Graph-based feature recognition for injection moulding based on a mid-surface approach

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GRAPH-BASED FEATURE RECOGNITION FOR INJECTION MOULDING BASED ON A MID-SURFACE APPROACH

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ABSTRACT

This paper presents a novel CAD feature recognition approach for thin-walled injection moulded and cast parts in which moulding features are recognised from a mid-surface abstraction of the part geometry. The motivation for the research has been to develop techniques to help designers of moulded parts to incorporate manufacturing considerations into their designs early in the design process. The main contribution of the research has been the development of an Attributed Mid-surface Adjacency Graph (AMAG) to represent the mid-surface topology and geometry, and a feature recognition methodology for moulding features. The conclusion of the research is that the mid-surface representation provides a better basis for feature recognition for moulded parts than a B-REP solid model. A demonstrator that is able to identify ribs, buttresses, bosses, holes and wall junctions has been developed using C++, with data exchange to the CAD system implemented using ISO 10303 STEP. The demonstrator uses a commercial algorithm (I-DEAS) to create the mid-surface representation, but the feature recognition approach is generic and could be applied to any mid-surface abstraction. The software has been tested on a range of simple moulded parts and found to give good results.

Keywords: Feature Recognition, mid-surface, STEP, injection-moulding

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1 INTRODUCTION

1.1 Motivation

The motivation for this research has been to help product designers to incorporate manufacturing considerations into their designs early in the design process. In the moulding industry it is common for product design and manufacture to be undertaken in separate companies and manufacturability is often not considered during the initial design phase, which often causes additional design iterations to achieve a manufacturable design.

Moulding design guidelines are available in design handbooks, and specify relatively simple geometric considerations to ensure that the part will fill and cool correctly. By following these basic guidelines the designer can achieve a more manufacturable design at the initial design phase, and should be able to reduce the number of iterations to optimise the design for manufacture.

The objective of this research has been to develop a feature recognition approach for moulded parts that could be implemented as part of a manufacturing advisor to identify features that may be expensive or difficult to manufacture early in the design process. It is intended that the feature recogniser would be used at a preliminary design stage to identify the important design features for moulding evaluation.

1.2 Research Approach

Feature recognition techniques for CAD have been widely researched in recent years, with most of the effort being focussed on feature recognition for machining applications. Feature recognition tools are important for the future development of Computer Aided Design because they provide better support for design for function or manufacturability than is possible in current systems. However, feature recognition has proved to be problematic to implement because it is difficult to develop a robust system that can be applied to a wide range of geometry types. One of the major problems in feature recognition is the difficulty of recognising feature interactions where several simple features interact to form a more complicated feature.[1]

The objective of this research has been to develop a novel feature recognition approach for thin walled parts, to support design for manufacture for injection moulding and casting processes. It has been observed in the literature that there has been very limited previous research into feature recognition for these types of parts, and existing feature recognition techniques are not well suited to moulded parts. The technique that has been developed uses a mid-surface abstraction from a CAD solid model of the part as the basis for feature recognition, and recognises shape characteristics that are important for mouldability evaluation. Design for manufacturability is particularly important for moulded parts because the constraints of the manufacturing process must be taken into account by the product designer in order to achieve a manufacturable design.

The paper is organised as follows: Section 2 of the paper is a review of the relevant literature, section 3 presents the graph structure that is used to capture the design topology and geometry, and section 4 presents the feature recognition methodology. The implementation of a demonstrator for the methodology is presented in section 5, with two case studies, and finally in section 6 the advantages and limitations of the approach are discussed, conclusions are drawn and future work defined.

2 LITERATURE REVIEW

Design for manufacture for moulded parts is particularly important because the cost and quality of parts manufactured using these processes is highly geometry dependent. Furthermore for these mass production processes a small change in manufacturing cost can have a major effect on the economics of a particular design.

A number of research projects have developed design for moulding tools using analytical methods or design by features approaches, but there does not appear to be significant research focussed on feature recognition for moulded parts. Knight, et al [2] developed a design for casting system aimed at the manufacturing engineer in which the user builds a simplified representation of the part using a library of standard shapes (for example filleted L sections, T and cross junctions, bars wedges and plates). The manufacturability of the part is then evaluated by combining the known behaviour of the simple shapes. Rosen, et al [3] developed a design for manufacturability tool for thin walled mechanical components based on a non-manifold geometry model that allowed them to evaluate tooling costs for injection moulding and die-casting. Their research used a design by features approach, and they did not attempt to integrate their tools with a standard CAD solid modeller.

Lu, et al [4] used a voxel based approach to identify the geometry characteristics of a part (e.g. thick areas for hot-spot detection) for casting evaluation. In their approach a 3D model of the part is subdivided into voxels (small cuboid volumes) and then the distance from every voxel to the part boundary is measured. Using this approach they are able to find variations in material thickness and identify potential hot spots in the casting. They assert that this approach is much more flexible than standard feature recognition techniques. Ravi and Srinivasan [5] also presented a novel method for the identification of hot spots in complex 3D castings based on analysing the geometric shape of the part. In their research 2D slices were taken through the part in orthogonal directions and the variations in thickness across each slice are plotted and combined to find heavy areas.

There has been a great deal of research into feature recognition for machined parts and graph based methods have been commonly used for feature recognition from CAD solid models. In graph based feature recognition the topology of the solid model is captured in a face-edge graph, and the graph is parsed to recognise high level design features. Joshi and Chang [6] developed a graph-based approach to feature recognition of machined features from a 3D solid model. Their approach uses an attributed adjacency graph (AAG) to represent the part shape, where the adjacency matrix incorporates an attribute to specify whether an edge is concave or convex. Features are recognised by traversing the AAG and searching for sub-graphs corresponding to predefined features.

More recently Gao and Shah [7] have further developed this approach to the concept of an extended attributed adjacency graph (EAAG) that supports several face and edge attributes. Their graph representation carries several geometric attributes associated with the nodes and arcs of the graph, and offers an improved ability to recognise interacting features. Both these techniques are applicable to manifold B-rep solid models.

