An approach for feature semantics recognition in geometric models

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Abstract

This paper describes a method for the recognition of the semantics of parts (features) of a component from a pure geometric representation. It is suitable for verifying product life-cycle requirements from the early stages of the design process. The proposed method is appropriate to analyse B-rep geometric models, and it is not limited to models described by planar and cylindrical surfaces, but it can handle several types of face shapes. In this work the concept of \textit{semanteme} is introduced. A semanteme represents the minimal element of engineering meaning that can be recognised in a geometric model. The semantemes recognised in a part of the model, which are potentially of engineering significance, are used to associate an engineering meaning to the part. This approach gives a wide flexibility to the proposed system, which is suitable to be used in different contexts of application, since it is possible to describe the reference context using the semanteme that the system can manage.

In this paper the implemented prototype system is briefly described. The prototype system takes advantage of neutral interfaces that allow geometrical and topological information to be retrieved from a commercial CAD system.

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1. Introduction

The geometric representation is a necessary part of the design process that supports any stage of it, from conceptual design to detailed design. As the design evolves, more details are introduced both in the geometry of the components and in the assembly structure in an implicit form. As the geometric representation evolves, more knowledge about the product is developed. Such knowledge usually incorporates information at a high level of abstraction. The final representation of the product defines the detail of the geometry of the components and the detail of the assembly. Unfortunately a large subset of the design data is non-geometrical and takes place before the geometry is detailed. All the knowledge introduced remains embedded in the geometric description and cannot be explicitly managed by the designer.

Several factors limit the successful use of solid models for processing industrial parts. Such limiting factors usually fall into the following two categories: incomplete product definition (only the nominal geometry can be defined; geometrical constraints such as symmetry, perpendicularity, parallelism and coaxiality cannot be defined; the designer’s intent cannot be stored) and low level product definition (it is not possible to use solid models as they stand to drive applications such as process planning or manufacturability evaluation).

A modern approach to the design of an industrial product involves the analysis of all those factors that affect the entire life cycle. All these factors will be introduced as requirements of the geometry of the components to be designed. In order to manage this information in any stage of the design process, it is necessary to associate them with the geometric description.

Feature-based representation is a technology for integrating geometric modelling and engineering analysis for the life cycle. The concept of \textit{feature} implies the association of a specific engineering meaning to a part of the model. The overall aim of feature-based representations is to convert low level geometrical information into high level description in terms of form, functional, manufacturing or assembly features.
The typical approaches used to create a feature-based representation scheme are automatic feature recognition and design by feature. Both of these two different approaches, which can be pursued in order to achieve a feature-based representation scheme, are complementary and useful to develop an operative-aided design system. The main purpose of automatic feature-recognition systems is to extract the knowledge enclosed in the geometrical representation of solid models and make it available for the activities required during the product life cycle.

A lot of work has been produced during the last 15 years towards the research of useful and effective automatic features recognition systems. Some results have been gathered in the field of recognising machining features in specific contexts but, usually, the proposed methods do not take into account different manufacturing processes in a unique integrated method. Furthermore these methods manage only a part of the whole engineering knowledge required in the design process of an industrial product.

In this paper, a method suitable for recognition and extraction of engineering knowledge implicitly held by geometric models is presented and critically discussed. The main task of this work is to define and implement a method for knowledge recognition that is unambiguous in knowledge definition.

The feature-recognition approach used in this work is briefly sketched in Fig. 1. In this figure the parts that have not yet been implemented are drawn in dashed lines. The proposed method performs automatic features extraction and recognition from a pure geometrical description of the model to be analysed.

In order to obtain a non-ambiguous semantic description of the model, an intermediate representation has been defined. Such representation, described in Section 3, enables the description of the solid model at a higher level of abstraction when compared with the description provided by the raw solid model B-rep format.

Some new criteria for the identification of parts that potentially allocate engineering meaning (generic feature, GF) are proposed in this work. The types of GFs introduced here discriminate parts of geometric models with respect to a wide range of engineering requirements. This topic is detailed in Section 6.

In this paper a new approach for semantic recognition is proposed, which performs the association of it to the geometric representation. The knowledge association is based on semanteme recognition. A semanteme, as discussed in Section 7, represents the minimal element of meaning that defines the semantics of the representation. This original approach provides high flexibility and effective capabilities in knowledge extraction.

The proposed method provides an efficient instrument to upgrade and improve knowledge extraction capabilities by defining specific semantics for specific domains of application. The capability of the system to handle a specific semantic is only limited by the number and type of the available semantemes and by the set of generic features that the system can extract. The developed software takes advantage of direct interfaces in order to retrieve topological and geometrical data from solid models. This approach makes it possible to exploit the computing facilities offered by commercial CAD packages, limiting geometrical and topological data processing efforts required to the prototype. Another advantage is that the system can be easily integrated with existing CAD packages.

2. Related research

Literature on feature recognition is wide and voluminous. Many works have been directed towards the recognition of features from solid models represented either in CSG or B-rep form. This brief review is focused on feature-recognition algorithms from B-rep models. This kind of representation has been recognised as the most common starting point for feature recognition [1], and it is also the starting point considered in this work.

Since boundary representations are built upon graph structures, a class of feature-recognition approaches is based on sub-graph isomorphism to match the features [2]. As stated by Wu and Liu [3], in graph-based approaches a feature is first represented by a graph structure that delineates the required topological and geometrical constraints for identifying a feature. Once the graph that identifies a feature class has been defined, it has to be searched in the B-rep structure, which is a graph as well. Some authors noticed that the adjacency information available from B-rep models are usually not adequate for feature recognition; for this reason a number of augmented graphs have been suggested.
Joshi and Chang [4] introduced the concept of attributed adjacency graph (AAG); a graph where nodes correspond to faces and arcs to edges; in addition each arc is assigned an attribute that stores whether the faces sharing the edge form a convex angle or not. Their recognition procedure is based on the definition of a set of predefined features based on topological (adjacency) and geometric relationships (angle formed by the faces). Features are considered as subgraphs of the complete AAG, and the feature-recognition procedure presupposes the identification of the subgraphs that corresponds to the predefined features. The described AAG technique is limited to polyhedral features and parts, and does not takes into account other information such as geometrical relations among faces.

