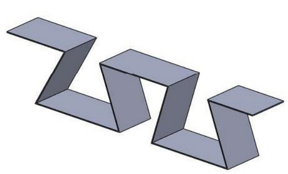
Interlocking feature	*Illustrative example*	*Eulerangle(E)*	*Joint surface(JS)*	*Characteristics*
Plain tongue andgroove		180^0	5≤JS≤9	IF, CWS, PDBJS=2, IDBJS =0,SDBJS
Tapered tongue and groove		180^0	5≤JS≤9	IF, CWS,IDBJS ≤2, PDBJS ≤1
Dovetailed step		180^0	3≤JS≤8	IF, CWS,IDBJS ≤2, PDBJS ≤1
Cylindrical tongueand groove		180^0	3	IF, CWS, CS
			4	IF, CWS, CS, PDFJS=1

Table 3: Classification of sequential compound MIFs (open)

Interlocking feature	*Illustrative example*	*Euler angle (E)*	*Joint surface(JS)*	*Characteristics*
Multi scarf		$0^0<E<180^0$	≥3	IF, OPWS, PDBJS>1, RDBJS
Compound plain tongueand groove		180^0	≥5	IF, OPWS, PDBJS >2, IDBJS=0,RDBJS
Compound tapered tongueand groove		$<180^0$	≥5	IF, OPWS, IDBJS >2, PDBJS =0,RDBJS
Compounddovetail		$>180^0$	≥5	IF, OPWS, IDBJS >2, PDBJS =0,RDBJS

joint features. Both sequential and mixed compound MIFs are further categorized intoopen or closed type as given in the Tables 3 to 6 with some illustrative example.

The elementary and compound MIFs are classified based on the MIFs attributes defined above andits extraction procedure is defined in the below section.

Table 4: Classification of sequential compound MIFs (closed)

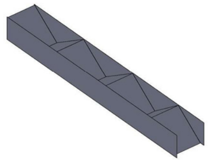
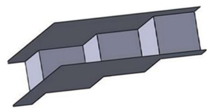
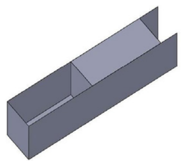
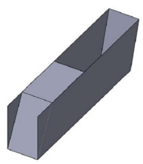
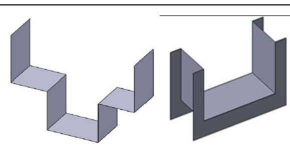
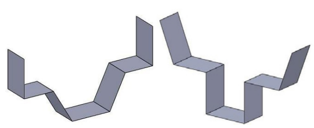
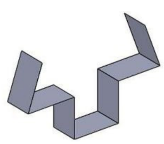
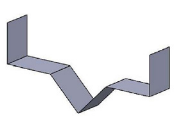
Interlockingfeature	*Illustrative example*	*Eulerangle(E)*	*Joint surface(JS)*	*Characteristics*
Multi scarf		180^0	≥ 5	IF, CWS, PDBJS>1, RDBJS
Multi step		180^0	≥ 5	IF, CWS, PDFJS >1, IDBJS=0
Compound plaintongue and groove		180^0	≥ 7	IF, CWS, PDBJS >2, IDBJS=0,RDBJS
Compound tapered tongueand groove		180^0	≥ 7	IF, CWS, IDBJS >2, PDBJS =1,RDBJS

Table 5: Classification of mixed compound MIFs (open)

Interlockingfeature	*Illustrative example*	*Eulerangle(E)*	*Joint surface(JS)*	*Characteristics*
Compound plain tongue and groove		180^0	≥ 7	IF, OPWS, PDBJS $\geq$2, IDBJS=0,SDBJS
Compound tapered tongue and groove		180^0	≥ 7	IF, OPWS, IDBJS $\geq$1, PDBJS$\geq$1,SDBJS
Compounddovetail		$>180^0$	≥ 7	IF, OPWS, IDBJS $\geq$1, PDBJS$\geq$1,SDBJS
Stepped tongueand groove		180^0	≥ 6	IF, OPWS, PDBJS$\geq$1, IDBJS=0, SDBJS

EXTRACTION OF MIFS

The extraction of MIFs is shown in Figure 4 as a flowchart and the detail procedures are defined in the below steps:

Step 1

The STEP file of the assembly CAD model is used in the visual studio platform along withopen cascade geometric library [18] to get the various geometric information. The root parts are determined by calculating the distance between the components between which the MIF exist using the extracted geometric information which is always zero.