Mid-surfaces have been investigated extensively for their ability to simplify geometry models for finite element analysis, and they have been applied to a lesser extent to casting and moulding research. Donaghy, Armstrong and Price [8], and Sheehy, et al [9] use the medial axis transform for dimensional reduction in finite element modelling. They search for geometry entities in the model that can be simplified by reducing their dimensionality; for example a long slender face may be reduced to a beam. Their work focuses on simplifying the part geometry through dimensional reduction, but it does not attempt to recognise design or manufacturing features from the geometry model. One technique that can be used to create a mid-surface from a solid model is the medial-surface transform. The medial-surface transform is the three dimensional equivalent of the medial-axis transform that was first proposed by Blum [10]. Algorithms that can calculate the medial- axis transform are now well developed, but a robust algorithm that can calculate the medial surface of any three-dimensional object is still the subject of research.

Several commercial tools offer working implementations of medial-surface or mid-surface algorithms. The medial surface transform from FEGS Ltd calculates the locus of an inscribed maximal sphere as it rolls around the interior of the part [11]. The mid-surface function implemented in EDS I-DEAS NX Series [12] selects pairs of faces from the solid part and calculates the mid-surface between each face pair; it then uses surface extension and trim operations to generate a mid-surface of the complete part.

3 METHODOLOGY

In this project a novel feature recognition approach for thin walled moulded parts has been developed which allows features to be recognised from the mid-surface abstraction of a 3D CAD solid model. It has been observed from the literature that the majority of previous feature recognition research has focussed on recognising machining features from fairly simple prismatic shaped parts, and follows a subtractive approach that reflects the material removal in a physical machining process. Feature recognition for moulded parts requires a significantly different approach because moulded parts often have complex freeform faces, and the manufacturing process is not sequential as it is for machining. The feature recognition methodology that has been developed in this research uses a mid-surface abstraction from the part geometry as the basis for feature recognition, and the feature recogniser parses a mid-surface geometry graph to identify moulding features. Using an abstraction from the CAD geometry as the basis for feature recognition means that the features that are recognised are not directly associated with the original CAD geometry; however associativity to the CAD geometry can be maintained by storing the surface pairing information that is generated during the mid-surface creation. It should be noted that this solution is not generic, and would be dependent on the algorithm that had been used to generate the mid-surface geometry.

3.1 Moulding Features

Moulding processes make significant demands on the product designer because, despite their flexibility to manufacture complex shapes, they also require that parts be designed with regard to the constraints of the manufacturing process. A review of design handbooks has shown that the features of interest for moulding evaluation are wall intersections, protuberances and wall thicknesses on the designed part. [13,14]

For plastic parts any increase in wall thickness will significantly increase the cooling time of each part that is manufactured, and thick walls may affect the part quality. The designer therefore needs to make use of ribs and other features to provide strength and rigidity on the part without increasing the wall thickness. The intersections between stiffeners and external walls need to be designed to allow the plastic to flow easily between walls, and to cool evenly without causing warping or sinking.

3.2 Mid-surface representation

The mid-surface of a part is a dimensionally reduced representation in which the part walls are modelled as surfaces with zero thickness. It can be visualised as the locus of the centre of a maximal sphere rolling around the interior of the part. For thin walled parts the mid-surface representation offers a simplified geometry and topology representation, which retains the main design characteristics of the original part. [9] Mid-surface representations have been widely used in engineering analysis for thin walled moulded parts. For example in finite element analysis it is common to use a mid-surface abstraction of a thin walled part to reduce the computational cost of performing the finite element analysis and for flow analysis in injection moulding several simulation tools use a mid-surface abstraction for mould filling simulations. [8]

A mid-surface representation is able to accurately model the shape of cast and injection moulded parts because these manufacturing processes require that parts be designed with thin, and relatively constant wall thickness. The mid-surface representation has a significant benefit over the true CAD geometry for moulded parts because the wall intersections that are important for mouldability analysis are directly accessible from the mid-surface without the need to process complex feature interactions.

In this research the EDS I-DEAS NX mid-surfacing function has been selected because of its availability and relatively robust functionality. However mid-surfacing tools in other CAE systems (Pro/ Engineer, MSC/ PATRAN and others) can produce similar results. The quality of the mid-surface that can be generated by this and other mid-surface algorithms is largely dependent of the shape characteristics of the geometry that is presented to them.

An evaluation of the use of mid-surfaces to represent the shape of moulded parts has been undertaken and published separately as part of the development of a knowledge based manufacturing advisor for CAD [15]. The I-DEAS mid-surface function was evaluated and found to be able to automatically generate accurate mid-surfaces for a range of parts, but in order to achieve good results it was important for the wall thickness to be small relative to the size of the features on the part and to be relatively constant. Small features and fillets may be lost during mid-surface generation, but these small features are of less importance for manufacturability evaluation than the overall layout and proportions of walls and junctions.

3.3 Data Exchange

In order to achieve a generic basis for the feature recognition process the data exchange with the CAD system has been implemented using a STEP AP203 physical file. The mid-surface representation is essentially a collection of faces that are connected along shared edges. The mid-surface is a non-manifold geometry because it contains edges that are adjacent to two, three or more faces but it is only a limited subset of a non-manifold geometry because it contains only faces bounded by edges with no dangling edges or closed volumes

The mid-surface geometry has been exported from I-DEAS using the AP203 Manifold Surfaces with Topology representation, which although it is a manifold surface representation, does provide some support for non-manifold geometries through its support for multiple open_shell entities in a model. There is some ambiguity in the implementation of the STEP AP203 standard by different software vendors and in the I-DEAS implementation the concept of multiply connected faces is fully supported in the AP203 output.

3.4 Geometry Representation

Graph based methods have commonly been used for feature recognition from CAD solid models for machining applications [6][7]. In a graph based approach a separate data structure is built to represent the geometry and facilitate the search for features. Features are recognised from the geometry graph by parsing the graph or matching sub-graphs to predefined templates. For example in the face adjacency graph (FAG) described by Shah, and Mantyla [1] the nodes of the graph represent the faces of the object, and the arcs represent the connectivity (edges) between those faces. The FAG is suitable for representing the topology of manifold solid models, but it is not suitable for representing non-manifold geometries because the formulation of the graph requires that each edge must connect exactly two faces, which is not true for non-manifold geometries such as the mid-surface.