The concept of structured face adjacency graph (SFAG), as a means for the representation of the shape of an object at the highest level of abstraction, has been introduced by Falcidieno et al. [5]. In their approach form features are classified into two groups: profile features, which do not alter the topology of the model, and topological features, which affect the topology of the model increasing the number of faces, edges and vertices. Topological features are subclassified into three categories: through holes; protrusions or depressions and connections. It is shown that such categories can be represented in terms of a structured face adjacency graph. The feature-recognition system, based on syntactic recognition, has been tested on polyhedral models.

Gao and Shah [6] proposed an approach that combines the conventional graph-based recognition with hint-based recognition. In this work, different types of graph, which are essentially extension of the AAG are defined: Extended Attributed Adjacency Graph (EEAG), Manufacturing Face Adjacency Graph (MFAG), Partly Concave Adjacency Graph (PCAG) and Concave Adjacency Graph (CAG). In addition the authors introduced the concept of virtual link (VL) as a face adjacency relationship that, as a result of feature interaction, is not contained in the B-rep of a part. The algorithm uses a library of predefined features (steps, blind steps, slots, chamfers, etc.) and a heuristic rule library for general features such as compound features, general pockets, through pockets and open pockets. Each feature is defined in terms of its EEAG and other data (feature parameters, access directions, obstacle faces, etc.). The proposed algorithm, tested on models composed of planar and cylindrical faces, can recognise isolated and interacting features and provide alternative interpretations for each set of interacting features.

One of the principal drawbacks of the feature-recognition techniques based on graph matching, is the difficulty in recognising interacting features. This is due to the fact that a feature characteristic pattern is altered when a feature intersects with other features. Hint-based reasoning has been introduced [7] to overcome this kind of pitfall. The basic concept of hint-based approaches is about having to search those characteristic traces that features leave in the nominal geometry of a part. Such traces represent hints for the potential existence of volumetric features even when features intersect. From a theoretical standpoint this approach is based on the so called presence rule, which states that a feature and its associated machining operations should leave a trace in the geometric representation of the part even when features intersect. For instance unless a cylindrical hole is completely removed by other intersecting features, its presence leaves at least one face in the final part, the cylindrical wall face. That face represents an evidence, a hint for the existence of the hole [27].

Hint-based reasoning has been extensively developed by Requicha et al. [8,9]. The work of Vanderbrande and Requicha [8] is mainly on automatic recognition of machinable features. The feature-recognition process begins from a solid model plus optional information as tolerance, attributes and functional form features. Features hints, which may result from particular combinations of part faces or by tolerance or attribute specification, are investigated and processed in order to generate the largest possible feature volume consistent with the available data. Features are then verified to check if they are machinable. The proposed approach has been tested for the recognition of holes, slots and pockets [8].

Marefat et al. [10,11] introduced an approach based on uncertainty reasoning for the extraction of knowledge from solid models. The proposed framework is based on the concept of evidence. Evidences are topological and geometrical relationships between a pair of faces that consider, for instance, if they are orthogonal, parallel and so on. Evidences are combined and propagated to determine a set of VLs that are used to create an augmented graph upon the original graph of the part. The resulting supergraph is then partitioned in order to obtain the features of the object. As noted by the authors, the proposed approach has been tested for a limited number of solid models described by planar faces and need to be generalised to identify and extract features described by curved surfaces.

Pal and Kumar [12] proposed an approach based on the concept of edge attribute, which is basically a function of edge equation. Such attribute is used to decide whether a set of surface patches represent a part of the engineering significance of the model. The recognition procedure is accomplished in four steps: (1) generation of random sets of surface path combinations; (2) key face detection (identification of the base face of a feature), (3) sequential connectivity pattern detection and (4) validation of the recognised feature by checking a specific rule given in terms of faces, edges and vertices (e.g. \( F + V - 1 = E \) for void pockets). The approach seems to be promising, even if the article does not entirely prove its applicability to real world mechanical components.

This brief literature review shows that a lot of work has been produced on feature recognition and in general on the extraction of engineering meaning from solid models. Related work, however, shows that there are still opened
issues that need to be further investigated. It can be noted, for instance, that in many cases, very restrictive assumptions are made about the geometry of the part to be recognised, since the considered models are often described in terms of just planar and cylindrical surfaces. Such assumptions usually are related to some levels of uncertainty in the recognition of the engineering knowledge. The effectiveness of a feature-recognition system relies on the range of topological and geometrical information it can handle. The methods discussed are dedicated to specific context and seem to be very rigid and therefore not suitable for of support a modern approach to industrial product design.

3. The intermediate model

Feature-recognition approaches are often hindered by some ambiguities related to the non-uniqueness of the object representation.

The first type of non-uniqueness is due to the way the solid model is constructed. It is well known that, the typical methods adopted to represent rigid solid used in CAD system, although unambiguous, are not unique [13]. Several tests, in fact, carried out with different commercial CAD packages, and even with the same system, however, with different modelling history, demonstrated how the same component can be described by means of different B-rep instances. Such representations may differ from each other both on the topological description of the model and also on the geometrical representation of the faces.

Typical factors that result in non-uniqueness of the geometrical model are:

- surfaces with compact mathematical representations (e.g. spheres, cylinders, torii) are tessellated with a different number of surface patches (for instance a cylinder may be described as having one or more cylindrical patches. Fig. 2);
- surface patches are described either in terms of analytical surfaces or in terms of NURBS.

The second type of non-uniqueness is due to the presence of some geometric elements that are not essential to the semantic evaluation of the geometric model, such as chamfers, rounds, fillets and reliefs. Usually the presence of these secondary features neither affects the engineering significance of the geometric model (Fig. 3) nor the recognition of local engineering features, however, geometric and topological variations introduced by secondary features may result in inefficient semantics classification in feature recognition [14].

In order to obtain a non-ambiguous semantic description of the model, we need geometric models to be described in a unique way. For this purpose an intermediate model is evaluated. This intermediate representation will be referred to as the Face-Based Boundary Representation (FBBR).

