An Intelligent Manufacturing Advisor for Casting and Injection-Moulding Based on a Mid-Surface Approach

Conference or Workshop Item

AN INTELLIGENT MANUFACTURING ADVISOR FOR CASTING AND INJECTION-MOULDING BASED ON A MID-SURFACE APPROACH

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Abstract.

Products that are manufactured using near net-shape manufacturing processes must be designed with regard to the constraints of the manufacturing process. The purpose of this research project is to develop a knowledge based manufacturing advisor to assist designers of products for casting and injection moulding. The manufacturing advisor is tightly integrated with a CAD solid modeller, and uses a novel feature recognition approach to identify the manufacturing features of the part. A mid-surface abstraction from the part's solid geometry is used as the basis for feature recognition, and it is argued that this is a better approach to feature recognition for this class of parts than a CAD solid model. Initial testing indicates that the feature recognition process is able to effectively recognise a range of features but that the quality of the feature recognition is dependent on the mid-surface representation that is generated.

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1. Introduction

In today's manufacturing industry there is continuous pressure to drive down costs and increase quality. Large manufacturing organisations now commonly undertake design and manufacture at different company sites, and the manufacture of components and sub-assemblies may be subcontracted to partner companies or suppliers. One of the consequences of this change is that designers are often separated from the manufacture of the products they design, and designers may be required to design products for manufacturing processes which they know little or nothing about. They can design for function and form, but do not have the necessary specialist skills required to optimise their design for manufacture.

The current generation of Computer Aided Design (CAD) systems provide advanced functionality for building geometry models, but they still have little or no understanding of the function or manufacture of the products they are used to design. Future developments in CAD will be associated with helping the designer to design for function, usability or manufacturability. Design for manufacture for moulded parts is particularly important because the cost and quality of parts manufactured using these processes is highly geometry dependent.

Other research projects have developed tools that allow a rapid assessment of potential manufacturing problems without the use of numerical simulation tools. Knight, et al, [Knight, et al, 1995] 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). Rosen et al, [Rosen, et al, 1992] 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, but they did not attempt to integrate their tools with a standard CAD solid modeller.

Lu et al [Lu, et al, 1995] 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 [Ravi & Srinivasan, 1989] 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.

Other research projects have used mid-surface or medial-surface techniques to facilitate the analysis of thin walled parts. 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. 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 [Blum, 1967]. 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.

Donaghy, Armstrong and Price [Donaghy, et al, 2000], [Sheehy, et al, 1996] 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. Quadros et al, [Quadros, et al, 2001] also use the medial axis transform for the generation of engineering-analysis models. Several commercial tools are available to calculate the medial or mid-surface of a CAD solid model. Working algorithms are available from FEGS Ltd (the medial object toolkit) [Price, 1995] and from SDRC I-DEAS (the mid-surface function) [SDRC, 2000].

This project uses a mid-surface abstraction to simplify the geometry of thin-walled parts that have been modelled in a CAD solid modeller, and applies feature recognition techniques to identify important features from the mid-surface model for manufacturability evaluation. The scope of the project is limited to design for casting and injection moulding, and the demonstrator has been developed to work with a limited sub-set of the feature types that would be found on real world parts. This paper focuses on the evaluation of the mid-surface as a basis for the manufacturability evaluation and the recognition of moulding features from the mid-surface model. The detailed theory of the graph representation and feature recognition algorithms that have been developed will be published separately [Lockett & Guenov, 2002]. In section 2 of the paper the project objectives are defined, section 3 presents an overview of the mid-surface approach, and an evaluation of the mid-surface model as a basis for feature recognition. In section 4 the feature classes and feature recognition approach are described, and section 5 provides an overview of the implementation of the demonstrator. Finally the advantages and limitations of the mid-surface approach are discussed, conclusions are drawn and future work defined.