An example is shown in Figure 1 where a simple T-shaped part has been modelled as a B-rep solid model. The model has 10 faces and 24 edges and the associated FAG graph has ten nodes representing the faces of the part, and 24 arcs representing the edges connecting the faces. The feature recognition techniques that have been developed for this type of geometry graph classify edges as concave, convex or smooth, and match patterns of concave/ convex edges to recognise features [1]. This approach is suited to prismatic parts, but the features that are of interest for moulding evaluation are difficult to identify by this means. For example to recognise the T-shaped feature in figure 1 the interaction between two adjacent "step" features and the base part would need to be recognised.

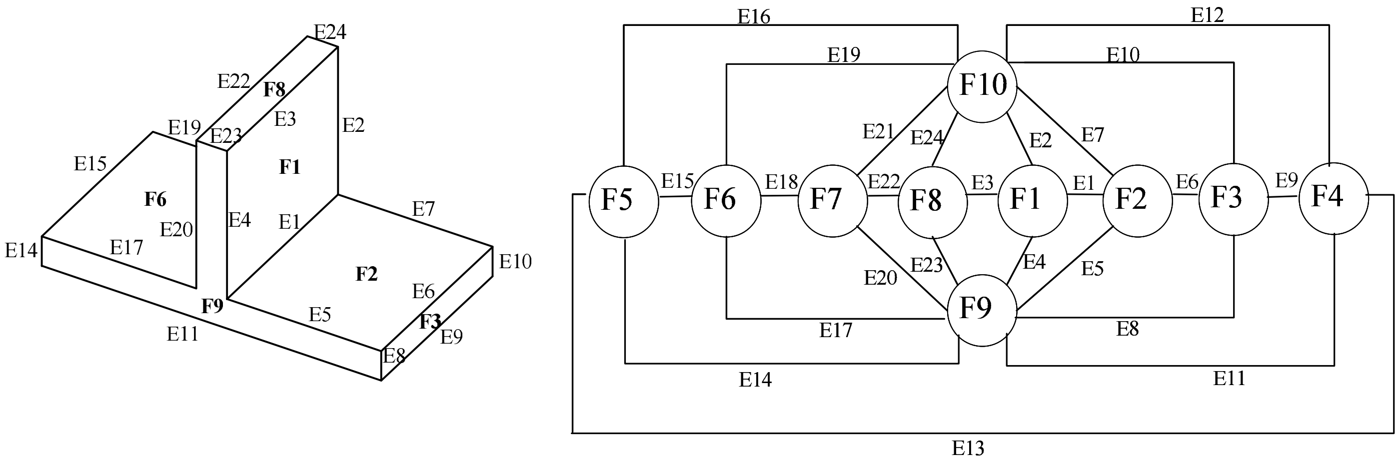
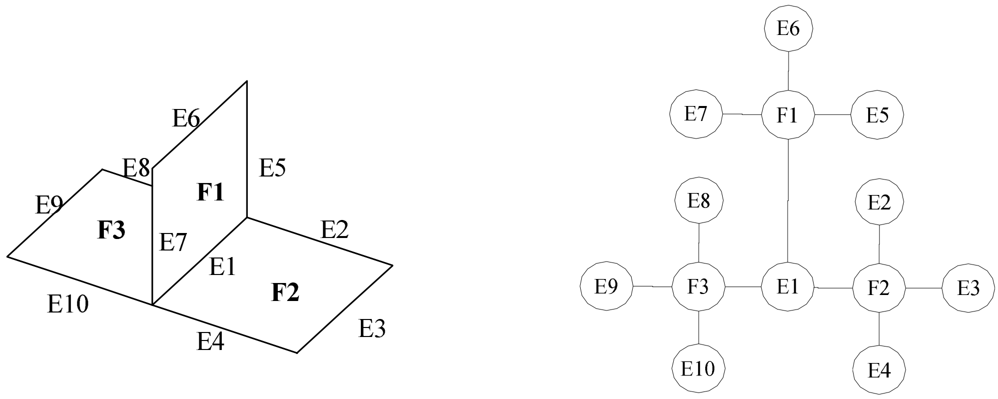


Figure 1. Face adjacency graph for a simple T- shaped part.

In a mid-surface model the faces may be connected in any combination, without the limitations defined for a manifold solid model. The mid-surface model is subset of a non-manifold geometry in which two-dimensional entities (faces) are bounded by edges, and may be multiply connected to other faces along their edges. A Mid-surface Adjacency Graph (MAG) has been developed to represent the mid-surface model topology for feature recognition. The standard FAG cannot be used for the mid-surface model because an edge can be adjacent to two, three or more faces, and this relationship cannot be represented on an FAG. The MAG therefore represents both the faces and edges of the model as nodes on the graph, with the graph arcs representing the connectivity between those faces and edges.

Figure 2 (a) shows the mid-surface representation for the T-shaped part, and contains three faces representing the three walls in the part, and 10 edges bounding those faces. The MAG shown in figure 2 (b) has 13 nodes representing the geometry entities in the model (three faces, and 10 edges), and 12 arcs representing the connectivity between the entities. By observation from the MAG shown in figure 2b it is clear that edge *E1* represents a junction between three faces because it is connected to faces *F1*, *F2,* and *F3*. This property provides much more direct access to wall relationships than is available from the original CAD geometry and the FAG.



(a) **(b)**

Figure 2 mid-surface representation and its associated mid-surface adjacency graph.

The MAG alone does not contain sufficient information to fully represent the mid-surface topology so it has been augmented to additionally capture important geometric attributes. An attributed MAG (AMAG) has therefore been developed that additionally identifies whether edges that belong to internal or external edge loops, and identifies edges that are reused in edge loops (for example where an edge extends to the interior of face).

An object oriented mid-surface model has been developed to store the mid-surface geometry and topology. The mid-surface model is an intermediate data structure that captures the mid-surface information generated by the CAD system, and is used to generate the AMAG. The mid-surface model stores the topology of the imported mid-surfaces along with selected geometric attributes such as face normal directions, curve characteristics, and surface types. The object model for the mid-surface model is shown in figure 3 below.

