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Abstract	This paper reports an algorithm to recognize and suppress interacting holes from CAD mesh models. The method includes hybrid mesh segmentation and template matching. The algorithm involves three steps, viz., preprocessing, hybrid mesh segmentation, and hole recognition and suppression. The hybrid approach is leveraged for interacting hole detection and parameterization along with hole chain. Finally, interacting holes are suppressed by the hole-filling algorithm. This algorithm has been implemented in VC++ and has been extensively tested on test cases extracted from various benchmarks, demonstrating the ability of the proposed algorithm to recognize and suppressed interactive holes, and it is found to be robust and consistent. The innovation lies in the automatic volumetric and nested interactions, multiple planer hole recognition and suppression without estimating curvature, and feature edge detection. The proposed technique is more effective than the existing approaches. Feature suppression finds application in mesh simplification.

Keywords (separated by '-')	CAD mesh model - Hybrid mesh segmentation - Interacting hole recognition - Hole suppression

Automatic Interacting Hole Suppression from CAD Mesh Models

Vaibhav J. Hase, Yogesh J. Bhalerao, Saurabh Verma and Vishnu D. Wakchaure

Abstract This paper reports an algorithm to recognize and suppress interacting holes from CAD mesh models. The method includes hybrid mesh segmentation and template matching. The algorithm involves three steps, viz., preprocessing, hybrid mesh segmentation, and hole recognition and suppression. The hybrid approach is leveraged for interacting hole detection and parameterization along with hole chain. Finally, interacting holes are suppressed by the hole-filling algorithm. This algorithm has been implemented in VC++ and has been extensively tested on test cases extracted from various benchmarks, demonstrating the ability of the proposed algorithm to recognize and suppressed interactive holes, and it is found to be robust and consistent. The innovation lies in the automatic volumetric and nested interactions, multiple planer hole recognition and suppression without estimating curvature, and feature edge detection. The proposed technique is more effective than the existing approaches. Feature suppression finds application in mesh simplification.

Keywords CAD mesh model · Hybrid mesh segmentation · Interacting hole recognition · Hole suppression

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1 Introduction

In many mechanical engineering parts, interacting holes constitute a significant percentage of features. Design engineers may be interested in modifying some hole parameters, whereas FEA engineer may prefer to suppress some holes to simplify the part model during Finite Element Analysis (FEA). The CAD mesh model can be simplified by suppressing the feature [1]. Hole suppression finds application in mesh simplification, dynamic simulation, manufacturing, and FEA.

From the last three decades, major research work has been carried out in extracting interacting features from a B-rep model [2]. Feature Recognition (FR) is the first step in feature suppression. However, recognizing and separating interacting feature is a difficult task. The existing approaches of Muraleedharan et al. [3], Adhikary and Gurumoorthy [4], and Attene et al. [5] fail to detect and separate interacting hole features, see Figs. 1 and 2.

The above observations inspire the research work reported in this paper. In this paper, a hole suppression framework is developed. This paper adopts a hybrid mesh segmentation approach for detecting interacting holes. The algorithm segments the CAD Mesh Models (CMM), generated from B-rep models using CAD software, into analytical surfaces like a plane, cylinder, cone, sphere, etc. After extraction of analytical surfaces, rule-based template matching approach is used for interacting hole recognition. Finally, the interacting holes are suppressed by hole-filling algorithm.

