Title:
User-Defined Machining Feature Recognition Based on Semantic Reasoning for B-rep Models

Authors:
Yingzhong Zhang, zhangyz@dlut.edu.cn, Dalian University of Technology
Fei Wang, 1755257660@qq.com, Dalian University of Technology
Tianbao Chen, a13271213579@163.com, Dalian University of Technology

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Introduction:
Machining features are a set of abstract shapes with machining semantics on parts, such as holes, boss, and slots, are associated with some manufacturing activities, and play a crucial role in the integration of CAD and CAM as they carry high-level information that can effectively link design and manufacturing [1]. Since 1980s, machining feature recognition has been a hot research direction in industry and academia. At present, many feature recognition approaches [2] have been proposed, which can mainly classified into two kinds: logic symbol based approaches and data driven approaches. However, currently there are still many issues and challenges in machining feature recognition. Excepting the issues on recognition efficiency, robustness and recognition of interacting features, most recognition systems are closed, namely, they can only recognize the features defined within in the system. In practice, due to different product structures, machining equipment and tools, it is difficult to define all machining features in a feature recognition system. It is necessary to make the recognition system open so as to recognize user-defined machining features.

From the current recognition approaches, it is difficult to recognize user-defined machining features with an opening way. On the one hand, the essence of features is related to a specific application domain, including machining shape, equipment and tools. On the other hand, the definition of features and recognition results needs to be commonly understood, shared, and passed on to various subsequent applications with heterogeneous systems. An open, scalable, and shared feature representation and recognition mechanism is required.

To effectively solve the above issues, it is necessary to apply the semantic technologies to the recognition of machining features because machining features are associated with considerable machining knowledge and shape semantics. Unfortunately, from the public literature, few works have considered the semantic recognition of machining features. Zhang et al. [3] developed a semantic approach to the automatic recognition of machining features. In their approach an ontology-based concept model and recognition approach using semantically representing the machining faces and machining features were proposed. There are still some shortage and limitations on recognition of user-defined machining.

Based on above analysis, this paper aims at the openness of feature recognition, focuses on the recognition for user-defined machining features, and presents an opening machining feature recognition framework for solid B-rep models using semantic representation and reasoning technology. The main contribution is that a novel recognition approach and framework is presented, in which all features to be recognized can be customized by users using defining and editing semantic rules. The recognition system implements feature recognition according to the user-defined feature semantic representation.

Main Idea:

Overview for the presented recognition approach

In order to realize the recognition for user-defined machining features, we propose a semantic recognition framework as shown in Fig. 1. The recognition framework consists of the following two layers:

- Machining feature representation layer

This layer includes three parts: (1) machining feature ontology, (2) Recognition knowledge rules, and (3) a machining feature library. The machining feature ontology defines all the machining feature concepts and other concepts involved in the recognition, which are defined as ontology classes by protégé tool [4]. Recognition knowledge rules are defined with SWRL (Semantic Web Rule Language) [5], which provide recognition knowledge and help recognition reasoning. The machining feature library consists of a set of defined machining features, including user-defined features. The machining feature concept is defined in feature ontology and the shape characteristic of each machining feature is defined using SWRL rules. As a result, Machining feature representation layer can be independent of the recognition layer, and users can define machining features by themselves according to requirements through protégé tool software.

- Machining feature recognition layer

First the B-rep model of the part to be recognized is input into the recognition layer, and all machining faces are identified and extracted from the B-rep model. A MFKG (Machining Face Knowledge Graph, MFKG) is constructed, in which a machining face is defined as a node of the graph, and the adjourn relation or the geometric spatial relation between two faces is defined as an edge of the graph. The adjourn relation includes convex adjacency, concave adjacency, and transition adjacency. Then each machining feature defined in the feature library is implemented semantic reasoning over the constructed MFKGs, and the recognition result is listed.