Although the definition of a face is straightforward if the boundary is described by planar surfaces, some rules must be defined when the geometrical model is composed of more complex shapes. In this work a face is unambiguously identified as a connected part of the boundary of the geometric model, characterised by a unique type of geometry with unique geometric parameters. As a consequence of this definition, a face consists of a unique smooth piece of the boundary. Each non-trimmed patch of the surface pertains to no more than one face of the object. A face can be composed of one or more adjacent surface patches, satisfying the characteristics required in the face definition, each one having its own mathematical definition.

The above definition of a face ensures that the FBBR is unique, regardless of the geometric model from which it has been generated. Secondary features are treated as attributes of the adjacency between neighbour faces.

The representation adopted in this work (FBBR) can be regarded as a labelled multi-graph structure, which is a n-ple \((V, E, [A_1, ..., A_n])\) of disjoint sets together with \(n + 1\) maps \(E \rightarrow |V|^2\) and \(A_j \rightarrow |V|^2\) for \(j = 1, n\).

![Fig. 2. Different B-rep descriptions of the same component.](image1)

![Fig. 3. Secondary feature is a label of the adjacency between neighbour faces.](image2)
The nodes of the graph \((v_i \in V)\) correspond to the faces of the geometric model. Every arc in the sets \(E\) or \(A_j\) connects two nodes in the set \(V\). An arc \(e_i \in E\) represents an adjacency between two neighbouring faces. For every pair of adjacent faces there exists a unique arc connecting corresponding nodes.

An arc \(a_{ij} \in A_j\) represents some relation between two faces. For every pair of faces, which have the same mutual relation, there is an arc defined by a specific map. For every type of mutual relation, a specific set \(A_j\) of arcs of the multi-graph exists (Fig. 4).

A specific map between faces is the mutual geometric relation or orientation. Mutual geometrical relations are properties that may occur either between two adjacent or between two non-adjacent faces.

Geometric relations between faces such as parallelism, perpendicularity and coaxiality, are usually very important since they are often associated with the engineering significance of the part. Such information on geometrical relations is also indicated, in literature, as shape regularities, and has been investigated by other researchers, mainly in reverse engineering. Martin et al. [28], for instance, introduced a taxonomy for shape regularities, which considers similarities in shape parameters (e.g. equal shape parameters and special values for shape parameters), axis directions (e.g. parallel directions and symmetrical arrangements of directions), axes (e.g. collinear axes and axes that intersect in a point) and positions (e.g. regular distances along a line or a grid).

In this work we considered, a set of geometric relations, which are very meaningful for semantic recognition in mechanical components: parallelism, perpendicularity, coaxiality and coincidence. In addition we take into account other characteristics of the model such as mutual visibility and accessibility of faces that, as detailed later, may have a great importance for the recognition of engineering features. The list of the properties taken in to account in the proposed framework are:

- **Parallelism** \((A_1)\): indicates parallelism between two planar faces, or between the axes of axisymmetric faces, or between a planar face and the axis of an axisymmetric face;
- **Perpendicularity** \((A_2)\): indicates perpendicularity between two planar faces, or between the axes of axisymmetric faces, or between a planar face and the axis of an axisymmetric face;
- **Coaxiality** \((A_3)\): indicates that two axisymmetric faces have the same axis is a relation which is peculiar of axisymmetric faces and is of primary importance for the understanding of the engineering significance of solid models. For instance all the axisymmetric surfaces of

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![Parallelism A1](image1)

Parallelism \(A_1\)

![Perpendicularity A2](image2)

Perpendicularity \(A_2\)

![Coaxiality A3](image3)

Coaxiality \(A_3\)

![Coincidence A4](image4)

Coincidence \(A_4\)

Fig. 4. Geometrical relations between faces.
a mechanical component can be turned in the same lathe set-up.

- **Coincidence** \((A_1)\): indicates two faces that have the same shape, same parameters and natural extension of one matches the other. This relationship identifies those faces that are trimmed by other features of the model;
- **mutual visibility** \((A_2)\): indicates if two faces are mutually visible. This concept is detailed in Section 4;
- **mutual accessibility** \((A_3)\): indicates if two faces are mutually accessible. This concept is detailed in Section 4.

### 3.1. Attributes of faces

Each node \(v_i \in V\), is assigned a label according to some specific characteristics or attributes of the face. The attributes supported by FBBBR are:

- **number of loops**: indicates the total number of loops of the face;
- **number of handles**: indicates the number equivalent handles of the face;
- **concavity**: indicates the concavity of the faces. A face of the model can be convex or non-convex. A face of the model is considered non-convex if one or both of the principal curvatures in at least a point of the face are negative. Otherwise it is considered convex.
- **geometry**: indicates the geometry of the face, in compliance with the taxonomy depicted in Table 1.
- **geometrical parameters**: indicate geometric characteristic of a particular shape (e.g. the radius and centre of a sphere, the axis the base point and the radius of a cylinder), as stated in Table 1.
- **face visibility**: indicates if a face is completely visible from, at least, one direction. A visible face has a non-empty visibility map.
- **face accessibility**: indicates if a face is completely accessible from, at least, one direction. An accessible face has a non-empty accessibility map. More details about accessibility and visibility of faces are provided in Section 4.

### 3.2. Attributes of face adjacencies

An arc \((e_i \in E)\) represents a topological adjacency between two faces. The attributes associated with a face adjacency are: (1) edge concavity and (2) presence of a secondary feature.

The concavity attribute has been used by other researchers [6] as a means to identify concave regions of the object. In most cases this attribute has been used on models described by planar faces. In such situations the definition of the edge concavity is an obvious consequence of the angle between the adjacent faces. In this work any type of free-form geometry can define the faces of the geometric model and the angle between faces may change along the common edge. In these cases the definition of edge concavity requires further specifications. The concavity attribute may indicate one of the following types of adjacency:

- adjacency along a convex edge: indicates that the angle between the faces sharing the edge is greater than 180° in any point in the edge;
- adjacency along a non-convex edge: indicates that the angle between the faces sharing the edge is less than 180° at least in a point of the edge;
- adjacency along a tangent edge: indicates that the angle between the faces sharing the edge is equal to 180° in any point of the edge.