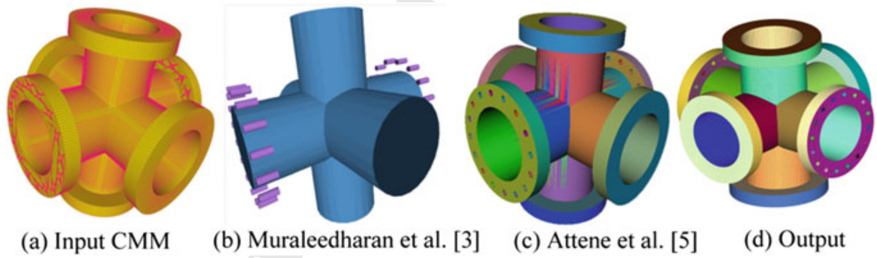

Fig. 1 Failure cases for intersecting volumetric feature

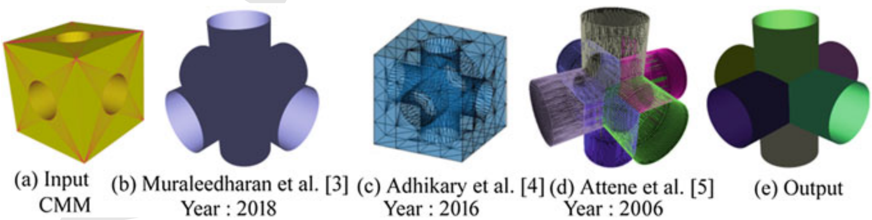

Fig. 2 Failure case of Muraleedharan et al. [3], Adhikary and Gurumoorthy [4], and Attene et al. [5]

1.1 Contributions

The main contributions of this research can be summarized as follows:

- Interacting hole recognition without curvature estimation.
- The FR algorithm does not need feature edges for extraction.
- The algorithm successfully recognized and suppressed interacting volumetric and nested features.

1.2 Outline

The rest of the paper is structured as follows: Sect. 2 provides a comprehensive review of relevant literature, and Sect. 3 illustrates a proposed methodology for interacting hole recognition and suppression. Section 4 defines hole feature taxonomy. Section 5 describes hole recognition. Section 6 illustrates hole suppression. Discussion based on results is provided in Sect. 7. Section 8 provides a case study to demonstrate interacting hole recognition and suppression. Section 9 presents conclusion and future scope.

2 Literature Review

Researchers intensively have proposed and implemented various manufacturing FR systems. A comprehensive review of various FR approach with their strengths and weaknesses is presented in the literature [6–8]. Exhaustive research has been carried out on feature recognition from the B-rep model. STL format is platform-independent [9] and is widely accepted and supported by most of the CAD software. As STL provides unique data translator utility [10], it will be more useful and practical to extract the features using STL format.

The edge-based scheme was proposed by Gao et al. [1], Mangan and Whitaker [11] and Razdan and Bae [12]. However, in CAD mesh model, the density of facets varies across the feature boundary. Hence, this approach cannot be used for recognizing complex interacting holes. Geometry-based FR approach partitions the object into meaningful surface primitives by utilizing geometric property like Gaussian curvature, mean curvature, dihedral angle, etc. for identifying feature lines [13]. However, feature line is sensitive to noise present in CMM. Most of the times, unable to detect or separate interacting features [3, 4].

Primitive fitting-based FR approach partitions the object into basic primitives based on primitive fitting clustering [5, 14, 15]. However, existing primitive extraction techniques rarely addressed complex interacting hole from CMM. Slice-based FR approach partitions the object by slicing. Adhikary and Gurumoorthy [4] pre-

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sented an algorithm to recognize free-form volumetric features without segmentation from CMM. Muraleedharan et al. [3] used a random cutting plane approach for feature extraction. However, the slice-based approach is unable to identify and separate interacting features [4]. STL models of mechanical parts have a diverse variety of triangles. Some researchers have taken efforts in estimating curvature along the boundary [12]. However, for recognizing cylinder or sphere, only curvature information (Gaussian curvature and absolute mean curvature) alone is not enough. An enormous amount of time is needed for discrete curvature calculation.

Further, Sunil and Pande [10] have attempted to recognize hole, dimple, flange, ridge, bend while Adhikary and Gurumoorthy [4] recognized and extracted free-form volumetric features. Muraleedharan et al. [3] identified holes, slots, pockets as well as interacting features CAD mesh model, but could not separate interacting features.