2. Objectives

The objective of this research project is to develop a manufacturing advisor that can provide designers with manufacturing advice while they are working within a CAD system. The research focuses on design for manufacturability for injection moulding and casting. The manufacturing advisor will help the designer to follow the design guidelines that would traditionally be learned from an experienced colleague or design handbook. Some examples of the types of guidelines that might be incorporated into the manufacturing advisor are:

* the recommended layout of wall junctions and intersections
* identification of heavy areas which may cause hot spots and shrinkage
* suggested fillet radii to aid material flow and cooling
* the optimal proportions for ribs and other protrusions to minimise sink marks
* suggested transitions in wall thickness
* solutions to common design problems based on past design cases

The overall objectives of the project are to develop a manufacturing advisor tool that:

i. provides tight integration with a standard CAD system

ii. incorporates robust feature recognition from moulded parts, without excessive computational complexity

iii. is able to identify potential manufacturing problems from a designed part and recommend design changes that would improve manufacturability

iv. allows the designer to visualise the proposed design changes on the part geometry.

3. Mid-surface Approach for Feature Recognition

Feature recognition techniques can be used to extract geometry and topology information from a CAD geometry model. Feature recognition has an advantage over feature based design in that it allows the user to model their design in a standard CAD system, and the user is not constrained to work with a standard library of design features provided by the design tool. A novel feature recognition methodology has been developed based on a mid-surface abstraction from the actual part geometry.

Feature recognition has been the subject of a great deal of research, particularly in relation to the automation of machining operations for CNC machined parts [Shah & Mantyla, 1990]. However there are two common problems that have been encountered in the development of feature recognition systems, firstly the explosion of computational complexity due to the large number of geometry entities, and secondly the difficulty of computing the interactions between intersecting features. The approach proposed in this project is based on the hypothesis that for moulded parts a mid-surface abstraction provides a better basis for feature recognition than the complete solid geometry, and that using a mid-surface approach overcomes some of the problems associated with feature recognition from a standard solid model. The mid-surface approach appears to have merit for cast and injection moulded parts because one of the requirements of these manufacturing processes is that parts be designed with thin, and relatively constant wall thickness, and a mid-surface representation is therefore able to capture the key geometric characteristics of the part shape but with a greatly simplified geometry model.

3.1 Evaluation of the mid-surface approach

An investigation has been undertaken into the use of mid-surfaces to represent the geometry of injection moulded and cast parts. Mid-surface algorithms use a variety of techniques to calculate the mid-surface of a solid object. The medial axis transform calculates the locus of an inscribed maximal sphere as it rolls around the interior of the part [Blum, 1967]. The SDRC I-DEAS mid-surface function [SDRC, 1999] selects pairs of faces from the solid part and calculates mid-surfaces between each face pair, then uses surface extension and trim operations to generate a mid-surface of the complete part. The effectiveness of these and other techniques is largely dependent of the shape characteristics of the geometry that is presented to them, and a major requirement is that the wall thickness of the part must be relatively constant and small compared to the size of the features of interest in the part.

Figure 1. shows an example of the mid-surface generation for a simple injection moulded part. The part has been modelled using a CAD solid modeller, with the main wall thickness (t) varying from 1.5 mm to 7.5 mm and protrusions from the main wall modelled at 2/3 the main wall thickness. The mid-surface has been generated for each variant of the model using the SDRC I-DEAS mid-surface tool. The results show that when the wall thickness is small relative to the other dimensions of the part (in this case less than or equal to 4.5 mm), the mid-surface accurately captures all the features of the part. The boss, rib, and buttress features are all accurately represented, and the complexity of the part has been significantly reduced. For this part the CAD solid model contains 40 surfaces, whereas in the mid-surface model there are only 17. Furthermore, the surface/ edge connectivity on the mid-surface directly describes the connectivity between the walls in the physical part, and the need to calculate feature interactions is greatly reduced.

When the wall thickness is increased above 4.5 mm the calculation of the mid-surface becomes less accurate. In this example when t = 6 mm the boss features become too small relative to the wall thickness to appear in the mid-surface, and are represented only as holes in the base wall. When t = 7.5 mm the overall shape breaks down because the fillet and rib features can no longer be resolved from the solid model. For this example the mid-surface representation is not valid when the wall thickness is greater than or equal to 6 mm, however for this type of part a main wall thickness of 2 – 4 mm would be appropriate, and wall thicknesses of greater than 4 mm are likely to cause cooling problems, and be uneconomic to mould.

