KBRE: A Knowledge Based Reverse Engineering for Mechanical Components

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ABSTRACT

This paper focuses on Reverse Engineering (RE) in mechanical design. RE is an activity which consists in creating a full CAD model from a 3D point cloud. The aim of RE is to enable an activity of redesign in order to improve, repair or update a given mechanical part. Nowadays, CAD models obtained using modern software applications are generally "frozen" because they are sets of triangles of free form surfaces. In such models, there are not functional parameters but only geometric parameters. This paper proposes the KBRE (Knowledge Based Reverse Engineering) methodology which allows managing and fitting manufacturing and/or functional features. Specific geometric algorithms are described. They allow extracting design intents in a point cloud in order to fit these features.

Keywords: reverse engineering, segmentation, feature, knowledge based engineering.
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1 INTRODUCTION

In mechanical engineering, Reverse Engineering (RE) is an activity which consists in creating a full CAD model of a given mechanical part from a 3D point cloud. The 3D point cloud is often provided by 3D scanners or as results of FEM approaches. The reasons people have to make RE operations are, most of the time: (1) the original design is not supported by enough documentation and no plan is available or correct; (2) the original provider of the considered mechanical part has disappeared and does not manufacture the component anymore. In this paper, the following context is considered: little information about the studied part and a 3D point cloud are available because the studied part has been scanned.

The CAD model provided by RE has to enable people to redesign the part in order to improve it, to repair its geometry or to update it. According to technological surveys, the CAD models provided by moderns RE CAD software applications (CATIA V5, PRO-Engineer, RapidForm, GeoMagic etc.) are more geometric models than real CAD models. They are mainly sets of complex free forms surfaces or primitive features. These are fitted into the 3D point cloud using geometric parameters. In a real CAD model, parameters are not only geometric but functional or because of some manufacturing processes (draft angle for example). Redesign activity can be very difficult if the parameterisation of the CAD model is "geometric" and not "functional". RE has to be performed by considering the original design intents.

In this paper, a KBRE (Knowledge Based Reverse Engineering) methodology is proposed to allow obtaining a CAD model which integrates design intents. As a hypothesis, design intents represent the knowledge of the studied part. The way features are modelled and parameterised [10]. These features materialise this knowledge. The RE methodology proposed in this paper has to allow creating a real CAD model as a set of features that are parameterised according to the design intents.

The main concept of KBRE is to define a feature according several points of views (functional point of view and manufacturing point of view), assuming the design intents. Then, this feature is fitted into the point cloud and if needed, is constrained with other features of the part (parallelism, symmetry etc.).

This paper is organized as follow. In section 2, a state of the art of geometrical approaches and RE methodologies is proposed. Then, the KBRE (knowledge based Reverse Engineering) methodology is illustrated in a section 3 through the example of a turbine blade.

2 THE STATE OF THE ART, THE REVERSE ENGINEERING WORKS

A full, accurate and automatic segmentation of a 3D point cloud is still a central problem in RE.
As said in the introduction, finding the design intents of a given part is the key to build a real CAD model. There are not many related works that suggest using original design intents.

2.1 The Segmentation

The segmentation of a meshed 3D point cloud is a research field which consists in the division of the 3D point cloud of a given object into a set of n point clouds representing the n features that compose this object. In RE, three segmentation techniques are commonly used. In a first place, region based technique uses spatial coherence of the data to organize the mesh into meaningful groups. Least squares approximation by plans is the simplest method. Besl and Jain's works [2] allow the classification of the mesh in three under regions: plans, convex and concave faces are recognized. The best techniques are based on the approximation by bi-polynomial surfaces [5] and allow the recognition about simple forms such as plan, cylinder, spherical and conical surfaces. To summarize, an adjacent region is absorbed if it satisfies the estimate by the polynomial surface of a given minimal order. If this adjacent region is not absorbed, the smoothing by a polynomial of superior degree is tried. The process stops when all regions are absorbed or when estimations with all polynomial degrees have failed. Current computers improve execution speed of polynomial degrees but this technique is sensitive to the noise of the cloud. Normal calculations or curvatures are often noised and edges are not clearly defined. In a second place, the technique used is the edge-based method that consists in intending to isolate discontinuities in the 3D point cloud. Break areas such as steps are recognized by discontinuities of normal and/or curvature orientation calculation. Points detection through parallel slicing sections is the simplest method. Sections are approximated by B-Splines [9]. Another technique consists in performing local characteristics [6]. In a third place, Hybird technique, which combines region and edge techniques, is used. For example, Yokoya and Alrashan [20] have performed the calculation of the discontinuities in the cloud. Region techniques are used in order to finalize the segmentation.