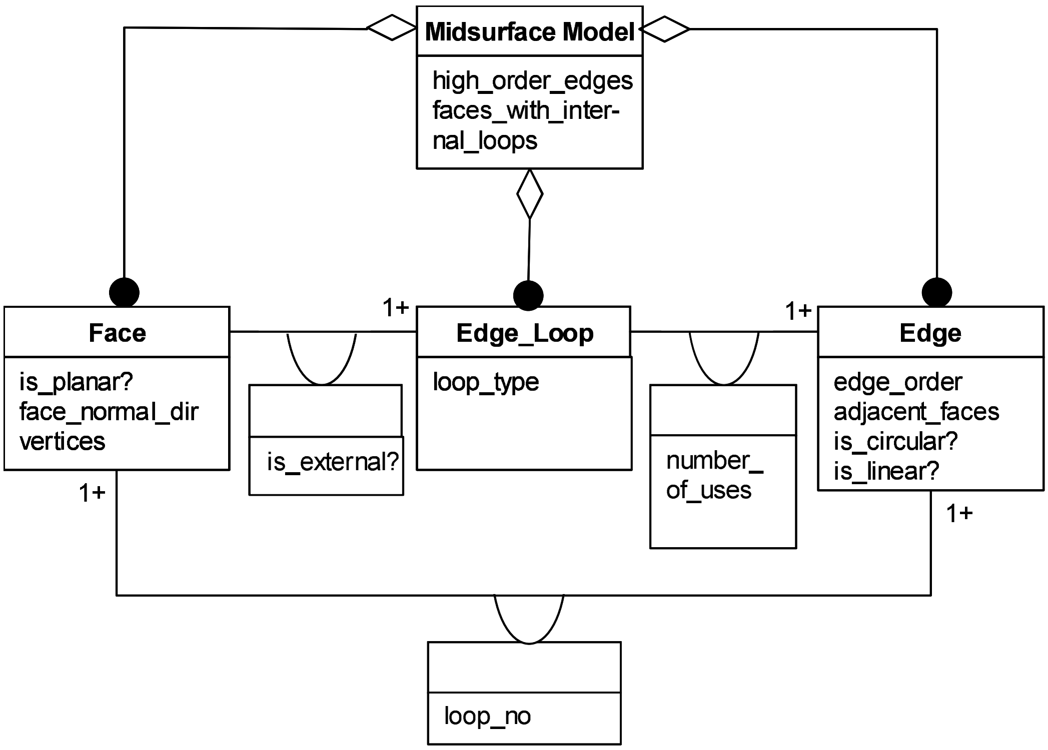


Figure 3. Object model representation of mid-surface model

4 FEATURE RECOGNITION PROCESS

The feature recogniser that has been developed parses the AMAG described in section 3 and searches for known patterns that identify moulding features. A face-edge adjacency matrix is constructed to represent the AMAG, and an algorithmic approach is used to perform the feature recognition. Further geometric evaluation is performed using the mid-surface model.

4.1 Feature Classification

For manufacturability evaluation it is necessary to recognise high-level design features that will impact the manufacturability of the part. The types of features that are important for moulded parts are ribs, bosses, buttresses, and holes as well as feature relationships such as the junctions between walls. In moulding processes these features considered with the wall thickness have a major impact on the manufacturability of the part, and its cost and quality.

Each face in the mid-surface model represents a wall or wall segment in the part, and can be considered to be a manufacturing feature. The feature recognition problem is therefore to identify the sub-types of wall features in a part, and to find the intersections and junctions between those features. The features that need to be recognised from the mid-surface model have been categorised into three main types – face features, junction features, and stiffener features. These feature types are shown in Table 1, along with their effect on manufacturability.

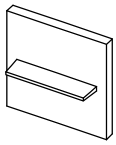
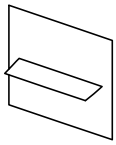
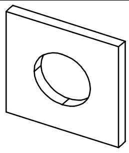
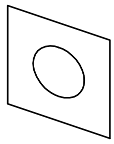
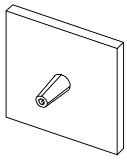
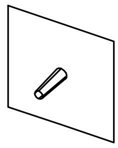
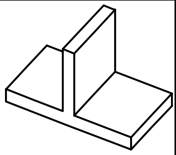
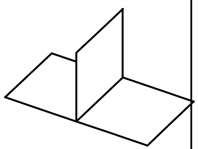
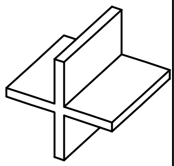
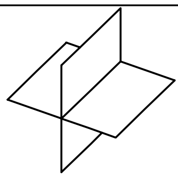
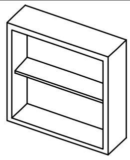
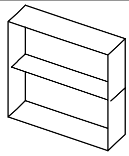
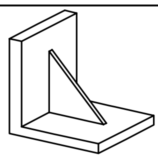
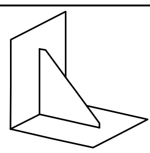
Feature Class	Feature Type	Solid Model	Mid-surface Model	Manufacturability Impact
Face Feature	**Fin**			Fins may affect the external wall quality at the attachment. Careful design of fin proportions can minimise problems [13]
	Hole			Small holes may be more economic to drill,may cause weld lines[13]
	Boss			The proportions of bosses are important for main wall quality. Supporting ribs may be required to react lateral forces [14]
Junction Features	**T-Junction**			High order junctions may cause sink marks or warping. Wall thickness proportions and angles are important [13]
	X-Junction			High order junctions may cause sink marks and warping. Where possible should be redesigned as two staggered junctions [13]
Stiffener Features	**Rib**			Ribs may cause warping or appearance problems – rib proportions are important[13]
	Buttress			Buttresses may cause warping or appearance problems – proportions are important[13]

Table 1 Summary of feature types and graph characteristics (Reproduced by Permission of ASME)

The features can be recognised from their AMAG characteristics. Table 2. shows the mid-surface geometry and associated graph segment for the feature classes from table 1. The graph segments are shown with two attributes associated with each graph arc. The first attribute identifies whether the edge is connected to an internal or external edge loop within the face (0 for external and 1 for internal), and the second attribute identifies how many times the edge is used in the face (for example if an edge extends into the interior of a face it will be used twice in the edge loop for that face). For clarity the edge-loop identifiers on not shown in this figure.