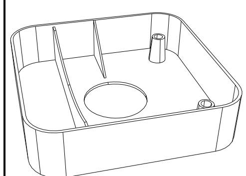
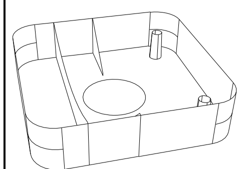
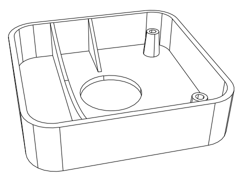
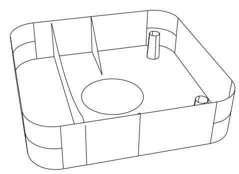
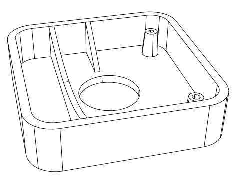
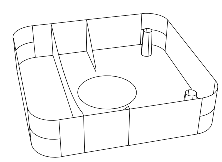
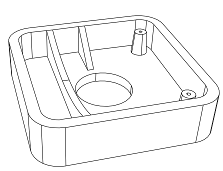
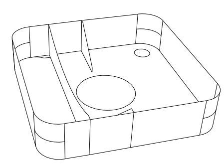
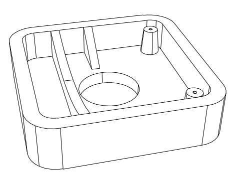
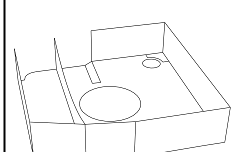
Wall Thickness (t)	Solid Part	Mid-surface Abstraction
1.5 mm		
3.0 mm		
4.5 mm		
6.0 mm		
7.5 mm		

Figure 1. Example of mid-surface generation for a simple moulded part

4. Feature Recognition and Classification

Although the injection-moulding and casting processes are able to manufacture parts with a wide range of complicated shapes, the number of different feature types that are used is often relatively small. A library of common moulding features has been defined, and the mid-surface geometry characteristics that can be used for feature recognition have been identified. In the manufacturing advisor the feature recognition process has been implemented using a graph-based approach. A geometry graph has been developed that is able to represent the mid-surface geometry, and the geometry graph is parsed to search for sub-graphs that match the feature types defined in the library.

On the mid-surface model each face represents a feature or wall segment. One of the major differences between feature recognition from the mid-surface model compared to that for a standard B-rep solid model is that the feature relationships are directly available from the geometry relations in the model. For example when three faces meet to form a T-junction on a mid-surface model there is a common edge that belongs to the boundaries of all three faces, and can be directly recognised as the junction between the faces; but on a solid model the existence of the walls and the junction can only be identified through the evaluation of complex feature interactions. The feature types that have been defined in the library, and their characteristics with regard to feature recognition are described below. Illustrations of the solid geometry, and mid-surface representation for each feature are shown in Figure 2.

4.1 Face Features

Features that are connected to the interior of a face are classified as face features. Face features are characterised by being connected to an inner face-loop that is attached to the interior of a face, rather than being connected along a bounding edge of a face. Holes, bosses, and fins are all examples of face features. The identification of face features at the beginning of the feature recognition process can help to simplify the remainder of the process, because once the face features have been identified, the geometry entities that represent them can be disregarded for the remainder of the feature recognition process.

4.2 Junction Features

A junction feature represents an intersection between two or more wall features along a common edge. Junction features are important for manufacturability evaluation because high order junctions can cause hot spots during mould cooling, junction features are also the building blocks for the stiffener features discussed below. The number of walls meeting along a common edge can be used to determine the order of a junction, and the junction order is used to aid the recognition of stiffener features. For example a T-junction is of order 3 because three faces are connected along a shared edge, and a X junction is of order 4.