All these techniques lead to surfaces based CAD model which limit possibilities of redesign. However, solutions exist such as the placement by the user of control points of curves [15]. These solutions are useful for complex surfaces such as airfoils but very sensitive to the noise of the point cloud.

2.2 The RE Methodologies

Three main methodologies can be described.

2.2.1 A CAD Environment

The VPERI [18] (Virtual Parts Engineering Research Initiative) project was created by the US Army Research Office in order to provide the vision, strategy, and engineering tools to help to solve legacy systems problem. The knowledge of the geometric shape and size is necessary but not sufficient to reproduce the part. Re-engineering and redesign need functional specifications information. A design interface is used in order to allow the addition of knowledge in the form of algebraic equations. The added engineering knowledge is the functional specification of the components, the physical laws that govern the behaviour and the spatial arrangement etc. This interface provides mechanisms that enable designers to ascertain that the functional requirements are fulfilled and helps designers to explore alternatives by assisting to make some changes. Knowledge arises from the analysis and is simply expressed and transcribed in variables that are interpreted by the VPERI tool. In the same way, the MERGE (Multiple Engineering Resources aGent Environment) system developed by Musuvathy et al [8] can be cited.

This methodology is a structured approach which allows building a perfect CAD model only if the knowledge can be described by algebraic equations.

2.2.2 Feature Extraction

The REFAB (Reverse Engineering Feature Based) [16] system uses machining features. Machining knowledge extraction is achieved implicitly by the user. The machining features are selected by the user among a suggested list. Next, the selected feature is fitted in the point cloud from a specified area given by the user.

Sunil et al [14] suggest extraction of manufacturing sheet features in a point cloud. Urbanic et al [17], about the RE methodology for rotary components from point cloud data, explain that features have accurate mathematical definitions or specifications for their geometry, and tolerances depending on functional requirements. They conclude that geometric primitives issued by one or more manufacturing process could be listed with their parameters.

For example, in rotary components, spindles and screws are standard geometries which could be classified in features.

This methodology considers specific features for a given point of view.

2.2.3 Constraint Fitting

Other references such as Fisher [4], Werghi [19] and Mills [7] explore "knowledge based" technique to overcome "frozen in" errors on 3D mesh by constraints fitting surfaces. The user's knowledge about the part is using an optimization algorithm. The shape and position parameters are found even with considerable noisy 3D point clouds.

2.3 Discussion

None of the references above propose a structured methodology which allows people to manage any type of knowledge. Nevertheless, the above references highlight two types of knowledge required to enable redesign operation [3]: The manufacturing knowledge and the functional requirements. A new RE approach, integrating these two types of knowledge, should allow explaining and justifying the presence of the features in the point cloud. These features could be modelled and parameterised using this knowledge. In the following section, the KBRE methodology is presented. It proposed such a new RE approach.

3 KBRE: KNOWLEDGE BASED REVERSE ENGINEERING METHODOLOGY

In this section KBRE is presented. It is illustrated using the example of a turbine blade. Step by step, the Reverse Engineering of this blade using KBRE is described.

3.1 The Aim and the Global Process

KBRE starts from a full 3D point cloud of the studied part and consists in applying two main activities (Fig.1):

- The knowledge analysis: Supported by a KBE system. It is a set of analysis tools in order to save, reuse and define features according to the manufacturing process and the functional specification.
- The knowledge extraction: This step allows fitting features from a point cloud in order to affect dimensions in the feature.

The KBRE approach aims to allow:

- To choose theoretical features among families of components and processes (machining, casting etc…)
- To define new theoretical features for specific cases of geometrical aspects.

(“Theoretical” means that the parameters of the feature have not value)

- To fit each feature in the point cloud in order to affect dimension.
- To constraint the different features one with each others in order to obtain a real CAD model of the studied part.