2.1 Literature Findings

The success of interacting hole suppression depends on the accuracy of interacting feature extraction. The above approaches are effective in recognition of simple features such as pockets, holes, slots, etc. To recognize the interacting features, the above approaches are not effective. So the hybrid mesh segmentation, which is a combination of vertex and facet-based region growing approach shall be used. From a literature review, it is evident that most of the researchers have focused on extracting limited and comparatively simple features. Recognition of complex and real-world features like interacting holes have not been addressed so far.

3 Methodology

The proposed algorithm involves three steps, viz., preprocessing, hybrid mesh segmentation, and interacting hole recognition and suppression. Figure 3 illustrates the overall strategy to extract interacting hole features from CMM which consists of the following steps: preprocessing, hybrid mesh segmentation, and interacting hole recognition and suppression.

3.1 Preprocessing

Input CAD Mesh Model
In this research work, we assume a valid STL model in ASCII or binary format as an input which is free from errors, hence, no need for model healing [10].

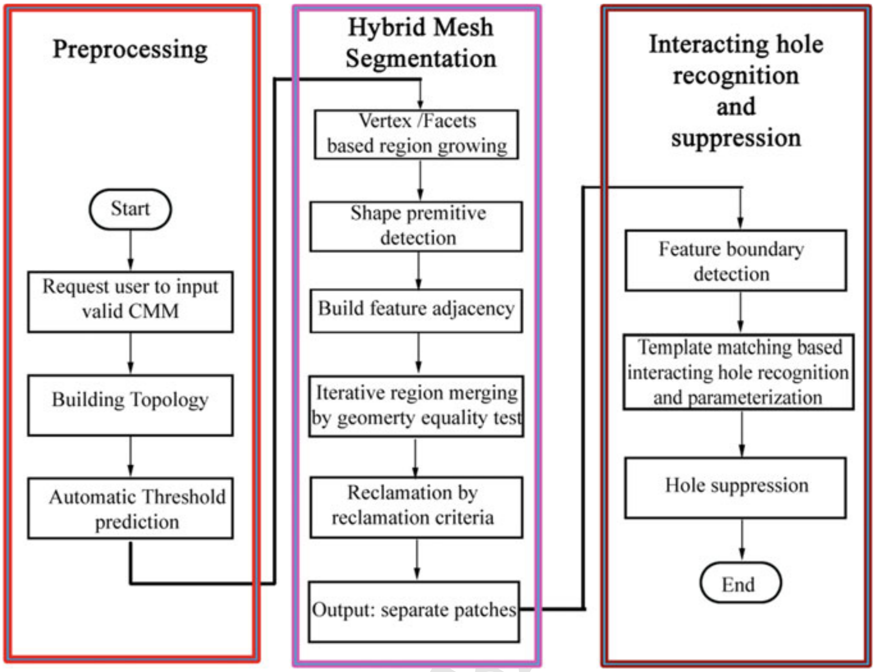


Fig. 3 Structure of the proposed methodology

Build Topology
The topology construction is crucial for feature extraction. First, build topology in the imported CAD mesh model and save faceted data in an appropriate data structure.

Automatic Threshold Prediction
The quality of hybrid mesh segmentation depends on area deviation factor (Threshold). The proposed algorithm adopts neural network-based intelligent threshold prediction to partition CMM. A detailed description of automating threshold prediction using the neural network is beyond the scope of this paper.

3.2 Hybrid Mesh Segmentation

Hybrid mesh segmentation uses region growing algorithms to clusters facets into groups. The approach is hybrid as we use the "Facet Area" property to group facets together, using a combination of vertex-based and facet-based region growing algorithms [16]. After segmentation, each facet group is subjected to several conformal tests, to identify the type of analytical surface it might be representing such as a cylin-