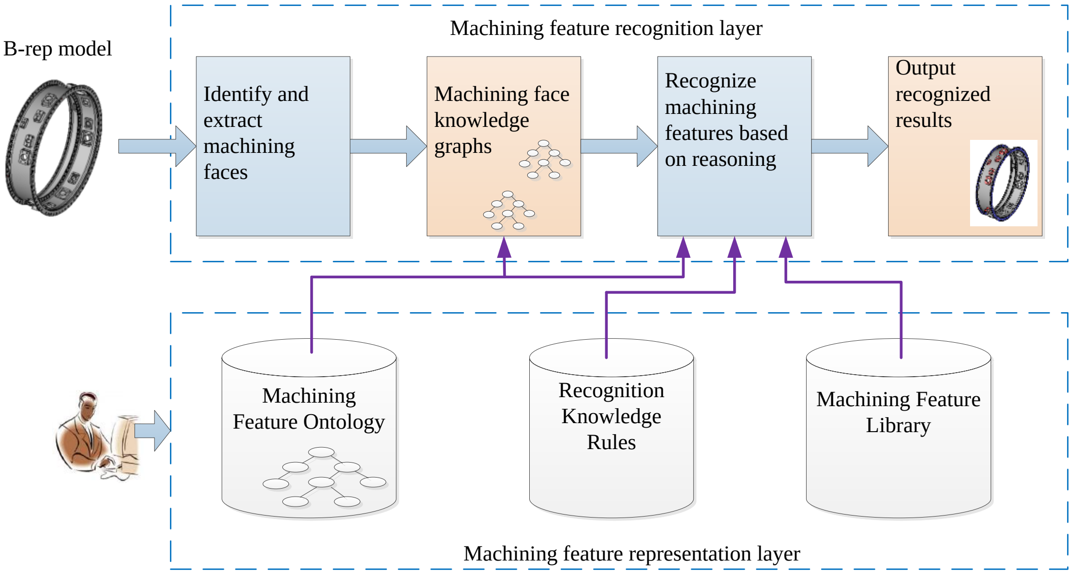


Fig. 1: The framework of the presented approach.

Semantic representation for machining features

As mentioned above, machining features are a set of abstract shapes with machining semantics on parts. The abstract shapes with machining semantics can be referred as a set of surfaces that are formed by removing the material volume in a single operation with a single tool on a single machine [3]. Hence, we give the following concepts:

- Machining faces

The geometric surface that is formed by removing the material volume is defined as the machining face.

A machining face corresponds to one or more geometric surfaces. Due to different cutting tools and different machining motion modes, machining faces with different characteristics will be formed. For example, the bottom face and side faces are generated by milling cutters, and the inner hole faces are formed by drilling.

Obviously, the bottom face and side face are concave surfaces in geometry. A geometric face that has a concave edge is identified as a concave face. Currently, there are many algorithms to determine the concavity and convexity of edges. However, due to the complexity of the B-rep models, an edge corresponds to many types of geometric curves, such as ellipse curves, spline curves, and T curves. If there is no edge direction information, the vector calculation method is difficult. This paper employs a method to determine whether an edge is convex or concave by calculating distances. Its basic principle is to move two points that locate on the two adjacent surfaces of an edge along the normal direction of the two surfaces, and the distance trend between two points of the convex edge and concave edge is completely different. We use this to judge whether an edge is convex or concave.

- Machining features

According to above analysis, a machining feature is determined by a set of machining faces and their topological and spatial relations. The combination of the machining faces is the condition to identify a machining feature. Hence, we can employ SWRL to represent machining features. An SWRL reasoning rule can be expressed in the form: Antecedent→Consequent, and the antecedent part and the consequent part can also be represented as the conjunctive formula of atoms: $a_1 \wedge a_2 \wedge, \ldots, \wedge a_n$ and $b_1 \wedge b_2 \wedge, \ldots, \wedge b_m$, respectively. Atom a_i and b_j (i=1,2…,n; j=1,2,…,m) can be in either of the forms $C(?x)$ or $P(?x, ?y)$, in which if x is an instance of class C, then $C(?x)$ holds; if x is related to y by property P, then $P(?x, ?y)$ holds. For example, a boss feature for milling has a top face and a set of closed side faces, which can be represented as the following rule:

$$\text{MachiningFeature}(?x) \wedge \text{hasFaces}(?x, ?b) \wedge \text{BottomFace}(?b) \wedge \text{hasFace}(?x, ?s) \wedge \text{InnerClosedFace}(?s) \\ \wedge \text{concaveAdjoin}(?s, ?b) \longrightarrow \text{Boss}(x)$$

where *BottomFace* is a bottom face concept, *InnerClosedFace* is a closed side face chain concept which denotes a set of closed side faces adjoined to each other surround the solid of the part. *BottomFace* and *InnerClosedFace* are elementary geometric concepts, namely, they cannot be used to instance matching but used to geometric test computation.