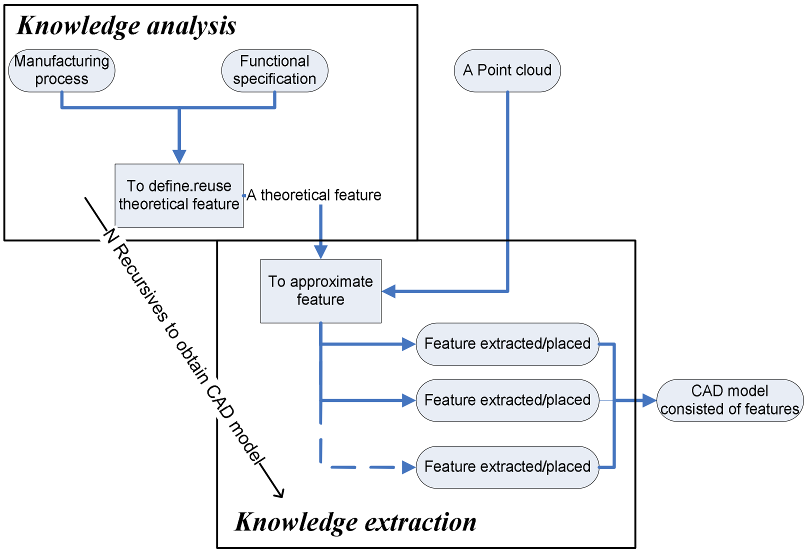

Fig. 1: The global process of KBRE.

The KBRE is a recursive process. Indeed, for each theoretical feature defined or chosen, the fitting operations (knowledge extraction) have to be performed in order to affect dimension.

3.2 The Knowledge Analysis Step

3.2.1 A KBE System for a RE Problematic

The knowledge analysis step aims to reverse the original product design cycle of the studied part. The original design process of the part has to be found. According to technological surveys [3], it appears that recursive approaches used for classic direct design can be also used for RE. In a design context, there are lot methodologies to support and save design knowledge during design process. This paper suggests to apply and to adapt the same methodologies for the RE context.

The KBE (Knowledge Based Engineering) approach is adapted [12] [13]. In the scientific literature, it seems that there are not KBE systems for RE. KBRE suggests a KBE approach for the knowledge analysis step which enables the traceability of the studied part. The IT (Information Technology) and how to incorporate the knowledge in KBRE methodology are not introduced in this paper but explained in [3]. The traceability is performed through the following steps:

- To identify a family of component: A family is a set of mechanical parts which defines a type of mechanical components such as: the piston, the housings, the crankshaft etc.
- To define scenario: The RE user can make different hypotheses about the function of the part or about the process used to manufacture it. These hypotheses lead to different definitions for each feature. By defining a scenario, the RE user make a choice. It is possible to create several CAD model according to several scenario.

- To define rules: For each feature, one or more rules (algebraic or not) are suggested regarding to the hypothesis made for this feature. These rules represent the "implicit knowledge". This kind of knowledge is a "textbox" which informs the user about the geometrical consequence in the part (feature). For each rule, KBRE suggests one or more theoretical feature.

Two points of views are proposed in the KBRE database: (1) the manufacturing view and (2) the functional specification view.

3.2.1.1 The Manufacturing View

The user can make hypotheses about the process planning of a part. DFM (Design For Manufacturing) concept is closed to the problematic. Based on DFM activities [11], KBRE suggests one or more theoretical features according to a classification of manufacturing processes [1]. In the example of the Reverse Engineering of the turbine blade, the user chooses to not consider the manufacturing view.

3.2.1.2 The Functional Specification View

A mechanical part, most of the time, has to answer to a need. As hypothesis, a part ensures one or more functions in a given environment (other parts, flow of energy etc.). "Function" and "Environment" terms lead to the concept of functional analysis. Two kinds of environments could be considered:

- "Material elements" such as the surrounding parts.
- "Immaterial elements" such as flow of energy etc.

Each interaction between the part and its environment represents a technical function. Based on the Reverse Engineering experience of the author, seven (7) types of technical functions are considered: (1) the mechanical link (ML); (2) the mechanical structure property (M/S); (3) the electromechanical (EM); (4) the gas/combustion (GC) for thermal properties; (5) the encumbrance (E) for the accessibility; (6) the hydraulic (H) aspects for the hydraulic properties and (7) the specific specification (SpS) for the own view of the user.