The presence of fillets, rounds, chamfers and grooves is typical of many real world mechanical components. Such features, indicated, in literature, as secondary features, usually represent VLs between two major faces of the model. The intermediate representation scheme described in this work incorporates information about minor features into a graph-based representation. Secondary features are not considered as faces of the model, but as attributes, which qualify the adjacency between two faces. An example is shown in Fig. 3. For a detailed description of the procedures adopted for the recognition of secondary features readers are referred to Ref. [14]. The secondary features considered in this work are: chamfers, grooves, rounds and fillets.

### 3.3. Dimensional attributes

An arc \(a_{ji} \in A_1\) represents a parallelism relationship between two non-adjacent faces. Associated to this relationship there is a dimension: the measure of the distance between the parallel geometric entities. This attribute identifies a dimensional parameter \((d_{ji})\) of the object. In general these dimensions are the main metric

### Table 1

Types of geometry considered

<table>
<thead>
<tr>
<th>Type</th>
<th>Subtype</th>
<th>Geometric parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Planar</td>
<td>Plane</td>
<td>Base point, normal vector</td>
</tr>
<tr>
<td>2 Ruled</td>
<td>Cylinder</td>
<td>Axis, base point, radius</td>
</tr>
<tr>
<td></td>
<td>Cone</td>
<td>Vertex, axis, half angle</td>
</tr>
<tr>
<td></td>
<td>Generic</td>
<td>Axis</td>
</tr>
<tr>
<td>3 Axisymmetric</td>
<td>Sphere</td>
<td>Centre, radius</td>
</tr>
<tr>
<td></td>
<td>Torus</td>
<td>Axis, centre, major radius,</td>
</tr>
<tr>
<td></td>
<td>Generic</td>
<td>minor radius</td>
</tr>
<tr>
<td>4 Ruled</td>
<td>Generic cylinder</td>
<td>Axis</td>
</tr>
<tr>
<td></td>
<td>Generic cone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Generic</td>
<td></td>
</tr>
<tr>
<td>5 Generic sweep</td>
<td>Generic</td>
<td>None</td>
</tr>
<tr>
<td>6 Generic</td>
<td>Elliptic points</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Hyperbolic points</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Generic</td>
<td>None</td>
</tr>
</tbody>
</table>
characteristics of a mechanical component and can play an important role in semantic recognition of a feature.

4. Visibility and accessibility maps

Visibility maps have been considered by various authors as important attributes in order to analyse mechanical components for manufacturing and automatic inspection planning purposes [15]. Applications have been described also for the design of dies and moulds [16]. Woo and Chen [17] introduced visibility maps as a means to determine the minimum number of axes required to machine a given component and the minimum number of set-ups. Medeiros and Kweon [18] as well as Spitz et al. [19] extended this concept considering, in the computations of visibility maps, the presence of some faces, which may hinder the access and visibility of other faces. In this case, if visibility is computed taking into account obstacles among faces, it is usually called accessibility.

Visibility and accessibility maps usually are stored through suitable data structures, which hold, for each considered entity (point, face, feature, etc.), all its accessible directions. Such directions are typically represented as points on the surface of a unit sphere. The unit sphere is usually discretised in a finite set of points enabling the visibility map to be stored as a matrix of Boolean variables one each indicating the accessibility of the entity with reference to a given direction.

A face is totally visible (accessible) if there is at least one direction along which all the points of the face are visible (accessible). A face is not visible (accessible) if there is not any direction along which the points of the face are visible (accessible). Accessibility attributes are computed using ray tracing with infinite length rays.

Two faces are mutually visible if every point of one face is visible (accessible) from every point of the other face (and vice-versa), otherwise the faces are considered not mutually visible. Mutual visibility identifies a relation between couples of faces. For this reason it is described in the FBBR description by the set of arcs denoted as $A_5$ (mutual visibility) and $A_6$ (mutual accessibility).

5. Geometric shape recognition

Solid modellers usually store geometrical information in terms of analytical and/or NURBS surfaces. A cylindrical surface, for instance, may be represented in one modelling system as a NURBS, otherwise in another system it may be stored in a procedural way in terms of its radius, axis and base point. If a surface is stored as a NURBS, there is no information about how the surface is constructed, in other words it is not known, a priori, if it represents a planar, a cylindrical, a conical surface, or something else.

Methods for shape interrogation and recognition have been discussed in literature by some authors [20–22]. The routine proposed in this work takes advantage, in particular, of the theoretical work of Elber and Kim [20], where the authors describe a set of necessary and sufficient conditions for a curve or surface to have a specific geometric shape. A shape recognition algorithm usually needs suitable tolerance values to be set in order to work accurately. For instance a surface with very low curvature values would be erroneously recognised as a planar surface if their curvature values were less than the given tolerance. This problem has been widely discussed in the domain of reverse engineering [21], where uncertainties associated both with the measuring process and with the shape errors of the components may hamper the recognition process. In this work, however, we assume shape recognition to be carried out on surfaces generated by CAD systems. Such assumption enables us to presume that the considered surfaces would be affected only by very small numerical errors. This makes it possible to apply very low tolerance values in order to avoid incorrect shape recognition.

In this work different types of shapes have been recognised and considered in order to extract semantics from the geometric model. The shapes considered are listed in Table 1. The developed algorithm is able to establish if a generic NURBS belongs to one of the shapes identified by the numbers from 1 to 7 in Table 1. For each recognised shape, its geometrical parameters are extracted, as depicted in the table. If a surface does not match any of the predefined shapes, it is classified as a generic free-form. The shape-recognition procedure is based on surface sampling, and requires calculation of partial derivatives up to the second order. The criteria used to recognise planar, cylindrical, conical and spherical surfaces relies on the investigation of intrinsic (i.e. parameterisation-independent) properties. For the recognition of generic surfaces of revolution and extrusion, it has been assumed that the rotation and extrusion direction of such surfaces, are the $u$ or $v$ iso-parametric directions. The recognition procedure tries to recognise shapes in compliance with a hierarchy of surface types, in order of geometric complexity, as depicted in Fig. 5. First the method checks if a surface is of a simple type (plane, cone or cylinder), then more complex shapes are checked (generic axisymmetric, generic ruled) and, eventually, if no specific shape has been recognised, the surface is considered as a generic free-form.