4.3 Stiffener Features

Stiffeners are structural features that are applied to provide additional strength or rigidity to a part. Ribs and buttresses are common types of stiffener features. A rib is an internal wall feature that is connected to other walls along several adjacent edges. The thickness and proportions of rib features are important in manufacturability evaluation because if they are not properly defined they can cause sink marks of filling problems. In general for a wall with four edges, if three of its edges are connected at order 3 or higher then the wall is considered to be a rib. A buttress feature is a stiffener feature that is connected to two or more adjacent faces and is distinguished from a rib by its connection to bounding edges that extend into the interior of the walls to which it is connected.

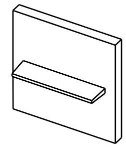
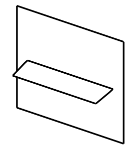
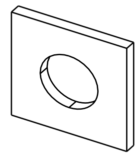
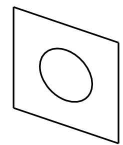
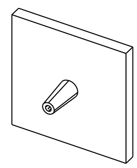
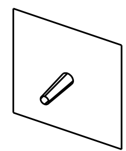
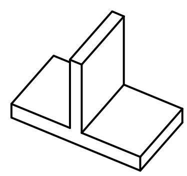
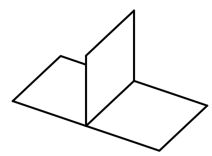
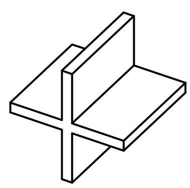
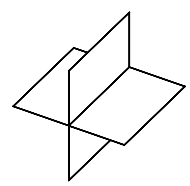
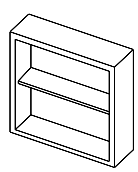
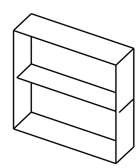
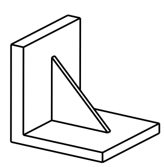
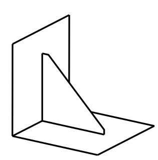
Feature Class	Feature Type	Solid Model	Mid-surface Model
Face Feature	**Fin**		
	Hole		
	Boss		
Junction Features	**T-Junction**		
	X-Junction		
Stiffener Features	**Rib**		
	Buttress		

Figure 2: Feature Types and their mid-surface representations

5. Implementation

A demonstrator for the feature representation and feature recognition process has been developed. Figure 3 shows a flow chart of the implementation of the overall manufacturing advisor. The input to the process is a B-Rep solid model of the part. In step 1 the mid-surface representation of the part is generated from the CAD solid model. Step 2. evaluates the geometry of the mid-surface model, extracting the geometric and topological information required for feature recognition and manufacturability evaluation. Step 3 generates the geometry graph representation of the model. Step 4 is the feature recognition phase, and finally in step 5 manufacturing rules are applied, and design changes are suggested. There may be several iterations through the process to completely evaluate a design. Design alternatives can then be generated and presented to the user.