Considering the turbine blade, in Fig.2, the APTE™ diagram, integrated in KBRE, allows the definition of the different functional theoretical features.

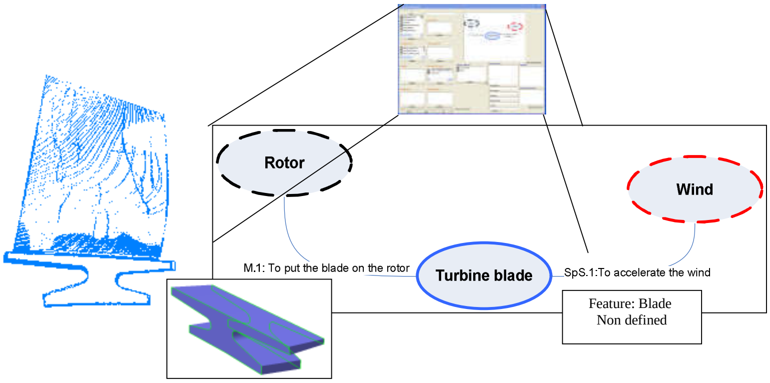

Fig. 2: Knowledge analysis step of a turbine blade example.

In Fig. 2, the turbine blade is in interaction with the two following environments:

- **The material environment:** *"Rotor"*
    - **Interaction**: *mechanical (M.1)*
        - **Rule**: *"To put the blade on the rotor"*
            - **Feature**: *"Foot_fasterner"*
                - The theoretical feature exists in the KBRE database and can be chosen.
- **The immaterial environment**: *"wind"*
    - **Interaction**: *specific specification (SpS.1)*
        - **Rule**: *"To accelerate the wind".*
            - **Feature**: "*Blade"*

- o The theoretical feature does not exist in the KBRE database and it has to be defined by the user as a new feature in the KBRE database.

The blade feature has to define and parameterised. To define it, the following design rule is used: *"Describe the blade using three (3) sections. Each section is parameterised. The radius leading edges and the radius trailing edges have to be defined".*
Such a rule is used to parameterise the blade by the experts of aircraft engine companies.
The next section explains how this feature can be defined in KBRE.

3.2.2 The Theoretical Definition

The "skin and skeleton" concept is used for the definition of a new theoretical feature [11]:

- Skin: It represents the functional surfaces.
- Skeleton: It represents the geometrical and topological structure.

A skeleton consists of six main elements:

- An initial section (IS).
- A final section (FS).
- Zero (0) or more intermediate sections (IntS).
- A trajectory (T): It represents the evolving sections in the space.
- Zero (0) or more behaviour laws (BL): It represents the evolving of the skin.
- A function (F): A protrusion, a sweep or a revolution in additional or removal material.

Geometric elements	***elements***	***Geometric support***
Point	IS, IntS, IF, T, BL	Plan,3D
Line	IS, IntS, IF, T, BL	Plan,3D
Circular	IS, IntS, IF, T, BL	Plan
Quadrilateral	IS, IntS, IF, T, BL	Plan
Ellipse	IS, IntS, IF, T, BL	Plan
Spline 2D	IS, IntS, IF, T, BL	Plan
Spline 3D	T, BL	3D

Constraints	***Parameters***	***Amount***
Congruence	R, Radius	mm
Concentricity	L, Length	mm
Tangency	A, Angle	°
Parallelism		
Perpendicular		
Constant angle		°
Constant length		mm

Tab. 1: The geometric elements (a), the constraints and parameters (b) of the skin and skeleton concept.

The Tab. 1 (a) shows the different geometric elements used in the "skin and skeleton" model. The knowledge is represented by the constraints, parameters and relationship between the different parameters. The Tab. 1 (b) shows the types of constraints and parameters.
Two natures of parameters are concerned:

- "Driving" parameter: It is a parameter which leads the geometry of a part or a feature.
- "Driven by": It is a parameter which is driven by the driving parameters using a law (analytical or not).

The law is defined by the user.

For example, considering bicycle wheel, the diameter of the wheel is a "driving" parameter. The number of spokes is a "driven" parameter. The number of spokes generally depends of the diameter of the wheel.