6. Generic features

With the term generic feature (GF) we indicate a part of a mechanical component that can be of particular significance from an engineering standpoint.

The recognition of the GFs of a model is a mandatory step of the approach discussed in this work. In order to identify generic features we need a set of rules that allow us to discriminate those parts of a model that might be associated with a non-negligible engineering meaning.
It is possible to recognise that, in the approaches proposed in literature, basically the following two kinds of GFs have been considered: protrusions and depressions. Both of them are usually located at a concave region of the model. Although this classification covers a fairly wide range of the most common technological features (e.g. pockets, slots, grooves, holes, etc.), it may not be entirely satisfactory for a reliable general-purpose application. It is obvious that the effectiveness of such a feature-based system depends, to a great extent, on the number of different GFs that it can manage. The set of the considered GFs must be chosen in order to cover a wide range of design requirements, taking into account the most common features that appear in the industrial components.

In this work we considered 13 different generic features. Their definitions are specified below, and the corresponding GFs are sketched in Fig. 6.

- **Smallest Concave GF (SCF):** a set of one or more adjacent faces such that: (1) they are either non-convex themselves or non-convex each other and (2) the edges at the border of a SCF are convex. It is a concave part nested in a larger concave part so that a SCF could be a part of a CF.
- **Concave GF (CF):** a set of adjacent SCF that are mutually visible. A convex region separates two different CF.
- **Axisymmetric GF (AF):** a set of adjacent axisymmetric faces with coincident axes (axis of the feature). An AF is also composed of those planar faces such that (1) their normal is parallel to the axis of the feature and (2) they are bounded by one or more axial-symmetric faces of the feature. The axis of the GF is a characteristic element of this feature.
- **Protrusion GF (PF):** a connected convex part of the surface separated from the rest of the model by a concave region. The edges at the border of a PF are non-convex and identify a loop of the arcs in FBBR.
- **Linear Sweep GF (SF):** a set of adjacent faces, such that (1) they are planar or cylindrical, (2) their common edges are all parallel to each other and (3) at least one adjacency at the border of the SF feature, is convex. A SF feature, from a technological point of view, cannot be considered manufacturable through extrusion. The direction of the edges is a characteristic parameter of this feature.
- **Extruded GF (EF):** a set of adjacent faces, such that (1) they are planar or cylindrical, (2) their common edges are all parallel to each other and (3) their adjacencies, with all the neighbour faces, pertaining to the rest of the geometric model, are convex.
- **Smallest concave axial-symmetric GF (SCAF):** a set of adjacent faces that satisfy the rule of an AF and are SCF or part of them. In other words this GF represents an axial-symmetric part nested in a larger concave part connected with the rest of the model by non-convex adjacencies.
- **Concave axial-symmetric GF (CAF):** a set of adjacent faces that satisfy the rule of an AF and are CF or part of them.
- **Non-connected axial-symmetric GF (DAF):** a set of non-adjacent AF having the same axes. This feature is
represented by a connected graph \((V, A_3)\) whose arcs represent coaxiality relations.

- **Protrusion axial-symmetric GF (PAF)**: a set of adjacent faces that satisfy the rule of an AF and are PF or part of them.
- **Linear Sweep Protrusion GF (SPF)**: a set of adjacent faces that satisfy the rule of an SF and are PF or part of them.
- **Non-connected Extruded GF (DEF)**: a set of non-adjacent EF with the same direction of extrusion.
- **Concave Extruded GF (CEF)**: a set of adjacent faces that satisfy the rule of a SCF and are EF or part of them.

A feature of the type AF usually identifies all those faces that can be machined in a unique setting of the shaft on the engine lathe. In Fig. 7a there is an example of a turned component that can be machined in three settings on the machining tool.

7. **Semantics extraction approach**

A feature-based representation scheme can formalise the description of the engineering meaning of a component and can associate it to its geometry.

In a syntactically correct representation, there is a correspondence between the elements of the modelling space \(M\) and the elements of the representation space \(R\). The correspondence between the elements of \(M\) and the elements of \(R\) is provided by representation schemes. The engineering meaning of a feature strictly depends on the application context. In order to build valid representation schemes, it is important to know the reference context and to identify its relevant characteristics. In order to use the same representation scheme for different domains of application, semantics must be defined in a dynamic manner. The capability to adapt semantics to different situations depends on the possibility of introducing a model of the context in the representation scheme.

There are two main problems in the process of defining the semantic of a feature-based representation scheme: the first is the capability to describe, in a useful form, the reference context, for instance the manufacturing process. The second is to find a valid method to link the engineering meaning to the related shape feature.

In this work in order to solve these problems, we introduced the concept of *semanteme*. A semanteme is a minimal element of meaning that defines the semantics of the representation. The definition of a feature involves the determination of the minimal set of semantemes that identifies the feature unambiguously. The semantemes are,
therefore, the primitive elements of a feature-based representation scheme that can define the semantics of a specific context. Semantemes may have a different relevance in different context. In some cases they might not represent any meaning. In other words the features semantics have to be considered as context-dependent.

The semantic recognition process requires that some semantemes can be recognised in a generic feature. The matching of the set of semantemes associated with a GF, together with a set of referring semantemes, provides the identification of the semantics of the feature (Fig. 8).

The semantemes refer directly to geometrical, topological and dimensional information that are available in the intermediate model (FBBR). A set of selected interpretation functions is required to recognise evidence and semantemes from a GF. Each of these functions is provided to recognise a specific set of semantemes. The semanteme recognition is a complex activity that involves the investigation of the geometrical and topological property of the generic feature. A semanteme can also be a complex entity that combines evidence deduced from the properties of the faces of the FBBR model. This is the case in the graph isomorphism semantemes described in a following paragraph. In some cases the semanteme recognition process could be aided by some hints derived from the modelling stage [9].