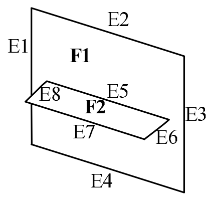
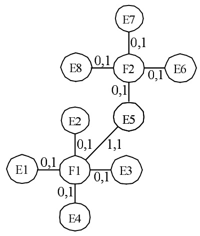
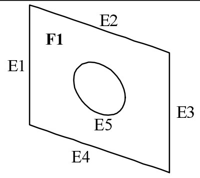
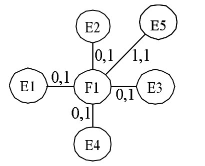
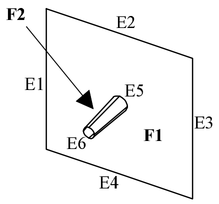
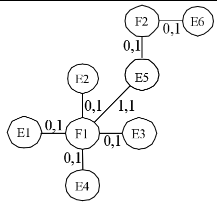
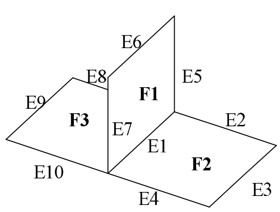
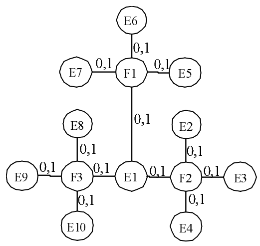
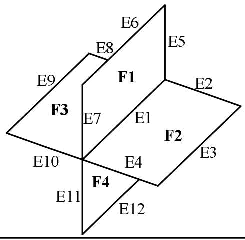
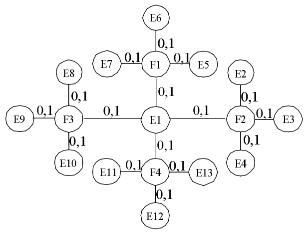
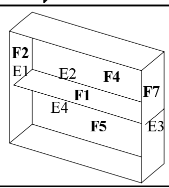
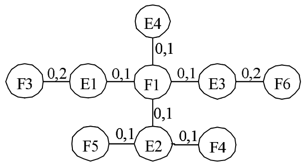
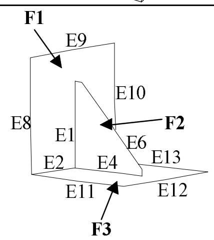
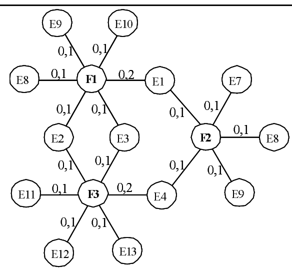
Feature Class	Feature Type	Mid-surface geometry	Attributed Mid-surface Adjacency Graph	Graph Characteristics
Face Feature	**Fin**			A **fin feature** is recognised by the existence of a single internal edge that is connected to one edge of another face. The connected face must be otherwise unconnected (e.g. F2).
	Hole			A **hole feature** is recognised by the existence of an internal edge loop that is not connected to any other faces (e.g E5).
	Boss			A **boss feature** is recognised by an internal edge that is connected to a cylindrical or conical face by a circular edge.
Junction Features	**T-Junction**			A **T-junction feature** is recognised by an edge that is used by three faces (e.g. E1). An attribute representing the angles between the faces is also required to complete the feature recognition.
	X-Junction			An **X-junction feature** is recognised as an edge that connected to four adjacent faces. The angles between the face normals should be 90º to fully identify the X-junction.
Stiffener Features	**Rib**			A **rib feature** is recognised as a face with three or more adjacent edges connected at order 3 or higher and at least one unconnected edge. (e.g. F1).
	Buttress			A **buttress feature** is recognised as a face with two adjacent edges connected at order 3 or higher, and the remaining edges unconnected (e.g. E1 and E4)

Table 2 – Attributed Mid-surface Adjacency Graphs (AMAGs) for simple feature types

4.2 Feature Recognition

The feature recognition process is undertaken in three stages – firstly the mid-surface model is parsed to construct a face-edge adjacency matrix that represents the AMAG, then the feature recognition algorithms perform an initial feature identification based on topology, and finally the feature recognition is completed by performing geometry checks using the mid-surface model.

4.2.1 Face-Edge Adjacency Matrix

Adjacency matrices can be used to represent graph structures for feature recognition from a CAD solid model [1]. The FAG for a manifold solid model with n faces can be represented using an $n \times n$ face adjacency matrix, where a 1 in the matrix indicates the existence of an edge connecting the two faces, and a 0 indicates that two faces are not connected. The face adjacency matrix assumes that each edge in the model connects exactly two faces (a requirement for a manifold solid).

In the AMAG both faces and edges are represented as nodes in the graph, so a *face-edge* adjacency matrix is required to represent the geometry graph. The complete *face-edge* adjacency matrix for a model with m edges and n faces is an $(n+m) \times (n+m)$ *matrix*, but since only the face to edge connectivity is required only an $n \times m$ a subset of the matrix is required to capture the graph topology.

The *face-edge* adjacency matrix for the T-shaped part in figure 2a is the 3 x 10 matrix shown in figure 4, which is a subset of the complete *face-edge* adjacency matrix for the T-shaped part, that would be a 13 x 13 matrix. The values in the matrix m represent the connectivity between the faces and edges in the graph, where m_{ij} = *1* means that edge *j* is a bounding edge of face *i*, and m_{ij} = 0 means that edge *j* is not a bounding edge of face *i*.

$$
\begin{array}{c c}
 & \begin{array}{cccccccccc} E1 & E2 & E3 & E4 & E5 & E6 & E7 & E8 & E9 & E10 \end{array} \\
\begin{array}{c} F1 \\ F2 \\ F3 \end{array} & \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix}
\end{array}
$$

Figure 4. Face-Edge adjacency matrix, for T-shaped part

4.2.2 Face-Edge Adjacency Matrix Attributes

The *face-edge* adjacency matrix that is constructed in the feature recogniser stores three attributes for each face-edge adjacency forming a three dimensional matrix. The attributes that are stored are:

- the edge loop id number
- an identifier for the edge loop within the current face (for outer edge loop = 0)
- the number of times the edge is used by the face,

Once the adjacency matrix has been constructed it can be used to evaluate some further properties of the model. The order of each edge (i.e. the number of faces connected to the edge) can be obtained by counting the number of non-zero values in an edge column. The number of edge loops in a face can be obtained by counting the number of edge loops in a face row. These properties of the adjacency matrix are used to aid the feature recognition process.