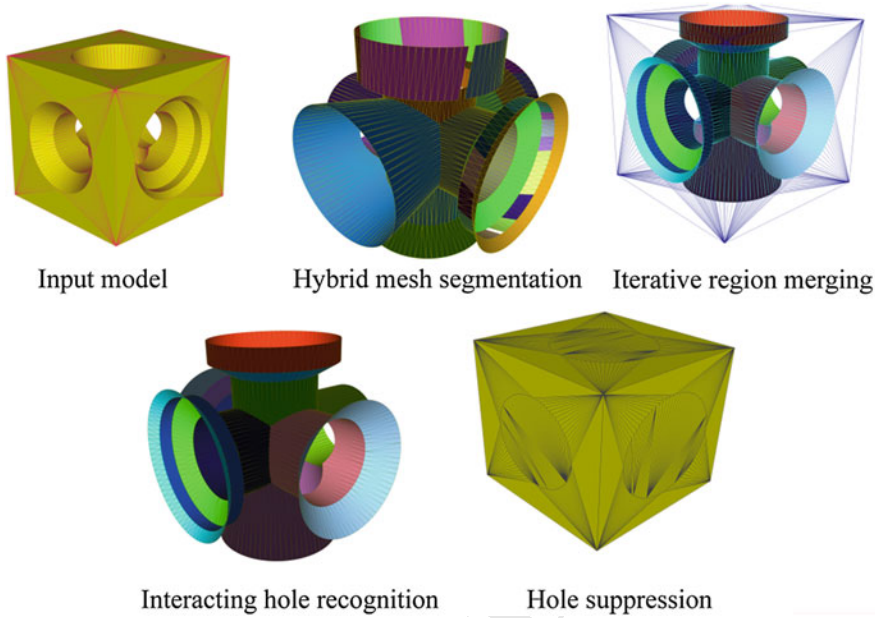


Fig. 4 Illustration of the proposed approach

der, cone, sphere, etc. [17]. Shape primitives detection gets the geometric parameters of the segmented mesh feature.

Iterative Region Merging

Hybrid mesh segmentation leads to oversegmentation. The oversegmented regions are need to be merged again to generate a single region. The proposed iterative region merging technique is based on geometry equality test. The iterative region merging technique repeatedly merged adjacent regions that have similar geometric property. After region merging, small cracks are observed close to the corner and at the region boundaries [18]. To make a watertight model, these uncollected facets are reclaimed into the surrounding identified regions (feature) based on reclamation criteria.

The developed hybrid mesh segmentation automatically segments CMM into meaningful primitives. The specific strategy for primitive detection is outlined in Fig. 4.

3.3 Interacting Holes Recognition and Suppression

The complex interacting holes and hole chains are detected by applying a set of rules based on adjacency information of the primitives detected in the previous step by template matching [16].

Finally, interacting holes are suppressed by hole deletion algorithm (see Sect. 6 for details).

4 Interacting Hole Taxonomy

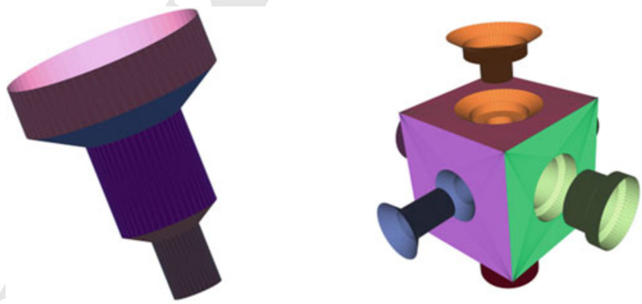
4.1 Hole Feature Interaction

In hole feature interaction, more than one feature interacts with each other. In this research work, the focus is on recognition and suppression of nested and volumetric interacting hole only. In volumetric feature interactions, the hole interacts with other features, sharing a common volume results in loss of concave edges [2]. In nested hole features, a set of holes shares the same axis. Figure 5a shows a hole chain which is a set of holes that are coaxial (sharing the same axis) and connected end to end. Figure 5b shows volumetric interactions wherein six different holes intersect.