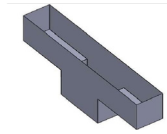
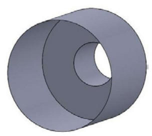
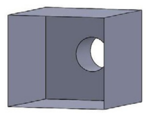
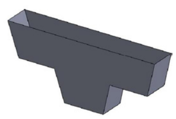
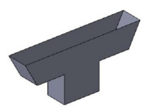
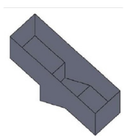
Step 2

In this step, the contact faces and joint surfaces involved at the joint location are determinedas shown in Figure 4 and detailed procedure for extraction are adopted by Das *et al*.[9]

Step 3

A joint feature is said to be an interlocking feature if it obeys the various conditions as defined in the section 3.2. After getting the interlocking feature, its various classification are done based on the various characteristic of joint surfaces like joint surface types, Euler angle of a joint feature [19] etc. to

Table 6: Classification of mixed compound MIFs (closed)

Interlocking feature	*Illustrative example*	*Eulerangle(E)*	*Joint surface(JS)*	*Characteristics*
Compound plain tongue and groove		180^0	≥9	IF, CWS, PDBJS >2, IDBJS=0, SDBJS
Compound cylindrical tongue and groove		180^0	≥5	IF, CWS, CS, PDFJS=1, PDBJS=0, SDBJS
Mixed cylindrical tongue and groove		180^0	≥7	IF, CWS, CS, PDBJS ≥2, IDBJS=0, SDBJS
Compound taperedtongue and groove		180^0	≥8	IF, CWS, IDBJS ≥2, PDBJS=1,SDBJS
Mixed planar tongue and groove		180^0	≥8	IF, CWS, IDBJS=1, PDBJS=2, SDBJS
Stepped tongue and groove		180^0	≥8	IF, CWS, IDBJS=0, PDBJS=2, SDBJS

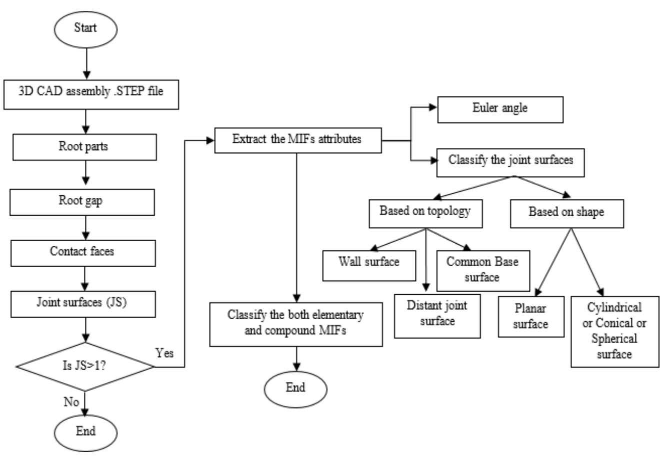


Figure 4: Flowchart for the extraction of MIF

capture both elementary and compound MIFs. The distant joint surfaces types like PDBJS, IDBJS, PDFJS, IDFJS, SDBJS and RDBJS are identified by offsetting the joint surface along the normal and the collision with the other surfaces are checked as described in section 3.2.

Step 4

The Euler angle is extracted using the pseudo code as given in the algorithm 1. The number of joint surface, its different types and Euler angle helps in extracting the both elementary and compound MIFs.