4.2.3 Algorithms for feature recognition

4.2.3.1 Face Features

Face features are classified as features that are attached to the interior of a face in the part and may be holes, slots, fins, bosses or other attached features. The graph segment for a simple hole feature can be seen in section 4.1, Table 2. The face feature recognition algorithm is able to identify features that are completely enclosed within a single face of the part, but future work will extend the approach to identify features that are connected to both the boundary and interior of a face. Once the existence of a face feature has been identified, further geometric processing is required to recognise the type of face feature. For example a boss is recognised by a circular edge connecting a face feature to an internal edge loop on its parent face. The algorithm for face feature recognition is shown below, and takes as its input a list of faces with internal edge loops, and a list of the orders of each edge, both of which can be obtained from the adjacency matrix.

```
Algorithm  Find_Face_Features
     begin
(1)        Let FACES-WITH-INTERNAL-LOOPS be a list of all the faces in the
           model with internal edge loops
(2)        for each face f in FACES-WITH-INTERNAL-LOOPS do
(3)             for each internal loop l in f do
(4)                  ATT-FACES[l] = {} ;list of attached faces for each loop
(5)                  for each edge e in l do
(6)                       if EDGE-ORDERS[e] > 1 then
(7)                            Add adjacent faces to ATT-FACES[l]
(8)                  end
(9)             end
(10)       if ATT-FACES[l] = {} then
(11)            Edge-loop l connects to a HOLE
(12)       else if  length (ATT-FACES[l] = 1) & (edge type = POLYLINE) then
(13)            edge-loop l connects to a FIN
(14)       else if  (edge type = CIRC_ARC) & (face type = CYL or CONICAL) then
(15)            edge-loop l connects to a BOSS
(16)       else
(17)            edge-loop l connects to an  UNKNOWN-FACE-FEATURE with
                attached faces ATT-FACES[l]
(18)       end
```

```
end
```

4.2.3.2 Stiffener features

Stiffener features such as ribs and buttresses are structural features that are used to add strength to the part. The stiffener features are identified from the AMAG as faces with specific patterns of adjacent high order and unconnected edges. The graph segment for a simple stiffener feature can be seen in section 4.1, Table 2. The order of each edge can be obtained from the attributed adjacency matrix and the ordered list of edges in each edge loop is read from the mid-surface model.

```
Algorithm Find_Stiffeners
    begin
        for each face f do
          let oel be the identifier for the outer edge loop
          let LIST-OF-EDGES[oel] be an ordered list of the edges in oel
          NO-OF-ADJ-HO-EDGES = 0 ; adjacent high-order edges
          MAX-ADJ-HO-EDGES = 0; max no. of adjacent high-order edges in loop
          NO-OF-UNCON-EDGES = 0 ; unconnected edges
          for each edge e in LIST-OF-EDGES[oel] do
             if EDGE-ORDERS[e] >= 3 then
                NO-OF-ADJ-HO-EDGES = NO-OF-ADJ-HO-EDGES + 1
                if NO-OF-ADJ-HO-EDGES > MAX-ADJ-HO-EDGES then
                      MAX-ADJ-HO-EDGES = NO-OF-ADJ-HO-EDGES
                end
             else if EDGE-ORDERS[e] = 2 then
                NO-OF-ADJ-HO-EDGES = 0
             else if EDGE-ORDERS[e] =1 then
                NO-OF-UNCON-EDGES = NO-OF-UNCON-EDGES+ 1
                NO-OF-ADJ-HO-EDGES = 0
             end
          end
          if (MAX-ADJ-HO-EDGES = 2) & (NO-OF-UNCON-EDGES >=1) then
                face f is a buttress feature
          else if (MAX-ADJ-HO-EDGES >= 3) & (NO-OF-UNCON-EDGES >=1) then
                face f is a rib feature
          end
    end
```

4.2.4 Geometric Checking

The topological feature identification described above is supported by further geometric checks to validate and categorise the features that have been recognised. The geometric checks that are performed for the various feature classes are summarised below.

4.2.4.1 Face Features

Face features are initially identified from their face-edge connectivity, then the geometric characteristics of the feature's edges and faces are used to complete the feature recognition. For example a boss is recognised as cylindrical or conical face feature that is connected to its parent face by a circular arc. A linear fin feature is recognised as a planar face feature that is connected to its parent face by a linear edge.

4.2.4.2 Junction Features

Junction features are the building blocks for stiffener features. The order of a junction can be recognised from the part topology, but the angles between the faces at the junction are also important for moulding features. The angle between faces is calculated by computing the surface normal for each face, and then calculating the angle between the surface normals. In the current implementation the angle checks are only performed for planar faces.

4.2.4.3 Stiffener Features

Stiffener features are primarily identified topologically, but the angles between faces of high order junctions are used to validate the stiffener features.

5 IMPLEMENTATION

A demonstrator for the feature recogniser has been developed and tested for a range of simple parts. Figure 5 shows a flow chart of the feature recognition process. The input to the process is a B-Rep solid model of the part generated using a CAD solid modeller. Step 1 is the pre-processing step in which a mid-surface representation of the part is generated from solid model and exported as a STEP AP203 file. In step 2. the mid-surface geometry is read from the STEP file and used to populate the mid-surface model. In Step 3 the attributed adjacency matrix is constructed from the mid-surface model, and in Step 4 the feature recognition is performed. The results are presented to the user graphically as a coloured STEP part 21 file that can be read into their CAD system, and a text report on the screen.