A properly defined semantic must be complete and unambiguous. The completeness of a semantic depends on the possibility of representing any engineering meaning, relevant in the application context, which is dependent on the descriptive capability of the representation scheme. The descriptive capability of a representation scheme defined in this work relies on the number and the types of the available semantemes, which are the basic descriptive elements. It is important that each recognisable semanteme discriminates a different specific characteristic of a generic feature that can be associated to the engineering meanings. The intersection of the set of characteristics that each semanteme can identify must be avoided.

A representation is unambiguous if there is a unique association of an engineering meaning to a generic feature. This means that for each representation of elements in $M$ there is a corresponding a single entity in $R$. In a feature-based representation this correspondence is the association of engineering requirements to geometric representations. This important property of representation schemes is strongly dependent on the capability of the semantemes that are used to discriminate the meaning of a generic feature. Obviously it is not possible to distinguish two generic features which have the same semantemes, but which are different from an engineering point of view.

When a new concept requires definition, and the available semantemes cannot recognise it, new semantemes need to be defined and implemented. In some cases the knowledge is very specific and the semantic recogniser can be constructed only in the structure of the element that support it. This is the case of the dimensional semanteme, which is specifically defined on the graph structure of the GF. This semanteme is detailed in Section 7.1.
The descriptive capability of the representation scheme affects also the completeness of the context definition. A given context is well defined only when the entire relevant feature pertaining to it can be represented as a different entity.

In this work following the sets of semantemes have been defined:

(A) Type of generic feature;
(B) Adjacency graph isomorphism;
(C) Verify if the GF graph representation is a cycle;
(D) Multi-graph isomorphism;
(E) Topology of the surface of the GF;
(F) Metric property of the GF;
(G) Visibility map evaluation;
(H) Accessibility map evaluation;
(I) Feature symmetry.

7.1. Type of generic feature (semanteme A)

The type of a generic feature is a key element to recognise a feature in a specific context. The rules to extract generic features are based on important properties such as concavity or axial-symmetry. For example in the domain of machining operations, a prerequisite to distinguish a turned part is its axial-symmetry, independently from other characteristics of the geometry.

In this work only criteria based on geometric and topological analysis of the model have been considered. Other criteria, based on geometric analysis and on other kinds of analysis (for example structural analysis) could be implemented in order to identify other types of GF and therefore identify parts of the geometric model to associate knowledge. Obviously by identifying other kinds of generic features the descriptive capability of a feature-recognition system can be widely improved.

7.2. Graph isomorphism semantemes and cycles graph (semantemes B, C and D)

The graph associated to a generic feature extracted from the geometric model is isolated and submitted to a graph isomorphism procedure. The graph associated to a GF is a labelled multi-graph with labels both on the nodes and on the arcs. An algorithm verifies the isomorphism of the graph extracted from a GF with the predefined set of reference graphs.

Some filters can affect the graph isomorphism procedure. These filters can exclude some labels or layers of the multi-graph structure from the graph isomorphism analysis. The identification of these filters is integrated in the semantic definition.

A taxonomy list of labelled multi-graphs is provided inside the feature-recognition system. This list of template multi-graphs does not provide a direct and explicit link to semantics as in the case of types of GF that are recognised based on some rules that discriminate engineering meaning. Multi-graph isomorphism performs a simultaneous analysis of many elements in a GF. The type of the multi-graph is simple evidence in the GF and it will be a very strong discriminative semanteme only when, in the semantic definition, it will be associated to a specific meaning.

The multi-graph isomorphism, proposed in this work, in some cases may be too specific and therefore not discriminative of a structural element of meaning (semantemes). For this reason the simple adjacency graph isomorphism and the cycle graph identification are assumed as disjoint semantemes.

The simple graph isomorphism semanteme manages much information related to the geometry of GFs and some information related to its topology. This is a very discriminative semanteme and it has been used in a different way in other works described in literature where it represents the unique identifying element used to recognise features.

The adjacency graph isomorphism-based semantemes are not identifiers of the topology of a generic feature, since in many cases where two distinctive features have the same graph structure, as shown in Figs. 9 and 10.

Although the graph isomorphism process can be used to identify other graphs that are cycles, the relevance of this characteristic of the GF is evaluated specifically as a distinctive semanteme. It is important to note that both the graph isomorphism and the cycle graph identification can recognise only topological attributes of the adjacency graph and do not take into account all the elements that are analysed in the multi-graph isomorphism analysis.

7.3. Topological semantemes (semanteme E)

This semanteme recognises the topological property of a surface associated to a GF. A surface is a topological space with some topological properties. Every bordered surface (open surface) can be reduced to three normal forms [23]. A bordered surface can be homeomorphic to one of the following forms:

- **Normal form I**: a sphere with holes;
- **Normal form II**: a connected sum of torii with holes;
- **Normal form III**: projective planes with holes.

The normal form III is related to non-oriented surfaces and is not taken into account in this work.

![Fig. 9. Generic features having the same graph structure.](image-url)
In order to analyse the feature topology, two invariant parameters are used [24]. The first parameter is the genus $g^0$ [24]: it gives the maximum number of non-intersecting lines that do not divide the surface into two regions. It is important to note that this topological parameter cannot be used to distinguish the normal form I from the normal form II, so another topological parameter needs to be defined.

The second parameter is the genus $g^p$ [23] that is equal to zero for bordered surfaces belonging to the normal form I and it is greater than zero for bordered surfaces belonging to the normal form II. The value of $g^p$ can be considered as the number of connected torii of a surface.

The genus $g$ and $g^p$ are evaluated under the assumption that the B-rep geometric model is Eulerian. The adopted approach takes advantage of the procedures described in Ref. [24].

The values of $g^0$ and $g^p$ provide elements to discriminate two or more GFs that may appear equal in a graph isomorphism evaluation. For instance we can consider the situation depicted in Fig. 9 where the features have the same graph but the topology of the surface, which describes the features, is different. In the first case the surface is homeomorphic to a disk with a hole; in the second case the feature is homeomorphic to a simple disk. Another example is depicted in Fig. 10, related to different types of axial cams, where, in the two depicted cases, the features are described by the same graph but present different surface topology.