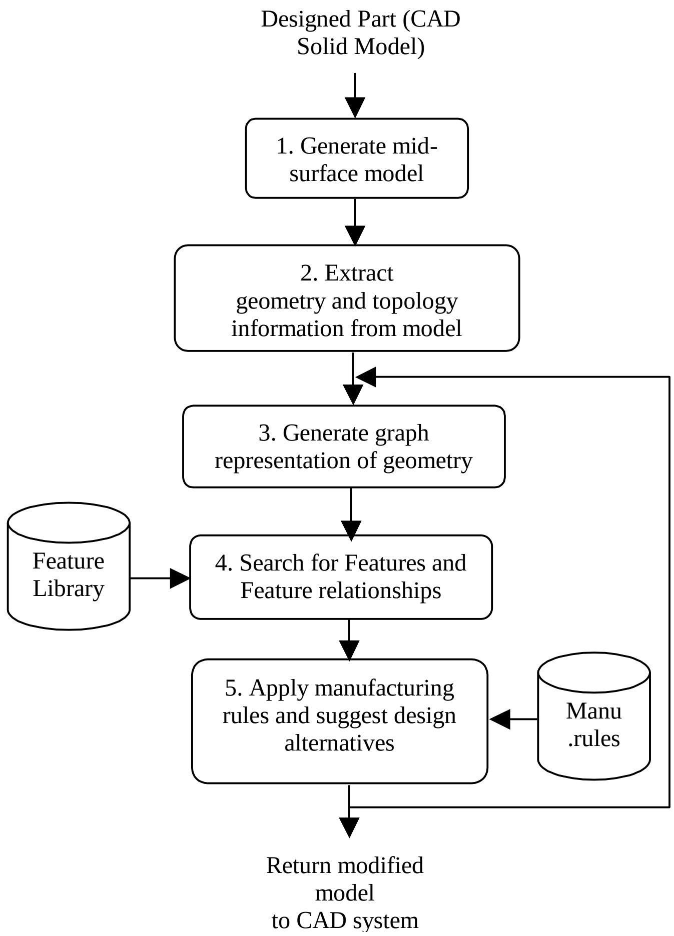
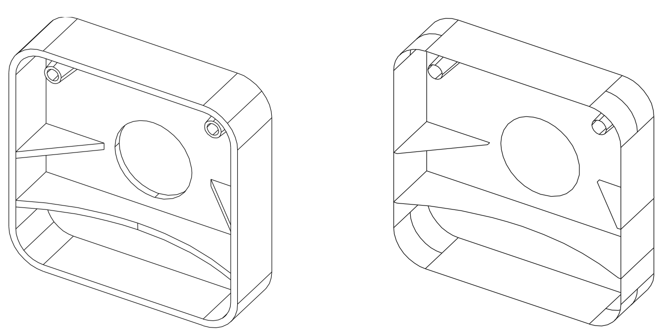


Figure 3 Flow chart of manufacturing advisor operation

The demonstrator uses the SDRC I-DEAS mid-surface function to generate the mid-surface model from a B-rep solid model. I-DEAS represents the mid-surface geometry as a non-manifold solid model that describes the geometry and topology of the mid-surfaces. The mid-surface model is then exported from I-DEAS using a STEP AP203 file, and the STEP AP203 file is parsed to extract the geometry information for use in the feature recognition process. The STEP standard has been used for data exchange to allow flexibility in the future if alternative mid-surface programs are investigated. The geometry information is then used to construct a geometry-graph representation of the mid-surface geometry. The graph structure captures the connectivity between the faces, face-loops, edges and vertices in the mid-surface geometry.

The programs have been developed using C++ and the interface to STEP uses the STEP Class Libraries from NIST (National Institute of Standards and Technology) [NIST, 2002].

Algorithms have been developed for feature recognition from the mid-surface geometry and the feature recognition process has been tested for a simple represented injection-moulded part and shown to work effectively. The feature recognition process begins by searching for internal face loops in the mid-surface model, and identifies face features that are attached to those loops. The internal face loops and any attached faces can then be disregarded for the remainder of the feature recognition process. The feature recognition continues by searching for edges that are common to more than one face, and identifies junction and stiffener features from the face-edge connectivity. Figure 4 shows an example of the results of the feature recognition process for a simple injection moulded part. The first picture shows a solid model of the part geometry, the second picture shows the mid-surface abstraction of the part, and the table provides a summary of the features that have been recognised from the part.



Features Recognised
1 Hole
2 Bosses
1 Rib
2 Buttresses
14 General Walls

Figure 4 Feature Recognition for a Simple Moulded Part

The mid-surface generation process has been tested for a range of parts, and Figure 5 shows the mid surface generation for a more realistic moulded part. It can be clearly seen that the mid-surface model effectively captures the main geometric characteristics of the part, including the main part wall, and the holes, and buttresses. There are however some problems with the mid-surface generation for this part, for example the filleted corner surfaces have not been modelled on the mid-surface model, and the buttress features extend above the top face of the part where the thinning process has reduced the total part height. This type of modelling error is caused by limitations in the mid-surface algorithm, and will only be resolved by the development of a more robust mid-surfacing technique.