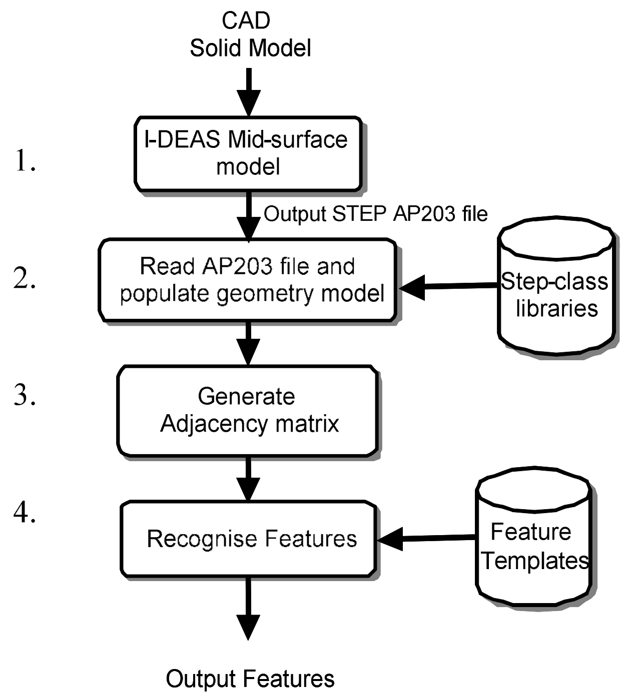


Figure 5 Flow chart of feature recognition process

The demonstrator has been implemented in GNU C++ on the Cygwin platform, and using the data modelling standard STEP for data exchange. The pre-processing step that generates the mid-surface model has been implemented using EDS I-DEAS NX Series [12], but any alternative mid-surfacing tool could be substituted as long as it is able to output the mid-surface geometry in the required format (STEP AP203 Part 21 file, Manifold Surfaces with Topology representation). The mid-surface model and feature recognition algorithms have been developed as a standalone application using object oriented C++, with the STEP Class Libraries from NIST (National Institute of Standards and Technology) [16] used to develop the STEP interface.

The STEP AP203 file is parsed to extract topology and geometry information and populate the mid-surface model. The STEP geometry representation has an eight-level hierarchy comprising open_shell, shell_based_surface_model, face_surface, face_bound, edge_loop, oriented_edge, edge_curve and vertex_point entities. In the mid-surface model the representation is simplified to a four-level hierarchy (midsurface_model, face, edge_loop, edge) with additional information captured as attributes of the geometry entities. The attributed adjacency matrix that represents the mid-surface adjacency graph is then constructed from the mid-surface model and stored as a three dimensional array of faces, edges, and attributes. The feature recognition algorithms make use of the adjacency matrix and mid-surface model when recognising features.

The STEP part 21 files require a small amount of pre-processing to overcome limitations in the NIST STEP toolkit. This pre-processing is performed automatically using an awk script, and the whole feature recognition process is initiated through a UNIX shell script.

5.1 Case Study 1– Simple Plastic Part

The feature recognition process has been tested for a range of moulded parts. The first case study is an idealised part with some common injection moulding features, which has been used to demonstrate the basic principles of the feature recogniser. Figure 6 shows the CAD solid model and mid-surface abstraction for the part. It can be clearly seen that the mid-surface model maintains the important geometric characteristics of the part, including the main part wall, and attached features.

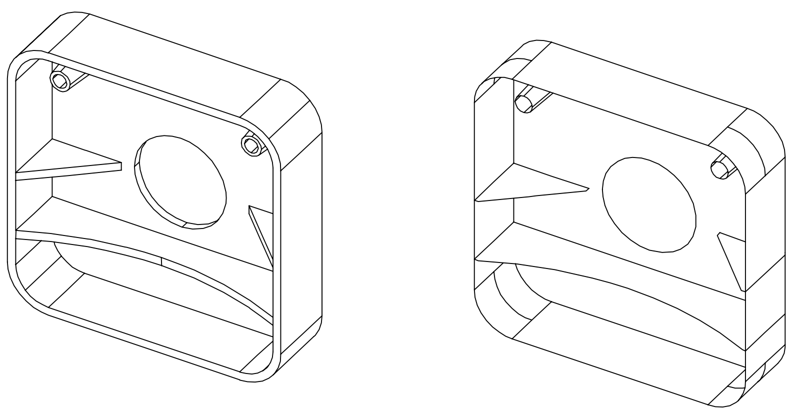


Figure 6. Solid model and mid-surface for a simple plastic part

The feature recogniser constructs a mid-surface model with 21 faces, 24 edge loops and 57 edges, and a 21 x 57 x 3 array representing the adjacency matrix. The results of the feature recognition process are generated as a text report and a colour coded STEP file. The results for the simple plastic part are shown in Figure 7 below.

```
SUMMARY of recognised Features
------------------------------
Loop 195 on Face 843 is a HOLE
Loop 328 on Face 843 connects to a FACE FEATURE
containing face(s) 197  463
Loop 461 on Face 843 connects to a FACE FEATURE
containing face(s) 164  330
Loop 504 on Face 506 is a BUTTRESS
Loop 1046 on Face 1048 is a RIB
Loop 876 on Face 878 is a BUTTRESS
```

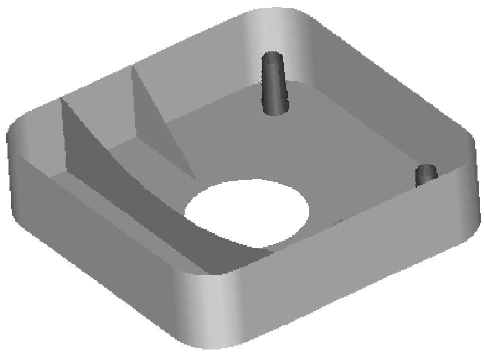


Figure 7: Feature recognition results for simple plastic part

5.2 Case Study 2 – Remote control casing

The second case study is a more realistic part representative of the type used in the domestic consumer products. The model is of one half of the casing of a remote control unit and contains several common moulding features.