7.4. Dimensional semantemes (semanteme F)

Dimensional characteristics of the feature can be discriminative elements in the semantic recognition process. In mechanical components the ratios between characteristic dimensions of a component are usually fixed by standards. For instance the ratio of the main dimensions of a keyhole are typically fixed so that the two shape feature in Fig. 11, that are the same both from a topological and a geometric point of view, do not represent the same functional feature. What enables us to distinguish the role of one feature from the other is the satisfaction of dimensional rules. For its intrinsic characteristics, dimensional semantemes are specific of a given GF and require the knowledge of the structure of the dimensional parameters to be defined. For instance the typical dimensional parameters of the features in Fig. 11 are the dimension $A$ and $B$. A useful semanteme is also the ratio, between these two dimensional parameters, that is characteristic for keyholes.

In this work dimensional parameters are associated to the arcs $A_1$, which identify the parallelism relation between faces, associated to the GF and to some characteristic parameter of a face (for example the diameter of a cylindrical face). The dimensional semantemes are defined according to both absolute and to relative criteria. The absolute criterion ensures that a dimensional parameter falls in a previously defined range. The referring range for this parameter could be deduced from the typical dimensional
values used in practical application and quoted in normative and handbooks. The relative criterion is based on the evaluation of the ratio between the two dimensional parameters of the feature. This non-dimensional parameter must be compared with a given value.

The dimensional semanteme constructor gives the possibility of selecting the dimensional parameters \(d_i; v_i, v_j \in GF\) of the GF and of associating them with a dimensional semanteme.

In the semantic construction, the class of referring values of the dimensional semantemes must be defined.

7.5. Visibility and accessibility maps evaluation (semanteme G and H)

The analysis of visibility or accessibility maps provides important information either on the manufacturability of a GF or on the possibility for a part to be assembled with other components.

A feature is visible (accessible) if the visibility map (accessibility map) is a non-empty set \((V_M \neq \emptyset)\). This semanteme can be conveniently defined by a logical parameter.

A visibility map analysis gives a local evaluation of the feature accessibility. A feature having a non-empty visibility map could not be completely visible if observed far away, since it could be hidden by other parts of the same component.

An accessibility map provides an absolute criterion of the feature accessibility estimation. A non-empty accessibility map \((A_M \neq \emptyset)\) ensures that the feature is visible and therefore accessible in any case.

A non-empty accessibility map is a necessary condition for a feature to be machined. The visibility map represents the set of the possible approaching direction to the feature.

In moulding, the demouldability of a feature can be assured by a favourable analysis of the accessibility map. The accessibility map represents the set of the possible drafting directions of the feature.

In assembly the possibility to joint a shape feature of a component with another depends on the mutual accessibility of the features. Visibility or accessibility maps of an assembly feature identify the set of the possible approaching direction of the feature.

7.6. Feature symmetry (semanteme I)

Feature symmetry is very discriminative evidence in many situations. An example is depicted in Fig. 12 where two Concave Extrude GFs can be recognised as different features provided that symmetry is checked.

The main difference between the two generic features is the presence of a plane of symmetry in the generic feature of the left component. Such information can be used to discriminate the machining process, since, for instance, it can be recognised that a T-slot milling cutter can machine the symmetric feature while the same machining cannot be applied to the other component.

An algorithm to recognise feature symmetry has been developed. The procedure verifies if the set of faces that makes up the feature has one or more planes of symmetry. The symmetry recognition procedure is based on the analysis of the inertia properties of the faces of the feature. It is well known that if a symmetry plane exists, it passes through the centre of mass of the figure and is perpendicular to a principal axis of it. The symmetry recognition procedure is accomplished in the two following steps:

- First the inertia tensor and the centre of mass of the feature are computed. The patches of the feature are sampled and a cloud of points is evaluated. The principal axes and the centre of mass are then computed from the sampled points. The planes that pass through the centre of mass and are perpendicular to the principal axes are potential planes of symmetry.

- Then the computed potential planes of symmetry are checked in order to verify if they are true planes of symmetry or not. In order to do this, given a potential symmetry plane, a reflection transform is applied with respect to it. The percentage of points that still are on the faces of the feature after the reflection indicates the probability of that plane to be a plane of symmetry.

Many tests performed on CAD models showed how the percentage is very close to 100% for symmetric features.

The parts depicted in Fig. 12 provide an example on how information on symmetry can be used to discriminate some properties of generic features in the domain of the process.

Fig. 12. A symmetric T-slot (machinable) and an asymmetric T-slot (non-machinable).

8. The implemented software

The proposed method has been implemented in a prototype software coded in C++. A commercial software library has been used in order to construct a direct interface with commercial CAD systems.

The method takes as input a solid model representation as exposed by the Geometry and Topology Query Interfaces V 1.0. These interfaces expose solid model
data through a B-rep graph representation [25]. A solid is described as a collection of the following objects: Shell, Face, Loop, Edge, Edge Use and Vertex. Different interfaces deal with the topology and the geometry of entities. The geometry interfaces are used to query all of the geometric data, while the topology interfaces specify the connections between the various elements of a body.

The geometric input is provided by a CAD package that supports the G&T interfaces. The feature-recognition module developed in this work can directly linked to a CAD package that supports the G&T interfaces. The prototype is based on a client/server architecture where the CAD package plays the role of the server, and the feature-recognition module represents the client. This approach enables data query in a ‘live’ fashion, and the client application is always kept current with design changes in the CAD model.

The overall control algorithm is sketched in Fig. 1 and the group of operations related to the semantic recognition process detailed in Fig. 8. At present, in order to perform the first test of the software, the engineering knowledge is defined in a rigid way so that the insertion of a new template feature requires the program to be rebuilt. The software automatically performs the features recognition and provides the association of the knowledge identified to the feature. The output of the software is a list of the predefined types of features that are recognised in the geometric model.

9. Applications

Some tests have been performed to recognise knowledge, both in the domain of the process and in the domain of the function, in a class of mechanical components: shafts.