Algorithm1: Determination of Euler angle

```
Input: Parts Pi, Pj
Output: Euler angle (E)
1.  J← Jointsurface(Pi,Pj)
For each surface J ∈ (Pi,Pj)
Surface-list(SL)=surfaces ← J ∈ (Pi,Pj)
End for
For each surface Si  ∈ SL
For each surface Si+1  ∈ SL
Ang=FaceNormal(Si).Angle (FaceNormal(Si+1)
Angle-list(AL)=angles ← Ang (Si, Si+1)
End for
End for
If (AL.Size( )!=0)
11.  E ← AL[0]
For each angle Ang ∈ AL
If (Ang > E)
E= Ang
End if
End for
Return E
End if
```

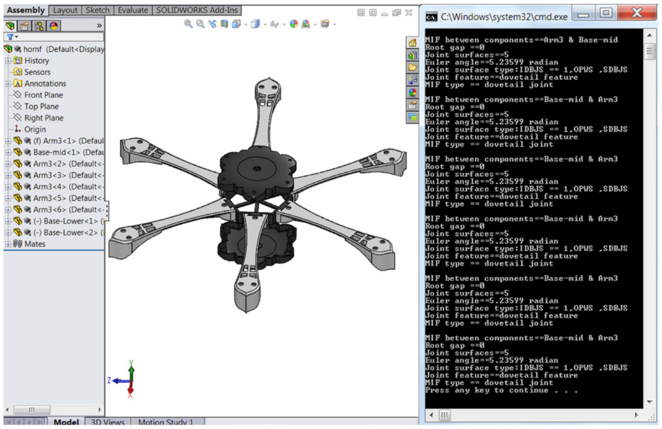


Figure 5 : Extraction of MIFs from hornet of an unmanned aerial vehicle (UAV)

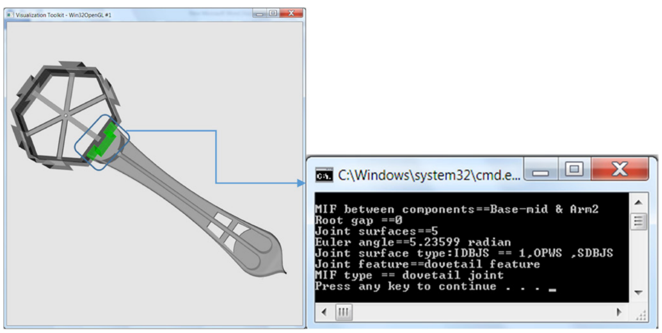


Figure 6 : An MIF between base-mid and arm2

Results of Implementation and its Details

An hornet of an unmanned aerial vehicle is used as an industrial CAD assembly model to validatethe proposed work. Open cascade 3D geometric kernel is used for extracting the mechanical interlocking features using Microsoft visual studio platform.

Figure 5 shows a hornet of an unmanned aerial vehicle which carry nine parts. The extracted variousMIFs types and its related attributes are shown in the Figure 5-6 and the adjacent text window displays the details about the various assembly feature information required for extracting the MIFs by the program.

Discussions

MIFs are used frequently in various lightweiht product due to its low cost as compared to riveting,welding and adhesive bonding, and also helpful for disassembly. In literature, various joining features have been extracted which are especially useful for adhesive bonding, riveting and welding process.[4,9] Although few studies about MIF are available,[8,9,12,14] however theyare limited to few elementary MIFs having one joint surfaces. Also compound MIFs[8,9] are rarely addressed. In most of the cases the MIFs are explicitly represented having little assembly feature information. The proposed method is able to identify mechanical interlocking features as characteristics composition of joint surfaces, the Euler angle by checking the existance ofinterlocking feature as shown in the result. Earlier in the literature, graph based technique[13,14] is used for the extraction of few elementary MIFs. This technique needs too much user input whichincreases the level of difficulty in complex assembly. Therefore, an extended algorithm isdeveloped to extract the MIFs.

The extracted MIFs conveys various information associated to mechanical interlocking joints. These interlocking feature information are helpful for deciding the process planner to select whether further any joining process is required or not depending upon the strength of the joint. So, this extraction of MIFs also helpful in assembly process planning of variant product design wherethere are variations in the liaison information due to change in the joint design.[20]

Conclusions and Future Work

An extended data structure for capturing the mechanical interlocking features (MIFs) from CAD has been developed in this research. The proposed algorithms are capable to capture bothelementary and compound MIFs. These algorithms relies on geometrical and topological information extracted from the root parts. A new classification of MIF is developed by capturing the existence of interlocking feature, Euler angle, and various joint surface types. In order to validate the proposed algorithm industrial CAD assembly model is used for implementation. Theproposed work can be extended to capture the MIFs involved between freeform form features.

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