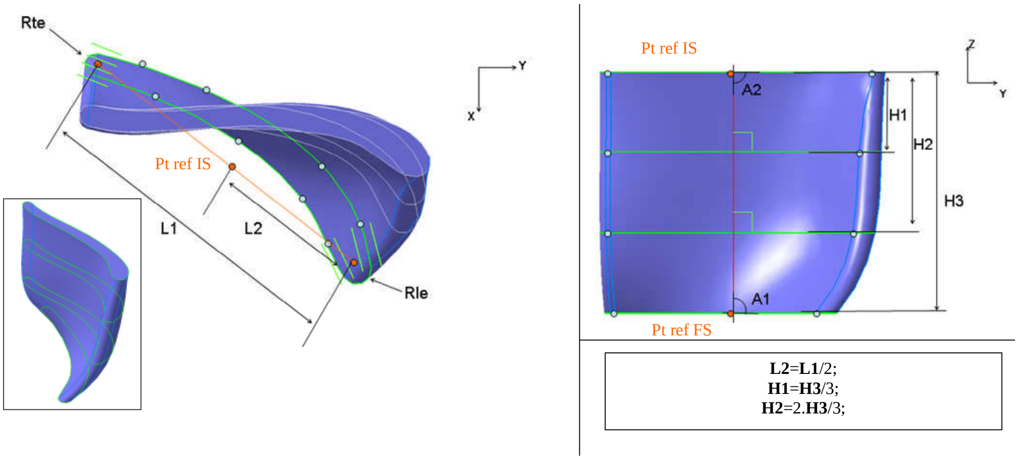

Fig. 3: The “blade” feature definition with its parameterisation.

In Fig. 3, the blade is defined as a theoretical feature:

- The sections IS is drawn. The user specifies two arcs of circle and two splines with four points. The tangency constraint between the splines and the arcs of circle is applied.
- According to the design rule describe in the end of the section 3.2.1.2 of this paper, three (3) sections are proportionally placed. A reference axis is created between the points **PtrefIS** and **PtrefFS**. It allows positioning the intermediate sections according to the perpendicular constraints. The driving parameter **H3** allows affecting the “driven by” parameters **H2** and **H1**.
- The Behaviour laws are defined by a 3D splines using extremities of each arc of circle of each section.
- The function is a multi sweep operation in additional material.

The “driving” parameters are:

- The **Rle** (radius leading edge) and the **Rte** (radius trailing edge) of each section.
- The Height **H3** of the blade
- The angle **A1** and **A2** for the placement of the IS and FS.
- The length **L1** for the width of each section.

The “driven by” parameters are:

- The length **L2** for the placement of the points **Ptref IS** and **Ptref FS**.
- The height **H1** and **H2** for the placement of the intermediate sections.

The analytic laws are:

$$
\begin{aligned}
L2 &= L1/2 \\
H1 &= H3/3 \\
H2 &= 2.H3/3
\end{aligned}
\qquad (3.1)
$$

The feature is correctly parameterised and constrained according a design rule. The parameters could be extracted from the point cloud.

3.3 The Knowledge Extraction

This step consists in extracting knowledge from a point cloud. In other terms, this step consists extracting the value of each parameter of a theoretical feature and its localisation. There are two mains operations:

- The segmentation as describe in the section 2.1.
- The building of the CAD model: The user put each theoretical feature in the segmented point cloud.

3.3.1 The Segmentation Step

The aim of the segmentation is to divide the point cloud in regions that correspond to theoretical features. Two kinds of segmentation are considered:

- Automatic segmentation: A simple region segmentation based on spherical region sample can be used. Five type of regions (plan, cylinder, cone, sphere, tore) can be detected.
- Manual segmentation: A manual segmentation can be used and combined with automatic segmentation for more complex areas. The user can add regions to create the point cloud corresponding to a complex theoretical feature.

The table
Tab. 2 explains the approximation tools used for the segmentation.

Automatic (region segmentation)	***Manual***	***Approximation tools***
Plan		Least square
Cylinder		Least square
Cone		Least square
Sphere		Least square
Tore		Least square
Free (no detected)		
Region user	Region	Sphere area

Tab. 2: The segmentation techniques and approximation tools.

In the Fig. 4(a) the pink region is specified by the user. After segmentation, the theoretical feature can be approximate.

3.3.2 The Theoretical Feature Approximation

To fit theoretical feature, the user has to select three areas in a point cloud:

- One ore more regions which correspond to the feature localization.
- Click on three or more points for the plan of the IS.
- Click on three or more points for the plan of the FS.