In the domain of the process the system can recognise machining features of the following types:

- Turning features (turning, facing and profiling);
- Milling features (side milling and end milling);
- Drilling features (different kinds of holes).

The same semantemes used for manufacturing features recognition have been used to create a taxonomy of functional features (Fig. 13). The method has been verified on functional feature recognition in many practical cases.

The selected semantemes are quoted in Fig. 12 where a capital letter indicates the type. Semanteme B is the graph isomorphism conducted by using some filters so that the labels of the geometry of the face and the label of the type of the adjacency to be taken into account are selected. These semantemes do not perform simply face adjacency graph isomorphism but they also consider the geometric properties of the feature faces that, in general, could be of any type. These semantemes do not perform simply face adjacency graph isomorphism but they also take into account the geometrical properties of the feature’s faces that, in general, could be of any type.

The simple face adjacency graph isomorphism is not sufficient to discriminate feature 1 from features 6 and 8 in Fig. 13 that are characterised by the same graph topology and have the same labels in the adjacencies. Three numbers separated by dots identify the type of the graph. The first number indicates the number of the faces of the GF and the second the number of arcs [1]. The third number indicates the progressive type of graph so that it identifies the graph not only for its topology but also for the specific combination of the labels of the nodes and of the arcs. This graph isomorphism is a very discriminative semanteme. Only two features in Fig. 12 (features 6 and 8) have the same graph.

In order to distinguish features 6 and 8 (in Fig. 13) the topological semanteme E proved to be useful. Two numbers separated by a dot describe the topological semanteme: the first number indicates the holes and the second the handles of the surfaces associated to the GF.

The semantemes A, B and E are not sufficient to identify the features in Fig. 12. A correct association of the knowledge to the GF requires other aspects to be analysed. The first aspect is the dimensional property of the feature (semanteme D, F) and the second aspect is the accessibility of the GF (semanteme G, H). The visibility and accessibility semantemes are evaluated by checking if the related maps are empty sets \( V_M = \emptyset \) or not \( V_M \neq \emptyset \).

The symmetry semanteme is important in order to verify the machinability of the some kinds of GFs.

The multi-graph isomorphism semanteme acts to define and identify the dimensional property of the generic features \( (D, F) \). The multi-graph description of the feature also supports the parametric definition of the GF. All the cases in Fig. 13, except case 7, refer to features that require dimensional properties to be tested in order to associate them with a specific functional role.

The labelled graph isomorphism semantemes (semanteme B), used to identify features in the examples in Fig. 13, seems to be very selective, although in practical application there could be different features characterised by the same graph representation. For example all the features (slots) in Fig. 14 have the same labelled graph so that they cannot be discriminated using only this semanteme. In practice these features are different both from a manufacturing and a functional standpoint. In this case the multi-graph isomorphism semanteme can provide an important hint. In the examples of Fig. 14 evidences related to the geometrical relation between the two extreme faces of the feature graph (features a and b have a multi-graph different from that of the feature c) can be recognised. A further hint useful for distinguishing feature a from feature b is the semanteme A (CEF and CF), but this semanteme cannot discriminate feature b from feature c, which are both CF generic features.

In some cases the method gives ambiguous evaluations of the features. A given shape feature could be
used to implement different functions so that it could be difficult to identify a unique association. In some cases the proposed method gives the possibility to robustly associate the knowledge about function with geometry. This is a preliminary requirement in order to develop an integrated system for design that can associate the function to the manufacturing process.

10. Conclusions

The Faces Based Boundary Representation described here is not only an evolution of the Faces Adjacency Graph used in other representations discussed in literature and applied in feature recognition [4,5,24,26]. An important difference of this representation is in the multi-graph structure that can
manage more properties such as mutual relations between faces that are not necessarily adjacent: parallelism, coaxiality and perpendicularity. Furthermore differences are in the number and types of the labels and attributes of the nodes and of the arcs of the graph. All these data are arranged in order to obtain a ‘unique’ representation of the model that we refer to as the intermediate model. Information stored in the intermediate model cover a wide range of data needed for engineering oriented semantic recognition. This information represents the first outcome of the recognition processes.

In this work a new approach for semantic definition and feature recognition is proposed. The main characteristics of the method are flexibility and effective capabilities in knowledge extraction. The semantic construction is based on the concept of semanteme: the minimal element of meaning that the system can manage and recognise in a geometric model. The descriptive capability of the proposed feature-based representation scheme depends mainly on the types and characteristics of the available semantemes.

The capability of this method has been tested through the analysis of manufacturing requirements and functional properties of mechanical components. Different kinds of machining contexts are taken into account in the system (turning, milling and drilling machining processes).

Good results have been obtained in the analysis of the mechanical design components in the domain of the process. Difficulties have been encountered in the automatic evaluation of the semantic related to the domain of the function. In this domain semantics cannot be effectively constructed using only those evidences that can be inferred from the pure geometric representation of the component; there are a lot of shape feature that can be used to satisfy different functional purposes. For this reason in order to obtain a valid feature-based representation in the functional domain a human intervention may be required.

The semanteme recognition process used in this work is based on the analysis of a pure geometric model. Knowledge is unconsciously, directly or indirectly, provided, by the designer, to the procedural representation of the geometric model. Integrating the geometric modelling system with the feature-recognition system may be an intersecting improvement of the proposed semantic recognition method. In this way other hints can be deduced directly from the modelling operations used to build the geometric model or from the history of the geometric modelling construction.

In order to obtain non-ambiguous feature recognition it is also important to be able to distinguish some optional element, like fillets, chamfers and reliefs, from the elements that more properly characterise the shape features. In the proposed method such elements are described as arc attributes of the graph representation and do not pertain to a node, which represent a face of the geometric model [14].

A problem in feature recognition is feature interaction. This problem has been largely discussed in Refs. [1,4,24]. In this work the features interaction problem has not been specifically treated, however, the proposed method takes into account information about relations among faces, such as coincidence ($a_{ij} \in \mathbb{A}_z$), that makes possible the identification of intersecting features. The proposed method could be used to improve other approaches discussed in literature and extend their applications to geometric models described by complex geometry.

References