- User-defined machining features

According to the semantic representation on machining features mention above, it is easy for users to define the machining feature according to their specific needs. Users only define ontology (terms) and SWRL knowledge rules for newly created machining features.

Machining face knowledge graphs

According to the semantic representation of machining features presented above, the task to recognition machining features first needs to identify and extract machining faces from B-rep models and then formally structure them into a knowledge graph in triple form.

The machining face knowledge can be represented as an directed graph: $G = <V, E>$, where V denotes a set of face nodes and E denotes a set of relation edges that link two nodes. A face node corresponds to a machining face. A relation edge corresponds to a type of adjacency relations or a type of spatial relations between two geometric faces. In this paper, we categorize the adjacency relation into four types: *concaveAdjoin*, *convexAdjoin*, *concaveTagent*, and *convexTagent*. The spatial relations are categorized into: *parallelTo*, *coplanarTo*, *coaxialTo*, etc. Fig. 2 provides an illustration on MFKGs.

User-defined machining features recognition using semantic reasoning

The so-called feature recognition is identification for the geometric surface based on the cognition of the shape and engineering meaning of the machining features. In this paper, we represent this cognition and engineering meaning as machining feature knowledge characterized by a set of concepts and explicit semantic rules. Hence, the feature recognition is converted into an issue on semantic reasoning for MFKGs using machining feature knowledge.

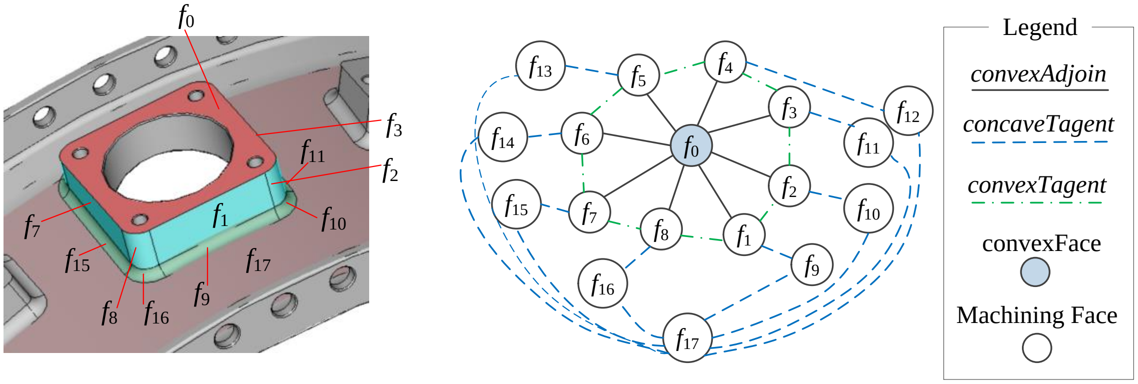


Fig. 2: Illustration for the part MFKG: (a) A part of geometric faces, (b) A part of the part MFKG.

The semantic reasoning mechanism is to determine the semantic satisfiability of machining feature rules for the constructed MFKGs. Suppose we have the knowledge base: $T \cup G \cup R$. T denotes the ontology, G denotes the facts of geometric faces in the part, and R denotes the knowledge rules (including recognition knowledge rules and defined feature rules). The main reasoning procedure is as shown in the following Algorithm 1.

The test of semantic satisfiability for rules is to find a solution. In the solution, all the variables in the rule are bound to a value (an instance or a data type value of the MFKG). If all the bounded values in a solution can make all the atoms in the rule body hold true, this solution is a feasible solution and can be output as the reasoning result.