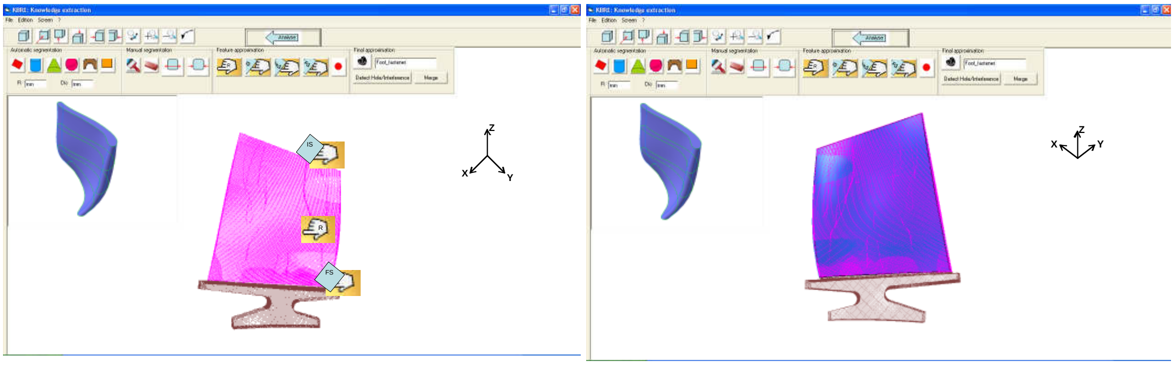

Fig. 4: The segmentation and region specification (a) and the feature approximation (b).

In Fig. 4 (a) and Fig.4(b), IS and IF sections are specified as well as the region in the segmented point cloud. Fig. 5(a) presents the approximation algorithm. This algorithm follows hierarchical operations:

- First, the 2D constraints are applied and then the 3D constraints.
- The parameters are valued considering the least square approximation, in their order of appearance during the theoretical feature definition.

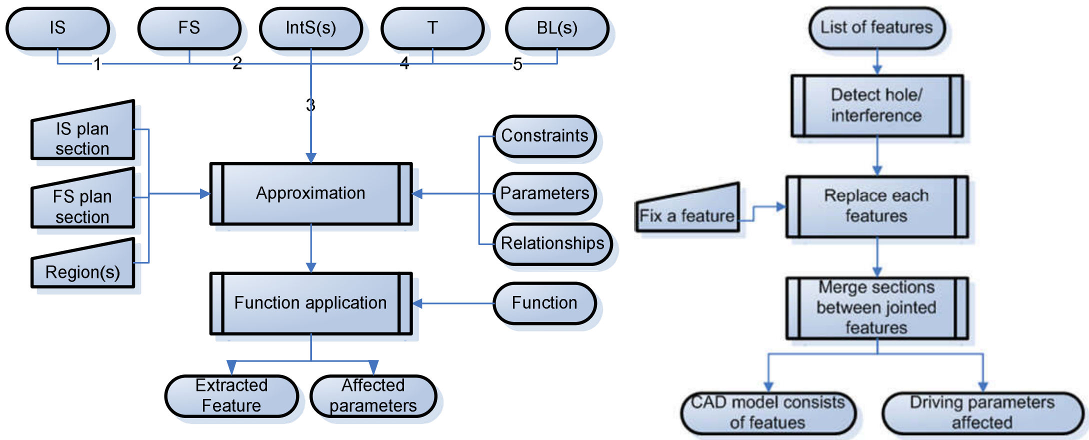

Fig. 5: the feature approximation algorithm (a) and the final approximation algorithm (b).

Each theoritical feature are fitted one by one in the point cloud.

3.3.3 The Final Approximation

The noise of the point cloud and the errors of approximation provide localisation errors between features. The aim of the final approximation is to remove “holes” and “volume interferences” between the different features.

The final approximation is done “feature by feature” according to a chosen reference feature. The user selects this feature. Considering the list of the features within the CAD model, the final approximation consists in the following actions:

- To detect hole and volume interference between the features.
- To replace each feature according to the reference feature and according to the constraints between the different features.

The global algorithm is shown in Fig. 5 (b). In the case of turbine blade, a hole between the foot and the blade is detected. In

Fig. 6, the hole is filled and the CAD model is now ended.