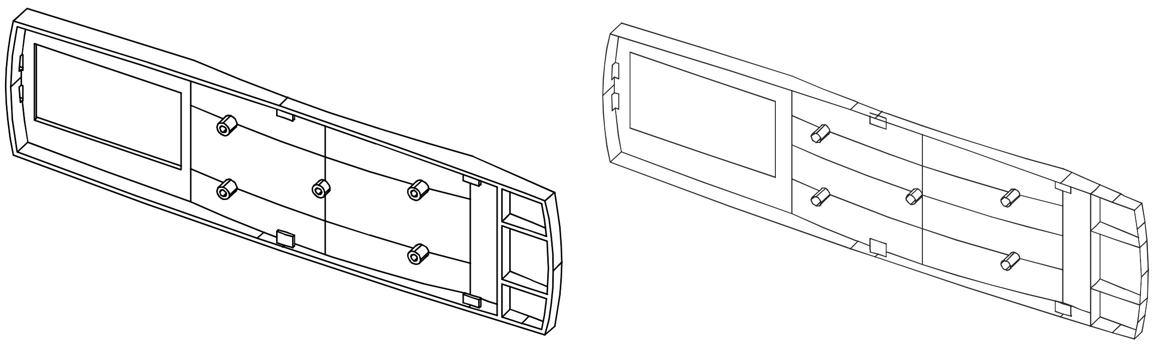


Figure 8. Solid model and mid-surface model for Remote Control part

The mid-surface model contains 33 faces, 43 edge loops and 99 edges and is more complicated than the first example because it has intersecting rib features, a curved surface and a face with multiple features. The mid-surface generation was performed automatically within the I-DEAS software, although a small number of unwanted surfaces had to be deleted manually from the mid-surface prior to feature recognition.

The feature recogniser identified one hole, five intersecting ribs, four fins, and five bosses, and the graphical output of the feature recognition process is a feature report and colour coded STEP model shown in figure 9.

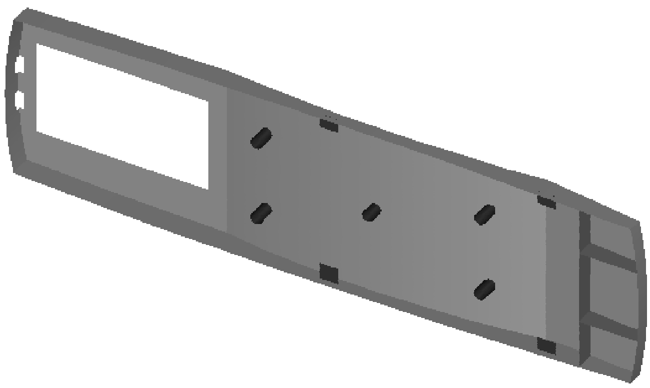


Figure 9 – Results of feature recognition process for remote control part

The results for this part are generally good, although they also show some limitations in the current version of the demonstrator. The two small holes at the end of the part are not recognised because their boundaries are formed from the combination of edge loops on two adjacent faces, and the hole recognition algorithm expects a hole to be attached to a single face.

6 SUMMARY AND CONCLUSIONS

In this paper a novel feature recognition approach for moulded parts has been presented based on a mid-surface approach. The main contribution of the work has been the application of feature recognition techniques to mid-surface models to allow the recognition of moulding features on thin walled parts. A new Attributed Mid-surface Adjacency Graph (AMAG) has been developed to represent mid-surface geometry, and a feature recognition methodology for moulding features has been implemented. The techniques that have been developed in the research build on existing graph-based feature recognition techniques that have previously been applied to machining feature recognition for prismatic solid models. [1,6,7] However, the existing techniques have been extended to support feature recognition for a new application area of moulded parts, and have required the development of a methodology that is applicable to non-manifold geometries.

The methodology presented in this paper has several advantages over other methods for moulded parts. Firstly, using the mid-surface as a basis for feature recognition makes the topology relationships required for thin walled feature recognition much more accessible than they are on a CAD solid model, and the relationship back to the CAD solid model geometry can be maintained. Secondly, using the mid-surface significantly reduces the number of feature interactions that need to be computed to identify thin wall features that are of interest for moulding evaluation, and thirdly the methodology is applicable to parts with complex curved surfaces in the main wall (although the current implementation of the demonstrator does not fully validate some feature types such as ribs if they have curved faces because the geometric checking has only been implemented for planar faces).

Most existing feature recognition techniques are aimed at machining features and assume that the part can be recognised as a base stock with machining features removed from it, but this approach is not suited to feature recognition for a moulded part that is entirely composed of intersecting thin walled sections. The mid-surface approach that is presented here provides a more promising basis for moulding feature recognition than existing techniques.

A demonstrator for the feature recogniser has been implemented using C++ and ISO 10303 STEP. The demonstrator has been tested on a variety of geometry models and produced good results for a range of moulded parts. The algorithms that have been developed are robust for a range of geometries and have been tested on parts with up to 60 mid-surface faces. Several limitations with the existing demonstrator have been identified and these will be investigated in future work:

1. The methodology that has been developed is dependent on the use of third party mid-surfacing tools to generate the mid-surface representation of the part prior to feature recognition, but the mid-surface is well established as an abstraction for finite element analysis and flow simulation on thin walled objects. It is acknowledged that there is not yet a fully robust mid-surfacing algorithm, but an existing commercial implementation has been found to give reasonable results for a variety of parts. The current generation of mid-surfacing algorithms work well for thin walled parts that have a relatively small variation in wall thickness, and these characteristics are well aligned with the requirements of moulding manufacturing process, and mid-surfacing algorithms are currently being implemented in a number of CAE tools.
2. The current implementation of the feature recogniser recognises only a limited number of moulding features, and the geometric checking is relatively simplistic. Future work will extend the approach to identify additional feature types, and to refine the geometric validation of the features that are recognised.

One current limitation is that the algorithms assume that each face on the part is represented by a single surface in the CAD model, but for some parts this assumption is not true and the feature recognition algorithms may not recognise the moulding features correctly. This limitation could be overcome by the implementation of a "face group" function that would group together tangentially connected faces prior to feature recognition.

Future work could also develop algorithms to recognise features that are more topologically complex than those currently supported. For example parts in which the faces are connected together to form loops of faces or features that form bridges from the interior of one face to the interior of another could be recognised using extensions to the feature recognition algorithms.

3. At present the output from the feature recogniser is in the form of a colour-coded STEP AP203 file of the mid-surface geometry, and a text report. A future objective is to map the recognised features back onto the original CAD solid geometry so that the features can be associated with the original CAD geometry as well as the mid-surface abstraction.
4. A knowledge-based manufacturing advisor for moulded parts is currently under development that will be integrated with the feature recogniser to assist inexperienced designers in the design of products for injection moulding or other near-net shape manufacturing processes.

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