Algorithm 1: User-defined machining features recognition

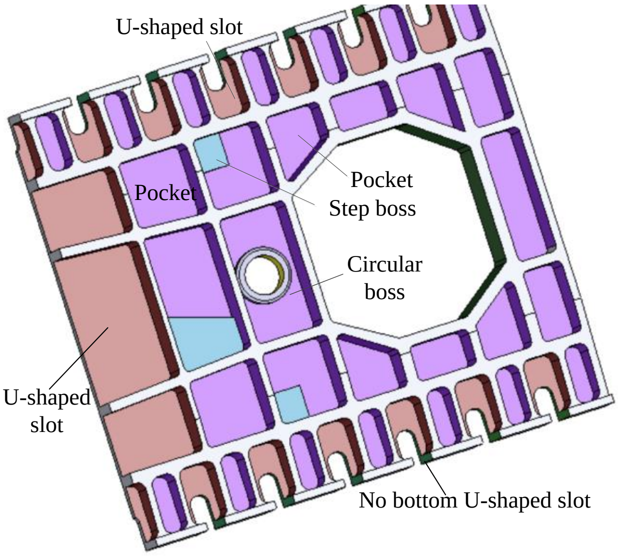
Input: A set of rules: R {R_1, R_2,..., R_n) and the MFAG of the part : G.
Output: A set of recognized machining features: F {f_1,f_2,..., f_m}

for i←1 **to** n **do**
  m←0;
  k←1;
  while k<q **do**
    Test antecedent of rule $R_i(a_1 \wedge a_2 \wedge, \ldots, \wedge a_q)$ by G;
    if a_k = 0 **then**
      break;
    end if
    k←k+1;
  end do
  if k=q **then**
    m←m+1;
    Add Consequent of rule R_i to F
  end if
end do

Implementation

The approach presented in this paper is implemented by programming using visual C++ in NX 12.0. The machining feature ontology and semantic rules are defined under the protégé tool and saved in OWL / XML format. The implementation procedure is as follows:

Firstly, the recognition program loads and parses the file of semantic definition for machining features, constructs the corresponding object class. Then the machining faces of a part B-rep model is identified and extracted to construct MFKGs of the part model. Perform feature recognition based on semantic reasoning for the constructed MFKGs and obtain the recognition results. Fig. 3 shows the result of feature recognition of a mechanical part and four rules of user-defined features.



MFeature(?*x*)∧hasFace(?*x*,?*b*)∧BottomFace(?*b*)
∧hasFace(?*x*,?*s*)∧TwoSideFace(?*s*)∧
concaveAdjoin(?*b*, ?*s*)→U-shapedSlot(?*x*)

MFeature(?*x*)∧hasFace(?*x*, ?*s*)∧
OpenNoBottomFaceChain(?*s*)→
NoBottomU-shapedSlot(?*x*)

MFeature(?*x*)∧hasFaces(?*x*, ?*b*)∧BottomFace(?*b*)∧hasFace(?*x*, ?*s*)∧OpenSideFaceChain(?*s*) ∧ concaveAdjoin (?*b*, ?*s*) ∧hasFaces(?*x*, ?*t*) ∧ convexAdjoin (?*t*, ?*s*)→StepBoss(?*x*)

MFeature(?*x*)∧hasFaces(?*x*, ?*b*)∧BottomFace(?*b*)∧hasFace(?*x*, ?*s*)∧SideFace(?*s*) ∧concaveAdjoin (?*b*, ?*s*) ∧ hasSurface(?*s*, ?*g*) ∧ CylindricSurface(?*g*)→CircularBoss(?*x*)

Fig. 3: A machining feature recognition case: (a) The recognition results, (b) Partial user-defined rules.

Conclusion:

Due to the diversity of product structure and machining methods, machining feature recognition is required to be open. Users can define machining features according to their own needs. This paper proposes a method based on semantic representation and reasoning to realize the recognition of custom machining features from the B-rep model. Independently on the recognition system, users can define the machining features to be recognized using ontology and knowledge rules. The recognition system performs semantic reasoning for the B-rep model according to the defined rules and obtains the recognition results. The presented recognition approach has been realized using C++ programming in NX system and demonstrates feasibility and good openness.

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