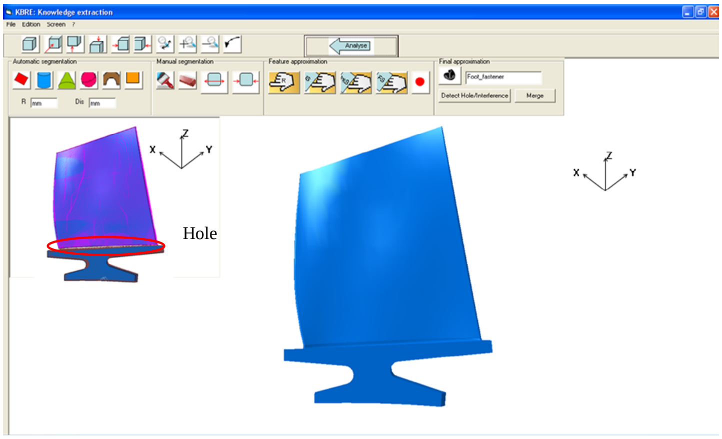

Fig. 6: The final approximation.

4 CONCLUSION

The main idea of KBRE is the interaction between a KBE approach and the point cloud. Knowledge analysis allows defining all theoretical features according to functional and/or manufacturing rules. Then, knowledge extraction allows affecting values to the parameters of the different theoretical features to provide the CAD model. In the example of the turbine blade, Fig. 7, the **Rle** (radius leading edge) and **Rte** (radius trailing edge) in are equal to 0.232 mm and 0.236 mm, according to the point cloud.

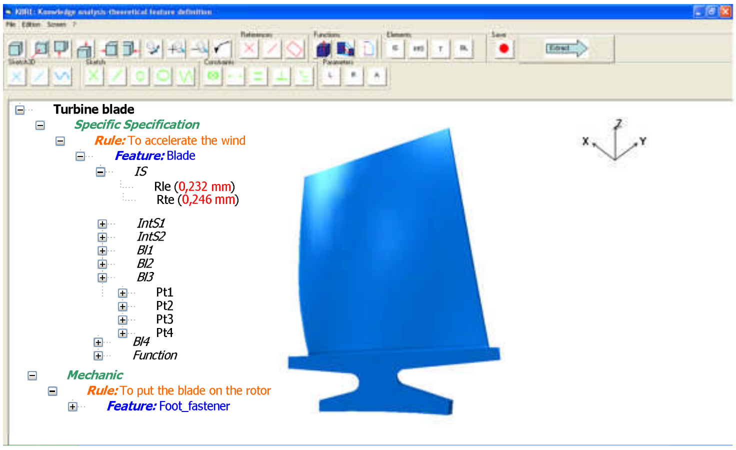

Fig. 7: The final CAD model.

As the CAD model is fully parameterised, the turbine blade can be redesigned by changing, for example, the height of the blade or the value of the radiuses. All the parameters of the different features can be modified. Because of the KBRE approach, these parameters are not “geometric” parameters but “functional” and “manufacturing” parameters.

5 DISCUSSION

The main concepts of KBRE have been developed with partners according to real industrial needs: Reverse Engineering of die tool and automotive mechanical components (Stabiliser bar of car, journal cross, etc.) [3]. A database of theoretical features has been created and it is available for customisation. Considering the implementation, the KBRE methodology uses the API of CATIA V5R16 to create theoretical features. These feature are created using the “skin and skeleton” model (Fig. 8).

Components	Type
IS & FS	Circular
	Ellipse
	Quadrilateral
	Triangular
T	Linear
BL (1 or n)	Linear

An example of features:

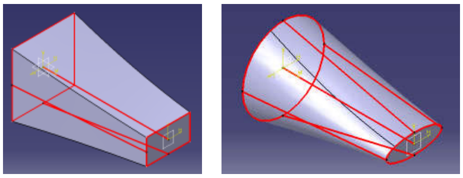

Fig. 8: An example of performed features.

The resulted CAD model is a CAD model with “functional” and “manufacturing” parameters. It aims to be close to the CAD model that the original designer of the part would have obtained.

KBRE can be applied if the shapes of the studied part can be fully described during the knowledge analysis. As further works, KBRE will have to consider the other shapes of the part such as the aesthetic surfaces. These ones are not yet considered by the KBRE methodology.