5 Interacting Hole Recognition

Once the analytical surfaces are extracted, the next step is to classify these surfaces. This section deals with interacting hole recognition and suppression. The algorithm addresses interacting feature detection using rule-based, template matching-based approach. The overall procedure for interacting hole recognition is described below:

1. Find the set of faces that can form a hole (cylindrical and conical faces).
2. Formulate geometry and topology rules for hole recognition. Hole forming faces are as follows:



(a) Nested features interaction

(b) Volumetric interaction

Fig. 5 Hole feature interactions

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   a. Coaxial (sharing the same axis)
   b. Connected end to end
   c. Order of coaxial faces is such that the top face has a maximum radius and the bottom face has a minimum radius.

3. Identify and classify the hole feature.
4. Find hole end type (through or blind).
5. Find hole parameters.

A detailed description of interacting hole recognition is reported by Hase et al. [16].

6 Hole Suppression

The CAD mesh model can be simplified by suppressing holes. Hole suppression includes recognition, deletion, and then filling. Since hole deletion is very simple, we focus on hole filling. Two hole-filling methods based on hole supporting faces type have been developed.

6.1 Planer Hole-Filling Method

If the support face type of a hole is a planner, the following steps have been carried out.

Algorithm for Hole Filling

1. Get a hole from hole list for suppression.
2. Get the top end center and bottom end center of a hole to be suppressed.
3. Get the top and bottom bounding loops of a through hole or get the only top bounding loop of a blind hole.
4. Identifying the vertices that used for hole filling
   a. For each hole to be suppressed, its top end center and bottom end center information is needed.
   b. Get all top/bottom loop points of a hole to be suppressed. New facets are added between the top/bottom loop points and center position (top end center and bottom end center).
5. Add new facets
   a. Get all vertices from the top bounding loop and a bottom bounding loop of a hole to be suppressed. New facets are added between the top/bottom loop points and center position (top end center and bottom end center).
6. The hole which was suppressed, deleted from hole list.

7. Repeat Steps 2–6 for all recognized interacting holes.
8. Lastly, write/store/display a new STL file.

6.2 Curved Hole-Filling Method

If the support face type of a hole is curved, planer hole-filling method is not desirable, as new facets are not compatible with base curved support face. To fill the hole effectively, we adopted the hole-filling algorithm [1] based on normal estimation and Poisson equations [19].

7 Results and Discussion

The success of interacting hole suppression depends on the accuracy of interacting feature extraction. Figures 1 and 2 show failure test cases of the recent approach of Muraleedharan et al. [3], Adhikary and Gurumoorthy [4], and Attene et al. [5] where the topology of the interacting features gets disturbed due to the change in geometry. The proposed technique is independent of feature boundary detection. It results in successful extraction of intersecting multiple planer features recognition and suppression.

The proposed approach does not depend on attributes like curvature, minimum feature dimension [4], number of clusters [5], number of cutting planes [3], and thickness of the slice [20]. Extensive experiments on CMM show that the proposed technique is more effective than the existing approaches.

8 Implementation and Testing

The proposed algorithm has been implemented and tested on VC++. The developed system can accept any STL file generated by a CAD system like Autodesk^{TM} Inventor^{TM} 2018. The system successfully recognized and suppressed the interacting holes. Figure 6 illustrates interacting hole recognition and suppression for CMM. Figure 6a shows the input model, Fig. 6b illustrates the holes recognized, and the final hole suppression result is shown in Fig. 6c based on the planer hole-filling method.

a. Input model b. Hole recognition c. Output:Hole suppression

Fig. 6 An example of feature suppression based on planer hole-filling method

9 Conclusion

In this research, an elegant method has been proposed and implemented for interacting hole recognition from CMM using a hybrid region growing approach. A rule-based, template matching approach is used for hole recognition. Comparing with existing recent approaches of Muraleedharan et al. [3], Adhikary and Gurumoorthy [4] on benchmark test cases, the proposed technique successfully recognized interacting holes and their geometric parameters and suppressed them efficiently. The hole suppressor has demonstrated its ability in recognizing and suppressing interacting holes successfully on benchmark test cases. The proposed approach is simple, more general, and reliable.

The future work may be extended to detect hole interaction attributes needed for downstream applications.

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