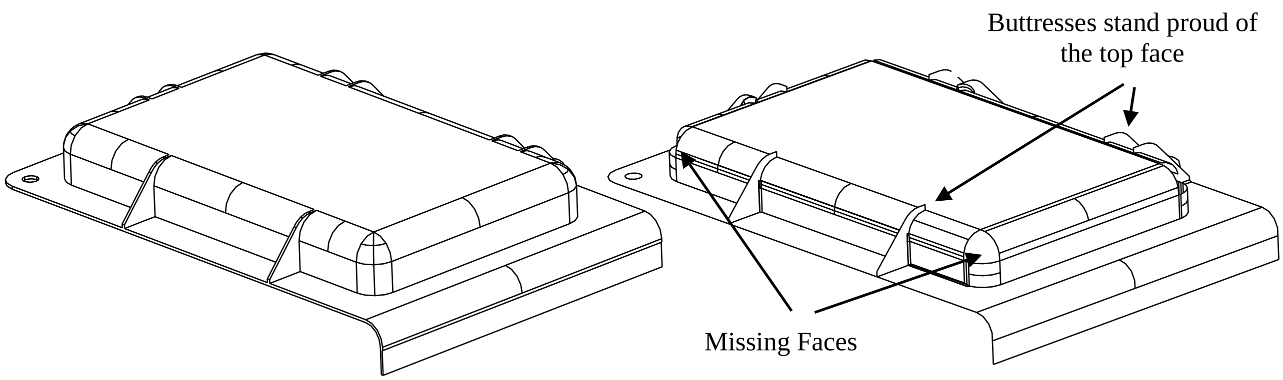


Figure 5 Mid-surface generation for a more complicated moulded part highlighting potential problems with mid-surface generation

6. Discussion

This paper has described the development of a manufacturing advisor for casting and injection-moulding based on a mid-surface approach. It has been demonstrated that a mid-surface model can effectively describe the major design characteristics of thin walled parts for both planar and curved geometries, and effectively captures the relationships between the geometry entities in a part. The mid-surface approach does though impose some limitations on the types of geometry that can be accurately represented. The mid-surface model is not able to model small features that are similar in size to the part wall thickness, and may not accurately represent parts that have walls of widely varying thickness, or heavy sections. However, these limitations are compatible with the requirements of the injection-moulding and casting manufacturing processes require designs that have thin walls of relatively constant thickness.

The demonstrator has been developed using the SDRC I-DEAS mid-surface function that is provided as part of the SDRC I-DEAS CAD/ CAM/ CAE system. The function uses a surface-pairing algorithm to construct the mid-surface faces, and was developed primarily for the simplification of solid models for finite element analysis. The I-DEAS function uses a fundamentally different thinning algorithm to the medial-surface type algorithms, and one benefit of the I-DEAS approach is that the resultant mid-surface is composed of a small number of smooth surfaces. In contrast for curved walls the medial surface functions tend to produce a set of facetted surfaces that would be more difficult to use as a basis for feature recognition. A limitation of the I-DEAS function is that it does not provide full reversibility to allow a solid model to be reconstructed from the mid-surface model, and that makes it more difficult to convert proposed design changes back into a solid model.

7. Conclusions and Future Work

This paper has presented an intermediate stage towards the development of a manufacturing advisor for casting and injection-moulding. The results indicate that the mid-surface approach provides a viable basis for feature recognition for cast and injection moulded parts. The approach is able to significantly simplify the feature recognition problem compared to that from a complete solid model, and removes the necessity to evaluate complicated feature interactions to identify wall type features.

The accuracy of the feature recognition process is highly dependent on the quality of the mid-surface that is generated from the solid model. Experiences with the I-DEAS mid-surface function show that for parts with a relatively constant wall thickness the results can be very accurate, but for parts with a widely varying wall thicknesses, very small features or complex curved wall intersections the mid-surface generation does not produce good results.

Future work will focus on the further development of the manufacturing advisor, including expansion of the library of feature types that can be recognised, and integration of the feature recognition system with a knowledge base of manufacturing rules. It will also planned to explore the reversibility of the mid-surface algorithms, with the objective of allowing a modified solid model to be visualised after design changes have been suggested.

8. References

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