KBRE is integrated in a project funded by the French national research agency (ANR) called PHENIX (Product History based rEverse engineering: towards an Integrated eXpert approach) which aims to develop a software tool that enables merging geometrical recognition and knowledge approach. In this tool, a PLM (Product Life cycle Management) will be integrated in order to manage multi-expertises and multi-knowledge.

REFERENCES

[1] Ashby, M. F.; Brechet, Y. J. M.; Cebon, D.; Salvo, L.: Selection strategies for materials and processes, Materials and design, 2004, 25, 51-67.

[2] Besl, J.; Jain, R.: Segmentation through variable order surface fitting, IEEE Trans. Pattern Anal. Mach. Intell, 1988, 167-191.

[3] Durupt, A.; Remy, R.; Ducellier, G.; Eynard, B.: From a 3D point cloud to an engineering CAD model: A knowledge product based approach for reverse engineering, Virtual and Physical Prototyping, 3:51-59, 2008.

[4] Fisher, R. B.: Applying knowledge to reverse engineering problems, Computer Aided Design, 36, 2004, 501-510.

[5] Hoffman, R. L.; Jain, A. K.: Segmentation an classification of ranges images, IEEE Trans. Pattern Anal. Mach. Intell, 1987, 606-620.

[6] Meyer, A.; Marin, P.: Segmentation of 3D triangulated data points using edges constructed with a c1 discontinuous surface fitting, Computer Aided Design, 36(1), 2004, 1327-1336.

[7] Mills, B. I.; Langbein, F. C .; Marshall, A. D.; Martin, R. R .: Estimate of frequencies of geometric regularities for use in reverse engineering of simple mechanical components, Technical report, Cardiff University, 2001.

[8] Musuvathy, S.; Johnson, D.; St.Germain, D. H.; Cohen, E.; Chimao, X.; Riesenfeld, R. F.; Henderson, T. C.: Integrating multiple engineering resources in a virtual environment for reverse engineering legacy mechanical parts. ASME International Design Engineering Technical Conference & Computers and Information in Engineering Conference, 2005.

[9] Sapidis, R.; Besl, P.: Direct construction of polynomial surfaces from dense range images through region growing, ACM transactions on graphics, 1995, 171-200.

[10] Shah, J. J.: Assessment of features technology, Computer-Aided Design, 23(5), 1991, 331-341.

[11] Skander, A.; Roucoules, L.; Klein Meyer, J-.S.: Design and manufacturing interface modelling for manufacturing processes selection and knowledge synthesis in design, International Journal of Machine Tools & Manufacture, 2008, 443-454.

[12] Skarka, W.; Application of MOKA methodology in generative model creation using CATIA, Engineering Applications of Artifcial Intelligence, 20, 2007, 677-690.

[13] Stokes, M.: Managing engineering knowledge MOKA: Methodology for knowledge based engineering applications, Professional Engineering Publishing, London, 2001.

[14] Sunil, V. B.; Pande, S. S.: Automatic recognition of features from freeform surface CAD Models, Computer-Aided Design, 40(4), 2008, 502-517.

[15] Tai, C. C.; Huang, M. C.: The processing of data points basing on design intent in reverse engineering, International Journal of Machine Tools & manufacture, 2000, 1913-1927.

[16] Thompson, W. B.; James de St Germain, J. H .; Stark, S. R; Henderson, T.: Feature- Based reverse engineering of mechanical parts, IEEE Transactions on Robotics and Automation, 15(1), 1999.

[17] Urbanic, R. J.; Elmaraghy, H. A.; Elmaraghy, W. H.: A reverse engineering methodology for rotary components from point cloud data, Int J Adv Manuf Technol, 2008, 1146-1167.

[18] VPERI, Virtuals Parts Engineering Research Initiative, The final report, (http://www.cs.utah.edu/gdc/Viper/Collaborations/VPERI-Final-Report.doc), 2003.

[19] Werghi, N.; Fisher R. B.; Robertson, C.; Ashbrook, A.: Object reconstruction by incorporating geometric constraints in reverse engineering, Computer-Aided Design, 31(6), 1999, 363-399.

[20] Yokoya, Y.; Levine, M. D.: Range image segmentation based on differential geometry: A hybrid approach, IEEE Trans. Pattern Anal. Mach. Intell, 11(6), 1989, 643-649.